OPTIMAL DESIGN OF A DISTRIBUTION TRANSFORMER USING ARTIFICIAL INTELLIGENCE TECHNIQUES

BY

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Dedication

To My Lovely Family

My Parents

For their continuous support, patience and advice

My sister Hiba and brother Maher

For believing in me and encouraging me throughout my research

And to my friend and brother in law Nicholas Paseiro for his positivity and confidence

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ABSTRACT

Full Name : Malek Ahmad Habli

Thesis Title : [Optimal Design of a Distribution Transformer Using Artificial Intelligence Techniques]

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A distribution transformer is one of the most important components in a power system network. In any distribution network, a huge number of transformers are installed. Finding a cost effective design of a distribution transformer is a challenging process, however if properly designed a large amount of savings will be achieved.

The transformer design is usually a complicated and time consuming process. In this research work, a comprehensive literature survey on distribution transformer design is conducted. Different mathematical models and solution techniques are discussed and a new objective function is proposed for oil immersed distribution transformer. Results for using different techniques to achieve an optimal design for which the requirements and constraints are met have been shown. The cost of the proposed transformers for two optimization techniques, namely, Genetic Algorithm and Simulated Annealing are compared with an industry used design based on Random Walk method. Results revealed that savings in total cost of about 8% to 13% are achieved for a variation of the cost of kWh from 5 to 8 halalas.

Keywords: *Distribution Transformer, Optimal Design, Genetic Algorithm, Simulated Annealing*

ملخص الرسالة

الاسم الكامل: مالك أحمد حبلي

عنوان الرسالة: التصميم الأمثل لمحولات التوزيع باستخدام تقنيات الّذكاء الإصطناعي

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محولات الطاقة للتوزيع هي من أهم المكونات التي تستخدم في الشبكة الكهربائيةّ، حيث يوجد عدداً هائلاً منها في كل الشبكات بمختلف أحجامها. العثور على تصميم منافس من حيث التكلفة أمرليس سهلاً ولكن ان وجد سيكون ذو توفير عال و هذا يؤي الى ارباح أكثر.

عادةً ما يكون تصميم محولات التوزيع امراً معقداً و يستغرق الكثير من الوقت كما ان إستيفاء و تحقيق المواصفات المطلوبة للمحولات هو عامل مهم لا بد من أحذه بعين الإعتبار. في هذه الاطروحة تم مراجعة شاملة لأساليب التصميم و طرح تقنية ناجحة لتصميم محولات التوزيع الى مستوى جهد أولي يصل حتى 13.8 ك.ف. و قدرة تحمل تصل الى 1000 ك.ف.أ، باستخدام خوارزميات الذكاء الصناعي. تم إستخدام طريقتين لإيجاد التصميم الأمثل. الطريقة الأولى هي حوارزمة الانظام الجيني و الطريقة الثانية هي حورازمية البرمجة بمحاكت الصلب لإيجاد الحل الأمثل.

تم وضع صياغة رياضية لتصميم محولات التوزيع بأسلوب تسلسلي. كما تم عرض النتائج التي تم الحصول عليها لتصميم المحولات بالطرق المقترحة. هذه النتائج تبرهن فعالية الطرق التي اقترحت واستخدمت وتبين نسبة تقليل التكلفة في مقدار مع التصميم التقليدي للمحول. وأثيتت الخوارزمية الثانية فعاليتها على الأخرة حيث أعادة تصميم ذو فعالية أفضل و توفير أكثرعلى المستحدمز

مفردات: محولات التوزيع، تصميم المحولات

CHAPTER 1

INTRODUCTION

Distribution transformers are one of the most important components in a power system network, where in any distribution network a huge number of distribution transformers are used. A transformer is a device with one or two magnetically coupled electric circuits by a common magnetic field that is used to transform voltage from one level to another. Distribution transformers are also the most varied types of transformers where in the Kingdom of Saudi Arabia a huge number of transformers are installed in the public electricity supply system ranging in size from 50 kVA to 1000 kVA [1].

When considering distribution transformers usually this refers to those transformers that step down voltages from transmission lines of up to 36 kV, to a voltage level that could be provided from an outlet at any commercial or private buildings such as offices and houses for connecting any electrical component. In the Kingdom of Saudi Arabia there are several primary rated voltages including 34.5 kV, and 13.8 kV. These voltages are all stepped down to a secondary (distribution level) rated voltage of 400 V, or 230 V.

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.

Manufacturing companies have introduced computer aided transformer design that help reduce the man hour needed, but mainly to reduce and optimize the amount of material needed and to reduce the delivery cycle time to the customer [2]. Computer design techniques will ensure that the user's requirements in addition to the standard design constraints such as efficiency, loaded and non-loaded losses, temperature rise and other constraints are all achieved. In the end this will give us a number of different designs which all guarantee the desired characteristics of the transformer. Even though all the designs meet the requirements, the transformers will have different parameters such as core radius, number of lamination layers, winding type and number of turns, and so on. This in turn indicates that the total cost for every transformer design will differ as the two main factors affecting the costs are; the amount of material used, and the total losses of the transformer [3]. For this reason finding an optimal design of an oil immersed transformer that uses minimal amount of material and has the least possible losses will be sufficient and economical.

No research has been done that includes all the design specifications, variables, and constraints of an oil immersed transformer, and then uses the given transformer specifications to optimize all design variables such as the core radius, winding turns, tank size, amount of oil used, and satisfies the constraints resulting in a lower overall capitalized cost. In this thesis the design process is optimized in order for a huge amount of savings to be made for owning and operating the transformer. A new mathematical model is found and the different artificial intelligence techniques implemented to obtain an optimal transformer design are considered and discussed.

Several objectives have been achieved in this thesis. The first objective is introducing a unique mathematical formulation that abides to the operational and practical constraints for an oil immersed transformer. An objective function with the aim of finding a design for minimizing the total capitalized cost of the transformer has been included, in which artificial intelligence techniques, namely, Genetic Algorithm and Simulated Annealing algorithms are used to optimize the oil type transformer design. Finally a detailed report with all the design variables is obtained, and to test its effectiveness compared with an available manufacturer's design.

The flow of the thesis is the following: Chapter 2 presents an up to date detailed literature review on the work done for the transformer design, with the different methods used and variables considered. Chapter 3 includes the proposed mathematical formulation of the oil immersed distribution transformer, with consideration of the practical aspects. In chapter 4 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 in order to ensure proper operation of the transformer. Chapter 5 deals with implementing the techniques used for optimization of the transformer design problem. Detailed discussion and comparison of the results is included in chapter 6. In addition, the optimized design of different transformer ratings is included. The effectiveness of the methods used is tested. Finally chapter 7 presents a conclusion of the work done and possible future improvements and additional research that could be achieved.

CHAPTER 2

LITERATURE REVIEW

Transformers are considered to be one of the most important components in any distribution power system. The main objective from the transformer designing process is to obtain the precise dimensions of all the components that make up the transformer and then forward them to the manufacturing line. The designer takes into account all given specifications provided by the customer or user, and uses the available material taking into account limitation in order to achieve an optimal design at lower cost [4]. The design of a transformer with certain specifications is not always unique, however there may be a number of slightly different designs all satisfying the required specifications.

Traditionally in the past, the design of any transformer was based on the imagination and art of the designing engineer. The first computer design of a transformer was achieved in 1955 [5]. Although earlier method used computer based designs the process was lengthy, time consuming and not very efficient such as reference [6] indicates that the design of a single phase transformer was based on a computer program optimized by the designer using trial and error. In recent papers more advanced techniques were used as the technology became available. Jaber [7], used geometric programming formulation in order to obtain and optimal transformer design, and this method ensured that the global optimum is attained. In other research papers, different approaches have been used to lower the manufacturing costs of the transformer in order to achieve large amount of savings. In [8], it states that a computer aided algorithm with the aim of minimizing transformer design costs have been demonstrated. Other optimization techniques such as coupling of finite element analysis with knowledge based design strategy and genetic algorithm is presented in [9-11]. In [12] a new practical approach for finding the global optimization of electromagnetic design of a distribution transformer has been introduced to capitalize the losses. In their approach finite element method was used for optimizing the design however none of the corporal design variables was optimized such as the core laminations or windings. The nonlinear mixed integer programming based approach discussed in [13] deals with the minimization of the total cost of the distribution transformer. The limitation is that only four design variables are optimized, and this limits the approach performance. Chaotic evolutionary approach has been used as well in [14] to optimize the transformer design but only transformer parameters related to the spatial dimensions have been considered, therefore including the remaining design variables could have different results.

Design procedure for a transformer employed for unusual loads such as a furnace for example is different [15]. A survey on the transformer design optimization methods presented in [16] reveals that there is an ongoing interest in application of advanced technique to obtain unique designs for a large range of transformer ratings, however very few publications are reported on the complete design optimization of oil immersed transformers.

Previous methods reported in the literature concentrate on optimizing some of the transformer variables to reduce the manufacturing or running costs mainly by optimizing the transformer core size or using a different winding construction, and some emphasis on reducing the losses in an active area of the transformer. However, non-took into account all the transformer variables in the optimization problem.

In this thesis, we are proposing a complete design optimization of the transformer by introducing an objective function that optimizes all the transformer parameters with added terms related to the oil and tank size, satisfying the operational and manufacturing constraints.

CHAPTER 3

METHODOLOGY OF THE OIL IMMERSED TRANSFORMER DESIGN

Transformers are manufactured over a wide range of ratings, typically ranging from ratings of few kVA to tens of MVA. The design process is not unique for every transformer, in fact the design concepts are very similar for all the different possible capacities. Variation in the design technique and formulas exist only when a different type of construction or material is used, such as different type of core, or a change in the winding construction is needed.

The design formulas included in this chapter refer to any distribution transformer with the following characteristics:

- Three phase oil immersed transformer
- Three legged, core type with a stacked circular core
- Layered round copper wire primary winding
- Copper foil for secondary winding

3.1 Transformer Core Design

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. The difference between the two types is illustrated in the following figure [17].

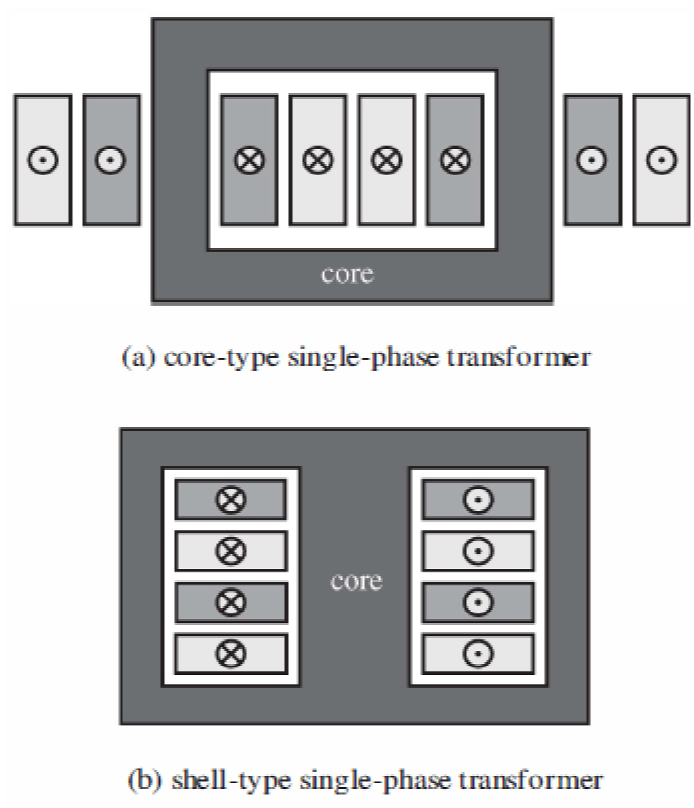

Figure 3. 1 (a) Core Type (b) Shell Type Single Phase Transformer Core Construction [17]

In the core type shown in part (a) of figure 1, the high voltage (HV) winding, lightly shaded region, is placed on the outside while the dark shaded low voltage (LV) is placed on the inside. By using this order we reduce the required insulation. Another 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 width will be needed. In order to increase the flux carrying area the core is fabricated using certain number of steps, for which each step has a certain width as shown in Figure 3.2. The step numbers for distribution transformers is usually five or less.

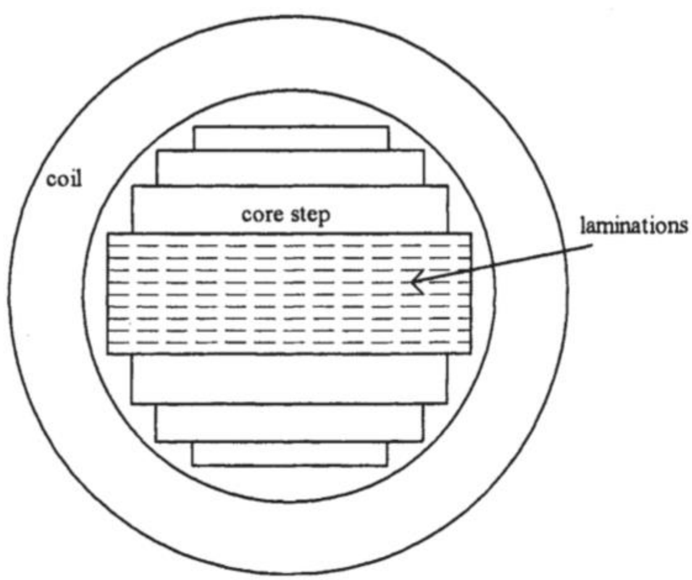

Figure 3. 2 Core Cross Section [17]

Transformer designers aim to achieve an optimal stacking pattern by maximizing the core area for a given number of steps, with all laminations at a given step having the same width. In figure 3.3 you can see the x and y geometric coordinates of the stacked sheet corners at which they touch the circle radius giving an optimal stacking arrangement.

