JIMMA UNIVERSITY
JIMMA INSTITUTE OF TECHNOLOGY
FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

REDUCING LOSSES IN A DISTRIBUTION TRANSFORMER: A CASE STUDY ON SELECTED DISTRIBUTION TRANSFORMER OF JIMMA TOWN, ETHIOPIA

BY

WONDEMAGEGN AHMED

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE
IN
ELECTRICAL POWER ENGINEERING

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ADVISOR: Dr. KINDE ANLEY

CO-ADVISOR: MOHAMMED AHMED

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DECLARATION

I, the undersigned, declare that the MSc. thesis entitled “**Reducing losses in a distribution transformer: a case study on selected distribution transformer of Jimma Town, Ethiopia**” is my work. No portion of the work presented in this thesis paper has been previously and concurrently submitted in support of another award or qualification either at this institution or elsewhere. Where material has been used from other sources has been properly acknowledged/ referred.

Wondemagegn Ahmed_ ________________________

Name Signature

Jimma, Ethiopia _________________________

Place Date

APPROVAL

We, the undersigned, certify that the thesis entitled “**Reducing losses in a distribution transformer: a case study on selected distribution transformer of Jimma Town, Ethiopia**” is the work of Wondemagegn Ahmed and that we hereby recommend it for acceptance by the school of graduate studies of Jimma university in partial fulfilment of the requirements for the degree of master of science in electrical power engineering. This thesis work has been submitted for examination with our approval as university advisor.

Dr. Kinde Anlay	___________________	___________________
Advisor’s Name	Signature	Date
Mohammed Ahmed (MSc.)	__________________	____________________
Co- Advisor’s Name	Signature	Date

As a member of the board of examiners, we certify that we have read, evaluated the thesis prepared by Wondemagegn Ahmed, and examined the candidate. We recommended that the thesis could be accepted as fulfilling the thesis requirements for the degree of Master of Science in Electrical Power Engineering.

_______________________________	__________________	________________
External Examiner	Signature	Date
_______________________________	__________________	________________
Internal Examiner	Signature	Date
_______________________________	__________________	________________
Chairperson	Signature	Date

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Apart from my effort, the success of this thesis work depends on the encouragement and guidelines of others.

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Wondemagegn Ahmed

ABSTRACT

Losses in distribution transformers are estimated as 30% of overall transmission and distribution losses. It is further estimated that the losses in all of the world's electrical distribution systems are about 1715TWh. One-third of these losses occur in the distribution transformers. In this thesis, a mathematical model is done and a new objective function is proposed for minimization of losses in a distribution transformer. This thesis presents a loss-reduced optimal design of three phases, 200kVA, 15/0.4kV, 50Hz, oil-immersed, core type distribution transformer. Two optimization techniques namely, Brute force search and Genetic algorithm are used in MATLAB® to obtain an optimum design of a distribution transformer that has minimum losses which met the requirements and constraints. The loss of a distribution transformer designed using both algorithms is compared, and then a comparison is made with transformer manufacturers' used design based on analytical method. The results from the optimization algorithm show that the design reduces the total losses on the existing distribution transformer selected for the study from 2,756.50W to 1,994.14W by 762.36W, thus representing a percentage reduction of 27.66%. If this saving is applied to the existing 49, 200kVA distribution transformers of the Jimma town route of the case study area, the saving will be 37,355.64W. If the optimally designed transformer is to be implemented on a larger scale across the electrical distribution networks of Ethiopia, the magnitude of savings would be huge. Moreover, the designed distribution transformer using the optimization algorithm has a slightly increased material cost, but it has the lowest total cost. Thus, the design is cost-effective.

Keywords: *Brute force search algorithm; Distribution transformer; Losses; Optimal design; Total cost*

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ABBREVIATIONS

BF	Building Factor
BFSA	Brute Force Search Algorithm
CL	Cost of Loss
CLL	Cost of Load Loss
CLKG	Core Loss Kilo Gram
CNLL	Cost of No Load Loss
CNo	Column Number
COMC	Core Material Cost
CRGO	Cold Rolled Grain Oriented
CUMC	Copper Material Cost
CW	Core Weight
CWH	Core Window Height
CWW	Core Window Width
CYL	Core Yoke Length
DT	Distribution Transformer
EEG	Ethio Engineering Group
EEU	Ethiopian Electric Utility
EMF	Electro Motive Force
GA	Genetic Algorithm
HT	High Tension
HTCWPP	High Tension Copper Weight Per Phase
HTMD	High Tension Mean Diameter
HTMH	High Tension Mechanical Height
HV	High Voltage
ID	Internal Diameter
IEC	International Electro-technical Commission
JDS	Jimma Distribution System
JIT	Jimma Institute of Technology
LHTC	Length of High Tension Copper
LL	Load Loss

LT	Low Tension
LTCWPP	Low Tension Copper Weight Per Phase
LV	Low Voltage
NL	No-Load Loss
OD	Outer Diameter
PEMI	Power Equipment Manufacturing Industry
SF	Stacking Factor
TCL	Total Core Loss
TL	Total Loss
TMC	Total Material Cost

CHAPTER ONE

1 INTRODUCTION

1.1 Background

Electrical power systems utilize several voltage levels using transformers to transfer voltages and connect parts of the power system with different voltage levels. One of these voltage transformations is being performed in the key component called a distribution transformer. A transformer that takes primary voltage and steps down it to a secondary distribution circuit is called a distribution transformer. A distribution transformer reduces the primary voltage to the utilization voltage [1].

Losses in distribution transformers are estimated as 30% of overall transmission and distribution losses. The efficiency of a typical distribution transformer is over 97%, which seems that it is satisfactory. But, this means that up to 3% of all electrical power generated is wasted in the transformer. These losses are far from negligible, and anything that can be done to reduce them has the potential to deliver huge savings [2].

The losses of the transformer consist of no-load losses and load losses. No-load losses are constant and appear throughout the lifetime of a transformer, while load losses vary and are only significant under higher load conditions [3], [4].

Earlier the design of a distribution transformer was usually based on traditional methods and techniques that have been found by the experience of design engineers. However this results in a very complex electrical design problem which meant that the process required long time and huge amount of resources were wasted by the experiments carried by the design engineers until a suitable design that meets the user’s required specifications such as rated power, primary and secondary voltage rating of winding, impedance value and other requirements are achieved. Thus, an algorithm based transformer design that help to reduce the man hour needed is introduced.

1.2 Problem Statement

The total electrical energy use per annual of the world is estimated at 21500TWh (1TWh is equal to 10^9kWh) and it is further estimated that the losses in all of the world's electrical distribution systems are about 1715TWh or about 7.97% of the total electrical energy consumed. About 30-35% of these losses occur in the distribution transformers.

As a distribution transformer data from EEU, JDS office (as depicted in appendix 1) indicates, here in Jimma town, on a single 200kVA distribution transformer there is a total loss of 2756.5W. Obtaining an optimum transformer design variables is essential for transformer loss reduction. Reducing a small number of losses from the above-stated value per transformer brings substantial energy savings for the utility.

1.3 Objectives of the Study

1.3.1 General Objective

The main objective of this thesis is to reduce losses in a distribution transformer using an optimization algorithm.

1.3.2 Specific Objectives

- To study and select the design variables of a distribution transformer that is designed using the analytical method.
- To design an optimal distribution transformer that has minimum losses using the Brute force search and Genetic algorithm.
- To compare the results of an optimally designed distribution transformer using Brute force search and Genetic algorithm with the analytically designed one.
- To compare the total cost of a distribution transformer obtained using the optimization algorithm with that of the currently used analytical design method.

1.4 Scope of the Study

The scope of the study is to analyze the losses in the existing distribution transformer and to design a loss-reduced 200kVA distribution transformer using the Brute force search and Genetic algorithm. In addition to this, the economic aspect of the transformer like the material and total cost of the transformer is part of this thesis work.

1.5 Significance of the Study

In thesis work, a distribution transformer that has a reduced total loss is designed. This helps the EEU to save a considerable amount of energy and makes the power distribution system more reliable. Moreover, the study helps transformer designers to find the optimal design variables within a few minutes.

1.6 Thesis Organization

The thesis work is organized into five chapters.

In chapter two, the basic theoretical background of a distribution transformer is presented and then different kinds of literature related to the title are reviewed.

In chapter three, the methods and materials used in the study are explained. The mathematical formulation of the distribution transformer with consideration of the practical aspects is briefly described. In this chapter, the objective function of the transformer design optimization is included along with all the design variables that will be considered for optimization, and the constraints that need to be satisfied to ensure proper operation of the transformer. The last part of this chapter deals with implementing the algorithms used for the optimization of the transformer design problem.

Detailed discussion and comparison of the results are included in chapter four.

In chapter five, the conclusion and recommendation of the work are given.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Related Works

The following published papers related to losses minimization of distribution transformers have been reviewed.

A. Alamoudi, I. and M. Al Bulushi (2015) [2] Have built a model of a three-phase distribution transformer to calculate transformer efficiency at different loading conditions on a MATLAB®. A typical 200kVA three-phase distribution transformer was modelled by MATLAB®. From the result, the load losses of this typical distribution transformer working at full load are 2800W and an efficiency of 98.1% was found for the distribution transformer working at full load.

M. Mohan and P. K. Singh (2014) [5] Have done electromagnetic model for the 3- phase distribution transformer 250 KVA 11/.416KV core type. This model-based upon using "ANSYS PROGRAM" to obtain lower losses. The results indicated that total losses for no-load and load conditions be 590 and 2990W respectively.

R. M. Sah and J. Srivastava (2013) [6] Have calculated losses due to linear load using analytical and simulation method and also have calculated losses due to harmonic load current by analytical method. A three-phase 200kVA distribution transformer is taken and losses have been calculated under linear load, using two methods. That is the computational method and simulation method. For the simulation method, a Simulink model of the transformer is designed, and finally, both methods has been compared.

Coelho, Leandro Dos S., et al. (2018) [7] Have developed a program for the design of a transformer using MATLAB®. The paper demonstrates a design of a three-phase, oil-immersed natural cooled distribution transformer of any value (power, primary voltage/secondary voltage), and 50Hz frequency in MATLAB software. The dimensions, as well as active cost, have been reduced in comparison to conventional methods using the same set of constraints.

M. Singh, M. Verma, A. Kanaujia, S. Rai, and A. Soman (2018) [8] Have reduced stray losses in distribution transformer using different materials of clamping. This paper demonstrates the estimation of stray losses and ways to reduce those using different clamping materials in distribution transformer 3 phase 100kVA.

In the above reviewed literatures attempts have been done to develop systematic transformer design procedures. But, some literatures discuss sub-problem of transformer design rather than discussing the entire transformer design problem. In addition to this some paper does not consider reducing the total loss of the transformer and the attempt made to reduce the total loss is not enough. Generally, it is possible to say that transformer losses can be reduced. The proposed design, under the specific study area, has reduced the losses in the existing distribution transformers and brings substantial energy savings for the EEU.

2.2 Transformer Basics

2.2.1 Definition of Distribution Transformer

A distribution transformer is a static device that is used to reduce the primary voltage to the utilization voltage by electromagnetic induction from one circuit to another at the same frequency

2.2.2 Working Principle of Transformer

A transformer is a very simple static (or stationary) electro-magnetic passive electrical device that works on the principle of Faraday’s law of induction by converting electrical energy from one value to another. Mutual induction between two or more winding is responsible for transformation action in an electrical transformer. Faraday's Laws of Electromagnetic Induction (second law) states that the magnitude of EMF induced in the coil is equal to the rate of change of flux that linkages with the coil. The flux linkage of the coil is the product of the number of turns in the coil and flux associated with the coil [1].

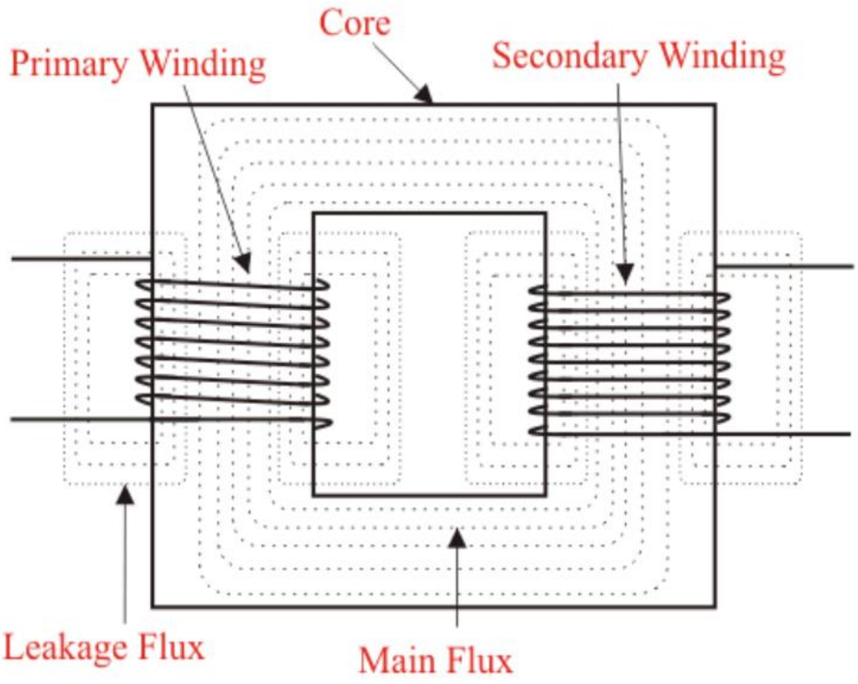


Figure 2.1 Working principle of transformer

2.2.3 Transformer Main Parts

A transformer has two main parts, which are: magnetic core and windings.

2.2.3.1 Transformer Core

Transformers are mainly classified depending on the construction of the core. There are two main types of classifications, core, and shell-type. In the core-type transformer, the windings are wrapped around the core forming a cylindrical-shaped coil while in the shell type the transformer core surrounds the windings [9].

The advantage of using the core type arrangement is that the leakage flux is reduced. The shell type arrangement is commonly used for very highly rated power transformers. The core type arrangement with a stacked core is used for the transformer design in this thesis. Ideally, a core with a circular cross-sectional area will have the maximum flux carrying capacity, however, this is not practically possible to construct as a vast number of different lamination widths will be needed. [9].

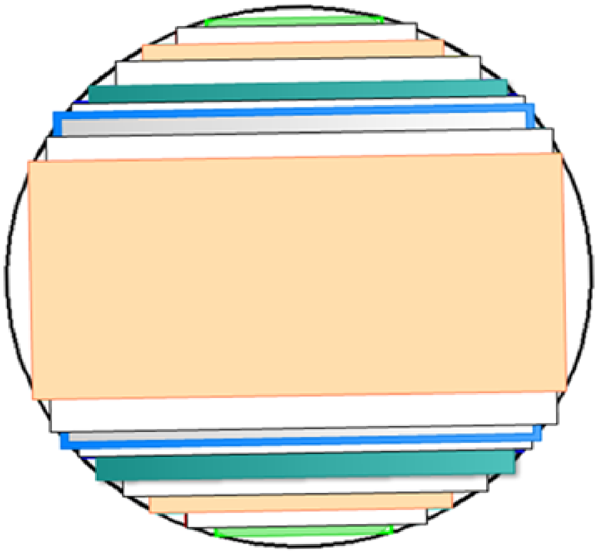


Figure 2.2 Core steps

Transformer cores are made of thin layers usually known as laminations of electrical sheets. The material used for the production of these sheet laminations is mostly CRGO steel with some percentage of silicone content and cut into a range of thicknesses that fall between 0.23 to 0.46 mm.

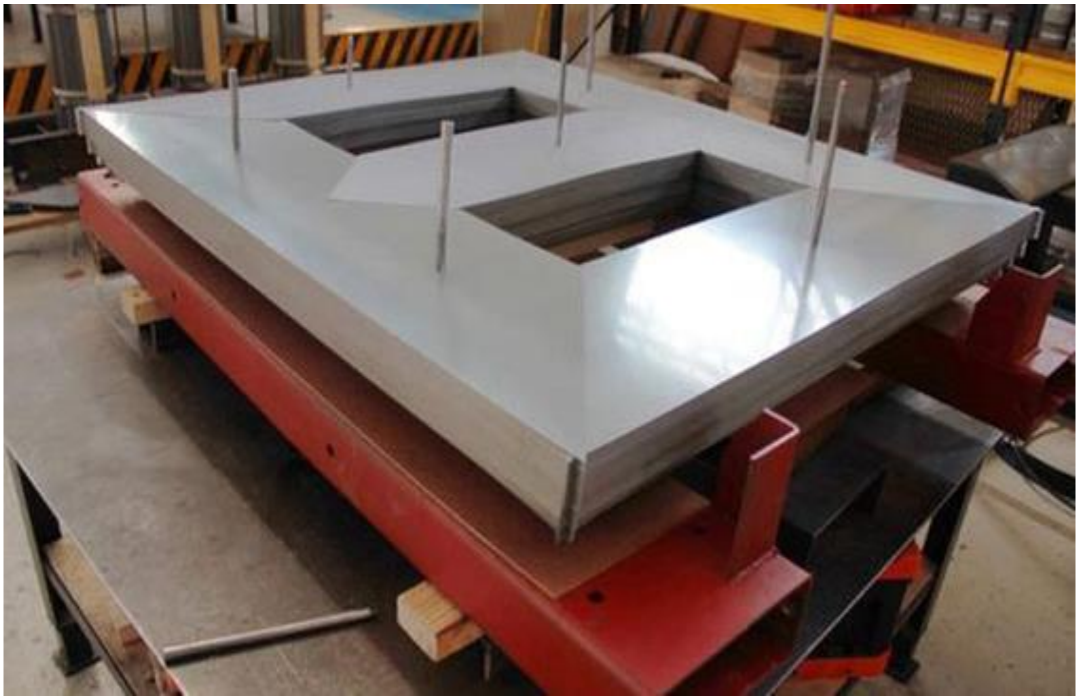


Figure 2.3 CRGO magnetic core

For the CRGO core type, the maximum value of flux density used in practice is in the region of 1.5 T, because at a flux density value close to or exceeding 1.9 T saturation in the core can be guaranteed.

A stacking factor is a correction number included to take into consideration the space lost between sheet laminations. The surface of every side of the lamination is provided with an oxide coating insulation layer. The stacking factor has a value less than one, but the closer it is to one the better is the material's stacking factor, and this can be done by using thicker laminations in the core. However, this will in turn significant effect on the eddy current losses in the core, and will increase by a ratio of square the thickness of the lamination. For this reason, thinner sheet laminations are preferable to reduce the eddy current losses although this will reduce the stacking factor.

The core building factor is a certain ratio used to increase the ideal core losses assumed by the designer. This percentage increase takes into account all the different factors that will add to the ideal losses in the core such as the gap between different laminations, especially at the corners of these laminations. Losses also increase because of the slitting and cutting of sheets which lead to burrs in the sheets.

2.2.3.2 Transformer Windings

For the transformer design layered winding construction is implemented for the high voltage side as this type of winding is mostly used on the primary side of distribution transformers.

The Primary winding of a transformer produces magnetic flux when it is connected to an electrical source. The secondary winding of a transformer is also called output winding. The flux, produced by primary winding, passes through the core and will link with the secondary winding.

Figure 2.4 Sectional view of distribution transformer HV and LV windings

2.2.4 Losses in Transformers

Like every machine, transformers also cannot work without energy losses. The transformer has no moving parts and so the mechanical losses are absent in it. Transformer losses are classified as load and no-load losses [1].

2.2.4.1 No-load Losses

No-load losses (also called iron loss or core loss) are constant and occur 24 hours a day, 365 days a year, regardless of the load, from the term no-load losses. They are present in the transformer core whenever the transformer is energized.

2.2.4.2 Load - Losses

Load-losses (also called copper losses or short-circuit losses) occur in the resistance of the winding of the transformer when it carries the load current. The total loss of copper in the transformer is obtained by adding both primary and secondary copper losses. Load losses vary according to the transformer loading [1].

2.2.5 The efficiency of a Transformer

The efficiency of a transformer is reflected in power (wattage) loss between the primary (input) and secondary (output) windings. An ideal transformer is 100% efficient because it delivers all the energy it receives. For a transformer operating with a constant voltage and frequency with a very high capacity, the efficiency may be as high as 98%. The efficiency, η of a transformer is given as:

$$\text{Efficiency}, \eta = \frac{\text{Output power}}{\text{Input power}} \times 100\% \tag{2.1}$$

$$= \frac{\text{Input power} - \text{Losses}}{\text{Input power}} \times 100\%$$

$$\eta = 1 - \frac{\text{Losses}}{\text{Input power}} \times 100\%$$

Here: Input, Output, and losses are all expressed in units of power.

CHAPTER THREE

3 METHODOLOGY OF TRANSFORMER DESIGN OPTIMIZATION

3.1 Study Area Description

3.1.1 Location

Jimma town is the largest town in South-Western Ethiopia. It is surrounded by the Jimma zone. It has a longitude and latitude of 36°50′E, 7°40′N respectively. Jimma has an area of 50.52 square kilometers. Specifically, the selected distribution transformer for the study is located at a longitude and latitude of 36° 50′ 44.65″ E, 7° 40′ 27.24″N respectively.

