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DEANSHIP OF GRADUATE STUDIES

This thesis, written by **MOHAMMED Y. ABU-SADA** under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ELECTRICAL ENIGINEERING**

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Dedication

To my parents

whom waited long for this

and

To my wife

who offered the support and patience throughout the thesis execution

Acknowledgment

I would like to express my thanks and gratitude to Allah, the Most Beneficent, the Most Merciful whom granted my ability and willing to start and complete this thesis.

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Thesis Abstract

Name: MOHAMMED YOUSEF ABU-SADA

Title: COST EFFECTIVE DESIGN OF CONVENTIONAL TYPE DISTRIBUTION TRANSFORMER USING OPTMIZATION TECHNIQUES

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Due to the huge number of distribution transformers yearly consumed and installed in the utility networks, it is always required and targeted to build transformers with the most economical cost. Achieving the guaranteed characteristics of transformers is an important factor that should be considered. It is well know that the transformer design task is time consuming. In this thesis a successful attempt for designing distribution transformers up to 34.5 kV and 1500 kVA using optimization techniques is presented. Two optimization techniques to obtain the optimal design of distribution transformers are proposed. Nonlinear programming (NL) algorithm is the first technique while the second one is Genetic Algorithms (GA). The transformer design mathematical formulation is explained in a systematic way for the conventional type of distribution transformers. Optimization methodologies and implementation results are presented. Results show the effectiveness of the proposed mathematical formulation of the transformer design problem and the reduction of total cost when compared to conventional designs.

Keywords: Distribution transformer, transformer design, Nonlinear constrained programming, Genetic Algorithm, Optimization.

خلاصة الرسالة

الاسم : محمد يوسف أبوسعدة
عنوان الرسالة: التصميم الأقل تكلفة لمحولات التوزيع التقليدية باستخدام طرق لايجاد التصميم الأمثل
الدرجة الممنوحة: ماجستير في العلوم
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بسبب الأعداد الكبيرة التي تستخدم وتركب سنوياً من محولات التوزيع في الشبكة الكهربائية ، فإنه من المطلوب دوماً تصنيع وعمل المحولات بأقل تكلفة إقتصادية. كما أن إستيفاء وتحقيق المواصفات المطلوبة للمحولات هو عامل مهم لابد من أخذه بعين الإعتبار. هذا بالإضافة إلى أنه من المعلوم أن تصميم المحولات مهمة تستغرق وقت طويل.

في هذه الرسالة ، تم طرح محاولة ناجحة لتصميم محولات التوزيع إلى مستوى جهد أولي 34.5 ك.ف. وقدرة 1000 ك.ف.أ ، باستخدام خوارزميات لإيجاد الحلول المثلى. استخدمت طريقتين لإيجاد التصميم الأمثل لمحولات التوزيع. الطريقة الأولى هي البرمجة اللاخطية والثانية هي خوارزمية النظام الجيني لإيجاد التصميم 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 مقارنة مع التصميم التقليدي للمحول.

مفردات: محولات التوزيع ، تصميم المحولات ، البرمجة اللاخطية المقيدة ، الخوارزمية الجينية.

درجة الماجستير في العلوم
جامعة الملك فهد للبترول و المعادن
مايو 2003 م

CHAPTER 1

1 Introduction

A transformer is a device with two or more stationary electrical circuits that are physically and conductively disjointed but magnetically coupled by a common magnetic field. Transformers are basically passive devices for transforming voltage and current.

Power transformers are usually categorized as *power* and *distribution* transformers. Distribution transformers are normally considered to be those transformers, which provide the transformation from 36 kV and lower voltages down to the level of final distribution network. In the Kingdom of Saudi Arabia, the rated primary voltages are 34.5 kV, 33 kV, 13.8 kV and 4.16 kV while the secondary rated voltages are 400 V and 231 V.

Distribution transformers are by far the most numerous and varied types of transformers used in electricity supply network. There are thousands of distribution transformers installed in the KSA public electricity supply system. They range in size from 50 kVA to 1500 kVA [1].

Transformer cost consists mainly of two parts. The capital cost of transformer and the system losses cost. In fact, minimizing transformer cost relies on the art of transformer design.

Transformer design can be considered as one of the most complex electrical equipments design problems. In transformer design, there are many characteristics and factors to be achieved such as the rated power, voltage ratings of windings, and pre-specified voltage impedance value, etc. At the end, a variety of designs can be found which guarantee the required characteristics of a transformer. These different end products differ in their design parameters such as core flux density and radius, dimensions of windings including radial and axial, secondary or primary number of turns, current densities of primary and secondary conductors, etc.

Even though the user requirements are achieved, the above parameters (i.e. core flux density and radius, dimensions of windings, etc.) play a main function in determining the transformer cost.

In this thesis the following objectives have been be achieved:

1. A mathematical formulation along with the operation and practical constrains of a distribution transformer cost have been developed. The cost include steel core and winding copper as well as the Losses (No Load Loss and Load Loss) cost, i.e. capital cost.

2. A computer based design program algorithm to select the optimal design parameters, i.e. copper size, core size, insulation thickness, etc. have been developed. This resulted in an objective function which is solved using non-linear programming and Genetic Algorithms.
3. To compare the total cost of a transformer obtained using the proposed algorithms with the total cost obtained using a ready made program.
4. To generate a complete transformer design report that includes all details of transformer design variables as well as to predict the transformer performance, i.e. Voltage Regulation, efficiencies, etc., of the designed transformer.

The flow of thesis presentation will be as follows:

Chapter 2 presents the up-to-date work reported in the literature for designing distribution transformers combined with the different trials for implementing optimization methodologies. The proposed mathematical formulation of distribution transformer design problem is presented in detail with consideration of practical aspects in chapter 3. Chapter 4 deals with optimization formulation of distribution transformer in which the design objective function, design variables, constraints are proposed. Implementation of nonlinear programming (NL) and Genetic Algorithm (GA) to distribution transformer design problem is introduced in chapter 5. Chapter 6 presents a construction of a transformer based on the mathematical formulation in chapter 3. This chapter presents also the effectiveness of the proposed NL and GA based algorithms in solving distribution transformer design problem. This is done through applications to different transformer sizes (kVA ratings and voltages). In chapter 7, conclusions of the present work are presented by highlighting the results obtained throughout this thesis. Possible future improvements and research work are also discussed in this chapter.

CHAPTER 2

2 Literature Survey

The normal practice in transformer design is to rely on an earlier design that has been used in manufacturing transformers with similar main characteristics such as voltage ratio, rated power, etc. Another method is to start a trial and error process by varying some of the design variables until achieving the required new specifications. Starting from scratch could lead to the same design but with more effort and time.

Although the above two methods are extensively used to get designs as per IEC and ANSI international standards, they do not guarantee a cost effective product.

Some attempts have been reported in the literature to develop systematic transformer design procedures. It is often to find literatures discuss sub-problem of transformer design rather than discussing the entire transformer design problem. Such sub-problems are transformer windings & core losses, calculation of transformer short circuit and leakage impedance, transformer thermal modeling & heat dissipation, and transformer insulation design. Some of these literatures will be briefly presented here.

Holland [2], described the results obtained from a rarely published method of calculating eddy losses in a thick conducting materials. The Surface Impedance formulation was used in a finite element software package which is applied to the design of large power transformers. The value and improvements obtained from the results of this paper are applicable power transformer design only. This paper gives more consideration to the losses due to eddies induced in steel fittings, clamps and the tank wall. Such losses are usually ignorable in distribution transformer design problem. Sullivan [3], introduced the squared-field-derivative method for calculating the eddy current (proximity-effect) losses in round-wire transformer and inductor windings. The derived method is capable of analyzing losses due to two-dimensional and three-dimensional field effects in multiple windings. The limitation of this method is due to using round wires only as a base of the analysis. In case of other shape, the losses would then depend on the orientation of the electromagnetic, somewhat complicating calculations. An analytical method for calculating eddy loss in a two-dimensional problem was presented by Koppikar [4]. The result of this method highlights the importance of considering the eddy losses of LV winding leads in power transformers design. Conversely, this method confirms the assumption of ignoring the eddy loss of LV leads in distribution transformer design problem.

An approach to eddy current analysis in foil windings, using a combination of numerical and closed form analytic solution was introduced by Odendaal [5]. Validation of this approach has been verified only by using a sample consists of few small foil turns and small stacked core, which may not be sufficient to assist the introduced method. A helpful study was introduced by Ram [6]. In this paper, a detailed loss and current distribution in the foil-wound low voltage winding of transformer using a finite-element analysis package are presented. The results obtained from the analyzed transformer provide the distribution transformer designer with preliminary expectation of the results by using different copper foil geometry and dimensions. On the other hand, some assumptions were considered in the study which may have an influence on the obtained results.