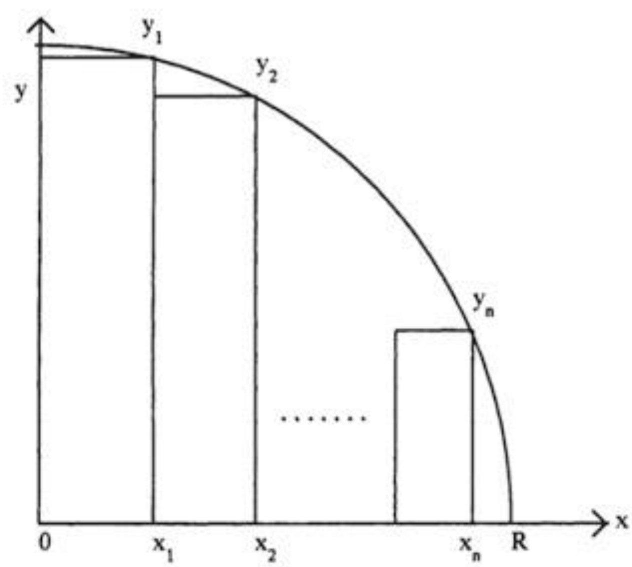

Figure 3. 3 Geometric Parameters to Find Optimum Step Configuration [17]

Transformer manufacturing companies will have standard width for the lamination sheets that are readily available for the designer, and usually the sheets width increase in increments of 5 or 10 mm.

The following table 3.1 is based on the work of R. Vecchio, and P. Feghali [18], for which the normalized solutions for various number of steps are displayed.

Table 3. 1 Normalized x Coordinates that Maximize the Core Area for a Given Number of Steps

Number of steps n	Fraction of circle occupied $A_n / \pi R^2$	Normalized x coordinates, x_i / R
1	0.6366	0.7071
2	0.7869	0.5257 0.8506
3	0.8510	0.4240 0.7070 0.9056
4	0.8860	0.3591 0.6064 0.7951 0.9332
5	0.9079	0.3138 0.5336 0.7071 0.8457 0.9494
6	0.9228	0.2802 0.4785 0.6379 0.7700 0.8780 0.9599
7	0.9337	0.2543 0.4353 0.5826 0.7071 0.8127 0.9002 0.9671
8	0.9419	0.2335 0.4005 0.5375 0.6546 0.7560 0.8432 0.9163 0.9723
9	0.9483	0.2164 0.3718 0.4998 0.6103 0.7071 0.7921 0.8661 0.9283 0.9763
10	0.9534	0.2021 0.3476 0.4680 0.5724 0.6648 0.7469 0.8199 0.8836 0.9376 0.9793

In practical cases because only certain number of sheet width are available for the manufacturer and also because the thickness of individual sheets are discretized the ideal circular core areas given in the table are not achievable. Instead the designer will readjust the stack dimensions to correspond with the nearest possible available selection.

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 Cold Rolled Grain Oriented (CRGO) steel with some percentage of silicone content, and cut into a range of thicknesses that fall among 0.23 to 0.46 mm, and could reach a width of 1 meter. Various grades of conventional grain oriented steels exist, such as M-4, M-5, M-6, and M-7, however the use of later developed low loss HI-B steels is preferable because it has a direct effect on reducing the core losses which in turn effect the total owning cost of the transformer. HI-B steel is available in the following grades M-0H, M-1H, M2H, M3H, and M-4H, where each specific grade has certain electrical, magnetic and physical properties, however the most important of these is the specific core loss (W/kg).

In Table 3.2 several steel grade options are presented with their relative thickness and code. The following are some options with reasonable prices and losses to obtain an optimal design hence will be considered for the purpose of this thesis.

Table 3. 2 Silicon Steel Grades

Electrical Steel Grade	Thickness (mm)	Grade Code
M-6	0.35	35M6
M-5	0.3	30M5
M-4	0.27	27M4
M-3	0.27	27M3
M-0H	0.23	23M0H
ZDKH	0.23	23ZDKH

ZDKH is a steel grade that has up to 8% lower losses than the low losses HI-B steel. Such low losses are achieved by introducing a laser etched material which in turn increases the cost for this specific steel grade.

Another material which has considerably lower losses when compared with conventional electrical steel is known as amorphous steel. However, this steel grade is not frequently used in the industry mainly due to the available strip sizes and also due to higher material cost.

The core's ideal cross sectional area is merely the summation of each single multiplication of each core step width and height. In practical situations the actual measured value of the core losses will vary from the designed core losses since an ideal cross sectional area is assumed in the designing stage.

When calculating the core losses and core area, two main factors shall be considered, and they are the core Stacking factor (SF) and Building factor (BF).

3.1.1 Stacking Factor (SF)

The 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 in order to reduce the eddy current losses although this will reduce the stacking factor.

The range of the stacking factor for conventional silicon steel sheets is between 0.95 and 0.98 depending on the lamination thickness that is used.

Table 3. 3 Lamination Thickness & the Corresponding Stacking Factor

Lamination thickness (mm)	Stacking Factor
0.23	0.96
0.27	0.965
0.3	0.97
0.35	0.975

The stacking factor plays an important role in calculating the total weight of the core, as it is multiplied by the ideal core area. Therefore it is crucial to choose proper lamination thickness to use corresponding stacking factor.

A final step to calculate the core weight is to multiply the result by the silicon steel density and the total length of the core. The density of the silicon steel used is 7.65 kg / cm^3, the value is usually provided by the steel manufacturer.

$$\textit{Core weight}\ (\text{kg}) = \textit{Ideal area}\ (\text{mm}^2) \times \textit{SF} \times \textit{Core length}\ (\text{mm}) \times 7.65 \times 10^{-4} \quad (3.1)$$

In which the total core length is:

$$\textit{Core length} = 3 \times \textit{Core-window height}\ (\text{mm}) + 2 \times \textit{Core-yoke}\ (\text{mm}) \quad (3.2)$$

The following figure 3.5 shows the lamination dimensions to be used for the calculation of the total core length.

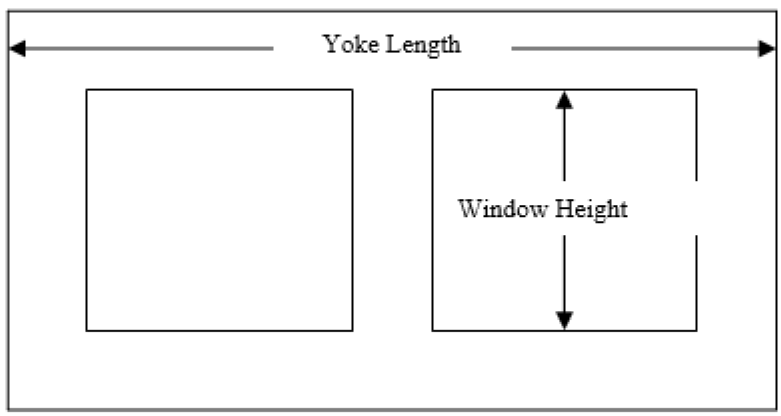

Figure 3. 4 Core Dimensions

In the following sub section, the building factor is explained and then the important role it plays for accurately calculating the core losses will be illustrated by adding the equations needed for the calculations.

3.1.2 Building Factor (BF)

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.

A specific building factor of the core will be set by the manufacturer. There could be a slight difference depending on the manufacturer. For the purpose of this thesis 1.15 is the set building factor for the core design calculation.

The main use for the building factor for the core calculations is to calculate the core losses, also known as the no load losses.

The following equation is used:

$$\text{Core Loss (W)} = \text{Core Weight (kg)} \times \text{Building Factor} \times \text{Loss / kg} \qquad (3.3)$$

The loss / kg is a value obtained based on two operation aspects. The first one being the operating frequency in (Hz) and the second aspect is the operating magnetic flux density (B) that can be calculated using the following equation:

$$B = \frac{V_t}{4.44 \times f \times A_{net} \times 10^{-4}} \qquad (3.4)$$

Where,

B = operating flux density (T)

V_t = volt per turn = $\frac{V_p}{S_{turn}}$

V_p = Secondary Rated Phase voltage (V)

S_{turn} = Secondary Number of turns

f = Operating frequency (Hz)

A_{net} = Core net area (cm^2)

3.2 Transformer Winding Design

The winding construction and design of a 3 phase oil immersed distribution transformer is not very similar to larger power transformers due to the excessive complexity that is introduced as the transformer power rating is increased. Nevertheless, basic principles for the windings construction are quite the same regardless of the transformer size and so will be applied in this section.

In the literature, several different types of windings are considered such as spiral, helical, disc and layered windings. Most manufacturers prefer the use of copper because of its high conductivity characteristics in addition to some excellent mechanical properties. The use of copper is cheaper than aluminum for the following range of transformers,100 KVA till 1000 KVA as stated by [19] in addition to that it has the benefit of saving money by minimizing the loaded losses which is considered to be a significant value in the total owning cost of the transformer which we trying to minimize.

For the purpose of transformer design in this thesis, layered winding construction is implemented for the high voltage (HV) side as this type of winding is mostly used on the primary side of distribution transformers.

Copper foil windings are usually used for the low voltage or the secondary side of a distribution transformer, due to the low voltage rating that is present at the secondary side. The advantage of using foil winding is to reduce the space needed for the windings by increasing the copper volume and in turn provide better magnetic coupling. Figure 3.5 below shows a copper foil roll used for the LV winding of a distribution transformer.

Figure 3. 5 Copper Foil for Secondary Winding

Using this type of winding, each turn of the copper foil winding covers the entire width of the layer. The foil is wound around a core with insulation paper between each successive layer until the required number of layers is reached. Strips of the conductor material are brazed along both edges at the start and end of the foil to form the winding leads [20]. This arrangement is used because it is a very cost effective method of manufacturing the LV winding of a distribution transformer with high capability of withstanding short circuit current.

Other types of winding constructions also frequently used for distribution transformers and not higher rated transformers. The higher voltage winding will have to tolerate voltages in the kV ranges hence a considerable amount of winding turns number are required therefore layered winding is used as discussed earlier. But because of the lower kVA rating in these type of transformers the volt per turn is typically very low, the current is also low and as a result the cross sectional area is considerably small as well. The copper wire used typically have a circular cross sectional area with an enamel covering.

3.3 Insulation Design

Transformers have precise and solemn insulation systems as in all other electrical equipment. Insulation is specifically required between components with a difference in potential. Various components are designed and included in order to work altogether to protect the transformer in abnormal operation conditions. Two types of insulations are used in a transformer, solid insulation which will be discussed in this section and liquid or oil insulation and this will be discussed in the following section.

Solid insulation in transformers is divided into main insulation and winding insulation.

3.3.1 Main Insulation

Typically know as major insulation system and includes pressboard barriers, spacers and clamps. The most important protection in this system as all designers agree is the insulation between the low voltage coil and the high voltage coil of the same phase, and also the low voltage winding to ground. In addition to that, major insulations are also needed between lead to lead and lead to ground spaces. The material that is usually used by manufacturers for insulation between the low voltage and high voltage windings in conventional distribution transformers is pressboard. Cellulose fibre which is treated and then compressed under high pressure is the raw material of which thick pressboard insulation layers are produced, and it has three main advantages. It acts as a dielectric, therefore isolates critical transformer components that exist at different voltage levels. It also supports the windings, and finally it creates cooling ducts for the oil and hence contributes to better thermal health of the transformer.

3.3.2 Winding Insulation

This is also known as the minor insulation system, and from the name it refers to the insulation between turn to turn of the coil and also section to section of the same coil. The material commonly used in this insulation system is synthetic enamel for the wires, pressboard between layers and even fluid insulation such as mineral oil. Layered winding construction is implemented for the primary side and copper foil winding is used for the secondary side of the distribution transformer in this thesis. Therefore, synthetic enamel coating is used for the primary side wires due to the presence of high voltage, and pressboard insulates the different layers of the winding. For the copper foil secondary side windings diamond dotted press paper (DDP) is mostly used for insulating the copper foil adjacent turns. The insulation layer bonds with the electrical conductors as well as other mutual insulation material layers due to the partial resin coating used in the diamond dotted paper within the windings, after the application of some heat and high pressure for a certain amount of time. Short circuit faults lead to large radial and axial mechanical forces in transformers, however these are safely tolerated by this internal strengthening of the coil.