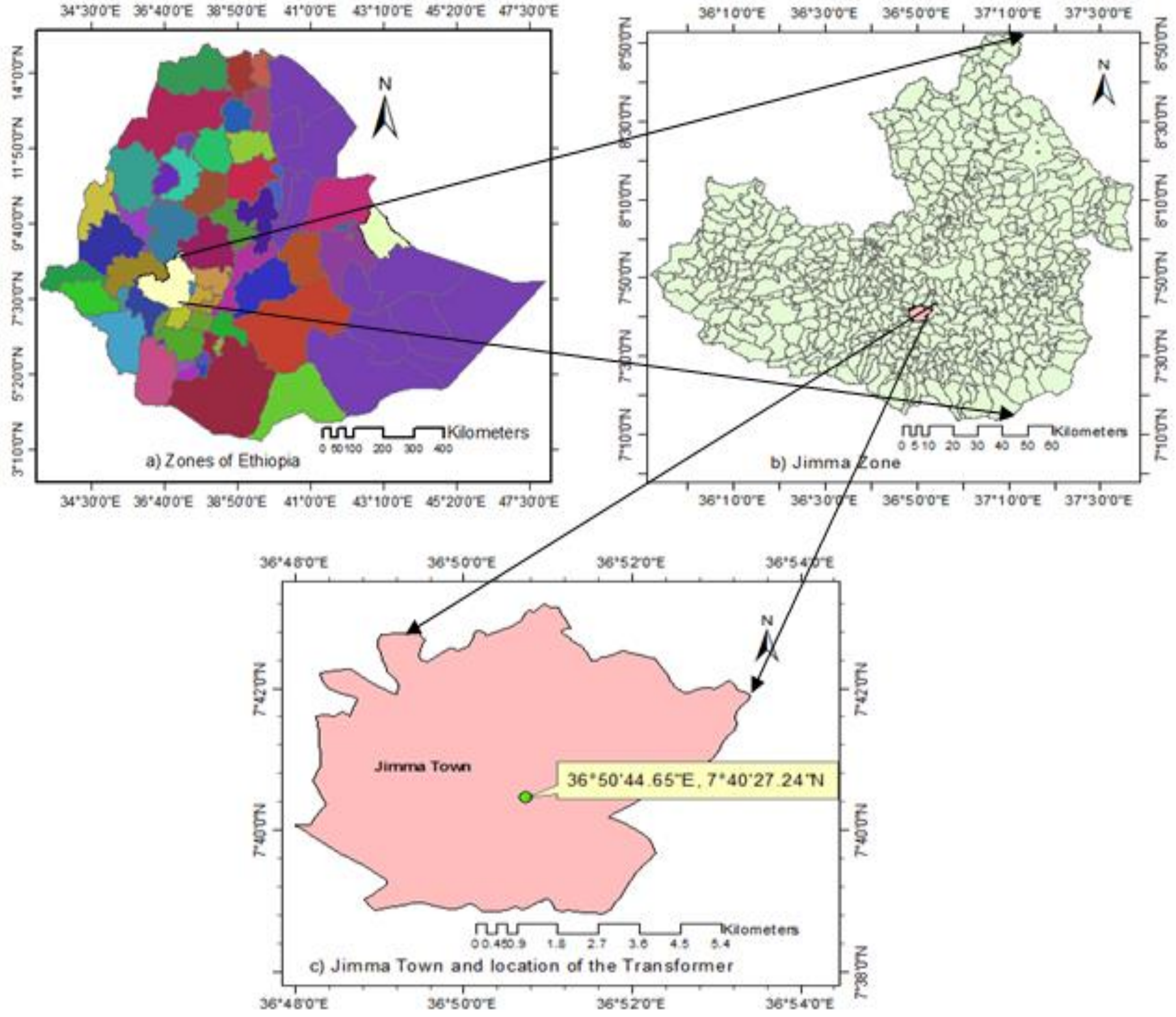


Figure 3.1 Map of the study area and location of the distribution transformer

Figure 3.2 Location of the Transformer from the Google Earth

3.1.2 Jimma Town Distribution System and Selected Distribution Transformer

There are two transformers in Jimma's old distribution substation. Transformer 1 and Transformer 2 have different voltage levels at their low voltage sides. The two transformers, installed at the Jimma distribution substation, are step-down transformers that reduce the incoming 132kV from Gilgel Gibe 1 substation to 15 and 33kV. The voltage at a 15kV level is distributed to five feeders of the Jimma town. Line routes are:

- Kochi line
- Jimma University (main campus) line
- City (Merkato) line
- KittoFurdisa (around JIT) line
- Agriculture campus line

In the town line route there are 200 distribution transformers; among these 49 are 200kVA distribution transformers (42 are 15/0.4kV and 7 are 33/0.4kV) (as depicted in appendix 2). Thus, the distribution transformer 200kVA, 15/0.4kV found at Jimma town, Ginjo Guduru Kebele around Mars number 4, installed more recently, is selected for the study. The reason for choosing the 200kVA rating is that it is greater in numbers among other ratings installed in the town.

3.2 Data Collection

The data presented by transformer manufacturer EEG-PEMI and the data from the study area presented by EEU, JDS office are used as secondary data for this thesis. The secondary data found from the above-mentioned two areas (as depicted in appendix 1) are shown in tables 3.1 and 3.2 below.

Table 3.1 DT secondary data from EEG-PEMI and EEU Jimma distribution office

No.	**Specifications**	**Values**
		EEG-PEMI and EEU, Jimma
1	Serial No.	20003088 and 20003140
2	Connection of HV/LV	Delta/Star
3	Number of phases	3
4	Frequency, Hz	50
5	Rated continuous power, kVA	200
6	Primary voltage (HV side) in V	15000
7	Secondary voltage (HV side) in V	400
8	Core material grade	27M4
9	Percentage impedance	4.23
10	LL in W	2417.60
11	NLL in W	338.90
12	Total Loss in W	2756.20
13	Efficiency in %	98.64

Table 3.2 Distribution transformer design variables from EEG-PEMI

No.	**Design Variables**	**Values**
1	Secondary number of turns	42
2	Core diameter in mm	145

3.3 Methodology

The procedural steps which are followed to realize and complete this thesis work are portrayed in figure 3.3.

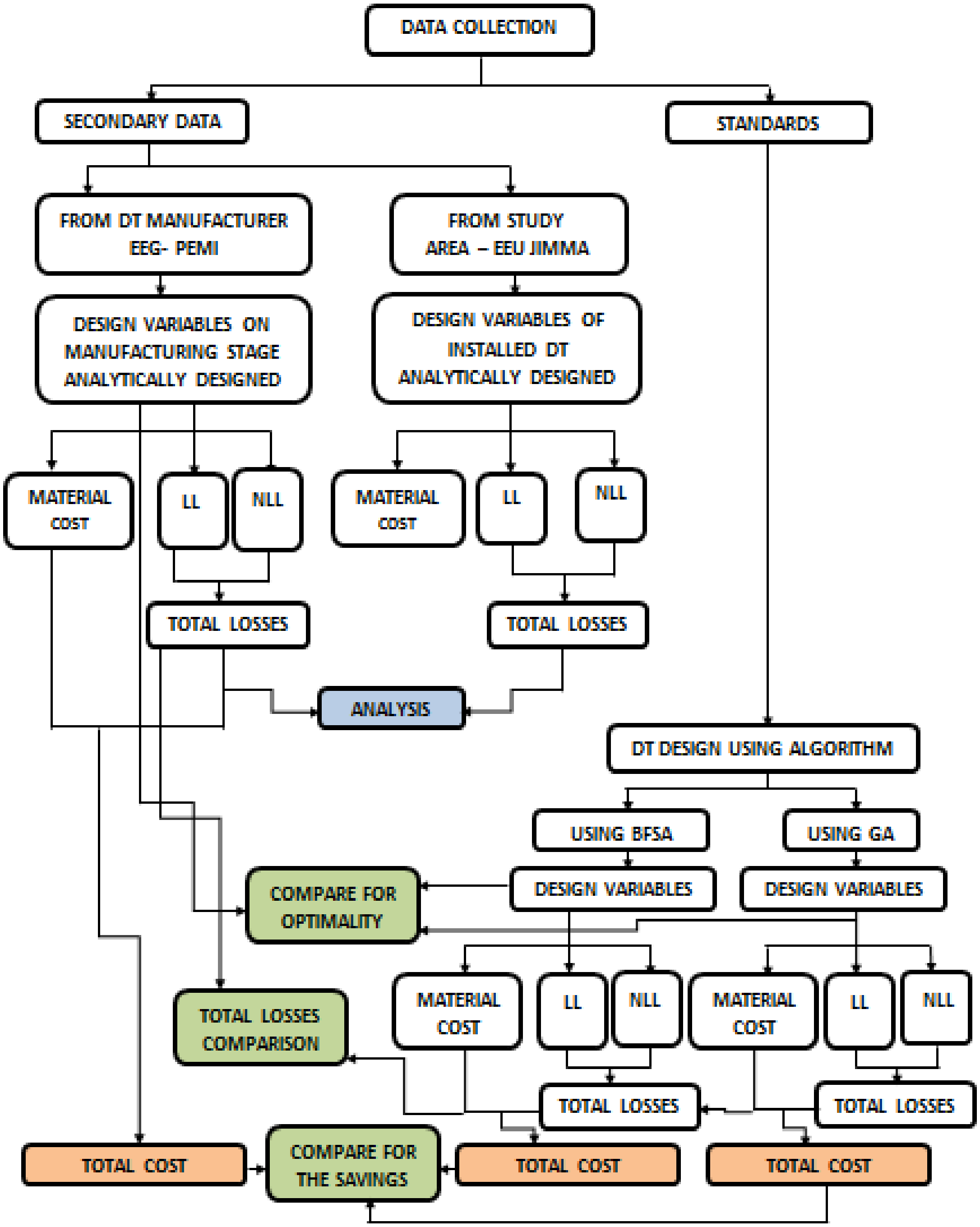


Figure 3.3 Methodology flow chart

3.4 Optimization of a Distribution Transformer Design

This section will list and discuss the characteristics of a distribution transformer, design variables that will be included in the design optimization tool to reach the needed design, the objective function to find the optimal design that has the minimum losses, and finally, the design constraints that are needed to ensure that obtained design functions with all the required operational characteristics.

3.4.1 Characteristics of a distribution transformer

Table 3.3 characteristics of a distribution transformer

CNo	**DT design parameters**	**Variable type**
1	Number of iterations	
2	Flat order	Design variable
3	Flat width	
4	Flat thickness	
5	Flat cross-section area	
6	Current density of flat wire	Constraint
7	LT layer/canal	
8	Secondary number of turns	Design variable
9	Diameter of core	Design variable
10	Flux density	
11	Volt per turn	
12	Area of core	
14	LT turns per layer	Design variable
15	LT canals	
16	LT mechanical height	
17	LT number of layers	
18	LT coil thickness	
19	LT outer diameter	
20	Coil height	
21	HT mechanical height	
22	N_HT max	
23	HT copper order	Design variable

24	HT active diameter	
25	HT total diameter	
26	HT cross-sectional area	
27	Current density round	
28	HT turns per layer	
29	HT turns per the last layer	
30	HT number of layers	
31	Insulation between layers	
32	HT layer per canal	
33	HT canals	
34	HT coil thickness	
35	LT inner diameter	
36	HT inner diameter	
37	HT outer diameter	
38	E	
39	H	
40	Core weight	
41	Core loss/Kg	
42	Total no-load loss	Constraint
43	H A/m	
44	LT mean diameter	
45	HT mean diameter	
46	LT total length	
47	HT total length of mid tap	
48	LT copper weight per phase	
49	HT copper weight per phase	
50	LT R20	
51	HT R20	
52	LT R75	
53	HT R75	
54	LT copper loss	

55	HT copper loss	
56	LT eddy loss	
57	HT eddy loss	
58	LT con. loss	
59	HT con. loss	
60	HT load loss	
61	LT load loss	
62	Total copper losses	
63	Total load-losses with strays	Constraint
64	Reactance of LT	
65	Calculated value of Z_1%	Constraint
66	Tolerance value of Z_2%	
67	Total transformer losses	Objective function
68	Cost of losses	
69	Core material costs	
70	Copper material costs	
71	Total material costs	
72	Total transformer costs	
73	Length of HT coil copper	
74	Weight of LT copper in 3Ø	
75	Weight of HT copper in 3Ø	
76	Total weight of copper	

3.4.2 Design Variables

A number of the design variables have to be optimized for the objective function to reach accepted designs. These design variables are:

- Secondary number of turns
- Core diameter
- Flat order
- LT turns per layer
- HT copper order

3.4.3 Objective Function

The main goal of experienced designers is to come up with an appropriate design that barely satisfies the operating requirements and characteristics requested by the customer. Conventional methods are normally used resulting in several designs that satisfy the customer's request; however, these designs will have different losses and any manufacturer tends to keep the losses as low as possible. The priority upon which the optimal design is selected is known to be the objective function of the design.

In this thesis, transformer design optimization techniques are used with the objective function of minimizing the total losses.

Therefore, the objective function is:

$$Minimize\ TL = \Sigma\,(NLL + LL) \tag{3.1}$$

Where TL is total losses in a distribution transformer

NLL is no-load loss of a distribution transformer in W

LL is load loss of a distribution transformer in W

3.4.3.1 No-load loss

The no-load loss of a distribution transformer is calculated by:

$$NLL = W_C \times BF \times Loss/kg \tag{3.2}$$

Where,

W_C is the weight of the core

BF is a building factor

Loss/kg is a specific loss

3.4.3.2 Load loss

The load loss in the transformer is given by:

$$LL = ohmic\ losses + stray\ losses \tag{3.3}$$

Where,

LL is load loss in ad distribution in W

Further, the ohmic loss is given by:

$$Ohmic\ losses\ = I_{HV}^2 R_{HV} +\ I_{LV}^2 R_{LV} \tag{3.4}$$

Where,

I_{HV} is primary (HV side) current per phase in A

R_{HV} is HV winding resistance per phase in Ω

I_{LV} is primary (LV side) current per phase in A

R_{LV} is LV winding resistance per phase in Ω

It is known, the primary (HV side) current per phase is given by:

$$I_{HV} = \frac{1000 \times kVA}{3 \times V_P} \tag{3.5}$$

Where,

V_P is the primary voltage in V

It is also known that the HV winding resistance per phase is given by:

$$R_{HV} = \frac{\rho_{Copper} \times MLT_{HV} \times N_{HV} \times 10^{-3}}{A_{wire}} \tag{3.6}$$

Where, ρ_{Copper} is the resistivity of electrolytic copper

3.4.4 Design constraints

Although each design variable is chosen arbitrarily from within a given range, the combination of the variables for the transformer's complete design has to adhere to all the operational constraints.

3.4.4.1 Load and No Load Losses

The total loss in a transformer is equal to the sum of the no-load and load losses. Manufacturers are forced to have designs with a limited amount of these losses, the constraint for the maximum losses are:

$$NLL \leq NLL_{\max} \tag{3.7}$$

$$LL \leq LL_{\max} \tag{3.8}$$

3.4.4.2 Current Density (Cd)

The current density in the copper conducting winding is usually forced below a specific reasonable value during the transformer design process. High values for current density must be avoided because this will result in an abnormal rise in the windings temperature gradient, and this will in turn not only require higher costs for maintaining a suitable cooling system, but also eventually result in transformer loss of life due to the aging and breaking down of the insulation material used for the windings. The transformer user usually defines HV and LV constraints for the current density as follows:

$Cd_{\min} \leq Cd \leq Cd_{\max}$ (3.9)

3.4.4.3 Percentage Impedance (%Z)

Transformer designers aim to achieve an optimal design that operates within the limits of the minimum and maximum specified transformer impedance value. For this reason, the main objective of a transformer designer is to obtain the best possible compromise between very low levels of impedance which in turn limits the fault current to a tolerable magnitude, and a high level of the impedance value that can be dealt with without the need of excessive system regulation. This puts pressure on manufacturers to have the smallest possible range of impedance values for their transformers. Manufacturers usually abide by international standards by which a very tight tolerance is allowed based on the standard. A tolerance of ± 10% is accepted according to the IEC60076 standard. The impedance value constraints can be expressed as the following:

$$\%Z_{min} \leq \%Z_G \leq \%Z_{max} \tag{3.10}$$

$\%Z_{min}$ is the minimum accepted impedance = $0.900\times\%Z_G$ as per IEC
$\%Z_{max}$ is the maximum accepted impedance = $1.100\times\%Z_G$ as per IEC
In which $\%Z_G$ is the guaranteed impedance value requested by the customer.
The formula commonly used for calculating percentage resistance is as follows:

$$R(\%) = \frac{LL\ (in\ kW)}{kVA} \times 100 \tag{3.11}$$

Where,
LL is Load Loss (W)
kVA is the rating of transformer, input data
Percentage impedance is the vector sum of percentage reactance and percentage resistance and is represented as:

$$Z(\%) = \sqrt{(X\%)^2 + (R\%)^2} \tag{3.12}$$

As per IEC standard percentage of short circuit impedance at rated current for the rated power up to 630kVA distribution transformers is 4%. For a distribution transformer with two windings, when the percentage of short circuit impedance value is less than 10% tolerance of ± 10% of the declared value is allowed [10].

3.4.4.4 Efficiency

The efficiency at rated load and unity power factor is calculated:

$$\%\eta = \frac{kVA}{kVA + NLL\ in\ kW + LL\ in\ kW} \times 100\% \tag{3.13}$$

$$\eta_{min} \leq \eta_{transformer} \tag{3.14}$$

3.4.4.5 Turns ratio

The design should satisfy the transformer turns ratio

$$\frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P} \tag{3.14}$$

3.5 Algorithms used for design optimization of a distribution transformer

In this section the two algorithms namely, BFSA and GA that are used for the transformer design optimization process are discussed.

3.5.1 Brute Force Search Algorithm

A Brute force search algorithm is a general problem-solving technique that computes all possible candidates for the solution and checks whether each candidate satisfies the problem's statement.

The algorithm is simple to implement and it will always find a solution if it exists, the method is also used when the simplicity of implementation is more important than speed. A Brute force search algorithm is a guaranteed way to find the correct solutions to a problem because it tests every possible candidate as an answer.

A brute force search algorithm is mostly selected due to its wide applicability, simplicity, and to yield reasonable results. Its weakness is its time complexities grow exponentially with problem size [12].

The transformer design algorithm using the BFSA for optimization is described in the following flow chart.

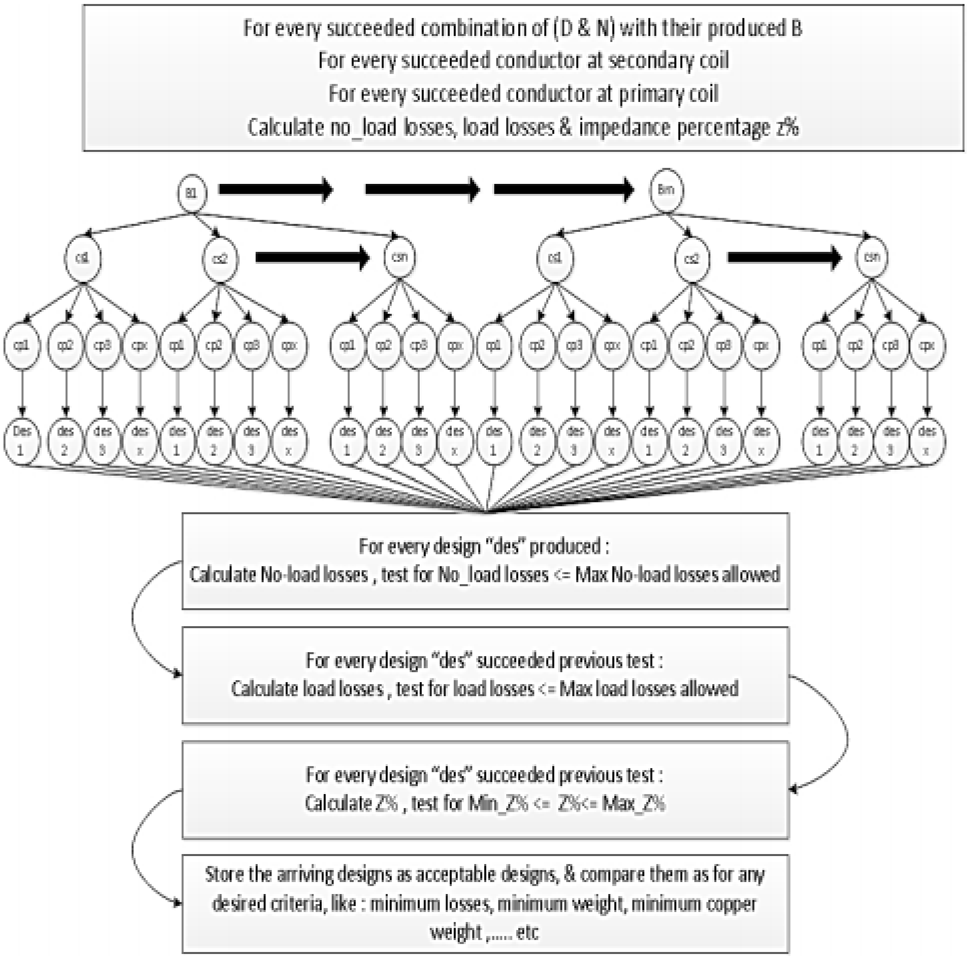


Figure 3.4 BFSA optimization flow chart

3.5.2 Genetic Algorithm

A genetic algorithm is a powerful heuristic optimization technique that operates on a population to return the optimum solution from that population. The basic idea is to maintain a population of candidate solutions by which survival of the fittest is achieved after engaging this population with selective pressure tests favouring only the better-fit candidates. To achieve the survival of the fittest requirement several operators need to be used; first, the selection operator selects possible strings according to the constraints, in which every string is a solution. Then crossover operator, in which the fitter strings are crossed over to obtain a new set of solutions with better fitness values after inhering good properties from the parent strings.

Finally, the mutation operator is used to mutate chromosomes enhancing better characteristics in the offspring that are not found in the parent strings. This can be better clarified by the following steps.

- Create initial population from prior values
- Evaluate fitness of possible solutions and select
- Crossover solutions to obtain fitter offspring
- New features produced in offspring by mutation
- Select fitter generation and repeat until required fitness is achieved

The genetic algorithm optimization's first step is the generation of a random pool of solutions. This method is done by setting an initial input as the start benchmark for the process, along with the design variables boundaries. To make sure that the saved offspring is of better fitness, the selection operator compares each solution of the total population by the best-fit individual and the represented by the objective function value.

The next step is a crossover of the fitter solutions; this is done selectively interbreeding members of the population in pairs to produce offspring. The fitter a member of the population the more likely it is to produce offspring. So basically the main use of these genetic operators is to facilitate the breeding process that results in offspring inheriting properties from their parents. The offspring are evaluated and placed in the population, possibly replacing the weaker members of the last generation. Thus, the search mechanism consists of three steps: evaluation of the fitness of each chromosome, selection of the parent chromosomes, and applications crossover and then mutation to the parent chromosomes. Finally, the stopping criteria must be included for the optimization process, and this could be when no significant improvement in the produced solution fitness is observed, or in the case where the maximum number of iterations has been achieved. The survival of the fittest principle ensures that the overall quality of solutions increases as the algorithm progress from one generation to the next.

The Genetic Algorithm is used in MATLAB to obtain an optimal distribution transformer design that has the lowest total losses and satisfies all the required operation characteristics and constraints.

The transformer design algorithm using the GA for optimization can be better understood from the following flow chart.