Linden & Tom [7] have summarized a thermal model for the design of rectangular layer windings for transformers. The model calculates thermal gradients across layers, to and from the core, and from the no-duct region under the core iron to the ducted region. The model evaluates the effects of cooling duct quantity, location, and size on the thermal performance. The predicted date of the transformer thermal model was not compared with the test data.

Jewel [8], proposed a single-phase transformer design. In his work, the transformer is designed based on some practical philosophy rather than on mathematical estimation of the cost. Two simple examples of transformer design have been presented while the scope of work covers only low rating and low voltage transformers. Furthermore, many practical factors contribute to transformer design were not considered or highlighted. A design optimization procedure for transformer analysis that involves only routine calculation is presented by Poloujadoff [9]. In this paper, a considerable amount of creativity, resourcefulness, initiative and good judgment is necessary to identify the various alternatives and to choose between them. A few criteria for the "optimum" design are inferred but not clearly stated.

Anderson [10] proposed a computer based optimization design of single phase transformers. It utilizes a routine which is used to guide the choice of the independent variables in such a way that the final design has usually the lowest cost. In essence, this routine does self-optimize its design. It appears that one simply enters some input variables and a program provides a design. Furthermore, there are no examples presented in this paper with regards to the software approach. The design independent variables are the width and the depth of the core leg and the current density, while the current density is set equal for the two windings. A PC-based transformer design and analysis program has been developed by Grady [11]. The program does not attempt to automatically optimize an objective function. Moreover, it is limited to the design of dry type transformer. Rubaai [12], describes a single-phase transformer design suitable for classroom training. The design does not include the effect of transformer design variables other than the core and coils. In a recent study, Geromel [13], used a methodology that allows the application of artificial neural networks in some specific stages of the transformer design. The paper does not consider the transformer cost.

Two different design procedures of large power transformers were analyzed and discussed by Boccaletti [14]. In the first procedure, the losses are not fixed a priori by the customer, and the designer must keep the cost of both the no load and load losses into account, i.e. free losses. The second procedure, the designer is required to respect assigned values of the losses, i.e. fixed losses. The design mathematical formulation was performed using trail and error method rather than using any optimization methodology. In the study application, the transformer has high MVA rating (63 MVA) and high primary voltage (132 kV).

Li Hui [15], represents an Improved Genetic Algorithm (IGA) optimization method applied to the power transformer design problem. The target of this method was to overcome the Simple Genetic Algorithm (SGA) common problems. The design was limited to the use of rectangular copper strip in primary and secondary windings.

Moreover, distribution transformers frequently use a type of winding construction not found in large transformers. The most frequently used winding construction is the copper foil winding in the low voltage side and wound primary wire [16].

None of the reported work formulated the transformer design problem as an optimization function that includes the transformer losses cost in the objective function. In recent published book [17], the work of power transformer cost minimization was done using a branch of optimization theory called geometric programming. In this study, the developed work appears to be suited to the needs of power transformers rather than distribution transformers. The cost function includes weight of primary and secondary windings' materials. No Load Loss and Load loss are also included in the cost function.

It is worth mentioning that all of the above literatures do not touch on the design of distribution transformers that use the layered windings with wound primary wire and secondary foil.

Therefore, this thesis is devoted for presenting a new mathematical formulation along with the operating and practical constraints of a distribution transformer. The cost includes the steel core, and the primary and secondary copper winding. The cost of losses (No Load Loss and Load Loss) is also included in the cost function of transformer. The developed formulation is valid for transformer ratings of 50 to 1500 kVA, with primary rated voltage range from 4.16 to 34.5 kV, with secondary rated voltage from 208 to 480 V and 60 or 50 Hz.

CHAPTER 3

3 Distribution transformer design formulation based on practical considerations

Transformer design formulation principles are mostly the same for the wide range of transformer capacities which ranges from a rating of few kVA up to transformers rated of hundreds of MVA. Variation in design formulation exists whenever a change in the construction used, such as different type of windings construction.

This chapter addresses distribution transformer design formulation, based on the following characteristics. The design is limited to:

a) Three phase oil-immersed, three-legged, core type.

b) Copper round wire primary layered winding construction.

c) Copper foil secondary winding construction.

d) Stacked circular core.

3.1 Transformer core design and selection

Sometimes, transformers are classified according to the construction of core. There are two types, core-form & shell-form. The basic difference between the two forms is illustrated in Figure 3.1. In a core-form design, the coils are wrapped or stacked around the core.

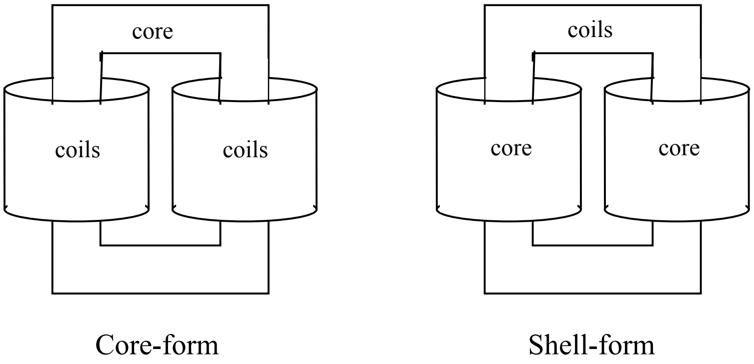


Figure 3.1 Core-form and shell-form transformer constructions

The core-form transformer is considered in this thesis. In stacked cores of core-form transformers, the coils are circular which surround the core. A core with circular cross-section is ideal to increase the flux carrying area. From practical point of view, this is not possible since it requires numerous ranges of laminations widths. Usually, a core is made of different number of steps as shown in Figure 3.2. For smaller cores of distribution transformers this could be as few as five or less. For larger transformers, this might be 11 steps or more.

A Transformer designer always tries to maximize the core area in order to obtain optimal stacking arrangement by using specific number of steps.

Figure 3.3 shows the geometric parameters which can be used to get the optimal stacking arrangements, namely the *x* and *y* coordinates of stack coroners which touch the circle of radius *r*.

In the work of Vecchio [17], the normalized *x* coordinates which maximize the core area for a given number of steps are given in Table 3.1.

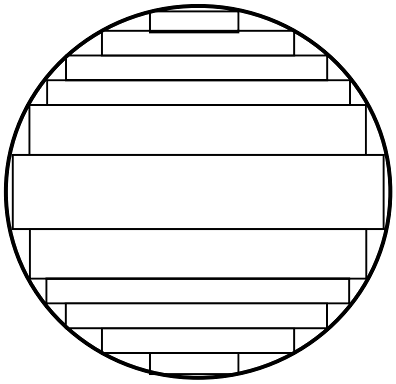


Figure 3.2 Six steps core section

It is a normal practice that transformer manufacturer will keep standard widths of sheets or do slitting based on certain sheet width increment such 5 or 10 mm. In this thesis, the considered steel width increment is 10 mm.

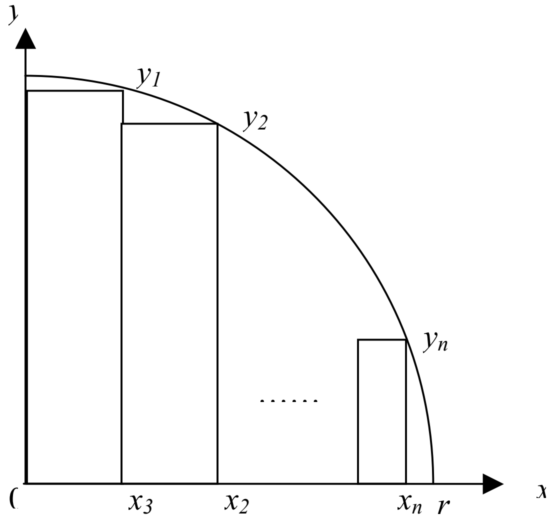


Figure 3.3 Geometric parameters for finding the optimum stacking step configuration

Cores of transformers are usually made of electrical sheet laminations that are mostly made from Cold Rolled Grain-Oriented (CRGO) steel with an approximate silicone content of 3%. They are usually in the range of 0.23 – 0.46 mm (9 – 18 mils) in thickness and up to 1 meter wide. Conventional grain-oriented steels are made in various grades, M-4, M-5, M-6 and M-7, while low loss HI-B steels are available in grades M-0H M-1H, M-2H, M-3H and M-4H. Later, Nippon Steel Corporation introduced laser-etched material with losses of 5-8% lower than HI-B steel, known as ZDKH grade. Each grade has different physical, magnetic, electrical and mechanical properties. The most important characteristic is the specific core-loss (W/kg). Obviously, reduced core-loss will influence the cost of the material and consequently transformer cost.