Empty spaces can be found between the insulation and the conductors due to partial coating, and this empty channels will trap air and moisture from the coils, which in turn are filled with the liquid insulation material. However danger of discharges from the entrapped gas is minimized by the use of DDP.

It took transformer designers several decades to come up with the best material bass for the diamond dotted press paper, in which a partial epoxy resin layer pattern has been printed on each side of the press paper. The typical dimension of a diamond dotted press paper is a side length of about 9.5 mm with separation between them of 6 mm. And as can be seen in figure 3.7, the epoxy resin print coat covers at least 36% of the area of each side of the paper.

Figure 3. 6 DDP Winding Insulation

Final insulation needed would be the insulation of adjacent phases, however the phases are not physically touching in anyway which makes the insulation system a lot simpler. Using pressboard as the insulating material is prominent in distribution transformers.

3.4 Cooling System Design

The generated heat in transformers can be dissipated a number of different ways into the surrounding atmosphere. To dissipate the extra heat generated by a distribution transformer, cooling ducts, corrugated fins or radiators are installed in addition to the oil tank. However for power transformers more complex techniques have to be considered for the cooling process such cooling fans and even oil pumps to assist the natural convection process of oil. Using oil for cooling is among the most efficient cooling techniques and this will be illustrated among in the next section (Transformer Oil). The distribution transformer cooling method used is the oil natural, air natural (ONAN) method as per IEC 60076 international standards.

The transformer's internal temperature has to be maintained within a certain limit, therefore transfer of heat from the internal core and interior winding is also a concern in addition to the dissipation of heat to the surrounding. Methods in which heat will transfer within and from a transformer will be discussed and they are conduction, convection and radiation.

3.4.1 Cooling by Conduction

Heat transfer by conduction in a transformer corresponds to the transfer of heat which is generated in the windings to the surrounding oil in the tank. The solid insulation that separates the two material, namely, the windings and the oil, therefore the conduction process is mainly influenced by the thermal resistivity of the insulation material, because conduction is directly proportional to the temperature difference, however is inversely proportional to the thermal resistivity. Other factors that also affect conduction in the transformer are the total surface area exposed and the thickness of the insulation [21]. The following equations best illustrate this process.

The temperature difference (θ) in ^{o}C is:

$$\theta = \frac{HL_{ins}}{KA_{ins}} \tag{3.5}$$

Where,

H = Material watt losses

A = Surface Area (m^2)

L = Insulation thickness (m)

K = Thermal conductivity of the Insulation = 6.51

To estimate the mean tank oil temperature based on the guaranteed average winding temperature rise the winding gradient temperature at steady state comparison can be used [22].

Winding Gradient Temp. = Average winding Temp – Mean tank oil Temp (3.6)

Therefore,

$\theta_m = \theta_a$ – Winding *Gradient* (3.7)

Where,

θ_m = Mean tank oil Temp

θ_a = Average winding Temp

3.4.2 Cooling by Convection

The use of oil in the transformer adds this specific method of heat transfer. Since the heated surface is immersed in mineral oil, heat moves by conduction from the hotter surface to the cooler surface, in this case the oil in the tank. The rise in temperature of the oil decreases its density, hence the less dense lighter oil now floats to the surface of the tank and is replaced by a more dense cooler oil creating a continues moving current. This increases the dissipation of heat from the internal heated parts of the transformer to the surroundings.

The following formula expresses heat transfer by convection versus the oil temperature rise:

$$W_c = K\theta_m^n \tag{3.8}$$

Where,

W_c = Heat Loss by Convection (watt/m^2)

K = 2.17

n = 1.25

The exponential constant n depends on the shape and area of the heated surface, for the purpose of the distribution transformer its value is the given.

3.4.3 Cooling by Radiation

Heat transfer by radiation occurs in transformers and any other heated object due to the simple principle that if a body has a temperature higher than its surrounding temperature, than heat energy in the form of waves will be radiated in to the surrounding atmosphere. The effective area for radiation is irrespective of the objects shape, instead it's the outside envelope of the object's surface. The total effective radiating surface of a transformer's tank whether composed of corrugated or a smooth surface can be found my multiplying the length and height of a stretched string drawn around the envelope. Another factor that has a major effect on the radiation capability of an object is the surface color of the object. For example pure black has an emissivity factor of unity, however other colors will have a lower factor and the lighter is the color the lower will the emissivity factor be. Therefore after the envelope area is calculated it has to be multiplied by the emissivity factor to obtain the true radiating surface area. The spray paint color for transformers usually used in the industry will have an emissivity factor of 0.95 and that is for gray paint [23].

All of this can be illustrated by the Stefan Boltzmann law on heat radiation as [24]:

$$W_R = \sigma E\left[(273 + T_{amb} + \theta_{m-oil})^4 - (273 + T_{amb})^4\right] \tag{3.9}$$

Where,

W_R = Radiant Heat Loss (watt/m^2)

σ = Stefan-Boltzmann Constant = 5.67×10^{-8}

E = Emissivity factor = 0.95

T_{amb} = Ambient temperature (^{o}C)

To estimate the winding's maximum temperature, the winding gradient is usually used. This is done by adding a specific multiple of the winding gradient to the top oil temperature in order to predict the highest possible winding temperature rise. Based on IEC 60076 standards the hot spot factor is 1.1 as in the following equation:

$$Max\ winding\ temp = Top\ Oil\ Temperature + 1.1 \times Winding\ Gradient \tag{3.10}$$

3.5 Transformer Oil

The oil in an oil immersed transformer performs a dual function as it acts as a cooling medium as has been discussed in the previous section and an insulating medium. In order to obtain best performance of the oil immersed transformer the designer has to have thorough understanding of the oil properties, and make sure that the operation conditions will be within the expected boundaries so the oil will perform as expected throughout its estimated operating life.

3.5.1 Oil as Coolant

The core and windings play the biggest role in heat production inside the transformer, as most or all of the energy losses occur in the copper from the windings or in the steel laminations of the core. These losses are observed in the transformer as heat, resulting in a noticeable temperature rise in all internal parts of the transformer. The use of mineral oil for cooling down the transformer is the most efficient technique as it combines all three methods of the heat transfer process. The oil absorbs the heat from the windings and core by conduction, then the heated oil moves up towards the top of the transformer by convection, and finally the heat is transmitted by radiation to the surrounding through the naturally cooled transformer's surface. Oil also tolerates very high temperatures, however there always is a temperature limit set to around 100 ^oC depending on the type of insulation material used.

3.5.2 Oil as Insulator

Insulating the transformer is a complicated process that combines a variety of different insulation material. All internal parts of the transformer operate at different electrical potentials, therefore it is necessary to isolate each part separately by insulating them. Insulation material has a direct effect on the transformer cost, in order to minimize the total owning cost of the transformer, the insulation separation must be reduced between all the parts. Transformer mineral oil is amongst the preferred insulation material used in transformers. One of the most important properties of the transformer's oil is its electrical strength also referred to as its breakdown voltage. Breakdown in the oil occurs under very specific conditions, for instance at a high temperature and voltage level in the presence of naturally occurring contaminating agents such as dust, carbon, and moisture. Other important properties of the transformer's oil include its physical and chemical properties, which in turn also give the transformer the ability to operate at the high electrical stress.

In addition to being able to withstand a wide range of AC voltages during normal operation conditions, the transformer has to be able to also withstand very high unanticipated voltages that last for a short period of time. These voltage levels usually occur from lightning strikes or abnormal operating conditions resulting of a fault. Advanced protection and heavy switch gear are included in the medium voltage (MV) level of the distribution system to protect the power system in case it's hit by a lightning strike. Faults that cause these abnormal voltage levels are not much of a concern since the transformer insulation is normally designed with lightning disturbance characteristics, which mean that the insulation that is sufficient to protect the transformer for the range of normal operating voltage levels will also be able to withstand very high voltages that occur for a short duration of time.

The given equations illustrate how the transformer's insulating press paper and pressboard thickness is an important factor on which the breakdown voltages depend upon.

In order to determine the insulation thickness needed between the winding layers the following practical equation is used as stated in [25]:

$$Thickness(mm) = \frac{Volt / turn \times terns / layer \times 2}{4400} \tag{3.11}$$

This will give the approximate number of insulating papers needed between adjacent layers. So if the insulation thickness was calculated to be 0.3 mm, and press paper are manufactured at a standard thickness of 0.125 mm, then this indicates that we need 3 press papers of insulation between each layer for insulation.

The impulse breakdown versus insulating paper thickness at 90 ^{o}C is can be found be equation 3.5 as reported in [26]:

$$E_{impulse}\left(\frac{kV_{peak}}{mm}\right)=\frac{79.43}{d^{0.275}} \tag{3.12}$$

The A.C and impulse breakdown of pressboard in oil at 90^{o}C is found using the following equations:

$$E_{ac}\left(\frac{kV_{ac}}{mm}\right)=\frac{27.5}{d^{0.26}} \tag{3.13}$$

$$E_{impulse}\left(\frac{kV_{peak}}{mm}\right)=\frac{91.2}{d^{.26}} \tag{3.14}$$

We have to keep in mind that the actual breakdown of the insulation in a transformer is influenced by several factors of the operation condition such as the winding assembly, vacuuming process, temperature and pressure of operation, drying degree of the core, the oil cooling and insulating properties, and the most important factor is the aging of the transformer. As stated previously the thickness of the press paper and pressboard will affect the breakdown voltage. Manufacturers will provide the breakdown voltage in oil depending on the insulation thickness and the characteristics of oil used in the manufacturing process of the transformer.

Clearance has to be included between any two internal components of the transformer for insulation and to avoid faults. The minimum clearance needed between the transformer's main components are displayed in accordance with the HV terminal level.

HV-HV Clearance $= \begin{cases} 10(mm) & HV \le 15kV \\ 20(mm) & 15kV < HV \le 34.5kV \end{cases}$

HV-LV Clearance $= \begin{cases} 10(mm) & HV \le 15kV \\ 20(mm) & 15kV < HV \le 34.5kV \end{cases}$

LV-Core Clearance $= 10\ (mm)$

HV-Tank Clearance $= \begin{cases} 50(mm) & HV \le 15kV \\ 70(mm) & 15kV < HV \le 34.5kV \end{cases}$

The steel tank is grounded, thus will be considered at the 0 V.

Detailed insulation construction of the distribution transformer, and the way the internal components are lined up can be seen in figure 3.8.

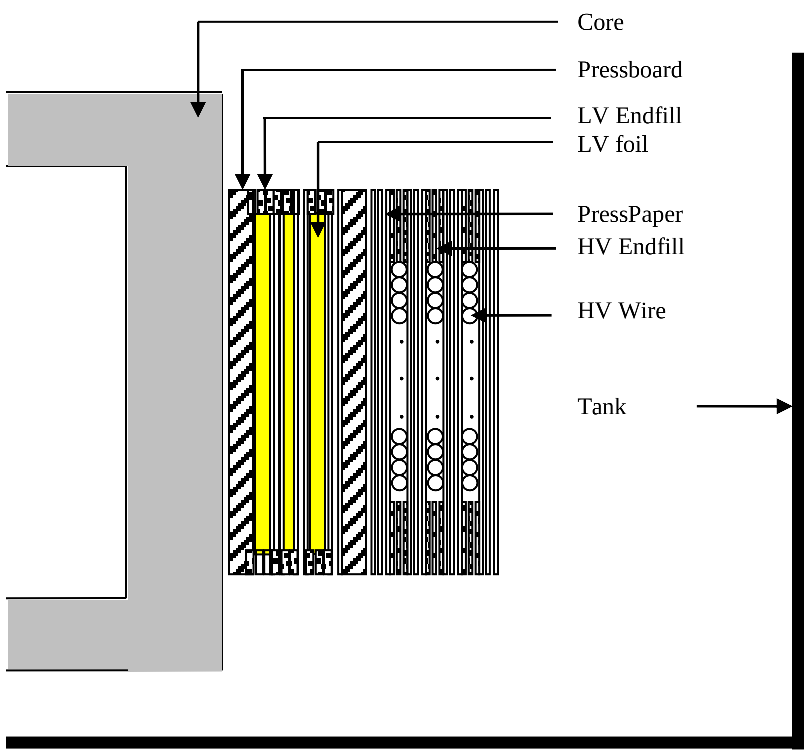

Figure 3. 7 Transformer Insulation Spacing Construction [23]

3.6 Transformer Impedance Calculation

Impedance is one of the main transformer characteristics that the manufacturer has to guarantee for the end user by meeting the specified minimum and maximum impedance values. The value depends on the transformer rating and manufacturers usually specify as small allowable range. The best way to refer to a transformer impedance is by expressing it as a percentage voltage drop of the transformer at full load. Percentage reactance and resistance of the windings are the two quantities that determine the percentage impedance of a certain transformer. This can be better understood by the formula that is used to calculate the transformer's percentage impedance [27]:

$$\%Z = \frac{I_{fl}\sqrt{R^2 + X^2}}{E} \times 100 \tag{3.15}$$

Where,

I_{fl} = Transformer Full Load Current

E = Transformer Open Circuit Voltage

R = Per Phase Coil Resistance

X = Per Phase Coil Reactance

3.6.1 Winding Resistance

The total winding resistance of the transformer can be calculated from the DC resistance of the conductor only, and this is because the cross sectional area of the conducting wire is very small. The transformer winding DC resistance is calculated using the following equation:

$$R = \frac{\rho \times L \times N}{A} \ (\Omega) \tag{3.16}$$

Where,

ρ = Resistivity of the Copper Conductor

L = Length of the Conductor

N = Number of Turns

The resistance calculated using the above equation has to be multiplied by three in order to obtain the total resistance of the transformer since we have a 3 legged core type transformer.