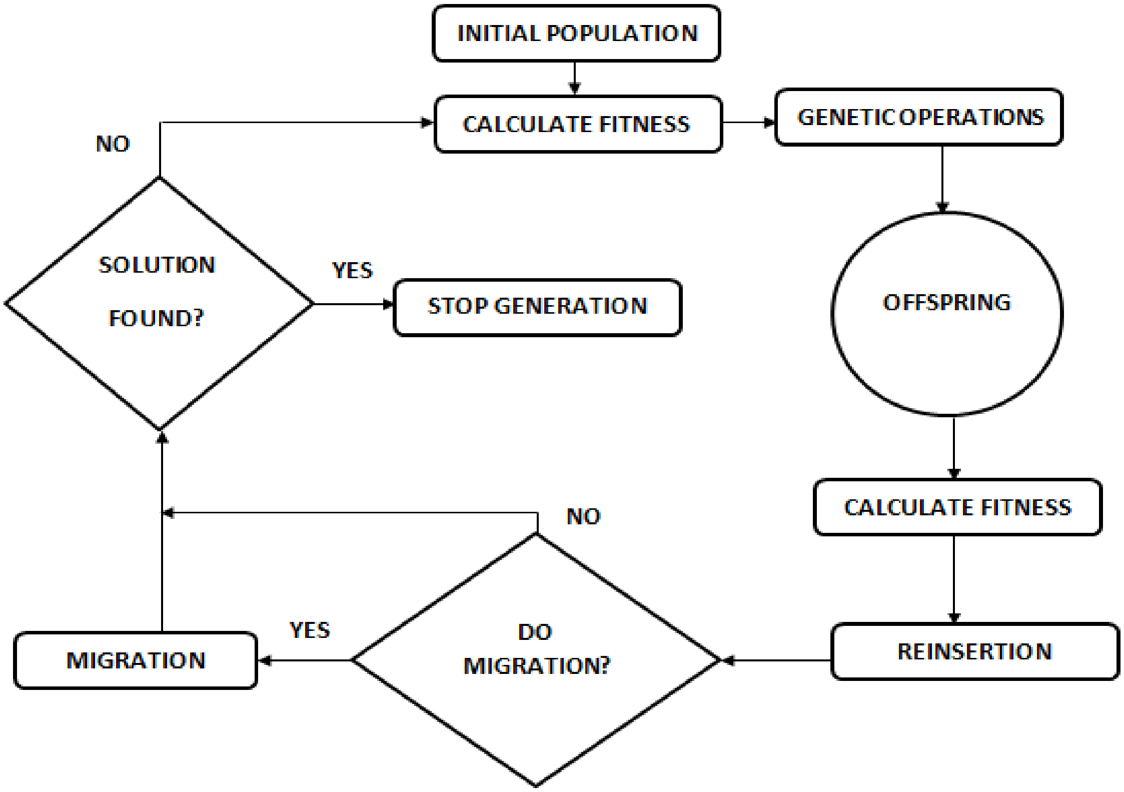


Figure 3.5 GA optimization flow chart

The execution of the algorithm can be listed as follows:

- Assign the fitness for the population
- The selection process in which individuals are chosen from the population
- Crossover of individual pairs within each subpopulation
- The upper and lower bounds of the decision variables need to be strictly considered to avoid having new individuals outside that range.
- Reinsertion of best offspring to replace worst individuals
- Most fit individuals are selected for migration between subpopulations

This process is repeated over again until the stopping criteria are reached either by exceeding the number of iterations or reaching the time limit or the fitness limit is achieved, and the fittest result is returned.

3.6 Implementation of algorithms for transformer design optimization

In this section, the actual implementation of the program for the design process is developed using the mathematical model of the transformer design. The section lists the steps of the implemented program and will briefly explain it starting from the data entry depending on the transformer characteristics until the final step which is the calculation of the total losses and costs of the transformer.

3.6.1 Input data

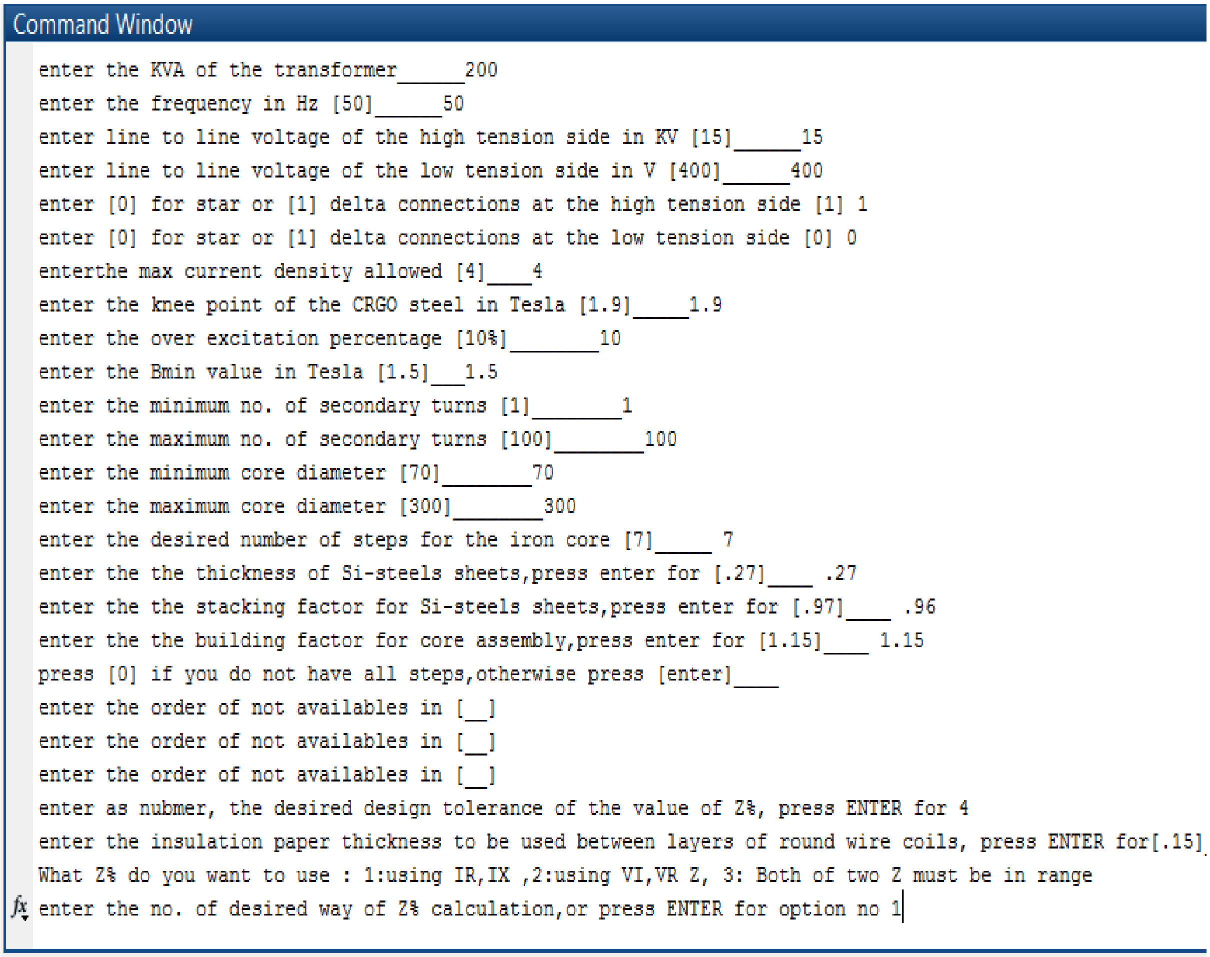
The data entry stage of the program is the first step in which the required transformer characteristics are set, most of these characteristics are provided by the customer, and the manufacturer only sets the standards to be used which could differ from one manufacturer to another.

Below are lists for the data entry for a three-phase core type oil immersed three-phase distribution transformer.

Transformer rating in kVA	200
Rated frequency in Hz	50
Primary voltage in volts	15000
Secondary voltage in volts	400
Connection of HV side	Delta
Connection of LV side	Star
Maximum current density allowed in A/mm2	4
Knee point of the CRGO steel in Tesla	1.9
Over excitation percentage in %	10
Minimum flux density value in Tesla	1.5
Secondary minimum number of turns in no.	1
Secondary maximum number of turns in no.	100
Minimum core diameter in mm	70
Maximum core diameter in mm	300
Number of steps for the iron core in no.	7
Thickness of Si-steels sheets in mm	0.27
Stacking factor for Si-steels sheets	0.97
Building factor for core assembly	1.15

- Guaranteed/allowed impedance value in % 4.0
- Insulation paper thickness used between layers of wire coils 0.15

The way in which the input data is entered into the optimization algorithm is given below.



```
enter the KVA of the transformer_____200
enter the frequency in Hz [50]_____50
enter line to line voltage of the high tension side in KV [15]_____15
enter line to line voltage of the low tension side in V [400]_____400
enter [0] for star or [1] delta connections at the high tension side [1] 1
enter [0] for star or [1] delta connections at the low tension side [0] 0
enterthe max current density allowed [4]____4
enter the knee point of the CRGO steel in Tesla [1.9]_____1.9
enter the over excitation percentage [10%]________10
enter the Bmin value in Tesla [1.5]___1.5
enter the minimum no. of secondary turns [1]________1
enter the maximum no. of secondary turns [100]________100
enter the minimum core diameter [70]________70
enter the maximum core diameter [300]________300
enter the desired number of steps for the iron core [7]_____ 7
enter the the thickness of Si-steels sheets,press enter for [.27]____ .27
enter the the stacking factor for Si-steels sheets,press enter for [.97]____ .96
enter the the building factor for core assembly,press enter for [1.15]____ 1.15
press [0] if you do not have all steps,otherwise press [enter]____
enter the order of not availables in [__]
enter the order of not availables in [__]
enter the order of not availables in [__]
enter as nubmer, the desired design tolerance of the value of Z%, press ENTER for 4
enter the insulation paper thickness to be used between layers of round wire coils, press ENTER for[.15]
What Z% do you want to use : 1:using IR,IX ,2:using VI,VR Z, 3: Both of two Z must be in range
enter the no. of desired way of Z% calculation,or press ENTER for option no 1
```

Figure 3.6 Input data to the algorithm

3.6.2 Lower and upper bounds

The lower and upper bounds of design variables are fixed based on practical manufacturability range and availability on market. The table below displays the lower and upper bounds of the design variables.

Table 3.4 Design variables lower and upper bounds

No.	Design Variables	Lower Bound	Upper Bound
1	Secondary number of turns	1	100
2	Core diameter	70	300

3.6.3 Transformer Design Constraints

Every design has to comply with a set of constraints according to standards to ensure a proper and safe operation of the transformer.

Table 3.5 lists the constraints used for the design of the 200kVA transformer.

Table 3.5 Design constraints for 200kVA distribution transformer

No.	Design constraints	Values
1	Current density A/mm^2	≤ 4
2	Maximum allowed load loss in W	< 2700
3	Maximum allowed no load loss in W	< 600
4	Guaranteed percentage of impedance in %	$3.6 \leq Z \leq 4.4$
5	Efficiency in %	≥ 98
6	$\frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$	

3.6.4 Process of design optimization

Next is the optimization process that takes place looking for an optimal transformer design. The process starts at the lower bound initial values and searches within the range of the upper and lower bounds using the specified non-linear inequality constraints.

3.6.5 Total losses calculation

After the optimal design variables are obtained, the no-load loss and load loss for the distribution transformer to be designed are calculated. Finally, a total loss is calculated by the summation of the no-load loss and load loss.

CHAPTER FOUR

4 RESULTS AND DISCUSSIONS

In this chapter, the results of the optimal transformer design found by implementing the Brute force search algorithm are presented and briefly discussed. Additionally, a comparison is made between the optimal design obtained using the algorithms and the analytical design obtained from the transformer manufacturer company.

4.1 Design optimization outputs using algorithms

The following figures shows the algorithm outputs of optimal design variables in which the distribution transformer loss is minimized and operational constraints are met.

Figure 4.1 shows the outputs from the BFSA that describes the minimum total losses of the transformer. The figure also shows the characters of the minimum total loss.

```
min_total_loss =

     1.994133261374044e+03

Watt

Char_of_min_total_loss =

   1.0e+06 *

  Columns 1 through 6

   0.018885000000000   0.000010000000000   0.000018800000000   0.000005400000000   0.000100661592654   0.000002867778335

  Columns 7 through 12

   0.000002000000000   0.000025000000000   0.000197000000000   0.000001509622862   0.000009237604307   0.000000027563726

  Columns 13 through 18

                   0   0.000015000000000   0.000001000000000   0.000288000000000   0.000002000000000   0.000018100000000

  Columns 19 through 24

   0.000239200000000   0.000320000000000   0.000280000000000   0.001704000000000   0.000015000000000   0.000003150000000
```

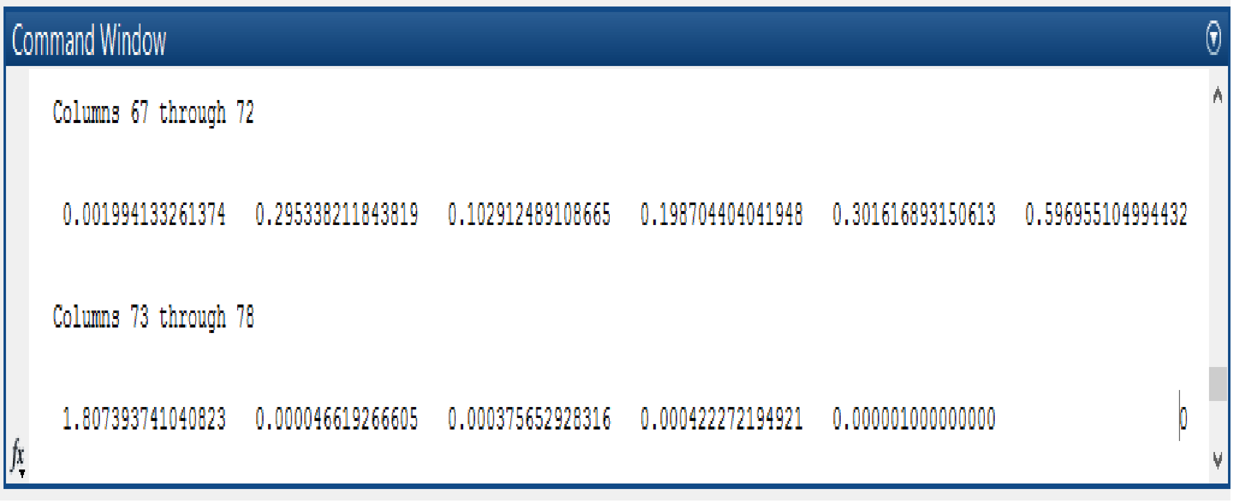
Figure 4.1 Outputs of algorithm - minimum total losses

Figure 4.2 shows the characters of the minimum total loss in the transformer from column 25 to column 66.

```
  Columns 25 through 30

   0.000003294000000   0.000007793113276   0.000000570304099   0.000084000000000   0.000024000000000   0.000021000000000

  Columns 31 through 36

   0.000000150000000   0.000097000000000   0.000001000000000   0.000078424000000   0.000203000000000   0.000259200000000

  Columns 37 through 42

   0.000416048000000   0.000429000000000   0.000334000000000   0.000656204100674   0.000000793423424   0.000598744860197

  Columns 43 through 48

   0.000383876508770   0.000221100000000   0.000337624000000   0.017365153392718   1.721478897716700   0.000015539755535

  Columns 49 through 54

   0.000125217642772   0.000000002974076   0.000003808272143   0.000000003616804   0.000004631277911   0.000904200959029

  Columns 55 through 60

   0.000274446098401   0.000030753885559   0.000119162022497   0.000013051016677   0.000000105634353   0.000948005861266

  Columns 61 through 66

   0.000393713755251   0.001341719616517   0.001395388401177   0.000000038561580   0.000003900930220   0.000004000000000
```

Figure 4.2 Characters of the min from column 25 to column 66

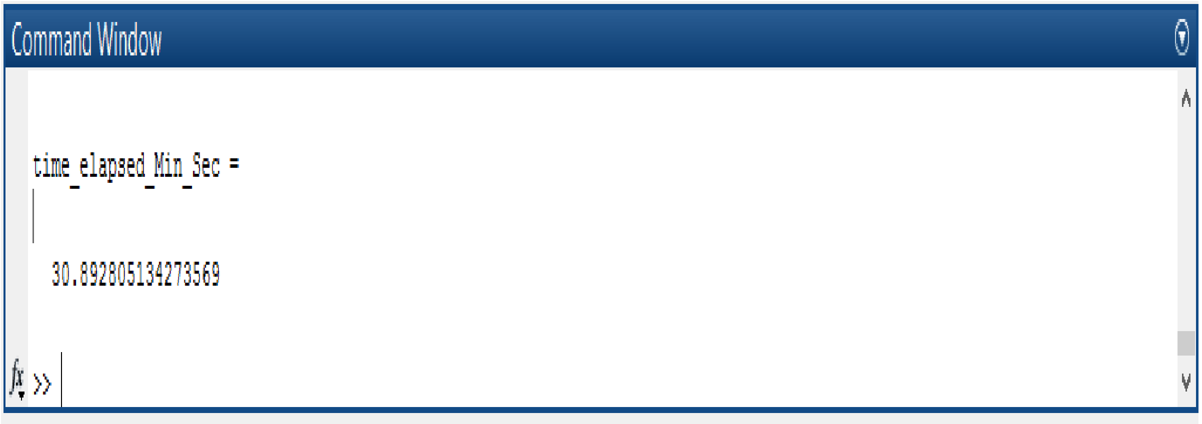
Figure 4.3 shows the characters of the minimum total loss in the transformer from column 67 to column 78.



```
  Columns 67 through 72

   0.001994133261374   0.295338211843819   0.102912489108665   0.198704404041948   0.301616893150613   0.596955104994432

  Columns 73 through 78

   1.807393741040823   0.000046619266605   0.000375652928316   0.000422272194921   0.000001000000000                   0
```

Figure 4.3 Characters of the min from column 67 to column 78

Figure 4.4 shows the time elapsed by the algorithm in the transformer design optimization process.

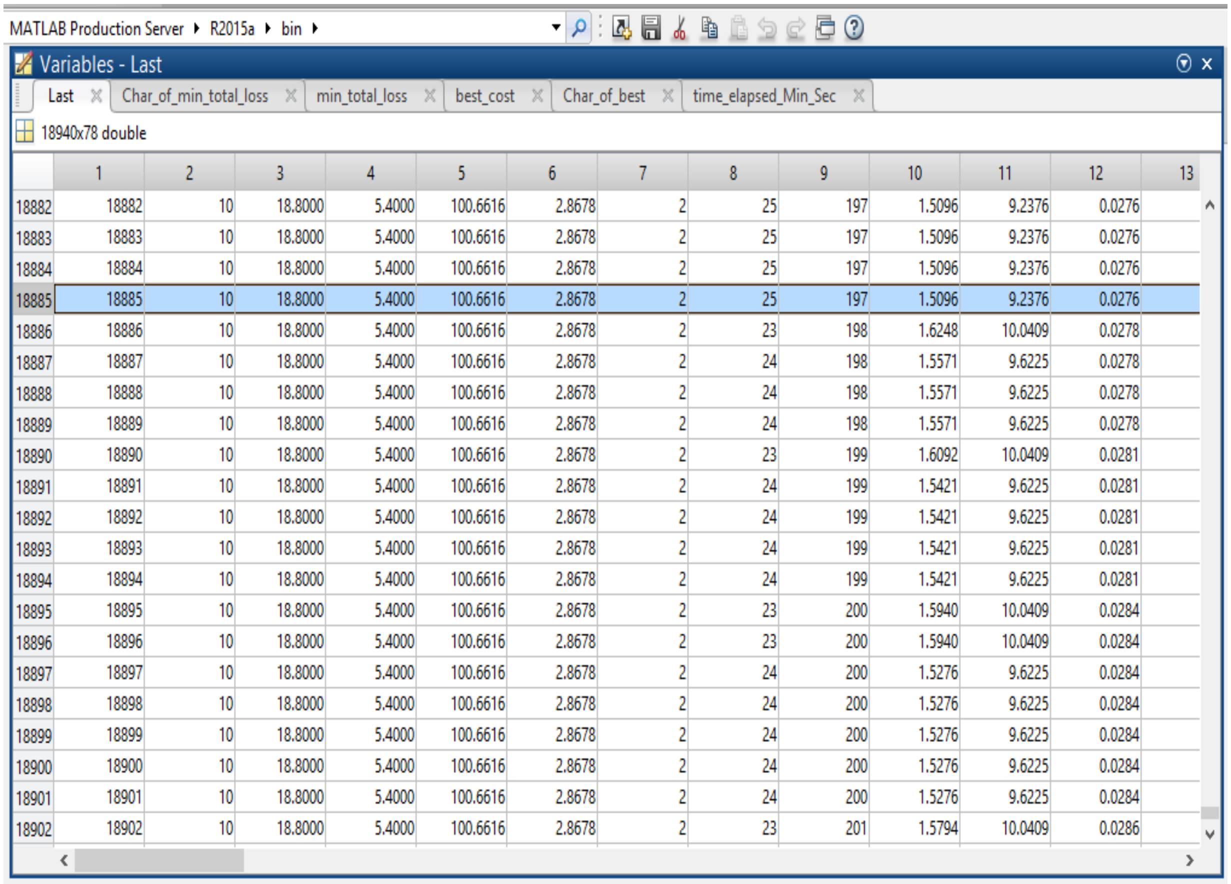


```
time_elapsed_Min_Sec =

  30.892805134273569

fx >>
```

Figure 4.4 Time elapsed

Table 4.1 shows the outputs of the algorithm from column 1 to column 12 that describes all characteristics of the optimized distribution transformer where total loss is minimum.