Table 3.1 Normalized *x* coordinates which 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

The manufacturer or supplier of electrical steel generally provides the user with loss curves which show the total loss per kilogram or pound as a function of flux density at the frequency of interest. Some of these curves are shown in Figure 3.4.

Considered grades in this thesis are M-6, M-5, M-4, M-3, M-0H and ZDKH. Sheets thickness is as in Table 3.2.

Table 3.2 Considered 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

It is worth mentioning that a new type of electrical steel known as "Amorphous" have appeared relatively recently which offer considerable reduction in losses compared to conventional electrical steel. The use of Amorphous steel is still limited due to the available size of strips which are only suitable to build small distribution transformers with a rating less than 50 kVA. Another reason of limitation in usage is the poor stacking factor (less than 0.9) due to the thinner used sheets.

The ideal cross section of area of the core results from the summation of individual multiplication of core step width and height. In practice, considering this ideal cross section area will result in considerable variation of designed core loss and measured values.

Tow factors should be considered in calculating the core area and core loss. These are known as *Stacking Factor* (SF) and *Building Factor* (BF).

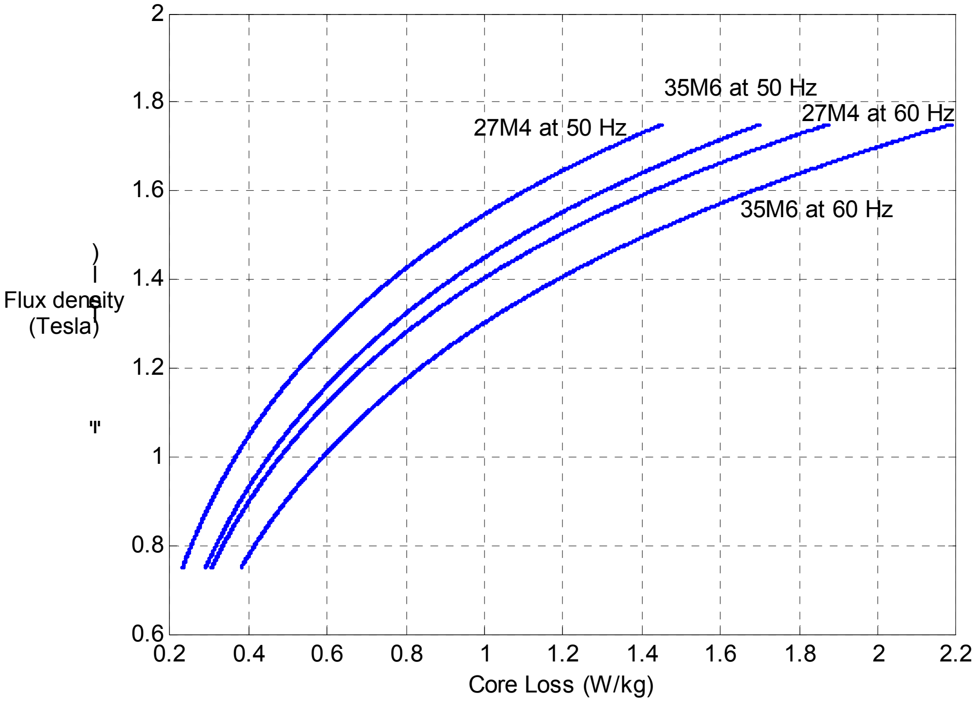


Figure 3.4 Core loss curves of M-4 & M-6 at 50 & 60 Hz

3.1.1 Core Stacking Factor (SF)

Stacking factor is a correction number that represents the space lost between laminations. Both surfaces of lamination (electrical sheet) are provided with an insulation of oxide coating (commercially known as Carlite). The stacking factor of lamination improves by using thicker laminations. This will increase the eddy current loss in proportion of square of the thickness of the lamination. Therefore, to reduce the eddy current losses, thinner laminations are preferable even though the stacking factor will go down.

In conventional silicone steel sheets, the stacking factor is in the range of 0.95 – 0.98 depending on the thickness of laminations.

In this thesis, the considered stacking factor for each lamination thickness is shown in Table 3.3.

Table 3.3 Stacking factor value for different lamination thickness

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

3.1.2 Core Building Factor (BF)

The building factor is a number which should be multiplied by the ideal core loss. It is the sum of different factors that increase the losses in the core such as the gap between different laminations at corners where the induction must overpass. Another factor that increases the loss is burrs produced by cutting and slitting of sheets [18]. The building factor of stacked cores is generally in the range of 1.1 – 1.3 which varies from manufacturer to another.

One of the main attempts which have led to an improvement in the joint designs is a step-lapped joint. By this attempt, the joint is made gradually in a step like manner. Five –step step-lapped core joint is shown in Figure 3.5.

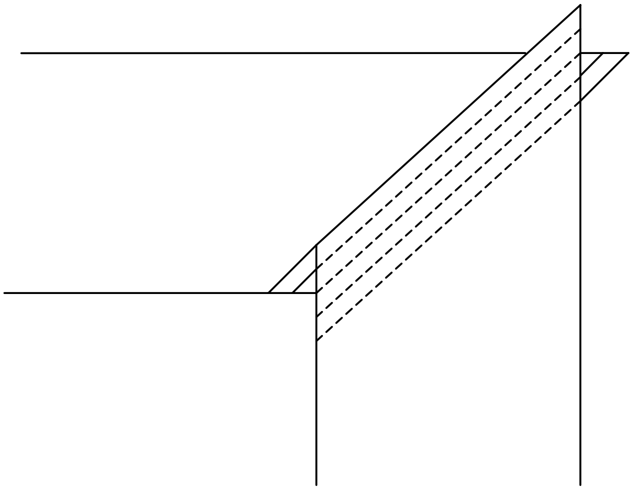


Figure 3.5 Five-step step-lapped core joint

The total weight of the core results from multiplying the ideal area of core by SF. This is then multiplied by the total length of core by the density of silicon steel.

Silicon steel density is usually provided by steel manufacturer which is considered as 7.65 kg/cm^3. Therefore, the core weight is:

$$\textit{Core weight}\ (\text{kg}) = \textit{Ideal area}\ (\text{cm}^2) \times SF \times \textit{Core total length}\ (\text{mm}) \times 7.65 \times 10^{-4} \quad (3\text{-}1)$$

where:

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

Figure 3.6 shows the core main dimensions

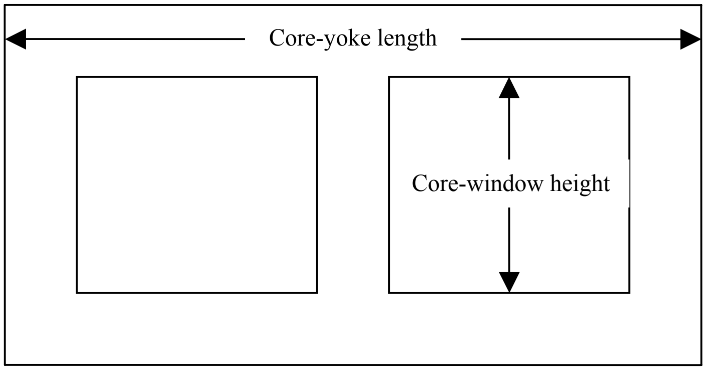


Figure 3.6 Core main dimensions

Therefore, the total core loss will be as follows:

$$\textit{Core Loss}\ (\text{W}) = \textit{Core weight}\ (\text{kg}) \times BF \times \textit{Loss/kg} \quad (3\text{-}3)$$

The *loss/kg* can be obtained from the core loss curves (Figure 3.4) based on the operating flux density (Tesla), where the operating flux density can be obtained from the following equation:

$$B = \frac{Vt}{4.44 \times f \times A_{net} \times 10^{-4}} \tag{3-4}$$

in which:

B = operating flux density (Tesla)

Vt = volt per turn = $\frac{V_{ps}}{Strn}$

V_{ps} = secondary rated phase voltage (Volt)

$Strn$ = secondary number of turns (Turn)

f = operating frequency (Hz)

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

3.2 Transformer windings and insulation design

The winding construction and insulation design of oil-immersed distribution transformers are different from the construction of large power transformers. However, the main principles can be applied with some modification when it is necessary.