Copper resistivity at 20^{o}C is given to be 1.724 × 10^{-8} Ω.m and the resistivity at any temperature of interest (T_{ref}) can be found. According to the IEC60076 standard the temperature reference for resistivity is 75 .

$$\rho = 1.724 \times 10^{-8} \left(\frac{T_{ref} + 234.5}{234.5 + 20} \right) \ (\Omega.\text{m}) \qquad (3.17)$$

The LV winding resistance in step down transformers is much lower than HV winding resistance. The reason for that is the noticeable voltage drop which results in a significant difference in the winding total number of turns. On the other hand the, the full load current on the secondary LV winding is considerably larger than the HV primary winding current which in turn increases the LV winding I^2R losses and this will be discussed in the following section.

Precise calculation of the both windings total mean length is required in order to accurately obtain the total resistance of the windings. The dimensions of the installed windings are a key factor to obtain the correct total windings mean length for both the LV and HV windings using the following equations:

$$MLT_{LV} = \pi\left(ID_{LV} + RD_{LV}\right) \tag{3.18}$$

Where,

MLT_{LV} = Mean length of LV winding (mm)

ID_{LV} = LV winding inside diameter (mm)

$$= Core\ diameter + (2 \times Gap_{core\text{-}LV}) \tag{3.19}$$

RD_{LV} = LV winding radial depth (mm)

$$= N_{LV} \times T_{foil} + N_{duct} \times T_{duct} + (N_{LV} - 1) \times T_{LV\text{-}ins.} \tag{3.20}$$

Where,

$Gap_{core\text{-}LV}$ = Core & LV Coil Clearance (mm)

N_{LV} = LV number of turns

T_{foil} = Copper Toil Thickness (mm)

N_{duct} = Number of Cooling Ducts

T_{duct} = Cooling Duct Thickness (mm)

$T_{LV\text{-}ins.}$ = LV Insulation Thickness (mm)

Next step is to carry similar calculation in order to obtain the HV winding length:

$$MLT_{HV} = \pi\left(ID_{HV} + RD_{HV}\right) \tag{3.21}$$

Where,

MLT_{HV} = Mean Length of HV winding (mm)

ID_{HV} = HV Winding Inside Diameter (mm)

$$= OD_{LV} + (2 \times Gap_{HV\text{-}LV}) \tag{3.22}$$

OD_{LV} = LV Winding Outside Diameter (mm)

$$= \left(ID_{LV} + 2 \times RD_{LV}\right) \tag{3.23}$$

RD_{HV} = HV Winding Radial Depth (mm)

$$= N_{HV} \times D_{wire} + N_{duct} \times T_{duct} + (N_{HV} - 1) \times T_{HV\text{-}ins.} \tag{3.24}$$

Where,

$Gap_{LV\text{-}HV}$ = HV & LV Coil Clearance (mm)

N_{HV} = HV Number of Layers

D_{wire} = Copper Wire Diameter (mm)

N_{duct} = Number of cooling ducts

T_{duct} = Cooling duct thickness (mm)

$T_{HV\text{-}ins.}$ = Thickness of insulation between HV layers (mm)

3.6.2 Winding Reactance

The leakage reactance in a transformer can be estimated in a number of different ways or methods according to [28, 29]. The method commonly used involves the estimation of flux in the terms of the windings dimension for different parts of the transformer and the use of flux leakage for different elements in the transformer.

Flux leakage reactance for a transformer is found using the following equation. The figure provided show how all the required parameters used to evaluate the reactance are obtained.

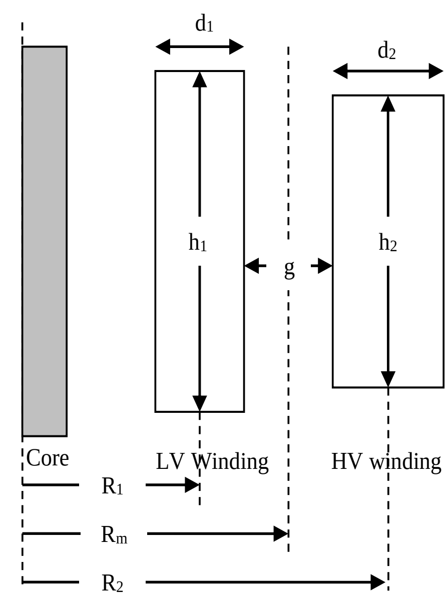

Figure 3. 8 Parameters for Leakage Reactance Calculation [23]

These parameters are used in the following equation to calculate the reactance in either the primary or secondary winding depending on which parameters are used.

$$X = \frac{(2\pi)^2 \mu_0 fVI}{(V/N)^2 h}\left\{\frac{R_1 d_1}{3} + \frac{R_2 d_2}{3} + R_m g\right\} \tag{3.25}$$

Where,

$h = (h_1 + h_2) / 2$

V = Phase Voltage

I = Phase Current

N = Number of Turns

μ_o = Permeability of free Space = $4\pi \times 10^{-7}$

V, *I* & *N* of the same winding, either primary or secondary must be used.

3.7 Load Losses

Loaded losses in a distribution transformer are losses generally due to the winding's resistance and stray losses which are produced by the presence of a load current. These are losses produced by the load current in the transformer. The main source of these losses come from the conductor coil due to the I^2R losses (power loss). Keeping in mind that for the coil resistance only the DC resistance is considered since the cross sectional area of the conducting wire is not large. The remaining loaded losses are mainly due to stray losses. In distribution transformers the main share of stray losses that take place in the windings usually consist of eddy current losses.

No load conditions are of interest and need to be considered since a transformer will draw current that will result in losses even if we open circuit the secondary winding. These losses concern users because they can occur over long periods of time. Even without open circuit losses, power system losses result from the reactive power drawn by the magnetizing current of the transformer in addition to voltage sag. The no load primary current is usually constrained for all the mentioned reasons. Another conditions of interest would be the full load conditions as it could be the case at which the transformer is required to operate even for short periods of time, but mainly for checking the regulation of the distribution transformer.

It is important to distinguish between eddy current losses in the transformer's windings, and this is normally due to the presence of leakage flux in the windings and eddy current losses in the transformer core which is part of no load loss discussed in a previous section. The total load loss are found as follows:

$$Load\ Loss = I^2R_{HV} + I^2R_{LV} + Eddy\ Loss_{HV} + Eddy\ Loss_{LV} + Miscellaneous\ Losses \quad (3.26)$$

Extensive calculations of the leakage flux is required at several different points of the windings in order to acquire an accurate value eddy current loss, nevertheless these exhaustive calculations are only required in specific cases when the harmonics component is too high in the system. However for the case of distribution transformer these calculations can be avoided and the eddy current losses for both the primary and secondary windings can be obtained using simplified and more practical formulae.

The assumptions used for calculating the eddy current losses are listed below [24]:

- The core opening's dimension considered vertically and the leakage flux lines are parallel, hence no effect is considered from the core.
- The leakage flux is maximum at the flux between the windings, and it decreases proportionally with the ampere per turn being lowest at the HV coil's surface.
- The leakage flux density is considered to be zero at the HV coil outside surface.

The simplified eddy losses equations now become [30]:

$$Eddy\ Loss_{LV} = 29259 \times 10^{-4}\, f^2\, \beta^2\, T_{foil}^{\ 2} \tag{3.27}$$

$$Eddy\ Loss_{HV} = 29259 \times 10^{-4}\, f^2\, \beta^2\, D_{wire}^2 \times 3/4 \tag{3.28}$$

In which β refers to the flux density in the space between the windings and is found using the following equation:

$$\beta = \frac{0.4\pi \times NI \times \sqrt{2}}{l} \tag{3.29}$$

Where,

f = Frequency (Hz)

D_{wire} = Primary wire diameter (mm)

T_{foil} = Secondary foil thickness (mm)

N = Winding Number of Turns

I = Phase current of winding (A)

l = length of leakage flux path (mm)

The length of the leakage flux path is approximately the average of the length of the two coil height. A factor of 3/4 has is multiplied by the eddy current HV losses due to the fact that a round wire is used in the construction of the HV primary winding. Finally, miscellaneous losses are added as the last value to the eddy and the I^2R losses in the loaded loss equation. And this is often done by manufacturers to take into consideration few additional losses that might arise once the distribution transformer is completely assembled. Losses added from such practical factors are just a few watts estimated to be 2% of the total calculated I^2R and eddy current losses for each winding.

CHAPTER 4

OPTIMIZATION OF THE OIL IMMERSED DISTRIBUTION TRANSFORMER DESIGN

This chapter will list and discuss the objective function with the aim of finding the optimal design, one which has the least capitalized owning cost, the design variables that will be included in the design optimization tool in order to reach the need design, and finally the design constraints that are needed to ensure that obtained design functions with all the required operational characteristics and at high efficiency.

4.1 Design Variables

A number of the design variables have to be optimized in order for the objective function to reach accepted designs. The lower and upper boundary of every design variable will be included in the optimization tool, then the optimization algorithm will generate a huge number of possible designs all within the design variables boundaries. However most of these designs will not be applicable and rejected by the objective function for one of many reasons. The design is rejected if the cost is higher than other possible designs or if one of the many constraints is not satisfied. Therefore the objective function only returns a combination of design variables having the lowest total owning cost. The design variables are listed:

- Primary Number of Layers (N_{HV})
- Turns Per HV Layer (*turns/layer*)
- Secondary Number of turns (N_{LV})
- Core Radius (r)
- Primary wire diameter (D_{wire})
- Secondary foil width (W_{foil})
- Secondary foil thickness (T_{foil})
- Secondary Number of Cooling Ducts ($N_{LV\text{-}duct}$)
- Primary Number of Cooling Ducts ($N_{HV\text{-}duct}$)
- Steel Tank Dimensions (*mm*)
- Volume of Mineral Oil (L)

The proposed variables all depend on each other in some way or another for example increasing the number of ducts will result in using a longer copper wire or foil for the winding as the ducts are placed in between the core and the windings. All the variables randomly chosen until an optimized design is reached, however the volume of oil and the tank size are calculated after the other variables are obtained as they are directly proportional to the core size, windings length and the general size of the internal components of the transformer.

The table below displays the upper and lower of the design variables that will be used for finding an optimal design. These bounds can be thought of as physical constraints or side constraints as they represent the limitation in the form of practical manufacturability or availability of these variables.

Table 4. 1 Design Variables Upper & Lower Bounds

Design Variables	Upper Bound	Lower Bound
Secondary Number of Turns	35	7
Core Radius (mm)	180	60
Primary Wire Diameter (mm)	3.8	0.3
Secondary Foil Width (mm)	600	130
Secondary Foil Thickness (mm)	2.9	0.6
Secondary Number of Cooling Ducts	2	1
Primary Number of Cooling Ducts	2	1
Primary Number of Layers	23	8
Turns Per HV Layer	250	65

4.2 Objective Function for Optimization

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 costs and any manufacturer tend to keep the costs as low as possible. Thus a priority has to be selected when comparing different designs that specify operational constraints in order to select the best design to be used. This priority upon which the optimal design is selected is known to be the objective function of the design. In this thesis optimization tools are used with an objective function of minimizing the capital cost of the transformer. When calculating the transformer cost, usually the capital cost is used as frequent transformer users do not care about the direct or material cost only, however the losses cost has to also be included. As discussed in chapter 3, losses in the core and winding of the transformer depend on many factors. So basically the capital cost of the transformer is the cost that includes both the materials cost and the losses cost which is divided into load and no load losses cost each of which has a predefined cost by SEC [1]. This makes the main target of any design is to have a minimal losses as well as material costs.

There the objective function becomes as follows:

$$Minimize\ FC = k\, \Sigma\, M_C + k\, \Sigma\, L_C \tag{4.1}$$

Where k_1 and k_2 are optional weighing factors.

$\Sigma\, M_C$ = *Materials cost*

= *Copper Wire Cost + Copper foil Cost + Silicon Steel Cost +*

Mineral Oil Cost + Steel Tank Cost (4.2)

&

$\Sigma\, L_C$ = *Losses cost*

$$= No\ Load\ Loss \text{ x } (SR/kW_{NL}) + Load\ Loss \text{ x } (SR/kW_{LL}) \tag{4.3}$$

4.2.1 Material Cost

The objective function for minimizing the costs and the input needed for calculations have been established, the next step is to show how each of these cost variables is calculated from the values that we have or we can obtain.