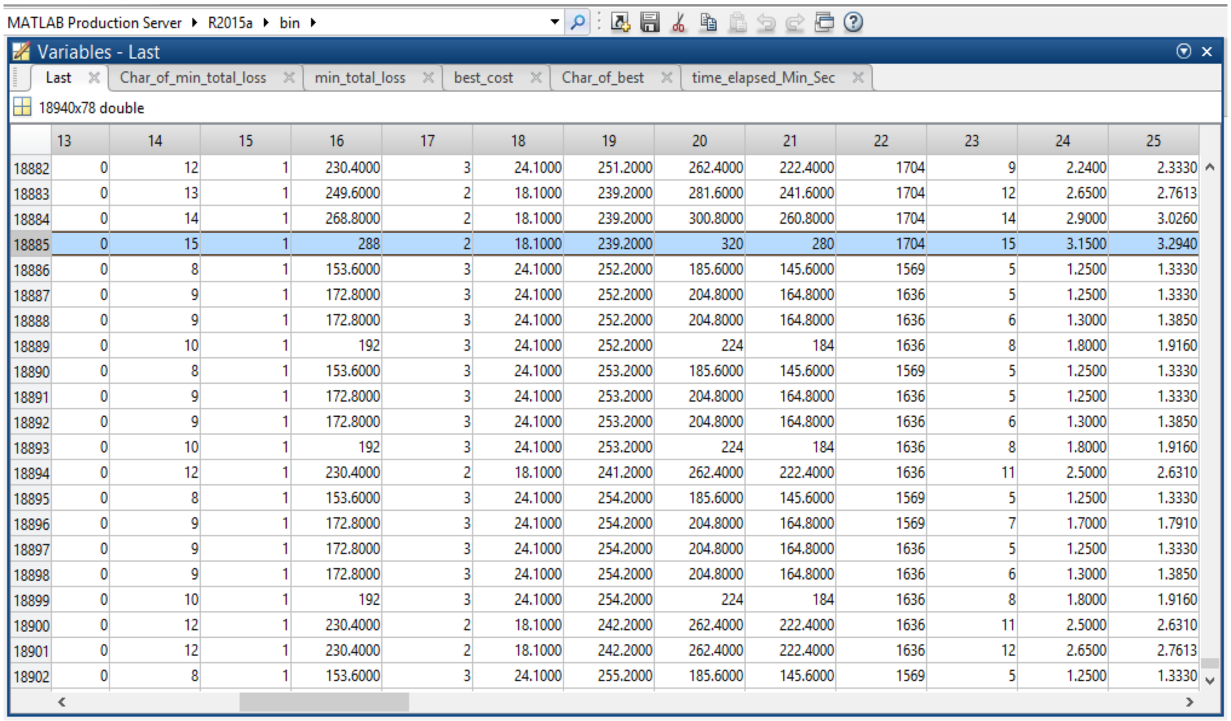
Table 4.1 Outputs of the algorithm from column 1 to column 12



	1	2	3	4	5	6	7	8	9	10	11	12	13
18882	18882	10	18.8000	5.4000	100.6616	2.8678	2	25	197	1.5096	9.2376	0.0276	
18883	18883	10	18.8000	5.4000	100.6616	2.8678	2	25	197	1.5096	9.2376	0.0276	
18884	18884	10	18.8000	5.4000	100.6616	2.8678	2	25	197	1.5096	9.2376	0.0276	
18885	18885	10	18.8000	5.4000	100.6616	2.8678	2	25	197	1.5096	9.2376	0.0276	
18886	18886	10	18.8000	5.4000	100.6616	2.8678	2	23	198	1.6248	10.0409	0.0278	
18887	18887	10	18.8000	5.4000	100.6616	2.8678	2	24	198	1.5571	9.6225	0.0278	
18888	18888	10	18.8000	5.4000	100.6616	2.8678	2	24	198	1.5571	9.6225	0.0278	
18889	18889	10	18.8000	5.4000	100.6616	2.8678	2	24	198	1.5571	9.6225	0.0278	
18890	18890	10	18.8000	5.4000	100.6616	2.8678	2	23	199	1.6092	10.0409	0.0281	
18891	18891	10	18.8000	5.4000	100.6616	2.8678	2	24	199	1.5421	9.6225	0.0281	
18892	18892	10	18.8000	5.4000	100.6616	2.8678	2	24	199	1.5421	9.6225	0.0281	
18893	18893	10	18.8000	5.4000	100.6616	2.8678	2	24	199	1.5421	9.6225	0.0281	
18894	18894	10	18.8000	5.4000	100.6616	2.8678	2	24	199	1.5421	9.6225	0.0281	
18895	18895	10	18.8000	5.4000	100.6616	2.8678	2	23	200	1.5940	10.0409	0.0284	
18896	18896	10	18.8000	5.4000	100.6616	2.8678	2	23	200	1.5940	10.0409	0.0284	
18897	18897	10	18.8000	5.4000	100.6616	2.8678	2	24	200	1.5276	9.6225	0.0284	
18898	18898	10	18.8000	5.4000	100.6616	2.8678	2	24	200	1.5276	9.6225	0.0284	
18899	18899	10	18.8000	5.4000	100.6616	2.8678	2	24	200	1.5276	9.6225	0.0284	
18900	18900	10	18.8000	5.4000	100.6616	2.8678	2	24	200	1.5276	9.6225	0.0284	
18901	18901	10	18.8000	5.4000	100.6616	2.8678	2	24	200	1.5276	9.6225	0.0284	
18902	18902	10	18.8000	5.4000	100.6616	2.8678	2	23	201	1.5794	10.0409	0.0286	

Table 4.2 shows the outputs of the algorithm from column 13 to column 25 that describes all characteristics of the optimized distribution transformer where total loss is minimum.

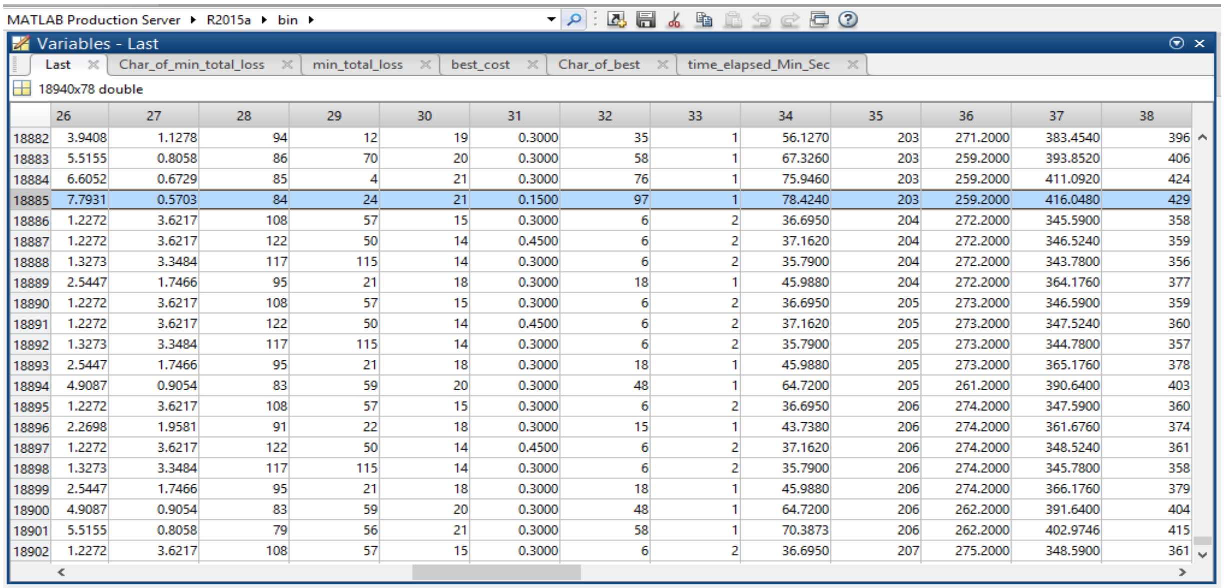
Table 4.2 Outputs of the algorithm from column 13 to column 25



	13	14	15	16	17	18	19	20	21	22	23	24	25
18882	0	12	1	230.4000	3	24.1000	251.2000	262.4000	222.4000	1704	9	2.2400	2.3330
18883	0	13	1	249.6000	2	18.1000	239.2000	281.6000	241.6000	1704	12	2.6500	2.7613
18884	0	14	1	268.8000	2	18.1000	239.2000	300.8000	260.8000	1704	14	2.9000	3.0260
18885	0	15	1	288	2	18.1000	239.2000	320	280	1704	15	3.1500	3.2940
18886	0	8	1	153.6000	3	24.1000	252.2000	185.6000	145.6000	1569	5	1.2500	1.3330
18887	0	9	1	172.8000	3	24.1000	252.2000	204.8000	164.8000	1636	5	1.2500	1.3330
18888	0	9	1	172.8000	3	24.1000	252.2000	204.8000	164.8000	1636	6	1.3000	1.3850
18889	0	10	1	192	3	24.1000	252.2000	224	184	1636	8	1.8000	1.9160
18890	0	8	1	153.6000	3	24.1000	253.2000	185.6000	145.6000	1569	5	1.2500	1.3330
18891	0	9	1	172.8000	3	24.1000	253.2000	204.8000	164.8000	1636	5	1.2500	1.3330
18892	0	9	1	172.8000	3	24.1000	253.2000	204.8000	164.8000	1636	6	1.3000	1.3850
18893	0	10	1	192	3	24.1000	253.2000	224	184	1636	8	1.8000	1.9160
18894	0	12	1	230.4000	2	18.1000	241.2000	262.4000	222.4000	1636	11	2.5000	2.6310
18895	0	8	1	153.6000	3	24.1000	254.2000	185.6000	145.6000	1569	5	1.2500	1.3330
18896	0	9	1	172.8000	3	24.1000	254.2000	204.8000	164.8000	1569	7	1.7000	1.7910
18897	0	9	1	172.8000	3	24.1000	254.2000	204.8000	164.8000	1636	5	1.2500	1.3330
18898	0	9	1	172.8000	3	24.1000	254.2000	204.8000	164.8000	1636	6	1.3000	1.3850
18899	0	10	1	192	3	24.1000	254.2000	224	184	1636	8	1.8000	1.9160
18900	0	12	1	230.4000	2	18.1000	242.2000	262.4000	222.4000	1636	11	2.5000	2.6310
18901	0	12	1	230.4000	2	18.1000	242.2000	262.4000	222.4000	1636	12	2.6500	2.7613
18902	0	8	1	153.6000	3	24.1000	255.2000	185.6000	145.6000	1569	5	1.2500	1.3330

Table 4.3 shows the outputs of the algorithm from column 26 to column 38 that describes all characteristics of the optimized distribution transformer where total loss is minimum.

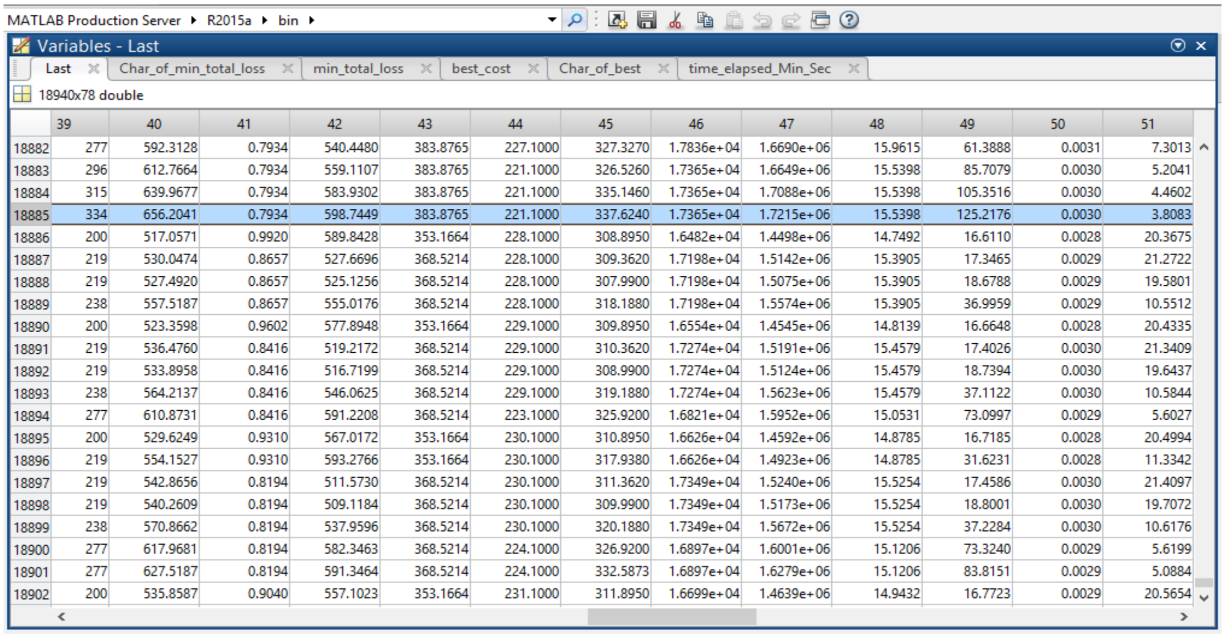
Table 4.3 Outputs of the algorithm from column 26 to column 38



	26	27	28	29	30	31	32	33	34	35	36	37	38
18882	3.9408	1.1278	94	12	19	0.3000	35	1	56.1270	203	271.2000	383.4540	396
18883	5.5155	0.8058	86	70	20	0.3000	58	1	67.3260	203	259.2000	393.8520	406
18884	6.6052	0.6729	85	4	21	0.3000	76	1	75.9460	203	259.2000	411.0920	424
18885	7.7931	0.5703	84	24	21	0.1500	97	1	78.4240	203	259.2000	416.0480	429
18886	1.2272	3.6217	108	57	15	0.3000	6	2	36.6950	204	272.2000	345.5900	358
18887	1.2272	3.6217	122	50	14	0.4500	6	2	37.1620	204	272.2000	346.5240	359
18888	1.3273	3.3484	117	115	14	0.3000	6	2	35.7900	204	272.2000	343.7800	356
18889	2.5447	1.7466	95	21	18	0.3000	18	1	45.9880	204	272.2000	364.1760	377
18890	1.2272	3.6217	108	57	15	0.3000	6	2	36.6950	205	273.2000	346.5900	359
18891	1.2272	3.6217	122	50	14	0.4500	6	2	37.1620	205	273.2000	347.5240	360
18892	1.3273	3.3484	117	115	14	0.3000	6	2	35.7900	205	273.2000	344.7800	357
18893	2.5447	1.7466	95	21	18	0.3000	18	1	45.9880	205	273.2000	365.1760	378
18894	4.9087	0.9054	83	59	20	0.3000	48	1	64.7200	205	261.2000	390.6400	403
18895	1.2272	3.6217	108	57	15	0.3000	6	2	36.6950	206	274.2000	347.5900	360
18896	2.2698	1.9581	91	22	18	0.3000	15	1	43.7380	206	274.2000	361.6760	374
18897	1.2272	3.6217	122	50	14	0.4500	6	2	37.1620	206	274.2000	348.5240	361
18898	1.3273	3.3484	117	115	14	0.3000	6	2	35.7900	206	274.2000	345.7800	358
18899	2.5447	1.7466	95	21	18	0.3000	18	1	45.9880	206	274.2000	366.1760	379
18900	4.9087	0.9054	83	59	20	0.3000	48	1	64.7200	206	262.2000	391.6400	404
18901	5.5155	0.8058	79	56	21	0.3000	58	1	70.3873	206	262.2000	402.9746	415
18902	1.2272	3.6217	108	57	15	0.3000	6	2	36.6950	207	275.2000	348.5900	361

Table 4.4 shows the outputs of the algorithm from column 39 to column 51 that describes all characteristics of the optimized distribution transformer where total loss is minimum.

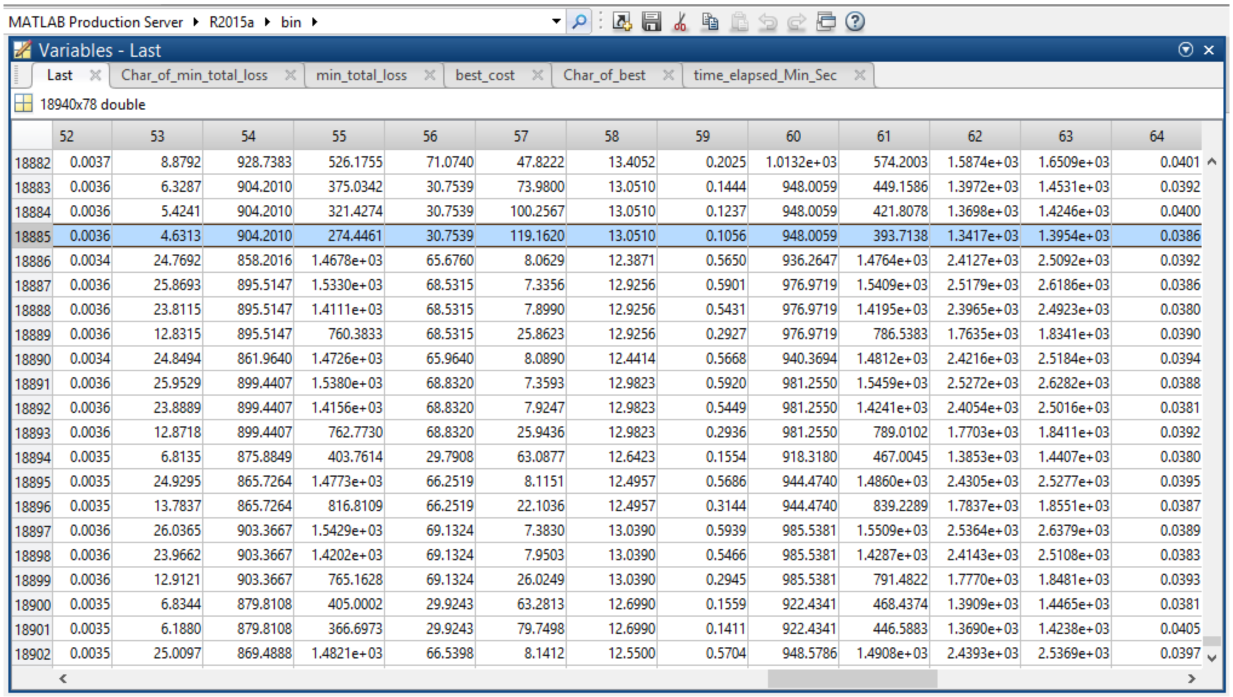
Table 4.4 Outputs of the algorithm from column 39 to column 51



	39	40	41	42	43	44	45	46	47	48	49	50	51
18882	277	592.3128	0.7934	540.4480	383.8765	227.1000	327.3270	1.7836e+04	1.6690e+06	15.9615	61.3888	0.0031	7.3013
18883	296	612.7664	0.7934	559.1107	383.8765	221.1000	326.5260	1.7365e+04	1.6649e+06	15.5398	85.7079	0.0030	5.2041
18884	315	639.9677	0.7934	583.9302	383.8765	221.1000	335.1460	1.7365e+04	1.7088e+06	15.5398	105.3516	0.0030	4.4602
18885	334	656.2041	0.7934	598.7449	383.8765	221.1000	337.6240	1.7365e+04	1.7215e+06	15.5398	125.2176	0.0030	3.8083
18886	200	517.0571	0.9920	589.8428	353.1664	228.1000	308.8950	1.6482e+04	1.4498e+06	14.7492	16.6110	0.0028	20.3675
18887	219	530.0474	0.8657	527.6696	368.5214	228.1000	309.3620	1.7198e+04	1.5142e+06	15.3905	17.3465	0.0029	21.2722
18888	219	527.4920	0.8657	525.1256	368.5214	228.1000	307.9900	1.7198e+04	1.5075e+06	15.3905	18.6788	0.0029	19.5801
18889	238	557.5187	0.8657	555.0176	368.5214	228.1000	318.1880	1.7198e+04	1.5574e+06	15.3905	36.9959	0.0029	10.5512
18890	200	523.3598	0.9602	577.8948	353.1664	229.1000	309.8950	1.6554e+04	1.4545e+06	14.8139	16.6648	0.0028	20.4335
18891	219	536.4760	0.8416	519.2172	368.5214	229.1000	310.3620	1.7274e+04	1.5191e+06	15.4579	17.4026	0.0030	21.3409
18892	219	533.8958	0.8416	516.7199	368.5214	229.1000	308.9900	1.7274e+04	1.5124e+06	15.4579	18.7394	0.0030	19.6437
18893	238	564.2137	0.8416	546.0625	368.5214	229.1000	319.1880	1.7274e+04	1.5623e+06	15.4579	37.1122	0.0030	10.5844
18894	277	610.8731	0.8416	591.2208	368.5214	223.1000	325.9200	1.6821e+04	1.5952e+06	15.0531	73.0997	0.0029	5.6027
18895	200	529.6249	0.9310	567.0172	353.1664	230.1000	310.8950	1.6626e+04	1.4592e+06	14.8785	16.7185	0.0028	20.4994
18896	219	554.1527	0.9310	593.2766	353.1664	230.1000	317.9380	1.6626e+04	1.4923e+06	14.8785	31.6231	0.0028	11.3342
18897	219	542.8656	0.8194	511.5730	368.5214	230.1000	311.3620	1.7349e+04	1.5240e+06	15.5254	17.4586	0.0030	21.4097
18898	219	540.2609	0.8194	509.1184	368.5214	230.1000	309.9900	1.7349e+04	1.5173e+06	15.5254	18.8001	0.0030	19.7072
18899	238	570.8662	0.8194	537.9596	368.5214	230.1000	320.1880	1.7349e+04	1.5672e+06	15.5254	37.2284	0.0030	10.6176
18900	277	617.9681	0.8194	582.3463	368.5214	224.1000	326.9200	1.6897e+04	1.6001e+06	15.1206	73.3240	0.0029	5.6199
18901	277	627.5187	0.8194	591.3464	368.5214	224.1000	332.5873	1.6897e+04	1.6279e+06	15.1206	83.8151	0.0029	5.0884
18902	200	535.8587	0.9040	557.1023	353.1664	231.1000	311.8950	1.6699e+04	1.4639e+06	14.9432	16.7723	0.0029	20.5654

Table 4.5 shows the outputs of the algorithm from column 52 to column 64 that describes all characteristics of the optimized distribution transformer where total loss is minimum.