3.2.1 Transformer winding construction

In distribution transformers, the layered winding construction is mostly adopted. Most of utilities prefer or accept copper windings only. This is due to its conductivity in addition to its excellent mechanical properties. Its value in transformers is particularly significant because of the benefits, which result from the saving of space and minimization of load losses.

Foil windings are frequently used as low-voltage windings in distribution transformers. In this form of construction, the winding turn of copper foil, occupies the full width of the layer. This is wound around a mandrel, with intermediate layers of paper insulation, to form the required total number of turns for the windings. Strips of the conductor material are welded or brazed along the edge of the foil at the start and finish to form the winding leads. This arrangement represents a very cost-effective method of manufacturing low-voltage windings and also enables a transformer to be built with good mechanical short-circuit strength.

In addition to the foil windings described above, distribution transformers frequently use other types of winding construction not found in larger transformers. Because of the low kVA ratings, the volt per turn is usually very low so that for a higher-voltage winding a considerable number of turns will be required. The current is also low and the turn cross-section area, as a result, is small too. The winding wires are frequently circular in section and enamel covered.

Low voltage and high voltage windings during construction are shown in Figure 3.7.

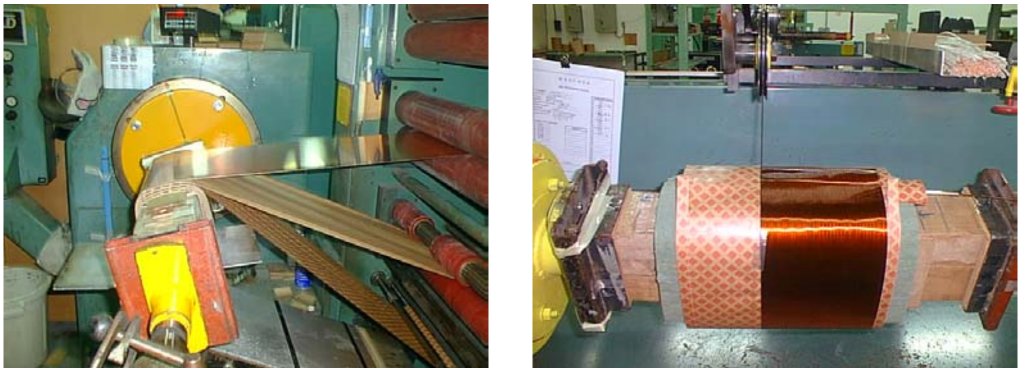


Figure 3.7 LV winding (left side) and HV winding (right side) during manufacturing

3.2.2 Transformer insulation design

Insulation is required in a transformer, wherever a difference in potential exists between two points. The insulation system in transformers, as in other electric equipments, consists of various components designed to work altogether to achieve the best *insulation coordination.* Solid insulating materials and transformer liquid insulation are mostly used in distribution transformers.

I) Solid insulating materials

Transformer solid insulation components vary and can be categorized based on the severity of potential deference to be insulated. These categories are as follows:

a) Major insulation

It is well known to the transformer designer that the main and most important insulation consists of the insulation between the high voltage coil and the low voltage coil in the same phase and from the LV coil to ground. In Medium and Low Voltage transformers, the insulation material used between High and low voltage coils are pressboard and cooling ducts, which are also used for cooling. A Pressboard represents a thick insulation paper made of extremely pure cellulose fiber, suitably treated at the wet stage of manufacturing process and then compacted at very high pressure.

b) Minor Insulation

This category is normally for the insulation between the adjacent turns in a coil and between different sections in the same coil. Synthetic enamel covered wires are normally used in Medium and Low voltage transformers. Foil windings are frequently used as low-voltage windings in distribution transformers. In this case, Diamond Dotted Presspaper (DDP) used to insulate the adjacent copper foil turns. Figure 3.7 shows diamond dotted presspaper being used in the construction of a distribution transformer. The diamond dotted presspaper represents an acceptable method high mechanical strength without the associated difficulty of impregnation in oil. The partial resin coating introduced into the winding with DDP, after application of heat and pressure for a time, leads to bonding of the electrical conductors with the layer insulation and mutual bonding of the insulation materials layers. The large axial and radial mechanical forces arising in the case of short circuit are safely tolerated by this internal strengthening of the coil. At the same time the partial coating leaves empty spaces between the insulation and the electrical conductors. Air and moisture can be quickly removed from the coils through these channels, which are then filled with liquid insulation material. Thus using the diamond dotted presspaper minimizes the danger of partial discharges due to gas entrapment.

The material base of diamond dotted presspaper is transformer presspaper, which has been proven and established in transformer construction for several decades. This presspaper is coated on both sides by printing process with a diamond pattern partial epoxy resin layer.

DDP has coating squares with a side length of 9.5 mm and a separation of 6.35 mm. This means approximately 36% of the total area of each side is print-coated with epoxy resin as shown in Figure 3.8.

c) Phase-to-Phase Insulation

This is for the insulation between the adjacent phases. Pressboard is dominant in this category.

II) Transformer oil

For both the designer and the user of an oil-filled transformer it can be of value to have some understanding of the properties of the transformer oil and an appreciation of the ways in which oil performs dual functions of providing cooling and insulation within the transformer. Such an understanding can greatly assist in obtaining optimum performance of the transformer throughout its operating life.

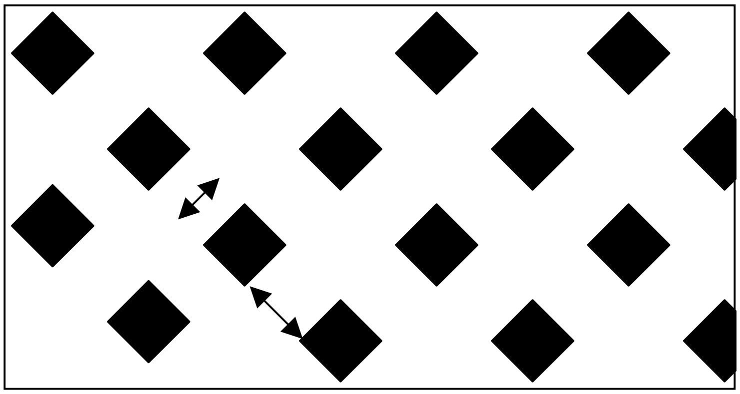


Figure 3.8 Structure of Diamond Dotted Presspaper

A closer look at the two functions of transformer oil is presented hereafter.

A) Oil as coolant

Copper and iron in core and coil produce the energy losses. These, of course, manifest themselves in the form of heat. This results in a rise in temperature of the transformer, i.e. core and windings, core frames, tank, or other parts. For the majority of transformers, the limiting temperature is set by the type of paper insulation (must be limited to somewhere in the region of 100^{o}C). For most of transformers, mineral oil is the most efficient medium for absorbing heat from the core and windings and transmitting it to the naturally cooled outer surfaces of the transformer.

B) Oil as an insulator

In all transformers there are a number of parts at different electrical potentials and there is a need to isolate these from each other. If the transformer cost is to be as minimal as possible, the separation between these different parts must be reduced. This means that the transformer must be able to operate at high electrical stress.

Transformer oil has many properties such as electrical, chemical, physical, etc. The Most important electrical property of transformer oil is *Electrical strength* (*breakdown voltage*). Breakdown voltage is the voltage at which breakdown occurs between two electrodes when oil is subjected to an electric field under prescribed conditions. It serves to indicate the presence of contaminating agents like moisture, fibrous materials, and carbon particles.

From the above, the transformer insulation system can be viewed as a composite insulation system which has more than one insulating material.

A transformer insulation system must be designed to withstand not only the AC operating voltages, but also the much higher voltages produced by lightning strikes or abnormal conditions. In normal practice, transformer is protected by different devices against lightning strikes in the level of MV system. Fortunately, the transformer's insulation can withstand higher voltages for shorter periods of time characteristics of lightning disturbances. Thus, insulation designed to be adequate at the operating voltage can also be sufficient for short duration higher voltages.