Starting with the material costs:

$$Copper\ Wire\ Cost = Weight_{wire} \times (SR / kg)_{copper} \tag{4.4}$$

(SR / kg) is the price of the copper wire per kilogram

$$Weight_{wire} = Copper\ Density \times C.S.\ Area\ of\ Wire \times 3 \times MLT_{HV} \times N_{HV} \tag{4.5}$$

Copper Density = 8940 kg/m^3

C.S. Area of Wire $= \dfrac{\pi \times D_{wire}^2}{4 \times 10^6}$

In which,

MLT_{HV} = Mean Length of HV Winding (mm)

$$= \pi(ID_{HV} + RD_{HV})$$

$$= \pi[(OD_{LV} + (2 \times Gap_{HV-LV})) + \mathrm{NL_{HV}} \times \mathrm{D_{wire}} + \mathrm{N_{HV\text{-}duct}} \times \mathrm{T_{duct}} + (\mathrm{NL_{HV}} - 1) \times \mathrm{T_{HV\text{-}ins}}] \qquad (4.6)$$

Where,

ID_{HV} = HV Winding Internal Diameter (mm)

OD_{LV} = LV Winding Outside Diameter (mm)

RD_{HV} = HV Winding Radial Depth (mm)

$Gap_{LV\text{-}HV}$ = HV & LV Coil Clearance (mm)

N_{HV} = HV Number of Winding Turns

NL_{HV} = HV Number of Layers

D_{wire} = Copper Wire Diameter (mm)

$N_{HV\text{-}duct}$ = Number of cooling ducts

T_{duct} = Cooling Duct thickness (mm)

$T_{HV\text{-}ins.}$ = Insulation Thickness of HV layers (mm)

The internal diameter and radial depth of the HV winding, ID_{HV} and RD_{HV} respectively can be calculated using the given equations in chapter 3, which is the same case as for ID_{LV} and RD_{LV} referring to the LV winding internal diameter and radial depth respectively.

$$Copper\ Foil\ Cost = Weight_{foil} \times (SR / kg)_{copper} \tag{4.7}$$

(SR / kg) is the price of the copper foil per kilogram

$$Weight_{wire} = Copper\ Density \times 3 \times MLT_{LV} \times N_{LV} \times T_{foil} \times Foil_{width} \times 1 \times 10^{-6} \tag{4.8}$$

In which,

MLT_{LV} = Mean length of LV winding (mm)

$$= \pi\left(ID_{LV} + RD_{LV}\right)$$

$$\begin{aligned} &= \pi[\left(\text{Core Diameter} + (2 \times \text{Gap}_{\text{core-LV}})\right) \\ &+ \text{N}_{\text{LV}} \times \text{T}_{\text{foil}} + \text{N}_{\text{duct}} \times \text{T}_{\text{duct}} + (\text{N}_{\text{LV}} - 1) \times \text{T}_{\text{LV-ins}}] \end{aligned} \tag{4.9}$$

Where,

N_{LV} = LV number of turns

T_{foil} = Copper foil thickness (mm)

N_{duct} = Number of cooling ducts

T_{duct} = Cooling duct thickness (mm)

$T_{LV\text{-}ins.}$ = Thickness of insulation between LV turns (mm)

$Gap_{core\text{-}LV}$ = Core to LV Coil Clearance (mm)

The next step is to calculate the cost of the steel tank, and this is a fairly simple process since the dimension of the tank are obtained according to standards once the core size has been found from the design process. The windings and insulation thickness is already calculated in previous equations. A clearance in the range of 50 mm to 70 mm has to be left between the closest of the internal components (HV winding) and the tank according to IEC60076 standards.

$$Cost\ of\ Steel\ Tank = Tank_{weight} \times (SR / kg)_{steel} \tag{4.10}$$

$(SR / kg)_{steel}$ is the price of mild steel per kilogram

$$Tank_{weight} = Mild\ Steel\ Density \times \Sigma\ Area\ of\ All\ Sides \times T_{steel} \times 1{\times}10^{-9} \tag{4.11}$$

$Mild\ Steel\ Density = 7850\ kg/m^3$

Where,

T_{steel} = Thickness of the Steel Used (mm)

The final step of the material cost calculation is finding the mineral oil cost. Therefore, the amount of oil needed has to be calculated and this is dependent on the volume of the tank, the amount of windings (copper) used and the size of the core. Since all of these are now available the total weight of mineral oil used in the transformer can be calculated.

The following equations are used to calculate the mineral oil weight used:

$$Mineral\ Oil\ Cost = Weight_{oil} \times (SR / kg)_{oil} \tag{4.11}$$

$(SR / kg)_{oil}$ is the price of mineral oil per kilogram

$$Weight_{oil} = Oil\ Density \times V_{oil} \times 0.95\ (kg) \tag{4.12}$$

$$V_{oil} = V_{tank} - V_{winding} - V_{core}\ (m^3) \tag{4.13}$$

$$V_{tank} = (Tank_{Length} \times Tank_{Width} \times Tank_{Height}) \times 10^{-9}\ (m^3) \tag{4.14}$$

$$V_{winding} = \frac{Weight_{wire} + Weight_{foil}}{\rho_{copper}}\ (m^3) \tag{4.15}$$

$$V_{core} = \frac{Weight_{core}}{\rho_{core}}\ (m^3) \tag{4.16}$$

Where,

V_{oil} = Volume of Mineral Oil needed (m^3)

V_{tank} = Total Volume of the Tank (m^3)

$V_{winding}$ = Volume of the HV & LV Windings (m^3)

V_{core} = Volume of the Silicon Steel Core (m^3)

Only 95% of the oil tank could be filled since the oil will expand when its temperature rises. Therefore the factor 0.95 is multiplied by the total volume of the oil needed in equation (4.12) as in [24].

4.2.2 Losses Cost

As mentioned earlier customers main concern is the total owning cost of the transformer, for this reason in addition to the material cost the capitalized losses cost have to be included in the calculation of the total transformer's cost.

NLL (W) = No Load Loss

= [*Ideal area* (mm^2) × *SF* × (*3* × *Core Window Height* (mm)

+ *2* × *Core Yoke* (mm)) × 7.65 × 10^{-4}] × *BF* × *Loss/kg* (4.17)

LL (W) = Load Loss

$$= I^2R_{HV} + I^2R_{LV} + Eddy\ \ Losses_{HV} + Eddy\ \ Losses_{LV} + Miscellaneous\ Losses$$

$$= 1.02 \times \left\{ \frac{3 \times I_{HV}^2 \times \rho_{copper} \times MLT_{HV} \times N_{HV}}{A_{wire}} + \frac{3 \times I_{LV}^2 \times \rho_{copper} \times MLT_{LV} \times N_{LV}}{T_{foil} \times W_{foil}} \right.$$

$$+ 29259 \times 10^{-4} \times f^2 \times \left[\left(\frac{0.4\pi \times N_{LV} I_{LV} \times \sqrt{2}}{l} \right)^2 \times T^2{}_{foil} \right.$$

$$\left. \left. + \left(\frac{0.4\pi \times N_{HV} I_{HV} \times \sqrt{2}}{l} \right)^2 \times D_{wire}^2 \times 3/4 \right] \right\}$$

(4.18)

According to the Saudi Electricity Company SEC specification No. 51 SDMS-04 the losses capitalized cost are set to be 4 SR per W and 11 SR per W for loaded losses and no load losses respectively.

4.3 Design Constraints

The design variables to satisfy all required operational and functional characteristics once chosen. Although each individual variable is chosen arbitrarily from within a given range, but the combination of the variables for the transformer's complete design have to adhere to all the operational constraints that will be discussed in this section.

4.3.1 Current Density (*J*)

The current density in the copper conducting winding is usually forced below a specific reasonable value during the transformer design process. Since the material used for the winding is a copper conductor, a typical value for the current density to be used is 1.5 A/mm^2 [29]. High values for current density most 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:

$$J_{\min} \le J \le J_{\max}$$

$$J_{\min} \le \frac{4I_{HV}}{\pi \times D_{wire}^2} \le J_{\max} \tag{4.19}$$

$$J_{\min} \le \frac{I_{LV}}{T_{foil} \times W_{foil}} \le J_{\max} \tag{4.20}$$

In which I_{HV} and I_{LV} stand for the HV phase current and the LV phase current respectively.

4.3.2 Maximum Flux Density (B)

The flux density is a very sensitive constraint in which designers tend towards making as high as possible. However, if the flux density is too high saturation in the core could occur and this need to be avoided under any circumstance. For the type of material used in the transformer's core, namely, grain oriented steel, the maximum value of flux density used in practice is in the region of 1.7 T, because at a flux density value close to or exceeding 1.9 T saturation in the core can be guaranteed. Therefore, flux densities near that value are avoided under any operation condition and this can be done based on the input voltage and variations in frequency. An advantage of increasing the operating flux density is that the weight of the core can be reduced, but the cost for that is an increase in the core losses. During the design optimization the designer's is to find an optimal combination for the flux density along with the appropriate core weight and losses.

The flux density constraint for the transformer's design is:

$$B \leq B_{\max}$$

$$\frac{V_{ps}}{4.44 \times f \times A_{net} \times 10^{-4} \times N_{LV}} \leq B_{\max} \tag{4.21}$$

In which V_{ps}, and A_{net} refer to the secondary phase voltage and the net cross sectional area of the core respectively.

4.3.3 Percentage Impedance (*%Z*)

Transformer designers aim to achieve a suitable and economic 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 the pressure on manufacturers to have the smallest possible range of the impedance values for their transformers. Manufacturers usually abide to 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, and only ± 7.5% tolerance is accepted according to the ANSI standards. The impedance value constraints can be expressed as the following:

$$\%Z_{\min} \leq \%Z_G \leq \%Z_{\max} \tag{4.22}$$

$$\%Z_{\min} = \text{The minimum accepted Impedance} = \begin{cases} 0.900 \times \%Z_G \ - as \ \ per \ \ IEC \\ 0.925 \times \%Z_G \ - as \ \ per \ \ ANSI \end{cases}$$

$$\%Z_{\max} = \text{The maximum accepted Impedance} = \begin{cases} 1.100 \times \%Z_G \ - as \ \ per \ \ IEC \\ 1.075 \times \%Z_G \ - as \ \ per \ \ ANSI \end{cases}$$

In which $\%Z_G$ is the guaranteed impedance value requested by the customer.

4.3.4 Winding Average Temperature Rise

Transformer manufacturers and user often have very specific limits regarding the winding average temperature rise, usually based on certain local standards by the electric utility and also depends on the surrounding atmosphere conditions. In order to properly stay within these limitations additional costs are involved especially when dealing with a dry type transformer. However, since for this thesis the design is for an oil immersed transformer, enduring the specified limit according to the international standards is more achievable. Designers often end up with transformer designs that have an average temperature rise close to the limit, however reducing the temperature rises to values much lower than the limit is always desirable as this will have a direct effect on the loaded losses. The constraints for the winding average temperature rise are given below.

$$\theta_{wtr} \leq \theta_{g-wtr}$$

$$\theta_{HV-wtr} = 0.8 \times \theta_{g-oil-tr} + \frac{LL_{HV} \times T_{HV-ins}}{A_{HV-ins} \times 6.51} \leq \theta_{g-wtr} \tag{4.23}$$

$$\theta_{LV-wtr} = 0.8 \times \theta_{g-oil-tr} + \frac{LL_{LV} \times T_{LV-ins}}{A_{LV-ins} \times 6.51} \leq \theta_{g-wtr} \tag{4.24}$$

Where,

θ_{wtr} = Winding Average Temperature Rise ( )

θ_{g-wtr} = Guaranteed Winding Average Temperature Rise ( )

θ_{HV-wtr} = HV Winding Average Temperature Rise ( )

θ_{LV-wtr} = LV Winding Average Temperature Rise ( )

$\theta_{g-oil-tr}$ = Guaranteed Top Oil Temperature Rise ( )

LL_{HV} = HV Winding Losses (W)

LL_{LV} = LV Winding Losses (W)

T_{HV-ins} = HV Insulation Thickness (mm)

T_{LV-ins} = LV Insulation Thickness (mm)

4.3.5 Winding Temperature Gradient

The windings of the transformer are constructed in a very precise manner to ensure that the maximum temperature gradient of the windings are not exceeded. Since the specified boundaries of the temperature rise that are considered along with the design of the steel tank imply maximum winding temperature values.

According to local standards of Saudi Arabia, and the Saudi Electricity Company (SEC) specification found in 51-SDMS revision 4 [1], a reasonable value for the winding temperature gradient is 21 based on a hot spot of 98 , in addition to a top oil temperature rise of 45 , and an average yearly ambient temperature of 30 . Therefore, the hot spot temperature formulas is the following:

$$\textit{Hot Spot temp} = \textit{Top Oil Temperature} + 1.1 \times \textit{Winding Gradient} \quad (4.25)$$

The HV and LV windings gradient constraint is [24]:

$$Gradient \le Gradient_{\max}$$

$$\frac{LL_{HV} \times T_{HV-ins}}{A_{HV-ins} \times 6.51} \le \frac{98 - \theta_{g-oil-tr} - T_{ambient}}{1.1} \tag{4.26}$$

$$\frac{LL_{LV} \times T_{LV-ins}}{A_{LV-ins} \times 6.51} \le \frac{98 - \theta_{g-oil-tr} - T_{ambient}}{1.1} \tag{4.27}$$

In which A_{HV-ins}, and A_{LV-ins} refer to the insulation area in touch with the mineral oil of the HV and LV winding respectively.