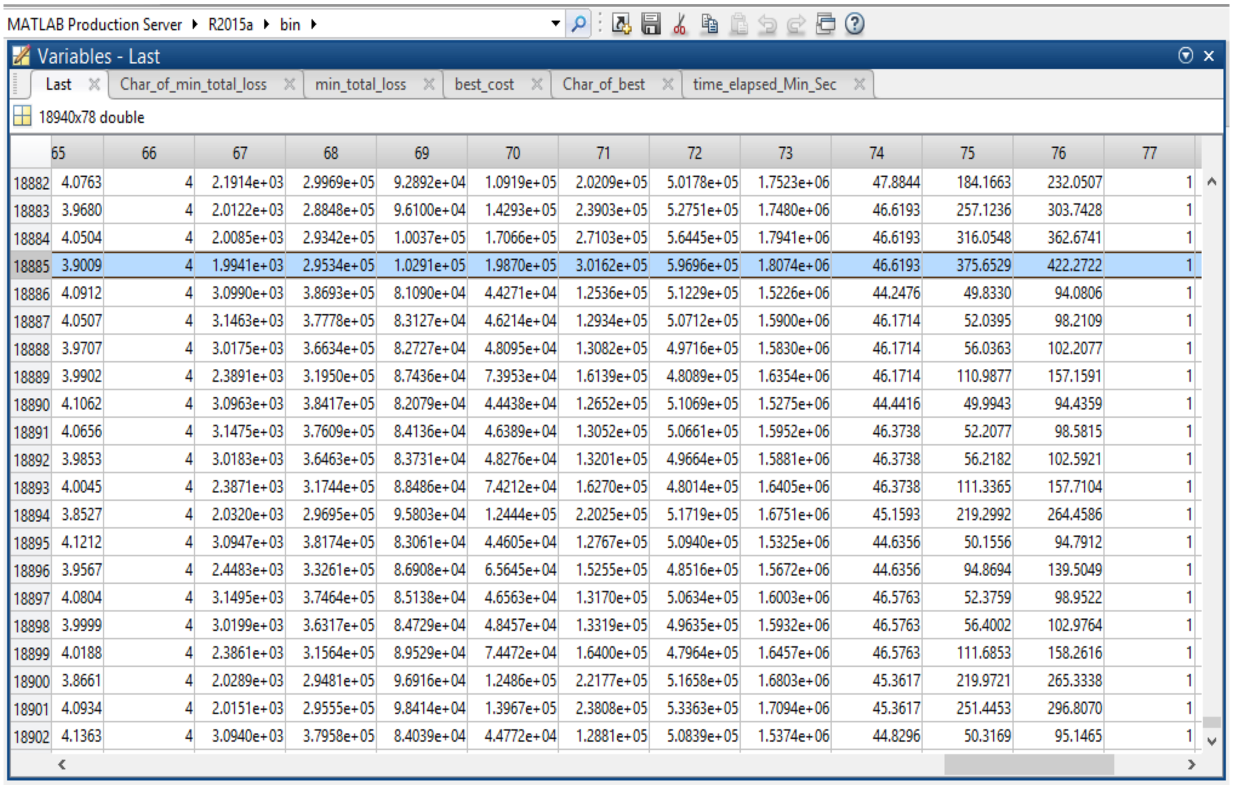
Table 4.5 Outputs of the algorithm from column 52 to column 64



	52	53	54	55	56	57	58	59	60	61	62	63	64
18882	0.0037	8.8792	928.7383	526.1755	71.0740	47.8222	13.4052	0.2025	1.0132e+03	574.2003	1.5874e+03	1.6509e+03	0.0401
18883	0.0036	6.3287	904.2010	375.0342	30.7539	73.9800	13.0510	0.1444	948.0059	449.1586	1.3972e+03	1.4531e+03	0.0392
18884	0.0036	5.4241	904.2010	321.4274	30.7539	100.2567	13.0510	0.1237	948.0059	421.8078	1.3698e+03	1.4246e+03	0.0400
18885	0.0036	4.6313	904.2010	274.4461	30.7539	119.1620	13.0510	0.1056	948.0059	393.7138	1.3417e+03	1.3954e+03	0.0386
18886	0.0034	24.7692	858.2016	1.4678e+03	65.6760	8.0629	12.3871	0.5650	936.2647	1.4764e+03	2.4127e+03	2.5092e+03	0.0392
18887	0.0036	25.8693	895.5147	1.5330e+03	68.5315	7.3356	12.9256	0.5901	976.9719	1.5409e+03	2.5179e+03	2.6186e+03	0.0386
18888	0.0036	23.8115	895.5147	1.4111e+03	68.5315	7.8990	12.9256	0.5431	976.9719	1.4195e+03	2.3965e+03	2.4923e+03	0.0380
18889	0.0036	12.8315	895.5147	760.3833	68.5315	25.8623	12.9256	0.2927	976.9719	786.5383	1.7635e+03	1.8341e+03	0.0390
18890	0.0034	24.8494	861.9640	1.4726e+03	65.9640	8.0890	12.4414	0.5668	940.3694	1.4812e+03	2.4216e+03	2.5184e+03	0.0394
18891	0.0036	25.9529	899.4407	1.5380e+03	68.8320	7.3593	12.9823	0.5920	981.2550	1.5459e+03	2.5272e+03	2.6282e+03	0.0388
18892	0.0036	23.8889	899.4407	1.4156e+03	68.8320	7.9247	12.9823	0.5449	981.2550	1.4241e+03	2.4054e+03	2.5016e+03	0.0381
18893	0.0036	12.8718	899.4407	762.7730	68.8320	25.9436	12.9823	0.2936	981.2550	789.0102	1.7703e+03	1.8411e+03	0.0392
18894	0.0035	6.8135	875.8849	403.7614	29.7908	63.0877	12.6423	0.1554	918.3180	467.0045	1.3853e+03	1.4407e+03	0.0380
18895	0.0035	24.9295	865.7264	1.4773e+03	66.2519	8.1151	12.4957	0.5686	944.4740	1.4860e+03	2.4305e+03	2.5277e+03	0.0395
18896	0.0035	13.7837	865.7264	816.8109	66.2519	22.1036	12.4957	0.3144	944.4740	839.2289	1.7837e+03	1.8551e+03	0.0387
18897	0.0036	26.0365	903.3667	1.5429e+03	69.1324	7.3830	13.0390	0.5939	985.5381	1.5509e+03	2.5364e+03	2.6379e+03	0.0389
18898	0.0036	23.9662	903.3667	1.4202e+03	69.1324	7.9503	13.0390	0.5466	985.5381	1.4287e+03	2.4143e+03	2.5108e+03	0.0383
18899	0.0036	12.9121	903.3667	765.1628	69.1324	26.0249	13.0390	0.2945	985.5381	791.4822	1.7770e+03	1.8481e+03	0.0393
18900	0.0035	6.8344	879.8108	405.0002	29.9243	63.2813	12.6990	0.1559	922.4341	468.4374	1.3909e+03	1.4465e+03	0.0381
18901	0.0035	6.1880	879.8108	366.6973	29.9243	79.7498	12.6990	0.1411	922.4341	446.5883	1.3690e+03	1.4238e+03	0.0405
18902	0.0035	25.0097	869.4888	1.4821e+03	66.5398	8.1412	12.5500	0.5704	948.5786	1.4908e+03	2.4393e+03	2.5369e+03	0.0397

Table 4.6 shows the outputs of the algorithm from column 65 to column 76 that describes all characteristics of the optimized distribution transformer where total loss is minimum.

Table 4.6 Outputs of the algorithm from column 65 to column 76



	65	66	67	68	69	70	71	72	73	74	75	76	77
18882	4.0763	4	2.1914e+03	2.9969e+05	9.2892e+04	1.0919e+05	2.0209e+05	5.0178e+05	1.7523e+06	47.8844	184.1663	232.0507	1
18883	3.9680	4	2.0122e+03	2.8848e+05	9.6100e+04	1.4293e+05	2.3903e+05	5.2751e+05	1.7480e+06	46.6193	257.1236	303.7428	1
18884	4.0504	4	2.0085e+03	2.9342e+05	1.0037e+05	1.7066e+05	2.7103e+05	5.6445e+05	1.7941e+06	46.6193	316.0548	362.6741	1
18885	3.9009	4	1.9941e+03	2.9534e+05	1.0291e+05	1.9870e+05	3.0162e+05	5.9696e+05	1.8074e+06	46.6193	375.6529	422.2722	1
18886	4.0912	4	3.0990e+03	3.8693e+05	8.1090e+04	4.4271e+04	1.2536e+05	5.1229e+05	1.5226e+06	44.2476	49.8330	94.0806	1
18887	4.0507	4	3.1463e+03	3.7778e+05	8.3127e+04	4.6214e+04	1.2934e+05	5.0712e+05	1.5900e+06	46.1714	52.0395	98.2109	1
18888	3.9707	4	3.0175e+03	3.6634e+05	8.2727e+04	4.8095e+04	1.3082e+05	4.9716e+05	1.5830e+06	46.1714	56.0363	102.2077	1
18889	3.9902	4	2.3891e+03	3.1950e+05	8.7436e+04	7.3953e+04	1.6139e+05	4.8089e+05	1.6354e+06	46.1714	110.9877	157.1591	1
18890	4.1062	4	3.0963e+03	3.8417e+05	8.2079e+04	4.4438e+04	1.2652e+05	5.1069e+05	1.5275e+06	44.4416	49.9943	94.4359	1
18891	4.0656	4	3.1475e+03	3.7609e+05	8.4136e+04	4.6389e+04	1.3052e+05	5.0661e+05	1.5952e+06	46.3738	52.2077	98.5815	1
18892	3.9853	4	3.0183e+03	3.6463e+05	8.3731e+04	4.8276e+04	1.3201e+05	4.9664e+05	1.5881e+06	46.3738	56.2182	102.5921	1
18893	4.0045	4	2.3871e+03	3.1744e+05	8.8486e+04	7.4212e+04	1.6270e+05	4.8014e+05	1.6405e+06	46.3738	111.3365	157.7104	1
18894	3.8527	4	2.0320e+03	2.9695e+05	9.5803e+04	1.2444e+05	2.2025e+05	5.1719e+05	1.6751e+06	45.1593	219.2992	264.4586	1
18895	4.1212	4	3.0947e+03	3.8174e+05	8.3061e+04	4.4605e+04	1.2767e+05	5.0940e+05	1.5325e+06	44.6356	50.1556	94.7912	1
18896	3.9567	4	2.4483e+03	3.3261e+05	8.6908e+04	6.5645e+04	1.5255e+05	4.8516e+05	1.5672e+06	44.6356	94.8694	139.5049	1
18897	4.0804	4	3.1495e+03	3.7464e+05	8.5138e+04	4.6563e+04	1.3170e+05	5.0634e+05	1.6003e+06	46.5763	52.3759	98.9522	1
18898	3.9999	4	3.0199e+03	3.6317e+05	8.4729e+04	4.8457e+04	1.3319e+05	4.9635e+05	1.5932e+06	46.5763	56.4002	102.9764	1
18899	4.0188	4	2.3861e+03	3.1564e+05	8.9529e+04	7.4472e+04	1.6400e+05	4.7964e+05	1.6457e+06	46.5763	111.6853	158.2616	1
18900	3.8661	4	2.0289e+03	2.9481e+05	9.6916e+04	1.2486e+05	2.2177e+05	5.1658e+05	1.6803e+06	45.3617	219.9721	265.3338	1
18901	4.0934	4	2.0151e+03	2.9555e+05	9.8414e+04	1.3967e+05	2.3808e+05	5.3363e+05	1.7094e+06	45.3617	251.4453	296.8070	1
18902	4.1363	4	3.0940e+03	3.7958e+05	8.4039e+04	4.4772e+04	1.2881e+05	5.0839e+05	1.5374e+06	44.8296	50.3169	95.1465	1

The results of the design variables from the analytically designed transformer and optimal transformer design variables found using the BFSA and GA are shown in table 4.7.

Table 4.7 Comparison of design variables

No.	**Design variables**	**Analytical**	**BFSA**	**GA**
1	Secondary number of turns	42	25	34
2	Core diameter	145	197	201

Table 4.8 Comparison of losses, percentage of impedance, and efficiency

No.	**Parameters**	**Analytical**	**BFSA**	**GA**	**Standard**
1	No load loss(W)	338.90	598.74	599.14	< 600
2	Load loss(W)	2417.60	1395.40	1490.50	< 2700
3	Total loss(W)	2756.50	1994.14	2089.64	< 3300
4	Efficiency (%)	98.64	99.01	98.96	≥ 98

The design output shows that the design variables using the analytical method are different from that of using the optimization algorithm.

Regarding the losses on the existing distribution transformers, a 338.90W no-load loss and a 2417.60W load loss thus, a total loss of 2756.50W were reported, this is an approved test report confirmed by the manufacturer EEG-PEMI by taking a sample test value of 200kVA distribution transformer delivered to the customer (as depicted in appendix 1). The designed transformer using the BFSA has a no-load loss of 598.74W and a load loss of 1395.40W, thus, a total loss of 1994.14W. The calculated percentage of short circuit impedance value 3.90% is acceptable as it is in the range of (3.6% to 4.4%) as stated on IEC 60076-1.

Figure 4.5 shows a comparison of the different designs for the total losses of the distribution transformer. The analytical design has the highest total losses. The BFSA and GA optimized designs have noticeably lower losses.

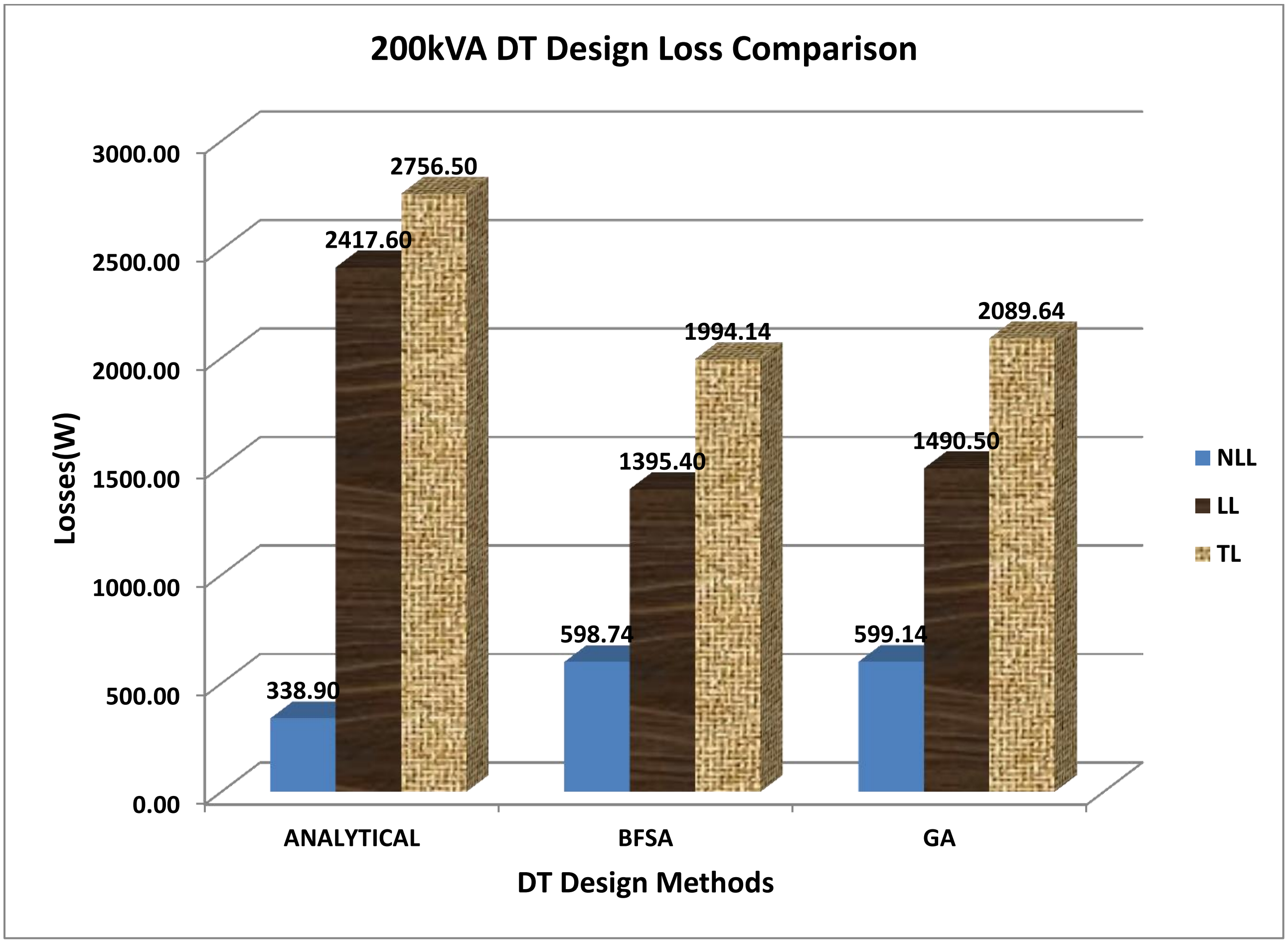


Figure 4.5 Losses comparison

Further, the optimally designed transformer has an efficiency of 99.01% which is higher than the transformer designed analytically.

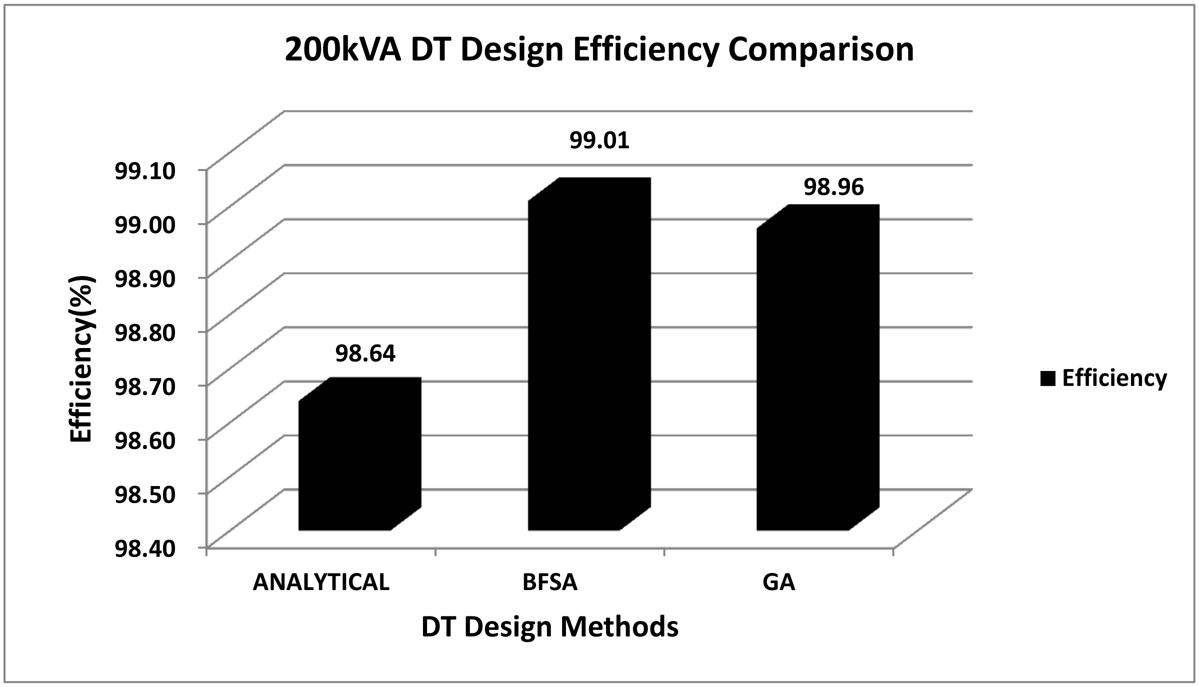


Figure 4.6 Efficiency comparison

In terms of energy saving, the optimal design using BFSA can bring 6,678.27 kWh/year (0.76236kW * 8760 h/year) savings per a single transformer.

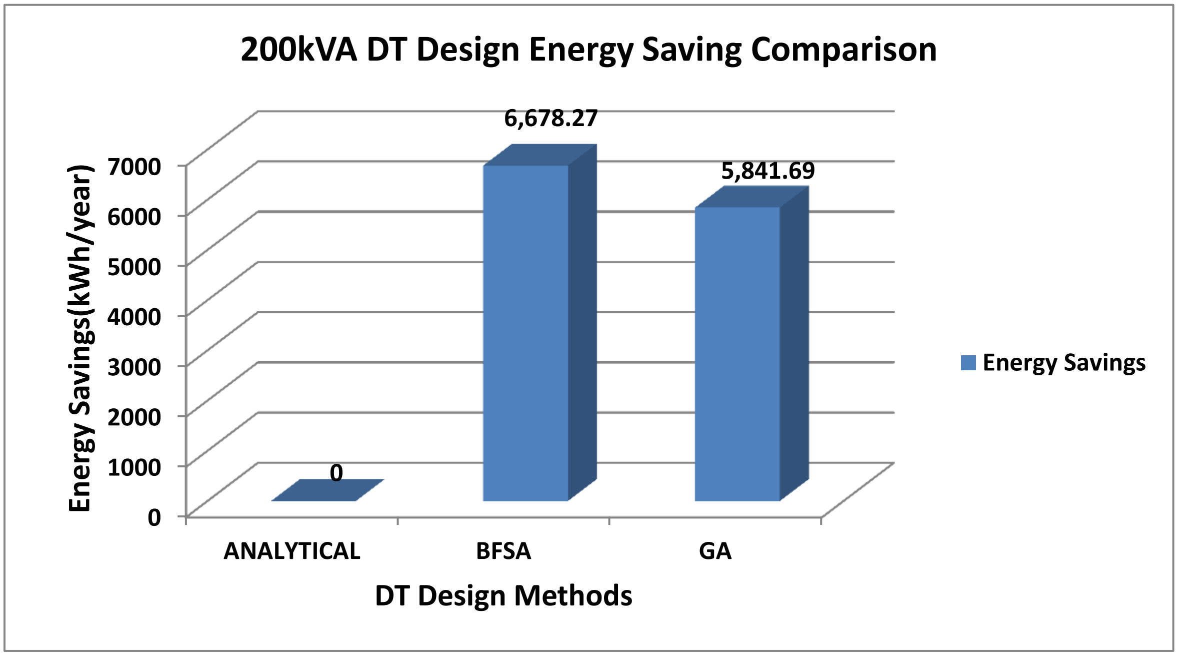


Figure 4.7 Energy saving comparison

From the results above it can be found that BFSA is the most suitable method because of:

- Its timing is competitive to other methods timing.
- It grants the optimum solution.
- It doesn’t need any additional toolboxes to run.
- It offers a lot of information; returns not only the optimum solution but also all possible accepted designs.

4.2 Cost Estimation

4.2.1 Material Cost of the Transformer designed using analytical method

The material cost (taking only major costs) of the designed distribution transformer using the analytical method is calculated in table 4.9

Table 4.9 Material cost of the designed transformer using analytical method

Material type	**Core material**	**Copper material**
Weight	370.73 Kg	516.574 Kg
Price	156.83 Birr/kg	470.56 Birr/kg
Total price	58,141.15 Birr	243,079.06 Birr
Total Material Cost	**301,220.21 Birr**	

Therefore, the designed transformer using the analytical method has a total material cost (by taking only major costs) of 301,220.21 Birr. The price does not include a few direct, indirect materials, and labour costs.

4.2.2 Total losses cost of the transformer designed using analytical method

The total losses cost of the transformer designed using the analytical method is calculated:

$$LC = (A*NLL) + (B*LL) \qquad (4.1)$$

Where,

LC is Losses cost

A factor = Cost of no load losses in Birr/W, In this case (A = 6.3 * 47.00 = 296.10) [14]

B factor = Cost of load losses in Birr/W, In this case (B = 1.8 * 47.00 = 84.60) [14]

1 USD = 47.00 Birr

NLL = No load losses in W

LL = Load losses in W

From the manufacturer EEG-PEMI given a sample test result certificate for 200kVA distribution transformer, the no-load loss is 338.90W and the load loss is 2417.60W. Hence, the total owning cost will be:

LC = (296.10*338.90) + (84.60*2417.60)

= 100,348.29 + 204,528.96

= 304,877.25 Birr

4.2.3 Total owning cost of the transformer designed using analytical method

The total owning cost is used to determine the money (Birr) value of the losses over the life of the transformer.

Total owning cost calculation [15]

$$TOC = MC + LC \qquad (4.2)$$

Where,

TOC is the total owning cost

MC is the material cost of the transformer

LC is Losses cost

From the above calculation, material cost is 301,220.21 Birr, and losses cost is 304,877.25 Birr. Thus, the total owning cost of the designed transformer using the analytical method is calculated as follows:

TOC (Analytical DT) = 301,220.21 Birr + 304,877.25 Birr

= 606,097.46 Birr

In Figure 4.3 a comparison of the different designs method for the 200 kVA distribution transformer is displayed in which the bars refer to the material, losses, and total costs. The analytical design method used by the transformer manufacturer shows to have the highest losses and total cost.