Some breakdown voltage formulas depend on insulation thickness as can be seen in the following equations for the transformer insulating pressboard and presspaper:

Palmer and Sharpley [19] report the impulse breakdown in paper versus thickness in mm at 90^{o}C as

$$E_{impulse} = \frac{79.43}{d^{0.275}} \quad \left(\frac{kV_{peak}}{mm}\right) \tag{3-5}$$

Clark [20] reports the breakdown voltage for paper at room temperature and a.c. test conditions as

$$E_{ac} = \frac{32.8}{d^{0.33}} \quad \left(\frac{kV_{rms}}{mm}\right) \tag{3-6}$$

Palmer and Sharpley [19] report the impulse breakdown and a.c. breakdown of pressboard in oil at 90°C as

$$E_{ac} = \frac{27.5}{d^{0.26}} \quad \left(\frac{kV_{ac}}{mm}\right) \tag{3-7}$$

$$E_{impulse} = \frac{91.2}{d^{.26}} \quad \left(\frac{kV_{peak}}{mm}\right) \tag{3-8}$$

The operating condition in actual transformer has several factors that influence the breakdown voltage of insulating materials such as drying degree of core & coil assembly, vacuuming process, operating temperature, operating pressure, level of loading, aging factor, etc.

Presspaper and pressboard are commercially produced in several thicknesses. Manufacturers usually provide two breakdown voltage levels to each thickness, dry breakdown and breakdown voltage in oil. Obviously, due to the difference in breakdown voltage and characteristics of oil that will be used in actual process of transformer manufacturing, such data can not be used as it is.

A quite fair and practical equation for determining the thickness of insulating paper between winding layers is the following equation

$$Thickness(mm) = \frac{Volt/turn \times turns/layer \times 2}{4400} \tag{3-9}$$

As an example of determining the insulation thickness, we assume that the volt/turn is 10 V/turn with 100 turns per layer results in approximate requirement of 0.45 mm presspaper between each two layers. When using 0.125 mm standard thickness presspaper, we need 4 sheets.

The following practical clearances between two adjacent HV coils, HV-LV winding and LV-core can employed safely:

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

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

LV-core clearance = 10 (mm)

Clearance between HV winding and transformer steel tank which is grounded (0 volt) can be considered as follows:

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

Detailed transformer insulation construction is shown in Figure 3.9.

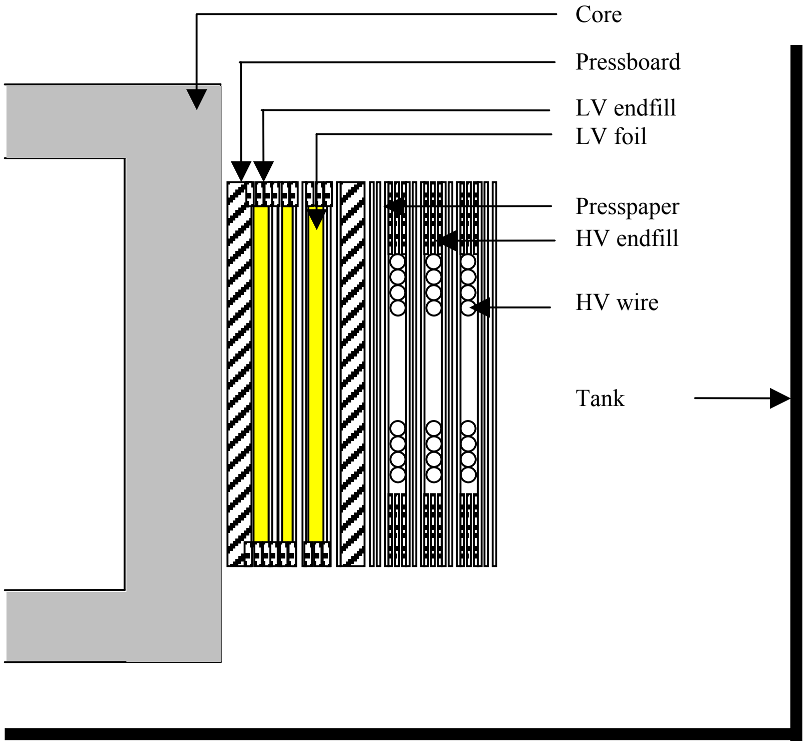


Figure 3.9 Transformer insulation construction

3.3 Transformer impedance and load loss calculation

3.3.1 Transformer winding impedance

One of the main transformer characteristics that end users or system designers request to be guaranteed is the transformer impedance. Transformer designers always seek to meet the limits of minimum and maximum values of specified impedance. In the case of distribution transformers, utilities specify a standard impedance value for each rating of transformer. The normal way to express the transformer impedance is as a percentage voltage drop in the transformer at full load current. This reflects the method which it is seen by the system designer. Percentage resistance and reactance of windings are the components that determine transformer percentage impedance. The general formula that specifies the percentage impedance is as follows

$$\%Z = \frac{I_{fl}\sqrt{R^2 + X^2}}{E} \times 100 \qquad (3\text{-}10)$$

where;

I_{fl} = Transformer primary or secondary full load current

E = Transformer primary or secondary open circuit voltage

R = coil resistance per phase

X = coil reactance per phase

A) Transformer winding Resistance

Since distribution transformer wires cross-sectional area is not large, we can use only the DC resistance of conductor to determine the windings resistance. DC resistance of transformer windings can be calculated as follows

$$R = \frac{\rho \times L \times N}{A} \ (\Omega) \tag{3-11}$$

where;

ρ = copper conductor resistivity at the temperature of interest

L = mean length of conductor turn

N = number of turns

A = cross section area of conductor

Resistance calculated by equation (3-11) must be multiplied by three to obtain the total windings resistance.

Copper resistivity at 20°C is 1.724×10^{-8} Ω.m can be recalculated at temperatures of interest (75°C or 85°C as per IEC60076 and ANSIC57 international standard respectively) as follows

$$\rho = 1.724 \times 10^{-8} \left(\frac{T_{ref} + 234.5}{234.5 + 20} \right) \tag{3-12}$$

In step-down distribution transformers, it can be always observed that the LV windings resistance is much lower than the resistance of HV windings, which is due to substantial difference in winding number of turns. However, the secondary windings full load current is much larger than primary windings current that increases the significance of LV windings resistance in calculation of I^2R losses which will be discussed later.

The accuracy of determining the windings resistance depends on how accurate the mean length of turn can be calculated. Obviously, winding dimensions play the main role in computing the mean length of turn which can be calculated as follows.

$$MLT_{LV} = \pi\left(ID_{LV} + RD_{LV}\right) \tag{3-13}$$

where;

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

ID_{LV} = LV winding inside diameter (mm) = $Core\ diameter + (2 \times Gap_{core\text{-}LV})$ (3-14)

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

$$= N_{LV} \times T_{foil} + N_{LV\text{-}duct} \times T_{duct} + (N_{LV} - 1) \times T_{LV\text{-}ins.} \tag{3-15}$$

in which

N_{LV} = LV number of turns

T_{foil} = Copper foil thickness (mm)

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

T_{duct} = Cooling duct thickness (mm)

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

$Gap_{core\text{-}LV}$ = LV coil to Core clearance (mm)

$$MLT_{HV} = \pi(ID_{HV} + RD_{HV}) \qquad (3\text{-}16)$$

where;

MLT_{HV} = Mean length of HV winding turn (mm)

ID_{HV} = HV winding inside diameter (mm) = $OD_{LV} + (2 \times Gap_{HV\text{-}LV})$ (3-17)

OD_{LV} = LV winding outside diameter (mm) = $(ID_{LV} + 2 \times RD_{LV})$ (3-18)

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

$= N_{HV} \times D_{wire} + N_{HV\text{-}duct} \times T_{duct} + (N_{HV} - 1) \times T_{HV\text{-}ins.}$ (3-19)

where

N_{HV} = HV number of layers

D_{wire} = Copper wire covered diameter (mm)

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

T_{duct} = Cooling duct thickness (mm)

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

$Gap_{HV\text{-}LV}$ = HV coil to LV coil clearance (mm)

B) Transformer winding Reactance

There are different techniques for the leakage-reactance evaluation in transformers such as the use of flux leakage and images techniques [21, 22]. The most common technique is the use of the flux leakage in different elements and estimation of the flux in different parts of transformer in terms of windings dimensions.

Transformer leakage reactance can be calculated using equation (3-20) and Figure 3.10 which shows the parameters used in leakage reactance evaluation [15].