4.3.6 Load & No Load Losses

Most costumers such as utilities, and factories do not look only at the purchasing cost of the transformer, however the total losses costs are also considered as these costs are quite considerable over the life time of the transformer. The total losses are of 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:

$$NLL \le NLL_{\max}$$

$$LL \le LL_{\max}$$

4.3.7 Induced Voltage

The insulation layer of press paper between the windings is designed to have certain withstanding capabilities. One of the major concerns is to withstand the induced voltage in both the internal and external windings. Thus constrains for the induced voltage can be written as follows [24]:

$$Induced_{LV} \leq Induced_{LV,\max}$$

$$Induced_{HV} \leq Induced_{HV,\max}$$

4.3.8 Efficiency

The insulation layer of press paper between the windings is designed to have certain withstanding capabilities [24].

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

$$\eta = \frac{S \times \cos\theta_L}{S \times \cos\theta_L \times NLL \times LL \times \left(\frac{S}{S_n}\right)^2} \times 100\% \tag{4.28}$$

Where,

S = Transformer Load (kVA)

S_n = Transformer Rated Power (kVA)

$\cos\theta_L$ = Power Factor

Optimization constraints of the transformer design process ae summarized in the following table.

Table 4. 2 Optimization Constraints Summary

Design Constrain	Primary Side	Secondary Side
Current Density	$J_{\min} \le \frac{4I_{HV}}{\pi \times D_{wire}^2} \le J_{\max}$	$J_{\min} \le \frac{I_{LV}}{T_{foil} \times W_{foil}} \le J_{\max}$
Flux Density	$B \le B_{\max}$	
Percentage Impedance	$\%Z_{\min} \le \%Z_G \le \%Z_{\max}$	
Winding Temp. Rise	$\theta_{wtr} \le \theta_{g-wtr}$	
LL & NLL	$NLL \le NLL_{\max}$ & $LL \le LL_{\max}$	
Induced Voltage	$Induced_{HV} \le Induced_{HV,\max}$	$Induced_{LV} \le Induced_{LV,\max}$
Efficiency	$\eta_{\min} \le \eta_{transformer}$	

CHAPTER 5

ARTIFICIAL INTELLIGENCE TECHNIQUES USED IN THE TRANSFORMER DESIGN OPTIMIZATION

The main aim of optimizing the transformer design by using artificial intelligence techniques is to obtain a design with the minimum owning capital cost, which also satisfies the design constraints and ensure that the design variables are within the practical upper and lower bounds. In this chapter an overview of the optimization process will be explained, in addition to that the artificial intelligent techniques namely, Generic Algorithm (GA) and Simulated Annealing (SA) that are used for the transformer design optimization process are presented and the implementation of these two techniques along with the input data required, initial values of the design variables, and finally the total cost calculation are discussed.

5.1 The Optimization Process

The optimization process is a huge part of mathematical modeling with a specialty in linear and non-liner programming constrained and unconstrained variables depending on the problem the designer aims to solve. The transformer design optimization problem is a very wide and general area as it falls into the non-linear programming division with a constrained multivariable design algorithm. The generality of this problem is also because of the nature of the design variables and the constrained objective function used for the transformer design. The general optimization mathematical model is stated as follows:

Subject to,

For i = 1, 2, …., R

In which **X** refers to *n* design variables, f (**X**) is the *objective function*, G_i (**X**) is known as *inequality constraints*, and *lb* & *ub* are the set of lower and upper bounds of design variables, respectively.

The objective function f (**X**) could be either linear, non-linear, or even an integer depending on its use and the required objective for the problem's solution. This also depends on the nature of the constraints used. In the transformer design process, it is recognisable from the mathematical formulation of the design that the problem we are dealing with results in nonlinear objective function along with nonlinear design constrains.

When dealing with a constrained optimization problem the first step is to transform the problem into a simpler sub problem in which its solution would be the iterative process basis. The transformation of the constrained variable problem to a simpler unconstrained one is often implemented in earlier methods of optimization by the use of a penalty function for the constraints near the limits boundary. Recently such problems are solved by the use of a sequence of parametrized optimization for which this process results in a convergence eventually to the optimal solution of the constrained optimization process.

5.2 Genetic Algorithm (GA)

Genetic Algorithms originated from the study of cellular automata by John Holland and his colleagues in 1975, in which they wrote a book indicating the research they have done regarding GA [30]. However only very recently the GA potential has been explored in solving combinatorial optimization problems. Nowadays GA is viewed as 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 favoring 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 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.

i. Create initial population from prior values

ii. Evaluate fitness of possible solutions and select

iii. Crossover solutions to obtain fitter offspring

iv. New features produced in offspring by mutation

v. Select fitter generation and repeat until required fitness is achieved

The genetic algorithm optimization 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. Once an initial population of N solutions have been generated the GA uses the three genetic operators mentioned previously to produce N new more fit solutions with better chances of survival with every following iteration. 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 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 basically 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 from the optimization toolbox in MATLAB has been used to obtain an optimal distribution transformer design. A design that has the lowest owning capital cost and satisfies all the required operation characteristics and constraints.

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

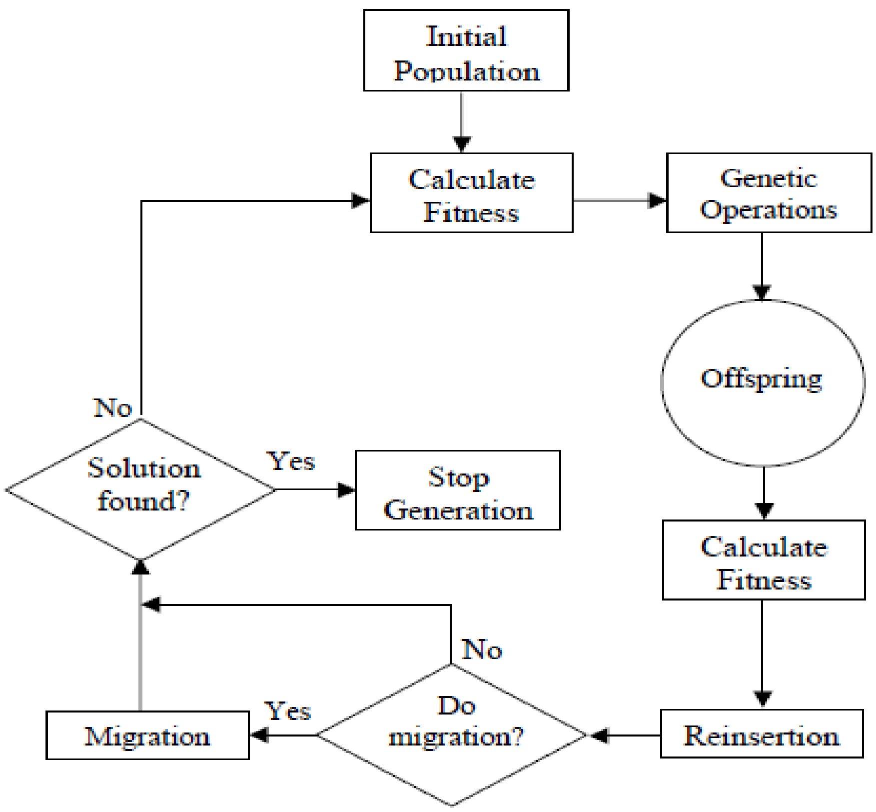

Figure 5. 1 Flow Chart of Proposed GA

Parameters have to be set in the optimization tools depending of the type of problem that need to be optimized. The GA parameters set for the transformer design algorithm are listed below.

- As discussed earlier the optimization process starts with a certain population, the population size is set to 200 which means that number of individuals per generation is 200, since there are more than 5 design variables.
- Because we have a vector of size greater than one multiple subpopulations are created, the size of each one specified by the vector entry.
- GA is a stochastic search process so it is very hard to estimate the number of generations upon which the GA converges towards the solution. By trial it was found that 120 generations is a good enough number for the GA to return required results.
- The mutation process makes random small changes in the allele of the individuals in the population in order to provide new genetic structure and enable the GA to search a broader space. Mutation rate is set to 0.001.
- The generation gap is the fractional difference in the size of subpopulations between different generations in order to reduce the number and choose only the best fit individuals.
- The insertion rate specifies the number of individuals that are produced in every generation to be placed back into the population. Insertion rate is set as a percentage of the number of individuals produced by default in the tool.

- ❖ Migration is the movement of individuals between subpopulations. The process of migration allows best individuals in one subpopulation replace worst individuals of another. Migration is controlled by three parameters, direction, fraction, and interval.

Once the parameters are set the GA optimization process can now be executed. First the algorithm starts with an initial population in which the number of individuals is equal to the subpopulation size multiplied by the generation gap multiplied by the number of individuals per subpopulation, and the decision variable of the individual is randomly chosen with the range of the upper and lower bounds of the decision variables.

The execution of the algorithm can be listed as follows:

a) Assign the fitness for the population
b) Selection process in which individuals are chosen from the population
c) Crossover of individual pairs within each subpopulation
d) Then mutation at the set rate of 0.001. The upper and lower bounds of the decision variables need to be strictly considered to avoid having new individuals outside that range.
e) Reinsertion of best offspring to replace worst individuals
f) Most fit individuals are selected for migration between subpopulations

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

5.3 Simulated Annealing

Simulated annealing is a metaheuristic combinational optimization technique that simulates the physical annealing process in the field of combinatorial optimization. The SA metaheuristic performs a stochastic search within the bounded space of the design variables [32]. Modifications to the current solution that increase the value of the objective function are allowed for a minimisation problem as opposed to other typical methods where only modifications that decrease the objective value are allowed. More precisely, a modification that reduces the objective value is always accepted, while a modification that increase the objective value is only accepted with a probability proportional to $exp\ (-\Delta E/T)$, where T is the temperature control parameter.

The probability of allowing an increase in the objective value of the function is much higher at high temperature of the control parameter. However, this probability quickly decreases as the temperature is reduced. Typically, the SA algorithm starts with a high temperature to perform a rough search of the bounded solution space. After that the temperature declines gradually in order for the optimization algorithm to concentrate on a specific region within the solution space [33].

The initial temperature value of T, the number of iterations to be performed at each temperature, the cooling (reduction) rate of the temperature value and the stopping criterion are determined by the so-called "the SA cooling schedule".

The analogy of a SA combinatorial optimization problem is based on the understanding that an optimization problem solution corresponds to configurations in a physical problem and that the energy of every configuration refers to the cost of the proposed solution [34]. Now we introduce a control parameter C_p to replace the temperature control parameter T. Hence the SA elements can be listed as the following:

- The current, trail, and best solutions are the optimized parameter sets at any iteration number.
- The acceptance criteria indicates that the current solution is chosen if it meets the set criteria regardless of the iteration number.
- At a given value of the control parameter C_p, two solution trails n_1, & n_2 can be randomly generated based on the acceptance criterion. The ratio n_2 / n_1 is known as the acceptance ratio.
- The cooling schedule specifies the set of parameters that indicate the convergence of the algorithm. The set of parameters include the initial value of the control parameter, a decrement function in order to decrease the value of C_p and a finite number of iterations. The decrement function used to decrease the control parameter value is given by $C_p = \mu\, C_p$ in which μ is a value smaller than 1, typically in the range of 0.80 to 0.99.
- The equilibrium condition is reached when the current solution does not change for some number of iterations.

- ❖ The process terminates under certain assigned conditions known as the stopping criteria. The conditions by which the search will terminate could be either the maximum allowable number of iterations is reached or the number of iterations since the best solution have been achieved is greater than a pre-specified number.

The execution of the SA algorithm can be summarized into the following steps:

a) First the control parameter initial value is set, then an initial solution is randomly generated. Calculate the objective function of that solution and set the solution as the current and best solution

b) A certain number of trail solutions is randomly generated within the neighborhood of the current solution.

c) Calculate acceptance ratio of the generated trail solution and check their acceptance criterion, then set the chain counter to zero if the acceptance criterion is acceptable.

d) Generate a trail solution and if the acceptance criterion is satisfied check whether or not the equilibrium condition is satisfied.

e) Check conditions for stopping criteria, if any is satisfied then search process stops.

5.4 Transformer Design Application

After explaining the different techniques that will be used for the design problem, in this section the actual implementation of the program for the design process is developed using the mathematical model of the transformer design. The program used is the MATLAB 2015 software in addition to the built in optimization tool having the artificial techniques discussed.

5.4.1 Initial Design Variables

A set of initial values for the design variables will need to be specified for the optimization process to start from regardless of the method used. The initial design values chosen are based on experience of transformer designers and this will greatly assist in reaching or converging to an optimal design. Transformers have a very wide range of ratings and there is a significant change in the design variables between one rating and another. In addition to the rating the primary side voltage plays an important role in the design process that is even for transformers of the same rating if the primary voltage is different this will result in a noticeable change in the design variables. Therefore it is only efficient to define the design initial values depending on the transformer rating as well as the voltage level of the primary side.