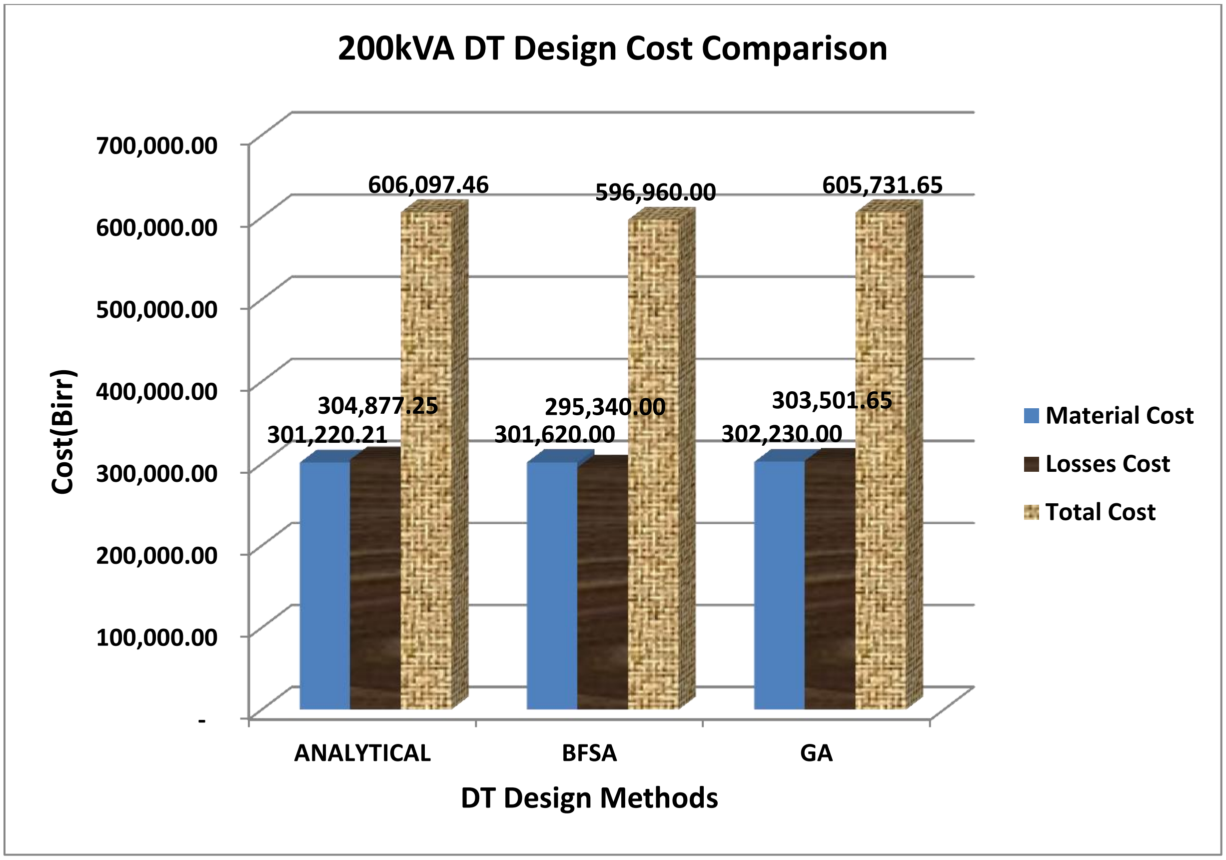


Figure 4.8 Cost comparison

Although the distribution transformer from the manufacturer EEG-PEMI has the lowest material cost, the designed distribution transformer using an optimization algorithm has the lowest total owning cost. Thus any customer who is willing to purchase the transformer should consider the total owning cost of that transformer rather than considering only the material cost. Transformer purchasing cost should be based on the total owning cost.

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This thesis considers analysis and design which gives all the acceptable solutions, design dimensions and performance parameters of a loss minimized distribution transformer. This thesis paper presented the analytical and algorithm-based design results regarding the reduction of distribution transformer losses. From the BFSA optimal design output, the no-load loss is 598.74W and the load loss is 1395.40W. The results from the optimization algorithm show that the design reduces the total losses on the existing distribution transformer selected for the study from 2756.50W to 1,994.14W by 762.36W, thus representing a percentage reduction of 27.66%. If this saving is applied to the existing 49, 200kVA distribution transformers of the Jimma town route of the case study area, the saving will be 37,355.64W. To put 37,355.64W savings into context: 37,355.64W is equivalent to 2,490 units of 15 W fluorescent light bulbs enough for 623 small houses (with 4 bulbs per house). In terms of energy saving, applying the design on the 49 distribution transformers can bring 327,235.40 kWh/year (0.76236kW * 49 * 8760 h/year). Note that, this is the saving associated with replacing only 49, 200kVA distribution transformer units. If the designed transformer is to be implemented on a larger scale across the electrical distribution networks of Ethiopia, the magnitude of savings would be huge. Moreover, the designed distribution transformer using an optimization algorithm has a slightly increased initial cost, but it has the lowest total owning cost. Thus, the design is cost-effective.

5.2 Recommendations

This thesis work does not include the design of the body/tank of the transformer. Thus, it is recommended to be included in future work for complete transformer design. The design is new and has not been tested earlier in service, thus it is further recommended if a proto-type transformer will be manufactured and the practical test would be made before undertaking commercial production.

6 REFERENCES

[1] A. Ibatullayeva, “Power Transformers in Electrical Transmission and Distribution Grids,” 2017.

[2] A. H. A. S. M. Ieee, A. Alamoudi, I. M. Senior, M. Ieee, and M. Al Bulushi, “Losses Reduction In Distribution Transformers,” vol. II, 2015.

[3] D. Li, L. Zhang, G. Li, Z. Lu, and S. Zhou, “Progress in Natural Science : Materials International Reducing the core loss of amorphous cores for distribution transformers,” Prog. Nat. Sci. Mater. Int., vol. 22, no. 3, pp. 244–249, 2012.

[4] T. Kefalas et al., “Energy Conservation by Low Loss Distribution Transformers Adapted to Load Characteristics,” no. c, pp. 1–6.

[5] M. Mohan and P. K. Singh, “distribution transformer with the Amorphous-CRGO core : an effort to reduce the cost of amorphous core distribution transformer,” vol. 7, no. 6, pp. 680–684, 2014.

[6] R. M. Sah and J. Srivastava, “Modelling And Simulation Of Distribution Transformer For Analysing The Transformer Losses Using Analytical And Simulation Method,” vol. 3, no. 3, pp. 984–987, 2013.

[7] “Design of Single and Three-phase Transformer Using MATLAB 1,3,4,” no. 2, pp. 188–193, 2014.

[8] M. Singh, M. Verma, A. Kanaujia, S. Rai, and A. Soman, “Reduction of Stray Losses in Distribution Transformer using different materials of Clamping,” pp. 5–7, 2018.

[9] Coelho, Leandro Dos S., et al. "Multiobjective optimization of transformer design using a chaotic evolutionary approach." IEEE Transactions on Magnetics 50.2 (2014): 669-672.

[10] M. Stevens, “LOT 2 : Distribution and power transformers,” no. January 2011.

[11] J. R. Lucas, I. E. E. Sri, L. Centre, J. R. Lucas, C. Lee, and S. Lanka, Historical Development of the Transformer, no. November. 2010.

[12] "Introduction to the brute force search algorithm," [Online]. Available: https://en.wikipedia.org/wiki/Brute-force_search.

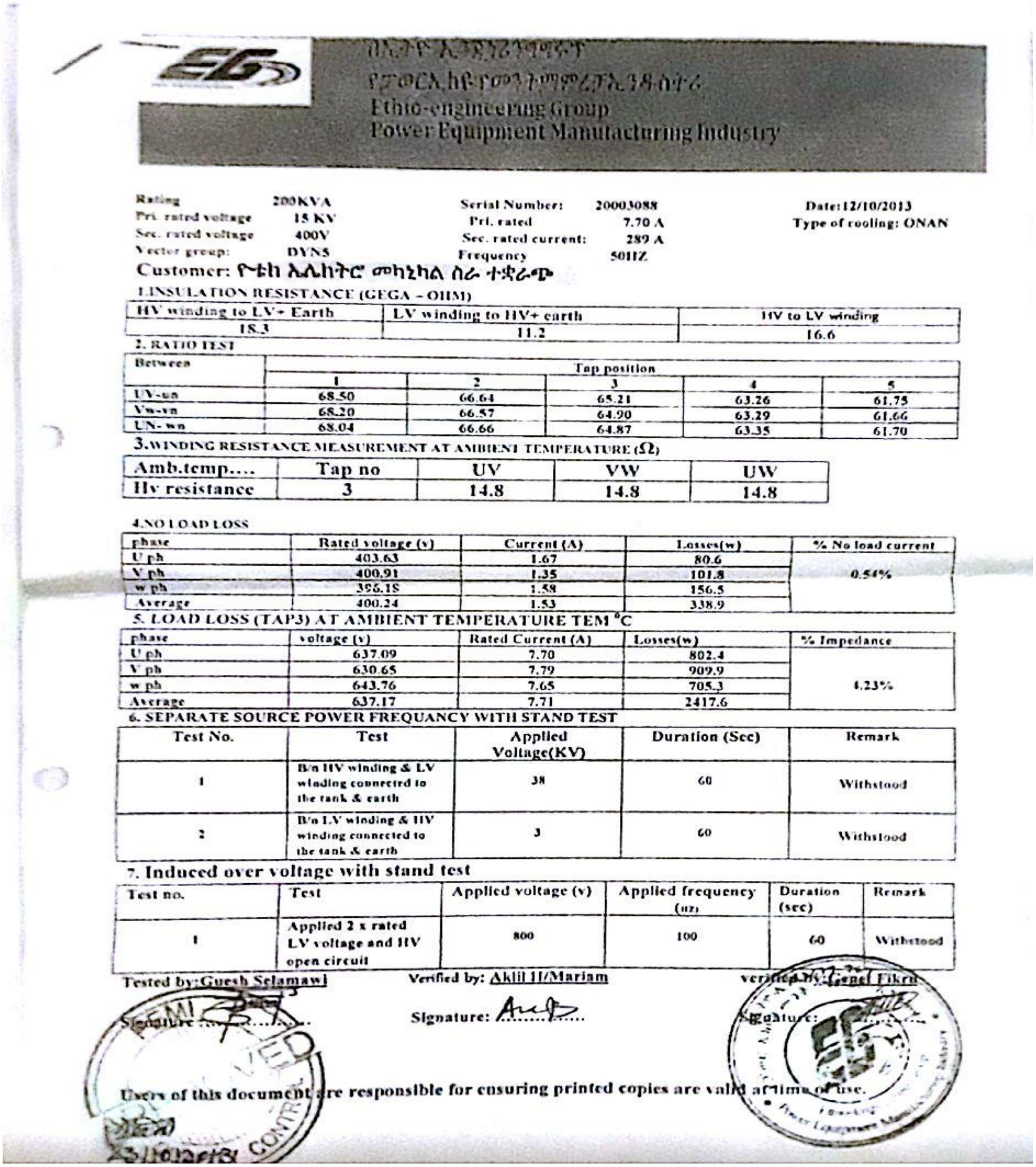
[13] I. The MathWorks, Global Optimization toolbox User's Guide, The MathWorks, Inc., 2016.

[14] J. C. Olivares et al., “Reducing losses in distribution transformers[J],” no. August 2013.

[15] O. Type, O. Immersed, and D. Transformers, “3-Phase Distribution Transformers 11 or 33 kV / 415-240V (Outdoor Type).”

7 APPENDICES

Appendix 1: Secondary data of distribution transformer from EEG-PEMI



የኢትዮ ኢንጂነሪንግ ግሩፕ
የፓወር ኢክዩፕመንት ማምረቻ ኢንዱስትሪ
Ethio-engineering Group
Power Equipment Manufacturing Industry

Rating	200KVA	Serial Number:	20003088	Date:12/10/2013	
Pri. rated voltage	15 KV	Pri. rated	7.70 A	Type of cooling: ONAN	
Sec. rated voltage	400V	Sec. rated current:	289 A		
Vector group:	DYN5	Frequency	50HZ		

Customer: የቴክ ኤሌክትሮ መካኒካል ስራ ተቋራጭ

1.INSULATION RESISTANCE (GEGA – OHM)

HV winding to LV+ Earth	LV winding to HV+ earth	HV to LV winding
18.3	11.2	16.6

2. RATIO TEST

Between	Tap position				
	1	2	3	4	5
UV-un	68.50	66.64	65.21	63.26	61.75
Vw-vn	68.20	66.57	64.90	63.29	61.66
UN- wn	68.04	66.66	64.87	63.35	61.70

3.WINDING RESISTANCE MEASUREMENT AT AMBIENT TEMPERATURE (Ω)

Amb.temp....	Tap no	UV	VW	UW
Hv resistance	3	14.8	14.8	14.8

4.NO LOAD LOSS

phase	Rated voltage (v)	Current (A)	Losses(w)	% No load current
U ph	403.63	1.67	80.6	0.54%
V ph	400.91	1.35	101.8	
w ph	396.18	1.58	156.5	
Average	400.24	1.53	338.9	

5. LOAD LOSS (TAP3) AT AMBIENT TEMPERATURE TEM °C

phase	voltage (v)	Rated Current (A)	Losses(w)	% Impedance
U ph	637.09	7.70	802.4	4.23%
V ph	630.65	7.79	909.9	
w ph	643.76	7.65	705.3	
Average	637.17	7.71	2417.6	

6. SEPARATE SOURCE POWER FREQUANCY WITH STAND TEST

Test No.	Test	Applied Voltage(KV)	Duration (Sec)	Remark
1	B/n HV winding & LV winding connected to the tank & earth	38	60	Withstood
2	B/n LV winding & HV winding connected to the tank & earth	3	60	Withstood

7. Induced over voltage with stand test

Test no.	Test	Applied voltage (v)	Applied frequency (HZ)	Duration (sec)	Remark
1	Applied 2 x rated LV voltage and HV open circuit	800	100	60	Withstood

Tested by:Guesh Selamawi
Signature: ....

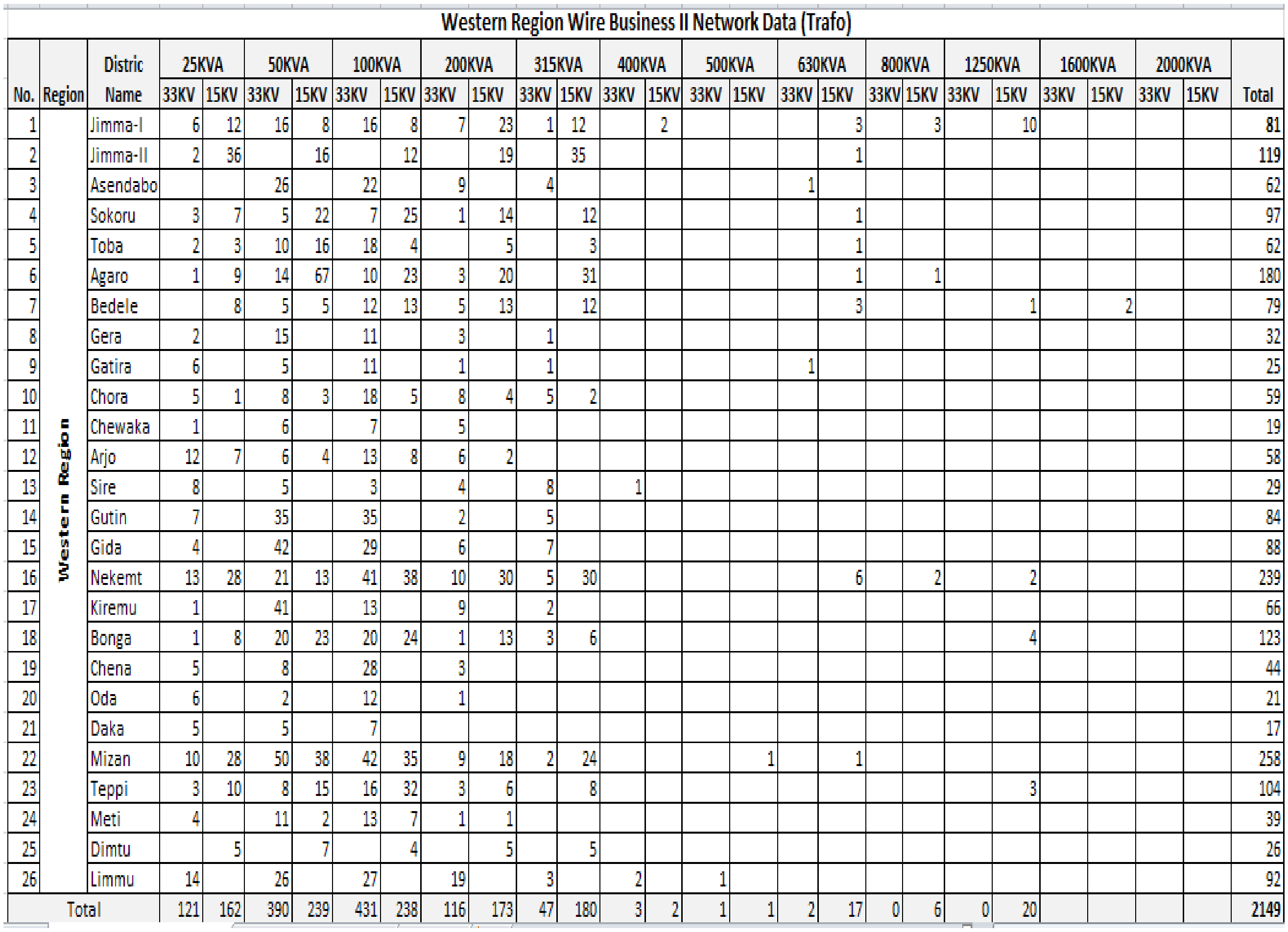
Verified by: Aklil H/Mariam
Signature: ....

verified by:Genet Fikru
Signature: ....

Users of this document are responsible for ensuring printed copies are valid at time of use.

(Source: Ethio-Engineering Group, Power Equipment Manufacturing Industry)

Appendix 2: Western Region Distribution System Transformer Data (Quantity)



Western Region Wire Business II Network Data (Trafo)

No.	Region	Distric Name	25KVA		50KVA		100KVA		200KVA		315KVA		400KVA		500KVA		630KVA		800KVA		1250KVA		1600KVA		2000KVA		Total
			33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	33KV	15KV	
1	Western Region	Jimma-I	6	12	16	8	16	8	7	23	1	12		2				3		3		10					81
2		Jimma-II	2	36		16		12		19		35						1									119
3		Asendabo			26		22		9		4						1										62
4		Sokoru	3	7	5	22	7	25	1	14		12						1									97
5		Toba	2	3	10	16	18	4		5		3						1									62
6		Agaro	1	9	14	67	10	23	3	20		31						1		1							180
7		Bedele		8	5	5	12	13	5	13		12						3				1		2			79
8		Gera	2		15		11		3		1																32
9		Gatira	6		5		11		1		1						1										25
10		Chora	5	1	8	3	18	5	8	4	5	2															59
11		Chewaka	1		6		7		5																		19
12		Arjo	12	7	6	4	13	8	6	2																	58
13		Sire	8		5		3		4		8		1														29
14		Gutin	7		35		35		2		5																84
15		Gida	4		42		29		6		7																88
16		Nekemt	13	28	21	13	41	38	10	30	5	30						6		2		2					239
17		Kiremu	1		41		13		9		2																66
18		Bonga	1	8	20	23	20	24	1	13	3	6										4					123
19		Chena	5		8		28		3																		44
20		Oda	6		2		12		1																		21
21		Daka	5		5		7																				17
22		Mizan	10	28	50	38	42	35	9	18	2	24				1		1									258
23		Teppi	3	10	8	15	16	32	3	6		8										3					104
24		Meti	4		11	2	13	7	1	1																	39
25		Dimtu		5		7		4		5		5															26
26		Limmu	14		26		27		19		3		2		1												92
Total			121	162	390	239	431	238	116	173	47	180	3	2	1	1	2	17	0	6	0	20					2149

(Source: EEU, Jimma district distribution system office)

Appendix 3: Matlab Source code for design optimization of a distribution transformer