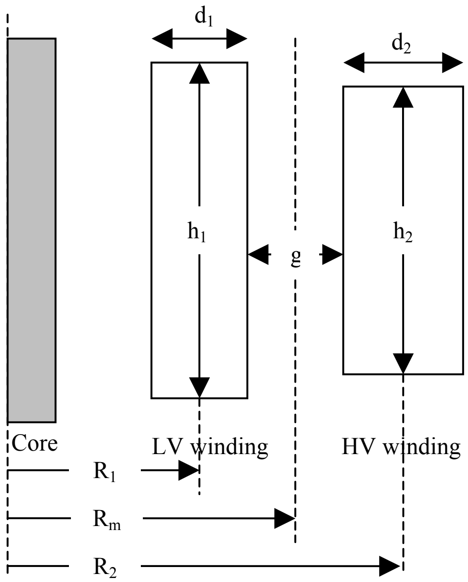


Fig 3.10 Parameters used for leakage reactance calculation

$$X = \frac{(2\pi)^2 \mu_0 fVI}{(V/N)^2 h}\left\{\frac{R_1 d_1}{3} + \frac{R_2 d_2}{3} + R_m g\right\} \tag{3-20}$$

where;

h = $(h_1+h_2)/2$

V = Primary or secondary phase voltage

I = Primary or secondary phase current

N = Primary or secondary number of turns

μ_o = Magnetic space constant = $4\pi \times 10^{-7}$

V, I & N must be of the same winding, i.e. all are for primary or secondary winding.

3.3.2 Transformer winding load losses

By definition the load loss of a transformer is that amount of losses produced by the presence of load current. The load losses of distribution transformers consist of losses due to the resistance of winding and stray losses.

The major source of load losses in transformer coil conductor is I^2R. Since the cross-sectional area of distribution transformer wire is not large, we can use only the dc resistance of conductor, i.e. I^2R_{dc}. The rest of load losses are mainly due to the stray losses. Stray losses are made of a number of components such as stray loss in transformer tank, stray loss in the clamping structure, and stray loss in the windings. Dominant portion of stray losses in distribution transformers takes place in the winding where it consists mainly of eddy current loss. It shall be clearly distinguished between eddy loss in transformer windings, which is due to presence of leakage flux in windings and eddy current loss in transformer core which is part of No Load Loss. Therefore:

$$Load\ Loss = I^2R_{HV} + I^2R_{LV} + Eddy\ Loss_{HV} + Eddy\ Loss_{LV} + Miscellaneous\ Losses \quad (3\text{-}21)$$

It is worth mentioning that I^2R_{LV} should include also the losses generated by LV leads due to ohmic resistance.

Eddy current losses can be calculated perfectly if leakage flux components at every point in windings are accurately calculated. Such detailed calculation is required when the leakage flux is excessive or harmonic content is high. Therefore, detailed calculation of flux distribution is not required in the case of distribution transformers, and hence eddy current losses can be calculated using some simplified and empirical formulas.

The assumptions and simplifications on which the eddy loss formulas are based are as follows:

1. The leakage flux density at the outside surface of the outside coil is zero. It increases with the distance from this face in proportion with the ampere turns until it becomes maximum at the space between windings.
2. The leakage flux lines are parallel to the vertical dimension of the core opening.

The average watts per kilogram of copper can be calculated using the following formulas [15, 16]

$$Eddy\ Loss_{LV} = 29259 \times 10^{-14} f^2 \beta^2 T_{foil}^{\ 2} \tag{3-22}$$

$$Eddy\ Loss_{HV} = 29259 \times 10^{-14} f^2 \beta^2 D_{wire}^{\ 2} \times 3/4 \tag{3-23}$$

Where;

β = flux density in the space between the windings (gauss) = $\dfrac{0.4\pi \times NI \times \sqrt{2}}{l}$ (3-24)

f = Frequency (Hz)

D_{wire} = Primary wire diameter (mm)

T_{foil} = Secondary foil thickness (mm)

N = Number of turns of winding

I = Phase current of winding (A)

l = length of leakage flux path (mm)

The factor of 3/4 is used in the eddy loss of HV winding is due to the use of round wire in primary windings. As an approximation, the length of leakage flux is considered as the average of length of two windings electrical height. Adding few watts as miscellaneous losses to the calculated I^2R and eddy loss is a normal and reasonable practice. This is due to existence of many factors that may increase the losses when transformer is completely assembled. Such few watts can be considered as 2% of the total calculated I^2R and eddy loss of each winding.

3.4 Transformer cooling system design

In oil-immersed transformers, the oil performs dual function as an insulating medium as well as a cooling medium. The heat generated due to transformer losses is dissipated to the surrounding air of transformer by use of oil inside transformer. The generated heat can be dissipated in many ways. In case of distribution transformers, the tank and some added radiators are sufficient to dissipate the heat generated by transformer, while additional way of cooling such as cooling fans or oil pumps are normally used in power transformers. Distribution transformers cooling method is identified as ONAN (oil natural, air natural) as per IEC60076 or OA (oil, air) as per ANSI C57.

The thermal problem of maintaining the internal temperature of the transformer within allowable bounds is concerned not just with the apparent aspect of disposing of the heat from the various transformer external surfaces but also with the transfer of heat from the interior of the windings.

3.4.1 Methods of heat transfer in transformers

Heat is transferred by three methods, namely, conduction, convection, and radiation. Each method of heat transfer must be handled individually.

A) Conduction

The heat transfer through any material by conduction is proportional to the temperature difference and inversely proportional to its thermal resistivity. Conduction is the method in which the heat generated in coils transfers to the tank oil. The material that separates the higher temperature substance (windings) and lower temperature substance (tank oil) is the solid insulation materials. For that reason, the temperature difference between windings and oil depends on thermal resistivity of the insulation material, insulation thickness and area of insulation in contact with winding and oil. Temperature difference due to conduction can be expressed as in equation (3-25) [22].

$$\theta = \frac{HL_{ins}}{KA_{ins}} \tag{3-25}$$

where;

H = Watts loss passing through the material.

A_{ins} = Area of surface (m^2).

L_{ins} = Insulation thickness (m)

θ = Temperature difference (^oC).

K = Thermal conductivity of insulation materials (watts/ (m^2) (^oC)/m) = 6.51

The winding gradient at steady state loading is the temperature difference between the average winding temperature and mean oil temperature in the tank, i.e.

Gradient = Average winding temperature – Mean tank oil temperature

The winding gradient can be used to estimate the mean tank oil temperature based on the guaranteed average winding temperature rise as

$$\theta_m = \theta_a - Gradient \tag{3-26}$$

where;

θ_m = mean tank oil temperature

θ_a = average winding temperature

B) Convection

When a heated surface is immersed in a fluid, heat is conducted from the surface to the cooler medium. An increase in the fluid temperature decreases its density. This creates moving currents that remove the lighter fluid which, in turn, is replaced by the heavier fluid. In this way, continuous process is created.

Heat transfer by convection versus mean tank oil temperature rise can be expressed by a simple formula [22] of the form

$$W_c = K\theta_c^n \tag{3-27}$$

where;

W_c = convective heat loss (watt/m^2)

K = constant = 2.17

n = exponential value ranging from 1.0 to 1.25, depending on the shape and position of the surface being cooled.

For plain vertical surfaces in air with heights ranging from about 600 mm and upward, the exponential n is 1.25.

C) Radiation

The transfer of heat by radiation takes place because all bodies raised to a temperature above their surroundings radiate heat energy in the form of waves. The area effective for radiation is the outside envelope of a surface irrespective of its shape. That is, for a tank composed of corrugations or of a plain surface, the true radiating surface is the product of the height and length of a taut string drawn around the envelope. This is true, however, only where the color of the surface has an emissivity factor of unity, such as a perfect black surface. If the emissivity factor is considerable less than unity, the effective radiating surface is less than the envelope area multiplied by the emissivity factor. However, the emissivity factor of most paints used in practice is close to unity, generally about 0.95.

The heat transferred by radiation is expressed by the Stefan-Boltzmann law as:

$$W_R = \sigma E\left[\left(273 + T_{amb} + \theta_{m-oil}\right)^4 - \left(273 + T_{amb}\right)^4\right] \tag{3-28}$$

where;

W_R = Radiant heat loss (watt/m^2)

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

E = Emissivity factor = 0.95 for light grey paint.