The transformer design process is categorized depending on the transformer's rating and the voltage level of the primary side as follows:

1) Transformers with a voltage level on the primary side of 13.8 kV or lower
2) Transformers with a voltage level on the primary side higher than 13.8 kV and lower than 34.5 kV.

The next category is the transformer classification based on its rating:

1) Rating ≤ 50 kVA
2) 50 kVA < Rating ≤ 100 kVA
3) 100 kVA < Rating ≤ 200 kVA
4) 200 kVA < Rating ≤ 300 kVA
5) 300 kVA < Rating ≤ 500 kVA
6) 500 kVA < Rating ≤ 750 kVA
7) 750 kVA < Rating ≤ 1000 kVA
8) 1000 kVA < Rating ≤ 1250 kVA

The categories for classification have been clearly listed, so now the initial values for these categories are listed in the following tables. These initial values are based on designs by experienced transformer designers using traditional designing methods. By having these initial values for the optimization process, there is a significantly greater chance that an optimal design with lower total cost will be achieved.

Table 5.1 provides the set of design variables initial values for all different categories listed above of the distribution transformer that will be used as the starting solution for all the optimization methods [23].

Table 5. 1 Initial Values of Design Variables for a Transformer having a 13.8 kV Primary Side or Less

Design variable	Transformer rating							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Secondary Num. of Turns	27	20	18	15	13	11	10	9
Core Radius	66	76	76	87	92	104	112	117
Primary Wire Diameter	0.71	1	1.4	1.7	2.2	2.7	3.2	3.5
Secondary Foil Width	160	190	300	350	400	420	470	530
Secondary Foil Thickness	0.25	0.4	0.55	0.7	1	1.4	1.7	1.9
Primary Cooling Ducts	1	1	1	2	2	2	2	2
Secondary Cooling Ducts	1	1	1	2	2	2	2	2
Primary Num. of Layers	16	14	11	9	9	9	8	8
Turns Per Primary Layer	192	165	185	188	170	140	138	135

The distribution transformer that will be designed in this thesis has a rating of 300 kVA and a primary side voltage level of 13.8 kV stepped down to 400 V on the secondary side. So the initial values used for the optimization process are the variables of column 4.

5.4.2 Program Stages

In this section the steps of the implemented program will be listed and briefly explained starting from the data entry depending on the transformer characteristics until the final step which is calculation of the total owning cost of the proposed design.

I) Data Entry

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 is a list for the data entry:

a. Transformer rating (kVA)
b. Primary Voltage (V)
c. Secondary voltages (V)
d. Rated Frequency (Hz)
e. Maximum Tapping Range (set to 5 for our design)
f. Primary and Secondary Connection (Delta or Star).
g. Core Building Factor (set by manufacturer)
h. Guaranteed Percentage Impedance
i. Applicable International Standard (IEC or ANSI) as a Fixed Reference For the Temperature that will be used for calculation of percentage impedance and load loss (standard used in this thesis is the IEC standards)

j. Guaranteed Winding Temperature Rise, Top Oil Temperature Rise and Average Yearly Ambient Temperature (   )
k. Core Material Grade, which will be a selection among six (6) grades from the table provided in chapter 3
l. Silicon Steel Price (SR / kg)
m. Copper Price (SR / kg)
n. Mild Steel Price (SR / kg)
o. Mineral Oil Price (SR / kg)
p. Capitalization Value of No Load and Load Losses (SR / W) these prices are usually set by the utility (SEC)
q. Maximum allowable No Load Losses and Loaded Losses (the allowable losses range is also set by SEC)

Unless mentioned otherwise all of the above data entries are values requested by the costumer depending the expected operation or needed use of the distribution transformer. Expect for the standard values entered for calculation such as the losses costs and the prices of the raw material.

II) Initial Values of the Design Variables

Depending on the transformer rating provided by the customer and the primary side voltage level, the design variables initial values can be determined from table 5.1.

III) Upper & Lower Bounds

The upper and lower bounds are fixed for the available and manufactural range for the design variables. These bound can be found in table 4.1.

IV) Process of Design Optimization

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

V) Rounding of the Obtained Results

The optimal design variables returned by the program have several decimal places, and the design of such values is not applicable in practice. Therefore each result is rounded up to fit the closest standard value.

VI) Total Cost Calculation

After the optimal design variables are obtained, the cost of these rounded values actually used for the design is calculated. These cost calculation includes the following; transformer tank dimensions and weight, amount in kilograms of oil used, and finally the transformer losses capitalized cost.

CHAPTER 6

RESULT & DISCUSSION

The proposed mathematical model for the transformer design along with the optimization process discussed are applied to the design problem in this chapter. A comparison is made between the designs obtained from different techniques used namely, the GA and SA algorithms, and designs obtained from a manufacturer's designing program.

6.1 Transformer Specifications, Variables and Constraints

In this section the rated values of the transformer used for the design are listed. These values are usually specified by the customer. The different design techniques will be applied for the following transformer specifications provided in Table 6.1.

Table 6. 1 Transformer Specifications

Parameter	Value
Power Rating	300 kVA
Primary Voltage	13800 V
Secondary Voltage	400 V
Phase	3 phase
Type	Oil Immersed Core Type
Frequency	60 Hz
Primary / Secondary Connection	Delta / Wye
International Standards	IEC 60076

Table 6.2 provides the lower and upper boundary of the transformer design variables that are to be optimized. The optimal parameters obtained will minimize the total cost of the transformer, as the objective function is subjected to minimize material used and losses.

Table 6. 2 Transformer Design Variables Limits

Design Variables	Upper Bound	Lower Bound
Secondary Number of Turns	35	7
Core Radius (mm)	180	60
Primary Wire Diameter (mm)	3.8	0.3
Secondary Foil Width (mm)	600	130
Secondary Foil Thickness (mm)	2.9	0.6
Secondary Number of Cooling Ducts	2	1
Primary Number of Cooling Ducts	2	1
Primary Number of Layers	23	8
Turns Per HV Layer	250	65

Note that the primary wire diameter, and the secondary foil thickness has to follow discreet values within the provided boundary since only certain sizes are manufactural and available for the designers.

Every design has to comply with a set of constraints according to standards to ensure a proper and safe operation of the transformer. Table 6.3 lists the constraints used for the design of the 300 kVA transformer.

Table 6. 3 Transformer Design Constraints

Constraint	Value
Current Density	1.5 A/mm^2
Flux Density	≤ 1.8 T
Winding Temperature Rise	45
Oil Temperature Rise	50
Guaranteed Impedance	3.6 ≤ Z% ≤ 4.4
Max. Loaded Losses	< 3200 W
Max. No Load Losses	< 680 W
Efficiency	≥ 98%

6.2 Transformer Design Using RW

By using the specifications of Table 6.1, the optimization process can start and an optimal design that satisfies all the constraints is obtained. For comparison purposes, the transformer has been designed as per standards by a local manufacturer using a Random Walk (RW) design method which is a designing program package used by the manufacturer. The RW design process works by changing the transformer's design variables in a systematic way, such as the core radius, the wire diameter and number of winding turns. Therefore the design obtained is not the actual global optimum. However this is considered as an optimal design in practice for some range of transformers. In the first column of Table 6.5 the transformer design variables using the RW method are displayed including the total cost of the transformer.

The RW method is used as it helps us compare the outcome of the other techniques used, and to decide whether it is better and the amount of savings that will result if any exist. The comparison proves that other methods not only have a cheaper designs but also transformers with lower losses and smaller overall size.

6.3 Transformer Design Using GA and SA

In order to get an optimal design for the transformer, the cost of the raw material used are given in table 6.3 [23]:

Table 6. 4 Raw Material Cost

Material	Cost (SR / kg)
Copper	14.5
Silicone Steel	7.5
Mineral Oil	5.5
Mild Steel	6

Loaded losses cost is set to be 4,000 SR / kW and the no load losses are evaluated at 11,000 SR / kW according to the local standards set by SEC. The total capitalized losses cost for the complete life of the distribution transformer is considered for the evaluation of both the no load and loaded losses. The lifetime of the transformer is in the range of 10 to 15 years, however for the purpose of calculating the losses in this thesis and according to the standards set by SEC the transformer life is evaluated at 10 years. Therefore, the optimal transformer design is found by implementing the two different optimization processes, and the returned design variables material cost, and losses cost are compared with the RW transformer design as shown on Table 6.4.

Table 6. 5 Transformer Design Variables Using RW Method & GA & SA Optimization Techniques

Design Variables	RW	GA	SA
Secondary Number of turns	15	14	16
Core radius (mm)	92	96	83
Primary wire diameter (mm)	1.9	2.4	2.4
Secondary foil width (mm)	279	328	394
Secondary foil thickness (mm)	0.9	1.4	0.9
Secondary Num. of Ducts	2	1	1
Primary Num. of Ducts	2	1	1
Primary Num. of Layers	12	16	12
Turns Per HV Layer	146	79	142
%IZ	4.04	4.04	3.983
Copper weight (kg)	239	342	384
Steel core weight (kg)	442	571	433
No Load Loss (W)	510	539	407
Load Loss (W)	2400	1294	1651
Oil Volume (L)	337	362	331
Oil Weight (kg)	300	323	296
Steel Tank Length (mm)	1200	1200	1050
Steel Tank Height (mm)	900	900	1100
Steel Tank Depth (mm)	650	650	500
Steel Tank Weight (kg)	120	120	115
Losses cost (SR.)	15210	11105	11081
Materials cost (SR.)	9148	11917	11208
Efficiency	98.05	99.04	98.91
Total Cost (SR.)	24358	22842	22289

Results compared provided a significant reduction in the total owning capitalized cost of the transformer. There is a saving of 6.62 % in the total cost by using the GA optimization in comparison with the random walk design, and a significant 8.5 % reduction in the total cost by using the SA optimization.

Figure 6.1 shows a comparison of the different designs for the losses cost as well as the total cost of the transformer. The RW design has the highest total and capitalized losses cost. The GA and SA optimized designs have a noticeably lower capitalized losses cost, and a lower total cost in general.

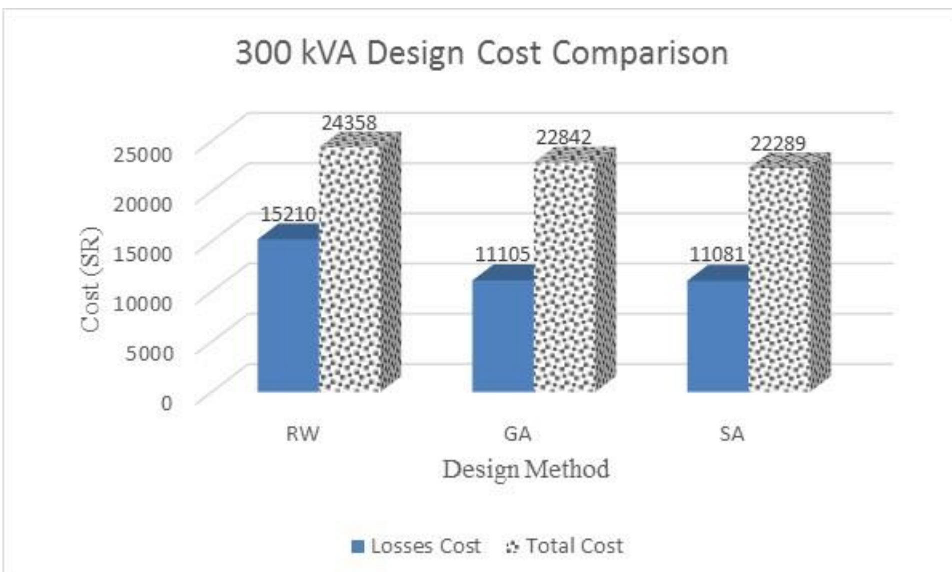

Figure 6. 1 Cost Comparison for 300 kVA Transformer

❖ **Comparison of GA and SA Designs**

In addition it is interesting to note that comparing the obtained optimal design variables using both methods we can see a substantial increase in the number of windings for the SA design, as a result the copper weight (kg) increased by a noticeable amount. However the core radius is in turn reduced using the SA optimization, and this as a result is a major advantage for our design as the core losses decreased and also the total size of the transformer was reduced. So not only the size of the transformer is smaller using SA which is an advantage especially when we are dealing with a pole mounted transformer, but also the total cost of noticeably lower.

In addition to the 300 kVA oil immersed transformer design optimized using the two optimization techniques, an optimized transformer design using the GA and SA optimization techniques are found for a transformer of 1000 kVA with the specifications given in Table 6.6.

Table 6. 6 Transformer Specifications for 1000 kVA

Parameter	Value
Transformer Rating	1000 kVA
Primary Voltage	13800 V
Secondary Voltage	400 V
Phase	3 phase
Type	Oil Immersed Core type
Frequency	60 Hz
Primary / Secondary Connection	Delta / Wye
Impedance	6%

For the design of the transformer with the specifications in table 6.6, the same design variable limits and constraints mentioned in Table 6.2, and Table 6.3 still apply with only a change in the guaranteed impedance which is now 6% with the standard 10% tolerance.