Brute force search algorithm source code

```
clear
clc
format long
P= input('enter the KVA of the transformer______');
ff=input('enter the frequency in Hz [50]______');
if isempty(ff)==1
ff=50;
end
Vhtl= input('enter line to line voltage of the high tension side in KV [15]______');
if isempty(Vhtl)==1
Vhtl=15;
end
Vltl= input('enter line to line voltage of the low tension side in V [400]______');
if isempty(Vltl)==1
Vltl=400;
end
Cht=input('enter [0] for star or [1] delta connections at the high tension side [1] ');
if isempty(Cht)==1
Cht=1;
end
Clt=input('enter [0] for star or [1] delta connections at the low tension side [0] ');
if isempty(Clt)==1
Clt=0;
end
cd_max=input('enterthe max current density allowed [4]____');
if isempty(cd_max)==1
cd_max=4;
end
Ihtl=P*1000/(Vhtl*1000*sqrt(3));
```

```
Iltl=P*1000/(Vltl*sqrt(3));
if Cht==0
Ihtp=Ihtl; % the current on phase = the current online
Vhtp=Vhtl/(sqrt(3));
else
Vhtp=Vhtl;
Ihtp=Ihtl/(sqrt(3));
end
if Clt==0
Iltp=Iltl; % the current on phase = the current online
Vltp=Vltl/(sqrt(3));
else
Vltp=Vltl; Iltp=Iltl/(sqrt(3));
end
knee=input('enter the knee point of the CRGO steel in Tesla [1.9]_____');
if isempty(knee)==1
knee=1.9;
end
ovex=input('enter the over excitation percentage [10%]________');
if isempty(ovex)==1
ovex=10;
end
Bmax=knee/(1+(ovex/100)); % firt constraint
Bmin=input('enter the Bmin value in Tesla [1.5]___');
if isempty(Bmin)
Bmin=1.5;
end
Na=input('enter the minimum no. of secondary turns [1]________');
if isempty(Na)==1
Na=1;
end
```

```
Nb=input('enter the maximum no. of secondary turns [100]________');
if isempty(Nb)==1
Nb=100;
end
Nlt=Na:Nb; % no of low tension turns (( high ampere ))
VperT=Vltp./Nlt;
Da=input('enter the minimum core diameter [70]________');
if isempty(Da)==1
Da=70;
end
Db=input('enter the maximum core diameter [300]________');
if isempty(Db)==1
Db=300;
end
Dc=Da:Db; % possible core dia
nn=input('enter the desired number of steps for the iron core [7]_____ ');
if isempty(nn)
nn=7;
end
th=input('enter the the thickness of Si-steels sheets,press enter for [.27]____ ');
if isempty(th)==1
th=.27;
end
SFactor=input('enter the the stacking factor for Si-steels sheets,press enter for [.97]____ ');
if isempty(SFactor)==1
SFactor=.97;
end
Bf=input('enter the the building factor for core assembly,press enter for [1.15]____ ');
if isempty(Bf)==1
Bf=1.15;
end
```

```
counter=0;
S= 50 :10:280;
reply = input('press [0] if you do not have all steps,otherwise press [enter]____ ', 's');
if reply == '0'
nS = input('enter the NOT available step sizes in the form [ ____ ]');
for i= 1 : length(nS)
t= S==nS(i);
S(t)=[];
end
end
for ii= 1:length(Dc);
n=nn;
D_CORE=Dc(ii);
s=S/2;
R=Dc(ii)/2;
y=s(s<R);
if n>length(y);
n=length(y);
end
yy=sort(combnk(y,n),2,'descend');
clear f
f(:,2:(n+1))=yy(:,1:n);
f(:,1)=f(:,1)+R; % entering the first column of R
[g,k]=size(f);
a(g)=0;
for j=1 : g
for i=2 : k
att=4*f(j,i).*((R^2-f(j,i).^2).^0.5 - (R^2-f(j,i-1).^2).^0.5);
a(j)=a(j)+att;
end
end
```

```
[arxx,M]=max(a); % value and order of best area achievable
core_corners=0 ;
Ac=arxx*SFactor/1000000;
for jj=1:length(VperT);
B=VperT(jj)/(4.44*Ac*ff);
if B>=Bmin
if B<=Bmax
counter = counter+1;
T(counter,:)=[Nlt(jj) Dc(ii) B VperT(jj) Ac core_corners];
end
end
end
clear y a yy s Y YY x xx qx X qX
end
exist_T=exist ('T');
if exist_T == 1
proceed1=1;
else
proceed1=0;
end
clear foil flat round cooling_cannels ins_paper tol_Z ins_th
foil(:,[2 3])=[400 0.3
350 0.37
370 0.6
340 0.72
400 0.72
415 0.95
400 1
517 0.8
420 1.2
460 1.5
```

```
550 1.4
500 2
600 2];
foil(:,1)=(1:length(foil));
foiledit=input('enter the order of not availables in [__]');
foil(foiledit,:)=[];
foil(:,4)=foil(:,2).*foil(:,3); %area
flat(:,[2 3])=[5 2
6 2.6
8.2 2.5
5.25 4
10.5 2.6
8.2 4.6
8.4 4.6
16.4 5
14.5 6
18.8 5.4];
flat(:,1)=(1:length(flat));
flatedit=input('enter the order of not availables in [__]');
flat(flatedit,:)=[];
flat(:,4)=flat(:,2).*flat(:,3);
roundss(:,[2 3])=[0.72 0.97
0.75 0.82
0.95 1.04
1 1.08
1.25 1.333
1.3 1.385
1.7 1.791
1.8 1.916
2.24 2.333
2.4 2.518
```

```
2.5 2.631
2.65 2.7613
2.8 2.9015
2.9 3.026
3.15 3.294
3.55 3.6575
3.75 3.861
4 4.111];
roundss(:,1)=(1:length(roundss));
roundedit=input('enter the order of not availables in [__]');
roundss(roundedit,:)=[];
roundss(:,4)=(pi *(roundss(:,2)).^2)/4.; %area
if Vhtl==15
if P<=50
max_no_load_loss=225;
max_load_losses=1150;
mean_Z= 4;
elseif P<=100
max_no_load_loss=290;
max_load_losses=1650;
mean_Z=4;
elseif P<=200
max_no_load_loss=600;
max_load_losses=2700;
mean_Z=4;
elseif P<=300
max_no_load_loss=650;
max_load_losses=3550;
mean_Z=4.75;
elseif P<=500
max_no_load_loss=1100;
```

```
max_load_losses=5500;
mean_Z=4.75;
elseif P<=750
max_no_load_loss=1300;
max_load_losses=7800;
mean_Z=6;
elseif P<=1000
max_no_load_loss=1650;
max_load_losses=10500;
mean_Z=6;
elseif P<=1500
max_no_load_loss=1650;
max_load_losses=17000;
mean_Z=6;
elseif P<=2000
max_no_load_loss=1700;
max_load_losses=22100;
mean_Z=6;
else
display('You have to enter some values manually')
max_no_load_loss=input('input the maximum allowable NO LOAD LOASSES ');
max_load_losses=input('input the maximum allowable FULL LOAD LOASSES ');
mean_Z=input('input the Granteed impedance value %');
end
end
if Vhtl==33
if P<=50
max_no_load_loss=225;
max_load_losses=1150;
mean_Z= 4;
elseif P<=100
```

```
max_no_load_loss=340;
max_load_losses=1550;
mean_Z=4;
elseif P<=200
max_no_load_loss=600;
max_load_losses=2700;
mean_Z=4;
elseif P<=300
max_no_load_loss=650;
max_load_losses=3550;
mean_Z=4.75;
elseif P<=500
max_no_load_loss=765;
max_load_losses=5500;
mean_Z=4.75;
elseif P<=750
max_no_load_loss=1000;
max_load_losses=7800;
mean_Z=6;
elseif P<=1000
max_no_load_loss=1650;
max_load_losses=10500;
mean_Z=6;
elseif P<=1500
max_no_load_loss=1650;
max_load_losses=17000;
mean_Z=6;
elseif P<=2000
max_no_load_loss=1700;
max_load_losses=22100;
mean_Z=6;
```

```
else
display('You have to enter some values manually')
max_no_load_loss=input('input the maximum allowable NO LOAD LOASSES ');
max_load_losses=input('input the maximum allowable FULL LOAD LOASSES ');
mean_Z=input('input the Granteed impedance value %');
end
end
tol_Z= input('enter as nubmer, the desired design tolerance of the value of Z%, press ENTER for 4 ');
if isempty(tol_Z)==1
tol_Z=4;
end
if Vltl <= 2000 %distance between low tension coil and the core
lt_core=6;
else
lt_core=8;
end
if Vhtl <=11 % clearances
lt_ht=8;
ht_ht=10;
coil_yoke=5;
cooling_canals_d=3.1;
hrht=16;
hrlt=14;
elseif Vhtl <=22
lt_ht=10;
ht_ht=12;
coil_yoke=7;
cooling_canals_d=6.1;
hrht=20;
hrlt=16;
```

```
else
lt_ht=12;
ht_ht=20;
coil_yoke=11;
cooling_canals_d=6.1;
hrht=20;
hrlt=16;
end
% as pessimistic situation : putting worse of found
% using the catalouge values
cl=[0.1 0.00417
0.2 0.0156
0.3 0.0337
0.4 0.0581
0.5 0.0887
0.6 0.125
0.7 0.168
0.8 0.216
0.9 0.271
1 0.38
1.1 0.41
1.2 0.488
1.3 0.575
1.4 0.675
1.5 0.792
1.6 .935
1.7 1.15
1.8 1.5
1.9 1.86];
% polynomials of core losses interpolation
prc=7;
```

```
cll=polyfit(cl(:,1),cl(:,2),prc);
% assigning the value suitable loss function to the rows of Flat based on
% the core diameter
% the costs in Birr currency
NLLC=296.10;
LLC=84.60;
Si_St=156.83;
Cu=470.56;
ins_th= input('enter the insulation paper thickness to be used between layers of round wire coils,
press ENTER for[.15]___');
if isempty(ins_th)==1
ins_th=.15;
end
tic
if proceed1==1
% flat low tension side
clear sharp_e Tnew Layer_lt mech_lt TperL_lt
flat_lt=flat;
[Rowz,Columnz]=size(flat_lt);
sharp_e(Rowz,1)=0;
for u= 1 :Rowz
if flat_lt(u,3) <1.6
sharp_e(u,1)=.5;
elseif flat_lt(u,3) <2.24
sharp_e(u,1)=.65;
elseif flat_lt(u,3) <3.35
sharp_e(u,1)=.8;
else
sharp_e(u,1)=1;
end
end
```

```
flat_lt(:,4)=flat_lt(:,4)+(pi-4)*sharp_e.^2; % real area
cdlt=Iltp./(flat_lt(:,4));
flat_lt(:,5)=cdlt;
t= flat_lt(:,5)>cd_max;
flat_lt(t,:)=[];
if isempty(flat_lt)~=1
counter=1;
[Trs,Tcs]=size(T);
for i= 1:Trs
for j = 1: T(i,1); % so: j= excatly as all possible TperL values
Tnew(counter,:)=T(i,:);
TperL_lt(counter,1)=j;
counter=counter+1;
end
end
Tnew(:,7)=TperL_lt;
flat_lt(:,6)=floor((flat_lt(: , 3).*(flat_lt(: ,5)).^2).\100); % no of layers between cooling canals
t= flat_lt(:,6)<=0;
flat_lt(t,6)=1;
clear TT
Stn=size(Tnew);
Sflat_lt=size(flat_lt);
TT((Stn(1)*Sflat_lt(1)),(Stn(2)+Sflat_lt(2)+1))=0;
counter=0;
mech_lt(Stn(1)*Sflat_lt(1),1)=0;
Layer_lt(Stn(1)*Sflat_lt(1),1)=0;
for i=1:Sflat_lt(1)
for j= 1:Stn(1)
counter=counter+1;
TT(counter,:)=[flat_lt(i,:) , Tnew(j,:) , 0];
TT(counter,14)=ceil(ceil(TT(counter,7)./TT(counter,13))./TT(counter,6))-1;
```

```
mech_lt(counter,1)=(TT(counter,2)+.4).*TT(counter,13); %with the insulation paper
Layer_lt(counter,1)=ceil(TT(counter,7)./TT(counter,13)); %NO. of layers at Low Tension
if TT(counter,14)==0
TT(counter,14)=1; %no of cooling canals
end
end
end
TT=[TT mech_lt Layer_lt]; %TT now has 16 elements
ins_lt=.6; % constant for flats .2X2 +.1X2
TT(:,17)= TT(:,16).* TT(:,3)+ TT(:,16).*ins_lt+TT(:,14).*cooling_canals_d; %thickness of low tension coil
TT(:,18)= TT(:,8)+2* TT(:,17)+lt_core; % outer diameter of low tension coil
TT(:,19)=TT(:,15)+2*(hrlt); % coil height at the low tension
if isempty(TT)==1
proceed=0;
else
proceed =1;
end
% coilh_ht=coilh_lt;
% mech_ht=coilh_ht-2*hrht;
N_ht=round((TT(:,7)*Vhtp*1000/ceil(Vltp))); % mean no of high tension turns
Nx_ht=round(N_ht*1.05); % no of high tension turns at last tap
TT(:,20)=TT(:,19)-2*hrht; % mechanical height of the high tension
TT(:,21)=Nx_ht; % no of high tension turns at last tap inserted in the final solution matrix
else
proceed=0;
end
else
proceed=0;
end
if proceed ==1
```

```
% round high tension side
round_ht=roundss;
round_ht(:,4)=.25*pi*round_ht(:,2).^2;
cdht=Ihtp./round_ht(:,4);
round_ht(:,5)=cdht;
t= round_ht(:,5)>cd_max;
round_ht(t,:)=[];
if isempty(round_ht)==0
round_proceed=1;
[rTT,cTT]=size(TT);
[rround_ht,cround_ht]=size(round_ht);
clear TTT
TTT(rTT*rround_ht,cTT+cround_ht)=0;
counter=0;
for j= 1:rTT
for i=1:rround_ht
counter=counter+1;
TTT(counter,:)=[TT(j,:), round_ht(i,:)];
end
end
TTT(:,27)=floor(TTT(:,20)./TTT(:,24))-1; % turns per layer
t=TTT(:,27)<1;
TTT(t,:)=[];
TTT(:,28)=mod(TTT(:,21),TTT(:,27)); % turns per last layer
TTT(:,29)=ceil(TTT(:,21)./TTT(:,27)) ; % no of layers
TTT(:,30)= ins_th*ceil(( (4*TTT(:,27).*TTT(:,10)./8500 ) - ( TTT(:,24)-TTT(:,23)
))*(2/3)/ins_th) ; % insulation between layers
TTT(:,31)=floor((TTT(:,23).*(TTT(:,26)).^2).\100); % no of layers between cooling canals
t= TTT(:,31)<=0;
TTT(t,31)=1;
TTT(:,32)=ceil( TTT(:,29)./TTT(:,31))-1; % no of canals
```

```
t=TTT(:,32)<=0;
TTT(t,32)=1; % min number of cooling canals =1
TTT(:,33)=TTT(:,29).*TTT(:,24)+TTT(:,29).*TTT(:,30)+TTT(:,32).*cooling_canals_d; % thickness of HT coil
else
round_proceed=0;
end
else
round_proceed=0;
end
if round_proceed==1
% No load losses ::: core losses
TTT(:,34)=TTT(:,8)+lt_core; % inner dia of low tension coil
TTT(:,35)=TTT(:,18)+2*lt_ht; % inner dia of high tension coil
TTT(:,36)=TTT(:,35)+2*TTT(:,33) ;% outer dia of high tesion coil
%Note:
% the 2mm cylinder is not considered because it is included in the ht_ht clearance
% E = distance between two following limbs in the core "between centers"
TTT(:,37)=ceil(TTT(:,36)+ht_ht); %= E
TTT(:,38)=ceil(TTT(:,19)+2*coil_yoke); % H
TTT(:,39)=((TTT(:,11).*(3*TTT(:,38)+2*TTT(:,8)+4*TTT(:,37))/1e3)) *7650; % core weight
TTT(:,40)=polyval(cll,TTT(:,9)); % w/Kg losses of core
TTT(:,41)=TTT(:,39).*TTT(:,40)*Bf; % core losses
% eleminating the violanting combinations
t=(TTT(:,41))>max_no_load_loss;
TTT(t,:)=[];
if isempty(TTT)==0
R_to_Z=1;
TTT(:,42)=TTT(:,7).*Iltp./TTT(:,2); % H== ampere/ axial meter
% mean lenght of low tension coil
TTT(:,43)=(TTT(:,34)+TTT(:,34)+2*TTT(:,17))/2;
```

```
%mean length of high tension coil
TTT(:,44)=(TTT(:,35)+TTT(:,35)+2*TTT(:,33))/2;
%total length of low tension coil
TTT(:,45)=pi*TTT(:,43).*TTT(:,7);
%total length of high tension coil at normal operation __the middle tap
TTT(:,46)=pi*TTT(:,44).*round(TTT(:,21)/1.05);
%weight of low tension coil per phase
TTT(:,47)=TTT(:,45).*TTT(:,4)*8890/1e9;
%weight of high tension coil per phase with the max no of turns
TTT(:,48)=(pi*TTT(:,44).*TTT(:,21)).*TTT(:,25)*8890/1e9;
% R20 for low tension
TTT(:,49)=(TTT(:,45)./TTT(:,4))*.00001724;
% R20 for high tension
TTT(:,50)=(TTT(:,46)./TTT(:,25))*.00001724;
% R75 for low tension
TTT(:,51)=TTT(:,49)*(234.5+75)/(234.5+20);
% R75 for high tension
TTT(:,52)=TTT(:,50)*(234.5+75)/(234.5+20);
% copper resistance losses at low tension
TTT(:,53)=3*(Iltp^2)*TTT(:,51);
% copper resistance losses at high tension
TTT(:,54)=3*(Ihtp^2)*TTT(:,52);
% eddy losses at low tension coil
TTT(:,55)=(TTT(:,3).^4).*(TTT(:,16).^2).*TTT(:,53)/1e5;
% eddy losses at high tension coil
TTT(:,56)=(TTT(:,23).^4).*(TTT(:,29).^2).*TTT(:,54)/1e5;
%connection losses at low tension coil
TTT(:,57)=Iltl*TTT(:,53)/2e4;
%connection losses at high tension coil
TTT(:,58)=Ihtl*TTT(:,54)/2e4;
%load losses at low tension
```

```
TTT(:,59)=TTT(:,53)+TTT(:,55)+TTT(:,57);
%load losses at high tension
TTT(:,60)=TTT(:,54)+TTT(:,56)+TTT(:,58);
% total copper losses
TTT(:,61)= (TTT(:,59)+TTT(:,60)) ;
%total load lossses with included stray losses
TTT(:,62)=(TTT(:,61))*1.04;
t=TTT(:,62)>max_load_losses;
TTT(t,:)=[];
end
if isempty(TTT)==1
R_to_Z=0;
end
else
R_to_Z=0;
end
if R_to_Z==1
% Z is to be calculated in two diferent ways
% The first is
% Z= I * sqrt(R^2 + X^2)/E *100%
% R : at 75C :: already found
% X : (2pi)^2*u0 *f*V*I/(h*(V/N)^2) *(R1*d1/3+R2*d2/3+Rm*g)
clear Last h R1 R2 g Rm X_Reactance R75lt R75ht R75lt_total Z1 Kk Zz dm VI VR Z2
h=((.5*(TTT(:,20)+TTT(:,15)))+(TTT(:,36)-TTT(:,34))./(2*pi))*1e-3;
R1=(.5*TTT(:,34)+.5*TTT(:,17))*1e-3;
R2=(.5*TTT(:,35)+.5*TTT(:,33))*1e-3;
g=.5*1e-3*(TTT(:,35)-TTT(:,18));
Rm=.5*((TTT(:,18)*1e-3)+g);
TTT(:,63)=((4*(pi)^2)*(4*pi*1e-7)*ff*Vltp*Iltp./((TTT(:,10).^2).*h))
.*(R1.*TTT(:,17)/3000+R2.*TTT(:,33)/3000+Rm.*g); % X Reactance
X_Reactance=TTT(:,63);
```

```
R75lt=TTT(:,51);
R75ht=TTT(:,52);
R75lt_total=R75lt.*(TTT(:,45)/1000)./(TTT(:,4)/1000000);
R_resistance=(R75lt+(R75ht/((Vhtp*1000/Vltp)^2)))*Iltp/(Vltp);
%Method 1
Z1=100*sqrt(X_Reactance.^2+R_resistance.^2);
% Method 2
Kk=1-(TTT(:,17)+lt_ht+TTT(:,33))./(10*pi*.1*TTT(:,15));
Zz=(lt_ht/10)+((TTT(:,17)+TTT(:,33))/30);
dm=(lt_ht+TTT(:,18))/10;
VI=Iltp*TTT(:,7).*Kk.*Zz.*dm./(806*.1*TTT(:,15).*TTT(:,10));
VR=(TTT(:,62)+TTT(:,41))/(10*P); % uses a the total losses as in Sudatraf excel files
Z2=sqrt(VI.^2+VR.^2);
% Method 3
% Z= Iltp * sqrt(R75lt.^2 + X_Reactance.^2)./Vltp * 100;
if zs==1
Z2=mean_Z;
end
if zs==2
Z1=mean_Z;
end
TTT(:,64)=Z1;
TTT(:,65)=Z2;
Last=TTT;
t=Last(:,64)>(1+tol_Z/100)*mean_Z;
Last(t,:)=[];
if isempty(Last)==0
t=Last(:,64)<(1-tol_Z/100)*mean_Z;
Last(t,:)=[];
if isempty(Last)==0
% To make the two types of Z in the range of stds as below
```

```
t=Last(:,65)>(1+tol_Z/100)*mean_Z;
Last(t,:)=[];
if isempty(Last)==0
t=Last(:,65)<(1-tol_Z/100)*mean_Z;
Last(t,:)=[];
if isempty(Last)==0
Last(:,66)=Last(:,62)+ Last(:,41); % Total TR losses
Last(:,67)=LLC*Last(:,62)+ NLLC*Last(:,41); %Cost of losses
Last(:,68)=Si_St*Last(:,39); % Core material Costs
Last(:,69)=Cu*(3*Last(:,47)+3*Last(:,48));% Copper material costs
Last(:,70)=Last(:,68)+Last(:,69); % Total materials cost si-st core and copper
Last(:,71)=Last(:,70)+Last(:,67); % Total Costs(Materials cost + Losses cost)
%Total length of high tension coil
Last(:,72)=pi*Last(:,44).*Last(:,21);
% Total weight of lt copper
Last(:,73)=3*Last(:,47);
% Total weight of Ht copper
Last(:,74)=3*Last(:,48);
% Total weight of copper in TR
Last(:,75)=Last(:,73)+Last(:,74);
Last(:,76)=1;
Last(:,77)=0;
R_Final=1;
else R_Final=0;
end
else R_Final=0;
end
else R_Final=0;
end
else R_Final=0;
end
```

```
else
R_Final=0;
end
clear
clc
design
stds
lt_flat
ht_round_2
losses_round_2
display('What Z% do you want to use : 1:using IR,IX , 2:using VI,VR Z, 3: Both of two Z must be in range')
zs=input('enter the no. of desired way of Z% calculation, or press ENTER for option no 1');
if isempty(zs)
zs=1;
end
Z_round_2
clc
if R_Final==0
Last=0;
display('NO SOLUTION FOUND')
end
ord= size(Last);
order={1:ord(1)}';
Last=[order,Last];
openvar('Last')
[min_total_loss, raw_order]=min(Last(:,67));
min_total_loss;
Char_of_min_total_loss= Last(raw_order,:);
[best_cost,raw_order]=min(Last(:,72));
best_cost;
```

```
Char_of_best= Last(raw_order,:);
time_end2=toc;
time_elapsed_Min_Sec=mod(time_end2,60);
clear
clc
design
stds
lt_flat
ht_round_2
losses_round_2
display('What Z% do you want to use : 1:using IR,IX ,2:using VI,VR Z, 3: Both of two Z must be in range')
zs=input('enter the no. of desired way of Z% calculation,or press ENTER for option no 1');
if isempty(zs)
zs=1;
end
z_round_2
clc
if R_Final==0
Last=0;
display('NO SOLUTION FOUND')
end
ord= size(Last);
order=[1:ord(1)]';
Last=[order,Last];
openvar('Last')
[min_total_loss, raw_order]=min(Last(:,67));
min_total_loss
display('Watt')
Char_of_min_total_loss= Last(raw_order,:)
[best_cost,raw_order]=min(Last(:,72));
```

```
best_cost;
display('Birr');
Char_of_best= Last(raw_order,:);
time_end2=toc;
time_elapsed_Min_Sec=mod(time_end2,60)
```