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

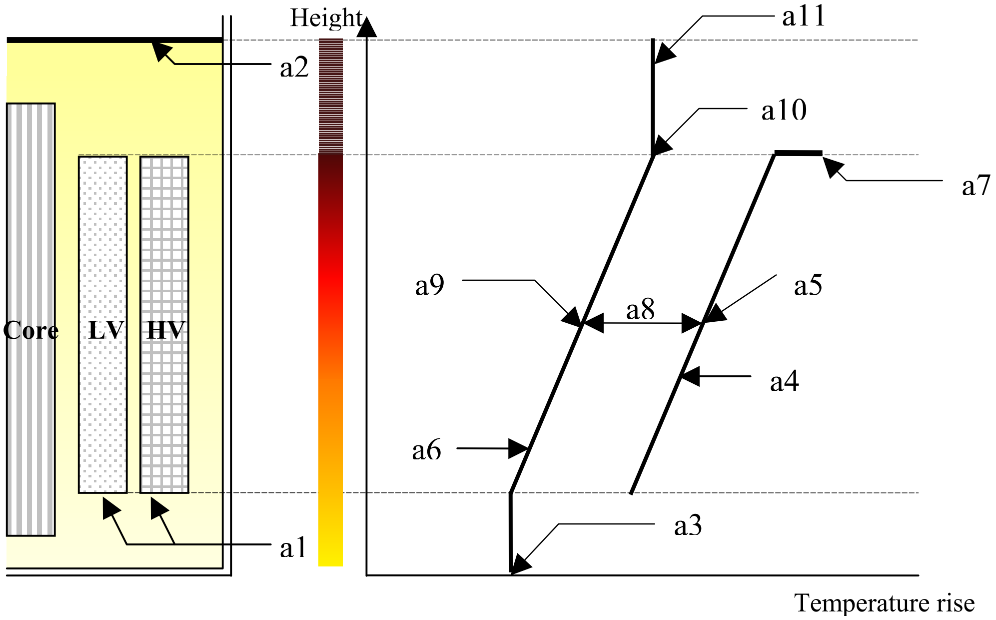
As per IEC60076, Part-2, the top oil temperature rise for natural oil cooled transformers with rating of 2500 kVA or less is 1.2 times the average of oil temperature.

The winding gradient is often used to estimate the winding's maximum temperature. A common procedure is to add some multiple of the gradient to the top oil temperature to arrive at the maximum temperature for that winding. For distribution transformers, this factor (hot-spot factor) is 1.1 as per IEC60076, Part-2.

$$\text{Max winding temp} = \text{top oil temperature} + 1.1 \times \text{Winding gradient} \qquad (3\text{-}29)$$

3.4.2 Temperature distribution in transformer

Figure 3.11 shows the temperature rise diagram of a distribution transformer in vertical plane. The oil temperature may be considered to increase linearly with height up the coil stack, reaching a maximum at the top of the windings. The temperature then remains constant to the oil level and is referred as the top oil temperature. Over the full height of the windings the temperature is parallel with that of oil, since the temperature gradients in the winding are assumed independent of vertical position.



a1 : Windings
a2 : oil normal level
a3 : oil temperature rise at tank bottom
a4 : windings temperature rise
a5 : average winding temperature rise
a6 : oil temperature rise
a7 : winding hot spot temperature rise
a8 : average winding temperature gradient
a9 : average oil temperature rise
a10: top oil temperature rise
a11: approximate oil temperature rise at tank top.

Fig. 3.11 Temperature rise diagram of distribution transformer

CHAPTER 4

4 Optimization formulation of the distribution transformer design problem

Based on the discussion made in chapter 3, the optimization objective function, design variables, design constraints are presented in the following sections.

4.1 Objective Function

The conventional design procedures aim at finding an acceptable and adequate design which merely satisfies the functional and other requirements of the problem. In general, there will be more than one acceptable design, and the purpose of optimization is to choose the cost effective one of many possible designs available that satisfy the prespecified constraints. Thus a criterion has to be chosen for comparing the different alternative acceptable designs and for selecting the best one. The criterion with respect to which the design is optimized is known as the *objective* *function*. The objective function in the transformer design problem is taken as the minimization of capital cost. The majority of transformer users do not buy transformers based on the direct cost. It is a normal practice to include transformer losses cost in the capital cost of transformer. Losses costs depend on many factors and vary from utility to another. Therefore, it is the main target of transformer designer to minimize both the losses cost and direct cost (materials cost). The capital cost of transformer is the cost that includes material cost as well as the no load and load losses cost based on predefined losses cost per kW by the user. Therefore, the objective function can be defined as follows

$$\text{Minimize } F_C = K_1 \sum L_C + K_2 \sum M_C \qquad (4\text{-}1)$$

where

$$\sum M_C = \text{Materials cost} = \text{copper wire cost} + \text{copper foil cost}$$

$$+ \text{cost of silicon Steel} \qquad (4\text{-}2)$$

$$\sum L_C = \text{Losses cost} = \text{No Load Loss} \times (SR/kW_{NL}) + \text{Load Loss} \times (SR/kW_{LL}) \qquad (4\text{-}3)$$

K_1 & K_2 are optional weighting factors

in which

$$\text{Copper wire cost} = \text{Weight}_{wire} \times (SR/kg)_{wire} \qquad (4\text{-}4)$$

where

$(SR/kg)_{wire}$ = copper wire cost per kilogram

$Weight_{wire}$ = copper wire weight (kg)

$$= Copper\ density \times 3 \times MLT_{HV} \times NT_{HV} \times \frac{\pi \times D_{wire}^2}{4 \times 10^6} \qquad (4\text{-}5)$$

$Copper\ density$ = 8930 kg/m^3

MLT_{HV} = Mean length of HV coil turn

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

$$= \pi\ [(OD_{LV} + (2 \times Gap_{HV\text{-}LV})) + N_{HV} \times D_{wire} + N_{HV\text{-}duct} \times T_{duct} + (N_{HV} - 1) \times T_{HV\text{-}ins}] \qquad (4\text{-}6)$$

where

ID_{HV} = HV coil inside diameter (mm)

RD_{HV} = HV coil radial depth (mm)

OD_{LV} = Outside diameter of LV coil

NT_{HV} = HV number of turns

D_{wire} = Copper wire covered diameter (mm)

$Gap_{HV\text{-}LV}$ = HV coil to LV coil clearance (mm)

N_{HV} = HV number of layers

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

T_{duct} = Cooling duct thickness (mm)

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

ID_{LV} and RD_{LV} are inside diameter and radial depth of LV coil respectively and can be calculated from equations (3-14) & (3-15).

$$Copper\ foil\ cost = Weight_{foil} \times (SR/kg)_{foil} \tag{4-7}$$

where

$(SR/kg)_{foil}$ = copper foil cost per kilogram

$Weight_{foil}$ = copper foil weight (kg)

$$= Copper\ density \times 3 \times MLT_{LV} \times N_{LV} \times T_{foil} \times Foil_{width} \times 1 \times 10^{-6} \tag{4-8}$$

MTL_{LV} = Mean length of LV coil turn

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

$$= \pi\ [(Core\ diameter + (2 \times Gap_{core\text{-}LV})) + N_{LV} \times T_{foil} + N_{LV\text{-}duct} \times T_{duct} + (N_{LV} - 1) \times T_{LV\text{-}ins.}] \tag{4-9}$$

$Gap_{core\text{-}LV}$ = LV coil to Core clearance (mm)

N_{LV} = LV number of turns

T_{foil} = Copper foil thickness (mm)

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

T_{duct} = Cooling duct thickness (mm)

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

NLL (W) = No Load Loss

= [*Ideal area* (cm^2) × *SF* × (*3* × *Core-window height* (mm)

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

LL (W) = Load Loss

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

$$=1.02\times\left\{\frac{3\times I_{HV}^2\times\rho\times MLT_{HV}\times NT_{HV}}{A_{wire}}+\frac{3\times I_{LV}^2\times\rho\times MLT_{LV}\times N_{LV}}{T_{foil}\times foil_{width}}\right.$$

$$+29259\times10^{-4}\times f^2\times\left[\left(\frac{0.4\pi\times N_{LV}I_{LV}\times\sqrt{2}}{l}\right)^2\times T_{foil}^2\right.$$

$$\left.\left.+\left(\frac{0.4\pi\times NT_{HV}I_{HV}\times\sqrt{2}}{l}\right)^2\times D_{wire}^2\times {}^{3}\!/_{4}\right]\right\} \tag{4-11}$$

The losses cost considered for distribution transformers in the Saudi Electricity Co. (SEC) specification No. 51-SDMS-5 rev. 01 are SR. 11,000 per kW and SR. 4,000 per kW for No Load Loss and Load Loss respectively.