Table 6.7 lists the optimized design variables of the transformer, and compares them using two techniques, namely, GA and SA compared with the manufacturers RW design.

Table 6. 7 Transformer Design Variables Using Random walk Design & GA & SA Optimization Techniques

Design Variables	RW	GA	SA
Secondary Number of turns	8	11	10
Core radius (mm)	222	194	186
Primary wire diameter (mm)	3	2.8	2.8
Secondary foil width (mm)	380	368	358
Secondary foil thickness (mm)	2	1.9	1.9
Secondary Num. of Ducts	1	1	1
Primary Num. of Ducts	1	1	1
Primary Num. of Layers	8	9	9
Turns per HV Layer	115	103	108
%IZ	6.10	6.04	6.05
Copper weight (kg)	494	480	486
Steel core weight (kg)	1138	998	957
No Load Loss (W)	1298	1162	1088
Load Loss (W)	11825	10377	10518
Oil Weight (kg)	519	547	533
Steel Tank Weight (kg)	285	255	245
Losses cost (SR.)	59578	54290	54040
Materials cost (SR.)	19221	18983	18726
Efficiency	98.92	99.18	99.21
Total Cost (SR.)	78859	73273	72766

We can clearly observe that the designs obtained by any of the optimization techniques is remarkably cheaper than the design obtained by the designing program used by manufacturers. For the 1000 kVA transformer using the design obtained by the GA saves around 7.08 % on the total owning cost of the transformer and the design obtained using the SA technique is 7.73% cheaper than the manufacturer's RW transformer design. This can be mainly attributed to the use of the strict constraints in the optimization techniques implemented.

In Figure 6.2 a comparison of the different designs for the 1000 kVA transformer is displayed by which the bars refer to the losses and total cost. The RW design used by the manufacturer shows to have a highest total and capitalized losses cost.

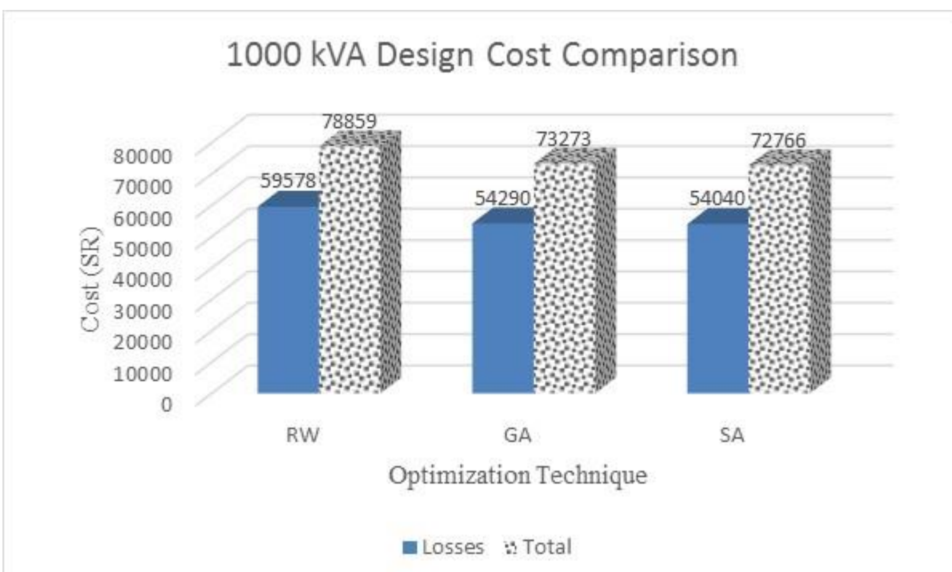

Figure 6. 2 Cost Comparison for 1000 kVA Transformer

6.3.1 Comparison of Different Transformer Rating (kVA)

The efficiency of the suggested optimization techniques has been established for small transformer ratings of 300 kVA and for high ratings of 1000 kVA. To prove that these techniques will also result in lower total medium size transformer cost, a 650 kVA transformer has been design and the results of every method are listed in Table 6.8.

Table 6. 8 Costs Comparison of Different Transformer Ratings

Rating	300 kVA			650 kVA			1000 kVA		
Method	RW	GA	SA	RW	GA	SA	RW	GA	SA
No Load Loss	510	539	407	1126	953	894	1298	1162	1088
Load Loss	2400	1294	1651	5077	4632	4681	11825	10377	10518
Losses Cost (SR)	15210	11105	11081	32694	29011	28558	59578	54290	54040
Material Cost (SR)	9148	11917	11208	13822	14157	14174	19221	18983	18726
Total Cost (SR)	24358	22842	22289	46516	43168	42732	78859	73273	72766
Percentage Saving	-	6.2%	8.5%	-	7.2%	8.1%	-	7.1%	7.7%

The percentage displayed in the last row of table 6.8 is the amount saved between using the obtained optimized GA and SA design compared to the industry used RW design. All savings are significant in the range of 7% to 8%.

6.4 Losses Cost Comparison at Different kWh Price

The losses capitalized cost as mentioned previously are set to be 4000 SR / kW and 11000 SR / kW for load and no load losses respectively. So if the transformer's life is estimated to be for 10 years, then the cost of the kWh can be calculated using the following equations:

$$\text{Cost of kWh}_{\text{Load Losses}} = \frac{4000}{8760*10}*100 = 5 \ \textit{Halala} \tag{6.1}$$

$$\text{Cost of kWh}_{\text{No Load Losses}} = \frac{11000}{8760*10}*100 = 13 \ \textit{Halala} \tag{6.2}$$

By the use of equations 6.1 and 6.2 we can deduce that SEC sets the kWh loss to be 5 Halala and 13 Halala for load and no load losses respectively. To show the effectiveness of the proposed optimal designs over the available RW design, Figure 6.3 illustrates the effect of the difference in the cost of load and no load kWh loss.

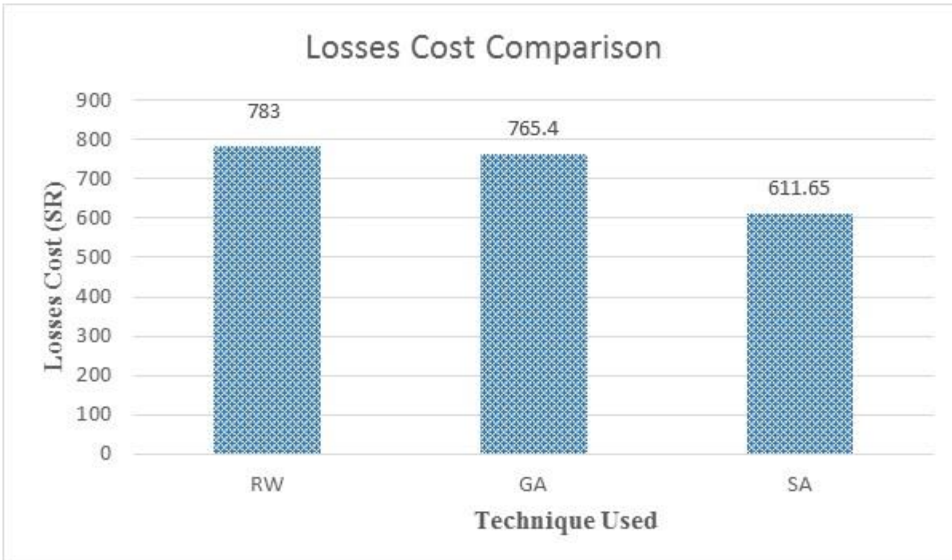

Figure 6. 3 Losses Comparison for Losses Cost set by SEC

The difference in the total amount of losses between the three designs has a direct effect on the total cost of the transformer, as the total cost is a summation of the fixed or material cost and the capitalized losses cost.

A final step to test the effectiveness of the techniques used is to investigate the effect of an increase in the kWh loss cost on the total price of the 300 kVA transformer. As can be understood from Table 6.9 the kWh losses costs are increased by 30% and then by 60%. The fixed (material) cost from Table 6.5 is then added and the total transformer cost is obtained.

Table 6. 9 Cost of kWh Effect on Total Transformer Cost

	No Load Loss Cost (SR)	Load Loss Cost (SR)	Total Losses Cost (SR)	Total Transformer Cost (SR)
Case I	Regular Price			
RW	5610	9600	15210	24358
GA	5929	5176	11105	23022
SA	4477	6604	11081	22289
Case II	30 % Increase in kWh Price			
RW	7293	12480	19773	28921
GA	7708	6729	14437	26354
SA	5820	8586	14406	25614
Case III	60 % Increase in kWh Price			
RW	8976	15360	24336	33484
GA	9487	8281	17768	29685
SA	7163	10566	17729	28937

Now the amount saved is calculated and compared for each case to obtain to total percent in savings. This will help us identify on whether or not an increase in the kWh price is an advantage for our design or not.

For Case I at the regular kWh loss price using the SA design results in a saving of 8.5% when compared with the RW design, however for Case II when the kWh price goes up by the 30% the savings made between these two designs increases to 11.4%. And finally for an inflation of 60% in the kWh price the savings made increases further to reach 13.6%. Using the GA design resulted in a savings of 6.2%, 8.9%, and 11.3% respectively when compared to the RW design. These results verify that using the optimized SA designs does not only save money on losses for the current market but is also more efficient and guarantees more savings in case SEC increases the loss kWh pricing. Figure 6.5 displays the change is costs for the different design methods.

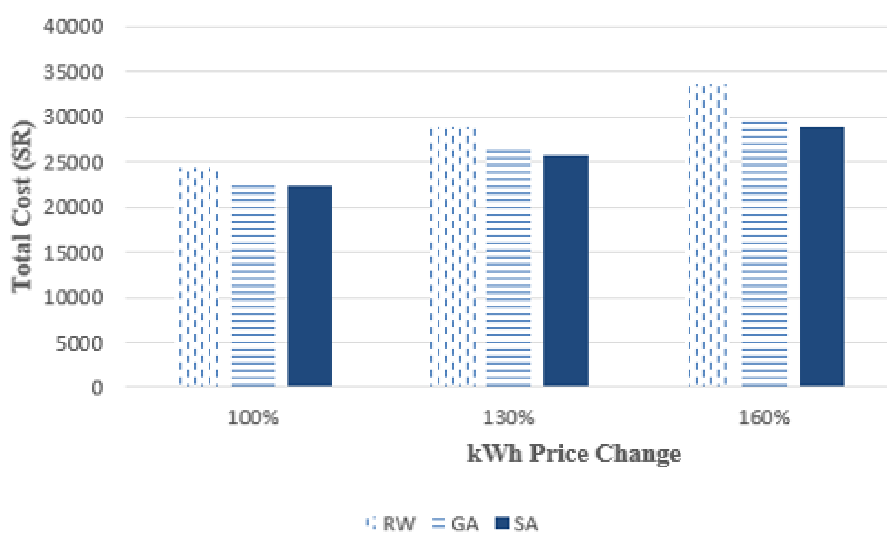

Figure 6. 4 Price Change of kWh Cost Comparison

Figure 6.5 displays the percentage saving between using any of the two optimization techniques compared to the RW design.

Figure 6. 5 Percentage Saving for kWh Price Change Using Optimization Techniques

6.5 Comparison with Different Designs

In table 2 the results obtained using SA algorithm is compared to the work done previously in the literature by Srivastava [35] for the design of a dry type transformer

Table 6. 10 Dry Type Transformer Design Variables Comparison

Design Variables	Srivastava [35]	SA
Core Weight (kg)	574	531
Copper Weight (kg)	294	316
Material Cost ($)	2286	2284
No Load Loss (W)	1150	1019
Load Losses (W)	3570	3314
Losses Cost ($)	7190	6532
Impedance	4	4.11
Efficiency	98.16	98.3
Total Cost ($)	9476	8816
Percentage		6.96%

As we can see the results show that the material cost is almost the same. However, the design obtained using SA results in a smaller core hence smaller transformer size, and has lower losses thus slightly more efficient.

CHAPTER 7

CONCLUSION & FUTURE WORK

In this research work, the potential of designing a cost effective oil immeresed distribution transformer using optimization techniques was investigated. The study started by learning what other researchers have done in this area and it was found that every designer uses a different and a unique technique in the design of the transformer according to the standards of the manufacturer and based on the requirments of the user. Although, very few have considered the use of optimiziation in the design process, each designer had considered different variables and constraints that are acceptable depending on the transformer ratings and other functional charectarestics that need to be met by the manufacturer. In the present optimized design, by using the GA and SA, unique design variables were obtained satisfying constrained bounds. The optimized designs resulted in a significant amount of savings as the use of GA and SA returned savings in the range of 6% to 9% depending on the size of the transformer. In addition it has been found that SA secures 2% to 3% more savings than GA.

It was also noticed that an increase in the kWh loss cost resulted in a significant increase in savings beyond the 9% when using the optimized desings.

For the future work:

- Experimenatal work to verify the optimized design
- Other optimization techniques can be used
- Mutliobjective optimization could be implemented
- Extension of the work for higher transformer ratings where forced cooling has to be incorporated

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