Genetic algorithm source code

```
Rated_Power_KVA = 100;
Frequency_HZ=50;
Line_Voltage_high_tension= 11;
Line_Voltage_low_tension= 433;
Connection_high_tension=1;% 1 for delta, 0 for star
Connection_low_tension=0;% 1 for delta, 0 for star
max_current_densit=4;
Line_current_high_tension=Rated_Power_KVA*1000/(Line_Voltage_high_tension*1000*sqrt(3));
Line_current_low_tension=Rated_Power_KVA*1000/(Line_Voltage_low_tension*sqrt(3));
if Connection_low_tension==0
phase_current_low_tension=Line_current_low_tension;
% the current on phase = the current on line
phase_Voltage_low_tension=Line_Voltage_low_tension/(sqrt(3));
else
phase_Voltage_low_tension=Line_Voltage_low_tension;
phase_current_low_tension=Line_current_low_tension/(sqrt(3));
end
if Connection_high_tension==0
phase_current_high_tension=Line_current_high_tension; % the current on phase = the current on line
```

```
phase_Voltage_high_tension=Line_Voltage_high_tension/(sqrt(3));
else
phase_Voltage_high_tension=Line_Voltage_high_tension;
phase_current_high_tension=Line_current_high_tension/(sqrt(3));
end
LT_No_Turns=s(1);
Core_Diameter=s(2);
Flat_Order=s(3);
Round_order=s(4);
LT_Turn_per_layer=s(5);
knee_point_Si_Steel=1.9;
over_exciting_perentage=10;
max_B_allowed=knee_point_Si_Steel/(1+(over_exciting_perentage/100)) ; % firt constraint
min_B_allowed=1.5;
Stacking_factor=.96;
Building_factor=1.15;
available_Si_Steel_sizes=[50,60,70,80,90,100,110,120,130,140,150,160,170,180,190,200,210,220,230,240,250,260,270,280];
n_NO_Core_steps=7;
Thickness_Si_Steel_sheets=0.27;
insulator_thickness_LT_layers=.6;
HT_insulator_thickness=.15;
%Area_full_set;
tol_z=2;
if Line_Voltage_high_tension==15
if Rated_Power_KVA<=50 ;
max_no_load_loss=225;
max_load_losses=1150 ;
mean_Z= 4;
elseif Rated_Power_KVA<=100
max_no_load_loss=290;
```

```
max_load_losses=1650;
mean_Z=4;
elseif Rated_Power_KVA<=200
max_no_load_loss=600;
max_load_losses=2700;
mean_Z=4;
elseif Rated_Power_KVA<=300
max_no_load_loss=650;
max_load_losses=3550;
mean_Z=4.75;
elseif Rated_Power_KVA<=500;
max_no_load_loss=1100;
max_load_losses=5500;
mean_Z=4.75;
elseif Rated_Power_KVA<=750
max_no_load_loss=1300;
max_load_losses=7800;
mean_Z=6;
elseif Rated_Power_KVA<=1000
max_no_load_loss=1650;
max_load_losses=10500;
mean_Z=6;
elseif Rated_Power_KVA<=1500;
max_no_load_loss=1650;
max_load_losses=17000;
mean_Z=6;
elseif Rated_Power_KVA<=2000;
max_no_load_loss=1700;
max_load_losses=22100;
mean_Z=6;
end
```

```
end
if Line_Voltage_high_tension==33
if Rated_Power_KVA<=50
max_no_load_loss=225;
max_load_losses=1150 ;
mean_Z= 4;
elseif Rated_Power_KVA<=100
max_no_load_loss=340;
max_load_losses=1550;
mean_Z=4;
elseif Rated_Power_KVA<=200
max_no_load_loss=600;
max_load_losses=2700;
mean_Z=4;
elseif Rated_Power_KVA<=300
max_no_load_loss=650;
max_load_losses=3550;
mean_Z=4.75;
elseif Rated_Power_KVA<=500
max_no_load_loss=765;
max_load_losses=5500;
mean_Z=4.75;
elseif Rated_Power_KVA<=750
max_no_load_loss=1000;
max_load_losses=7800;
mean_Z=6;
elseif Rated_Power_KVA<=1000;
max_no_load_loss=1650;
max_load_losses=10500;
mean_Z=6;
elseif Rated_Power_KVA<=1500;
```

```
max_no_load_loss=1650;
max_load_losses=17000;
mean_Z=6;
elseif Rated_Power_KVA<=2000;
max_no_load_loss=1700;
max_load_losses=22100;
mean_Z=6;
end
end
if Line_Voltage_low_tension <= 2000 %distance between low tension coil and the core
LT_Core_clearance=6;
else
LT_Core_clearance=8;
end
if Line_Voltage_high_tension <=11 % clearances
LT_HT_clearance=8;
HT_HT_clearance=10;
Coil_Yoke_clearance=5;
cooling_canals_diameter=3.1;
Side_Ring_clearance_HT=16;
Side_Ring_clearance_LT=14;
elseif Line_Voltage_high_tension <=22
LT_HT_clearance=10;
HT_HT_clearance=12;
Coil_Yoke_clearance=7;
cooling_canals_diameter=6.1;
Side_Ring_clearance_HT=20;
Side_Ring_clearance_LT=16;
else
LT_HT_clearance=12;
HT_HT_clearance=20;
```

```
Coil_Yoke_clearance=11;
cooling_canals_diameter=6.1;
Side_Ring_clearance_HT=20;
Side_Ring_clearance_LT=16;
end
core_losses_chart=[0.1 0.00417
0.2 0.0156
0.3 0.0337
0.4 0.0581
0.5 0.0887
0.6 0.125
0.7 0.168
0.8 0.216
0.9 0.271
1 0.38
1.1 0.41
1.2 0.488
1.3 0.575
1.4 0.675
1.5 0.792
1.6 .935
1.7 1.15
1.8 1.5
1.9 1.86];
% polynomials of core losses interpolation
prc=7;
cll=polyfit(core_losses_chart(:,1),core_losses_chart(:,2),prc);
% assigning the value suitable loss function to the rows of Flat based on
% the core diameter
% the costs in Birr currency
No_Load_loss_Cost=296.10;
```

```
Load_loss_Cost=84.60;
Si_Steel_cost=156.83;
Copper_cost=470.56;
flat=[5 2 .65 14.5
6 2.6 .8 14.5
8.2 2.5 .8 14.5
5.25 4 1 14.5
10.5 2.6 .8 14.5
8.2 4.6 1 14.5
8.4 4.6 1 14.5
16.4 5 1 14.5
14.5 6 1 14.5
18.8 5.4 1 14.5];
% Area flat
flat(Flat_Order,5)=(flat(Flat_Order,1).*flat(Flat_Order,2))+(pi-4)*(flat(Flat_Order,3).^2);
%Flat_Order integer from 1 - length (flat)
Flat_wire_Section_area=flat(Flat_Order,5);
Flat_wire_Current_density=phase_current_low_tension/Flat_wire_Section_area;
price_cu_lt_per_kg=flat(Flat_Order,4);
rounds=[0.72 0.97 14.5
0.75 0.82 14.5
0.95 1.04 14.5
1 1.08 14.5
1.25 1.333 14.5
1.3 1.385 14.5
1.7 1.791 14.5
1.8 1.916 14.5
2.24 2.333 14.5
2.4 2.518 14.5
2.5 2.631 14.5
2.65 2.7613 14.5
```

```
2.8 2.9015 14.5
2.9 3.026 14.5
3.15 3.294 14.5
3.55 3.6575 14.5
3.75 3.861 14.5
4 4.111 14.5];
rounds(Round_order,4)=(pi *(rounds(Round_order,1)).^2)/4.;
%Round_order integer from 1 - length (round)
Round_wire_Section_area=rounds(Round_order,4);
price_cu_ht_per_kg=rounds(Round_order,3);
Round_wire_Current_density=phase_current_high_tension/Round_wire_Section_area;
% integer from 1 to 100
Voltage_per_Turn=phase_Voltage_low_tension/s(1);
best_AREA=A_Areas(Core_Diameter-69,n_NO_Core_steps-3);
Core_Cross_Section_Area=best_AREA*Stacking_factor/1000000;
B=Voltage_per_Turn/(4.44*Core_Cross_Section_Area*Frequency_HZ);
LT_No_layer_between_cooling_canals=floor((flat(Flat_Order,2).*(Flat_wire_Current_density.^2).\100));
%no_layer_between_cooling_canals
if LT_No_layer_between_cooling_canals <= 0
LT_No_layer_between_cooling_canals = 1;
end
LT_No_cooling_canals=ceil(ceil(LT_No_Turns./LT_Turn_per_layer)./LT_No_layer_between_cooling_canals)-1; % Qty. of cooling canals
if LT_No_cooling_canals <= 0
LT_No_cooling_canals = 1;
end
LT_mechanical_height=(flat(Flat_Order,1)+.4).*LT_Turn_per_layer;
LT_No_layer=ceil(LT_No_Turns./LT_Turn_per_layer); % NO. of layers at Low Tension
```

```
LT_coil_Thickness=LT_No_layer* flat(Flat_Order,2)+LT_No_layer*insulator_thickness_LT_layers+LT_No_cooling_canals.*cooling_canals_diameter; %thickness of low tension coil
LT_outer_diameter = Core_Diameter + 2* LT_coil_Thickness+LT_Core_clearance; % outer diameter of low tension coil
LT_coil_height= LT_mechanical_height +2*(Side_Ring_clearance_LT); % coil height at the low tension
HT_No_turns_middle_tap=round((LT_No_Turns*phase_Voltage_high_tension*1000/ceil(phase_Voltage_low_tension))); %mean no of high tension turns
HT_No_turns_last_tap=round(HT_No_turns_middle_tap*1.05); %no of high tension turns at last tap
HT_mechanical_height=LT_coil_height -2*Side_Ring_clearance_HT; % mechanical height of the high tension
HT_Turn_per_layer=floor(HT_mechanical_height./rounds(Round_order,2))-1; % turns per layer
HT_Turn_per_last_layer =mod(HT_No_turns_last_tap,HT_Turn_per_layer); %turns per last layer
HT_No_layer=ceil(HT_No_turns_last_tap/HT_Turn_per_layer);
% no of layers
HT_total_insulator_thickness_layers =HT_insulator_thickness *ceil(((4*HT_Turn_per_layer.*Voltage_per_Turn./8500) -(rounds(Round_order,2)-rounds(Round_order,1)))*(2/3)/HT_insulator_thickness) ; %insulation between layers
HT_No_layer_between_cooling_canals=floor((rounds(Round_order,1).*(Round_wire_Current_density).^2).\100); % no of layers between cooling canals
if HT_No_layer_between_cooling_canals<=0
HT_No_layer_between_cooling_canals=1;
end
HT_No_cooling_canals =ceil(HT_No_layer./HT_No_layer_between_cooling_canals)-1; % no of canals
if HT_No_cooling_canals <=0
HT_No_cooling_canals =1; % min number of cooling canals=1
end
```

```
HT_coil_Thickness=HT_No_layer.*rounds(Round_order,2)+HT_No_layer.*HT_total_insulator_thickness_layers+HT_No_cooling_canals.*cooling_canals_diameter; % thickness of HT coil
LT_inner_diameter =Core_Diameter+LT_Core_clearance; % inner dia of low tension coil
HT_inner_diameter =LT_outer_diameter+2*LT_HT_clearance; %inner dia of high tension coil
HT_outer_diameter =HT_inner_diameter+2*HT_coil_Thickness ;%outer dia of high tesion coil
E =ceil(HT_outer_diameter+HT_HT_clearance); %= E
H =ceil(LT_coil_height+2*Coil_Yoke_clearance); % H
Core_weight =((Core_Cross_Section_Area.*(3*H +2*Core_Diameter +4*E )/1e3))*7650; % core weight
Core_loss_per_kg =polyval(cll,B); % w/Kg losses of core
Core_total_loss=Core_loss_per_kg*Core_weight*Building_factor; % core losses
% mean dia of low tension coil
LT_mean_diameter=(LT_inner_diameter+LT_outer_diameter)/2;
%mean dia of high tension coil
HT_mean_diameter=(HT_inner_diameter+HT_outer_diameter)/2;
%total length of low tension coil
LT_total_wire_length_per_phase=pi*LT_mean_diameter.*LT_No_Turns;
%total length of high tension coil at normal operation __the middle tap
HT_total_wire_length_per_phase_middle_tap=pi*HT_mean_diameter.*HT_No_turns_middle_tap;
%total length of high tension coil at __ the Last tap
HT_total_wire_length_per_phase_Last_tap=pi*HT_mean_diameter.*HT_No_turns_last_tap;
%weight of low tension coil per phase
LT_copper_weight_per_phase=LT_total_wire_length_per_phase.*Flat_wire_Section_area*8890/1e9;
%weight of high tension coil per phase with the max no of turns
HT_copper_weight_per_phase_Last_tap=HT_total_wire_length_per_phase_Last_tap.*Round_wire_Section_area*8890/1e9;
% R20 for low tension
LT_R20=(LT_total_wire_length_per_phase./Flat_wire_Section_area)*.00001724;
% R20 for high tension
```

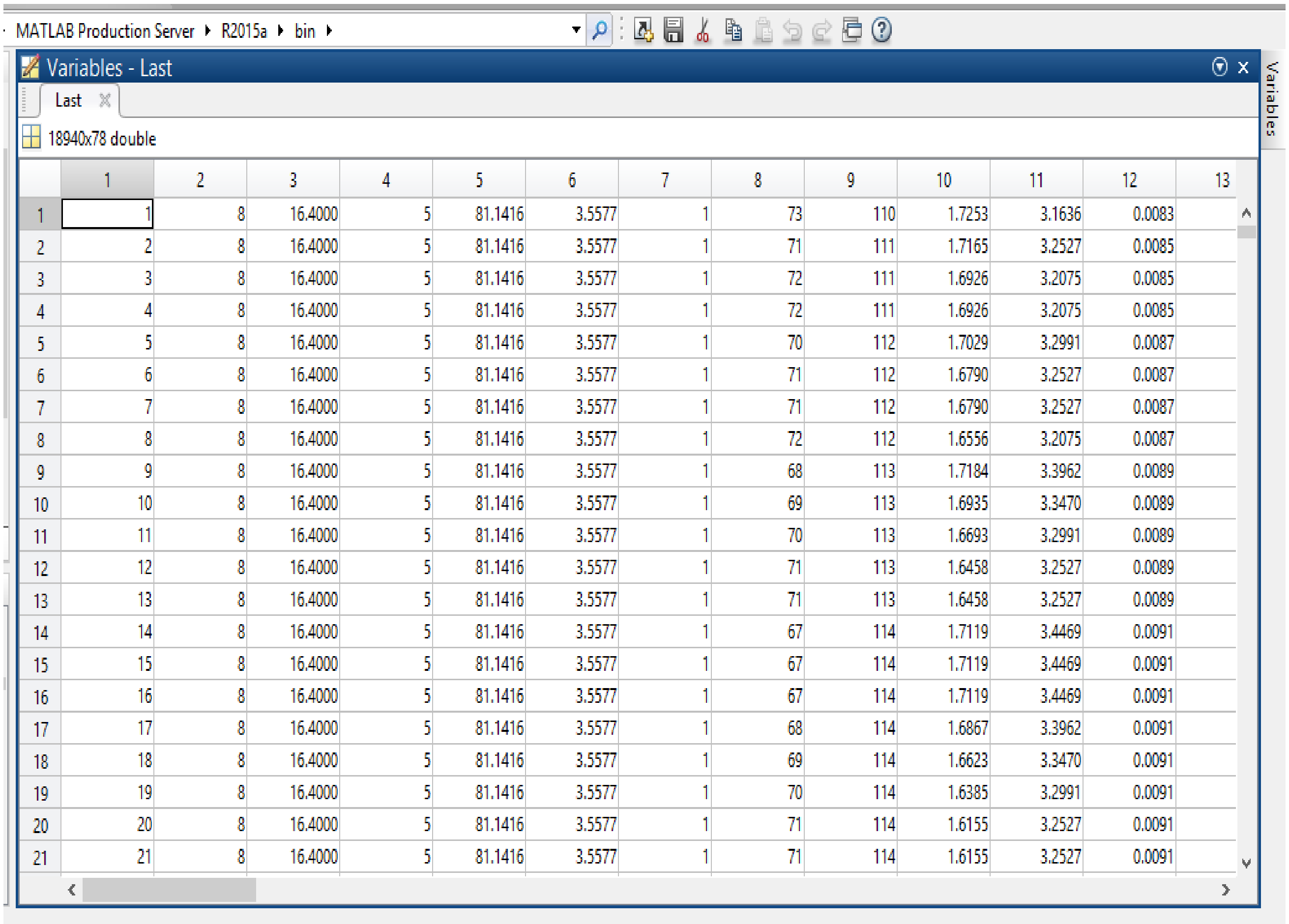
```
HT_R20=(HT_total_wire_length_per_phase_middle_tap./Round_wire_Section_area)*.00001724;
% R75 for low tension
LT_R75=LT_R20*(234.5+75)/(234.5+20);
% R75 for high tension
HT_R75=HT_R20*(234.5+75)/(234.5+20);
% copper resistance losses at low tension
LT_Resistance_losses=3*(phase_current_low_tension^2)*LT_R75;
% copper resistance losses at high tension
HT_Resistance_losses=3*(phase_current_high_tension^2)*HT_R75;
% eddy losses at low tension coil
LT_eddy_losses=(flat(Flat_Order,2).^4).*(LT_No_layer.^2).*LT_Resistance_losses/1e5;
% eddy losses at high tension coil
HT_eddy_losses=((rounds(Round_order,1).^4).*(HT_No_layer.^2).*HT_Resistance_losses)/1e5;
%connection losses at low tension coil
LT_connection_losses=Line_current_low_tension*LT_Resistance_losses/2e4;
%connection losses at high tension coil
HT_connection_losses=Line_current_high_tension*HT_Resistance_losses/2e4;
%load losses at low tension
LT_Load_losses=LT_Resistance_losses+LT_eddy_losses+LT_connection_losses;
%load losses at high tension
HT_Load_losses=HT_Resistance_losses+HT_eddy_losses+HT_connection_losses;
% total copper losses
sum_Load_Losses= (LT_Load_losses+HT_Load_losses) ;
%total load lossses with included stray losses
Total_Load_Losses=sum_Load_Losses*1.04;
%Method 1
h=(.5*(HT_mechanical_height+LT_mechanical_height)+(HT_outer_diameter-LT_inner_diameter)./(2*pi))*1e-3;
R1=(.5*LT_inner_diameter+.5*LT_coil_Thickness)*1e-3;
```

```
R2=(.5*HT_inner_diameter+.5*HT_coil_Thickness)*1e-3;
g=.5*1e-3*(HT_inner_diameter-LT_outer_diameter);
Rm=.5*((LT_outer_diameter*1e-3)+g);
Reactance=((4*(pi)^2)*(4*pi*1e-7)*Frequency_HZ*phase_Voltage_low_tension*phase_current_low_tension./((Voltage_per_Turn.^2).*h)).*(R1.*LT_coil_Thickness/3000+R2.*HT_coil_Thickness/3000+Rm.*g); % X Reactance
Resistance=(LT_R75+(HT_R75/((phase_Voltage_high_tension*1000/phase_Voltage_low_tension)^2)))*phase_current_low_tension/(phase_Voltage_low_tension);
Zpercentage=100*sqrt(Reactance.^2+Resistance.^2);
%Method 2
Kk=1-(LT_coil_Thickness+LT_HT_clearance+HT_coil_Thickness)./(10*pi*.1*LT_mechanical_height);
Zz=(LT_HT_clearance/10)+((LT_coil_Thickness+HT_coil_Thickness)/30);
dm=(LT_HT_clearance+LT_outer_diameter)/10;
VI=phase_current_low_tension*LT_No_Turns.*Kk.*Zz.*dm./(806*.1*LT_mechanical_height.*Voltage_per_Turn);
VR=(Total_Load_Losses+Core_total_loss)/(10*Rated_Power_KVA);
Zpercentage2=sqrt(VI^2+VR^2);
%total length of high tension coil
HT_total_wire_length_last_tap=pi*HT_mean_diameter.*HT_No_turns_last_tap;
Total_losses=Core_total_loss+Total_Load_Losses; % total TR losses
losses_cost=Load_loss_Cost*Total_Load_Losses+No_Load_loss_Cost*Core_total_loss; %Cost of losses
core_cost=Si_Steel_cost*Core_weight; % core material Costs
copper_cost=(3*price_cu_lt_per_kg*LT_copper_weight_per_phase+3*price_cu_ht_per_kg*HT_copper_weight_per_phase_Last_tap);% copper costs
Total_material_cost=core_cost+copper_cost; % total materials cost si-st and copper
TR_Total_cost=(Total_material_cost+losses_cost); % TOTAL COSTS MATERIALS + LOSSES
```

```
% total weight of lt copper
LT_total_copper_weight=3*LT_copper_weight_per_phase;
% total weight of Ht copper
HT_total_copper_weight=3*HT_copper_weight_per_phase_Last_tap;
% total weight of copper in TR
TR_total_copper_weight=HT_total_copper_weight+LT_total_copper_weight;
format long
available_Si_Steel_sizes=[50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
220 230 240 250 260 270 280];
minimum_core_D=70;
maximum_core_D=300;
A_Areas(maximum_core_D-minimum_core_D+1,7)=0;
A_Areas(:,1)=[minimum_core_D:maximum_core_D]'
r_row=1;
c_counter=1
for Core_Diameter=minimum_core_D:maximum_core_D
c_column=2;
for n_NO_Core_steps= 5:10
best_AREA=coresteps_sub_prog(Core_Diameter,available_Si_Steel_sizes,n_NO_Core_steps);
A_Areas(r_row,c_column)=best_AREA;
c_column=c_column+1;
c_counter=c_counter+1
end
r_row=r_row+1;
end
function [C,Ceq]= conns_flat_round(s)
s=round(s);
formulae_tr_design_flat_round;
C1=B-max_B_allowed;
C2= min_B_allowed-B;
C3= Round_wire_Current_density-max_current_densit;
```

```
C4= Flat_wire_Current_density-max_current_densit;
C5= Total_Load_Losses-max_load_losses;
C6= Core_total_loss-max_no_load_loss;
C7=-1*Zpercentage +(1-tol_z/100)*mean_Z;
C8=Zpercentage - (1+tol_z/100)*mean_Z;
C9=-1*Zpercentage2 +(1-tol_z/100)*mean_Z;
C10=Zpercentage2 - (1+tol_z/100)*mean_Z;
C11=s(5)-s(1);
C=[C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11]';
Ceq=[];
end
function TR_Total_cost=designee_flat_round(s)
s=round(s);
formulae_tr_design_flat_round;
clear
format long
tic
n=5;
opts = gaoptimset('StallGenLimit',500,'TolFun',1e-100,'Generations',300);
[ga_x,fval_ga,flag,outpuuts]=ga(@designee_flat_round,n,[],[],[],[],[1 70 1 1 1 ],[100 300 10 18
100],@conns_flat_round,[1 2 3 4 5],opts)
s=ga_x;
formulae_tr_design_flat_round;
toc
```

Appendix 4: Sample outputs of transformer design optimization algorithm



	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	8	16.4000	5	81.1416	3.5577	1	73	110	1.7253	3.1636	0.0083	
2	2	8	16.4000	5	81.1416	3.5577	1	71	111	1.7165	3.2527	0.0085	
3	3	8	16.4000	5	81.1416	3.5577	1	72	111	1.6926	3.2075	0.0085	
4	4	8	16.4000	5	81.1416	3.5577	1	72	111	1.6926	3.2075	0.0085	
5	5	8	16.4000	5	81.1416	3.5577	1	70	112	1.7029	3.2991	0.0087	
6	6	8	16.4000	5	81.1416	3.5577	1	71	112	1.6790	3.2527	0.0087	
7	7	8	16.4000	5	81.1416	3.5577	1	71	112	1.6790	3.2527	0.0087	
8	8	8	16.4000	5	81.1416	3.5577	1	72	112	1.6556	3.2075	0.0087	
9	9	8	16.4000	5	81.1416	3.5577	1	68	113	1.7184	3.3962	0.0089	
10	10	8	16.4000	5	81.1416	3.5577	1	69	113	1.6935	3.3470	0.0089	
11	11	8	16.4000	5	81.1416	3.5577	1	70	113	1.6693	3.2991	0.0089	
12	12	8	16.4000	5	81.1416	3.5577	1	71	113	1.6458	3.2527	0.0089	
13	13	8	16.4000	5	81.1416	3.5577	1	71	113	1.6458	3.2527	0.0089	
14	14	8	16.4000	5	81.1416	3.5577	1	67	114	1.7119	3.4469	0.0091	
15	15	8	16.4000	5	81.1416	3.5577	1	67	114	1.7119	3.4469	0.0091	
16	16	8	16.4000	5	81.1416	3.5577	1	67	114	1.7119	3.4469	0.0091	
17	17	8	16.4000	5	81.1416	3.5577	1	68	114	1.6867	3.3962	0.0091	
18	18	8	16.4000	5	81.1416	3.5577	1	69	114	1.6623	3.3470	0.0091	
19	19	8	16.4000	5	81.1416	3.5577	1	70	114	1.6385	3.2991	0.0091	
20	20	8	16.4000	5	81.1416	3.5577	1	71	114	1.6155	3.2527	0.0091	
21	21	8	16.4000	5	81.1416	3.5577	1	71	114	1.6155	3.2527	0.0091	