4.2 Design Variables

The objective function has many variables that need to be optimized. The proposed design variables are:

a) Secondary Number of turns (N_{LV})

b) Core radius (r)

c) Primary wire diameter (D_{wire})

d) Secondary foil width (W_{foil})

e) Secondary foil thickness (T_{foil})

f) Secondary No. of cooling ducts ($N_{LV\text{-}duct}$)

g) Primary No. of cooling ducts ($N_{HV\text{-}duct}$)

h) Primary No. of layers (N_{HV})

i) Number of turns per HV layer (*turn/layer*)

4.3 Inequality constraints

The design variables cannot be chosen arbitrarily; rather, they have to satisfy certain specified functional and other requirements. The restrictions that must be satisfied to produce an optimal design are collectively called design constraints. Based on the proposed design variables, the following constraints are defined.

1) Current Density (J)

A normal practice in transformer design process is to keep the current density of copper winding conductor below a certain reasonable value. A typical value of current density in copper winding conductor is 3 A/mm^2 [17]. High current density requires maintaining adequate cooling arrangement for windings. Ultimately, high current density may produce abnormal windings temperature gradient that will result in faster aging of insulation materials and consequently transformer loss of life. In some cases, the transformer user defines a maximum value of copper current density. The HV & LV constraints of current density are J_{max} & J_{min} as follows:

$$J_{\min} \le J \le J_{\max} \tag{4-12}$$

$$J_{\min} \le \frac{4I_{HV}}{\pi \times D_{wire}^2} \le J_{\max} \tag{4-13}$$

$$J_{\min} \le \frac{I_{LV}}{T_{foil} \times Foil_{width}} \le J_{\max} \tag{4-14}$$

where I_{Hv}, I_{LV}, $Foil_{width}$ are HV phase current, LV phase current and foil width respectively.

2) Maximum flux density (*B*)

The designer of transformer would like to ensure that the flux density is as high as possible. On the other hand, he should avoid saturation within core. For Grain oriented silicon steel, saturation may occur at the magnetic flux densities exceeding

1.9 T. Based on the input voltage and frequency variations, a suitable value of flux density can be adopted to avoid any chance of core saturation under operating conditions. By increasing the operating flux density the net weight of core can be reduced, but this leads to an increase in the core losses. In the optimization process, this will be taken care of when looking for the optimal values of flux density and corresponding net weight and core loss. A practical value of maximum flux density is 1.7 T for Grain oriented silicon steel. Accordingly, the flux density inequality constraint will be as follows

$$B \leq B_{\max} \tag{4-15}$$

$$\frac{V_{ps}}{4.44 \times f \times A_{net} \times N_{LV} \times 10^{-4}} \leq B_{\max} \tag{4-16}$$

where V_{ps}, A_{net} are secondary phase voltage and core net cross section area respectively.

3) Percentage Impedance (*%Z*)

The transformer designer does not seek to obtain the lowest transformer impedance but to meet the limits of minimum and maximum values specified by the system designer to suit the economics of the system design. System designers constantly strive to achieve the best compromise between the lowest level of impedance, which will limit fault currents to an acceptable magnitude and the highest level, which can be tolerated without resulting in excessive system regulation. As a result they are invariably aiming to restrict transformer manufacturers to tightest possible tolerance limits on impedance value. Usually, manufacturers are restricted to a tolerance specified in international standards, such as IEC60076 and ANSI C57.12.00, in which tolerances are specified as ± 10% and ± 7.5% respectively. For that reason, impedance voltage is an important constraint that must be considered during optimization process. The percentage impedance constraint can be expressed as follows:

$$\%Z_{min} \leq \%Z \leq \%Z_{max} \tag{4-17}$$

where

$$\%Z_{min} = \text{minimum allowable impedance value} = \begin{cases} 0.9\times\%Z_G & \text{as per IEC} \\ 0.925\times\%Z_G & \text{as per ANSI} \end{cases}$$

$$\%Z_{max} = \text{minimum allowable impedance value} = \begin{cases} 1.1\times\%Z_G & \text{as per IEC} \\ 1.075\times\%Z_G & \text{as per ANSI} \end{cases}$$

in which $\%Z_G$ is the guaranteed impedance value

4) Average winding temperature rise ($\theta_{w\text{-}rise}$)

It is the usual practice that transformer users to limit the average winding temperature rise to a particular value based on the available records of atmospheric conditions. In most cases, this requirement will involve additional cost. On the other hand, transformer designer aims to design transformer with an average temperature rise close to the limit. In most cases, user endures the limits specified in international standards, whereas the requirement of reducing standard values is desirable. The winding temperature rise constraint will be as follows

$$\theta_{w\text{-}rise} \leq \theta_{Gw\text{-}rise} \tag{4-18}$$

$$\theta_{HV-W-rise} = 0.8 \times \theta_{TG-oil-rise} + \frac{LL_{HV} \times L_{ins-THV}}{6.51 \times A_{ins-HV}} \leq \theta_{Gw-rise} \tag{4-19}$$

$$\theta_{LV-W-rise} = 0.8 \times \theta_{TG-oil-rise} + \frac{LL_{LV} \times L_{ins-TLV}}{6.51 \times A_{ins-LV}} \leq \theta_{Gw-rise} \tag{4-20}$$

in which

$\theta_{Gw\text{-}rise}$	is the guaranteed average winding temperature rise
$\theta_{HV\text{-}W\text{-}rise}$	is the HV average winding temperature rise
$\theta_{LV\text{-}W\text{-}rise}$	is the LV average winding temperature rise
$\theta_{TG\text{-}oil\text{-}rise}$	is the guaranteed top oil temperature rise
LL_{HV}	is HV winding load loss

LL_{LV} is LV winding load loss

$L_{ins\text{-}THV}$ is HV winding insulation thickness

$L_{ins\text{-}TLV}$ is LV winding insulation thickness

5) Winding temperature gradient

The specified limits of temperature rise considered in conjunction with the design of the tank imply maximum values for the winding temperature gradient. Therefore, the windings should be formed in such a way that these values are not normally exceeded.

A reasonable value of winding temperature gradient is 21^{o}C based on a hot spot temperature of 98^{o}C, top oil temperature rise of 45^{o}C, and average yearly ambient temperature of 30^{o}C reported by the Saudi Electricity Company (SEC) specification 51-SDMS-05 revision 01. The hot spot temperature can be calculated from the following formula

$$\textit{Hot spot temp.} = \textit{top oil temp. rise} + \textit{average yearly temp.} + 1.1 \times \textit{gradient} \qquad (4\text{-}21)$$

The gradient constraint of HV and LV windings are as follows:

$$Gradient \leq Gradient_{\max} \qquad (4\text{-}22)$$

$$\frac{LL_{HV} \times L_{ins-THV}}{6.51 \times A_{ins-HV}} \leq \frac{98 - \theta_{TG-oil-rise} - T_{ambient}}{1.1} \tag{4-23}$$

$$\frac{LL_{LV} \times L_{ins-TLV}}{6.51 \times A_{ins-LV}} \leq \frac{98 - \theta_{TG-oil-rise} - T_{ambient}}{1.1} \tag{4-24}$$

where $A_{ins\text{-}HV}$ and $A_{ins\text{-}HV}$ are the are of HV and LV insulation in touch with oil respectively and $T_{ambient}$ is the average annual ambient temperature.

6) Maximum No Load and Load Losses

Regularly, transformer manufacturers are restricted to design and build transformers with limited No Load Loss (*NLL*) and Load Losses (*LL*) values. This requirement, if available, must be considered during optimization process as a constraint as follows

$$NLL \leq NLL_{max} \tag{4-25}$$

$$LL \leq LL_{max} \tag{4-26}$$

In summary, the transformer design optimization constraints can be written as shown if Table 4.1.

Table 4.1 Transformer design optimization constraints

Constraint	HV winding	LV winding
Current Density (*J*)	$J_{\min} \leq \frac{4I_{HV}}{\pi \times D_{wire}^2} \leq J_{\max}$	$J_{\min} \leq \frac{I_{LV}}{T_{foil} \times Foil_{width}} \leq J_{\max}$
Max. flux density (*B*)	$\frac{V_{ps}}{4.44 \times f \times A_{net} \times N_{LV} \times 10^{-4}} \leq T_{\max}$	
Percentage Impedance (*%Z*)	$\%Z_{min} \leq \%Z \leq \%Z_{max}$	
Average winding temperature rise ($\theta_{w\text{-}rise}$)	$Gradient_{HV} \leq Gradient_{\max}$	$Gradient_{LV} \leq Gradient_{\max}$
Maximum No Load and Load Losses	$NLL \leq NLL_{max}$ $LL \leq LL_{max}$	

4.4 Design variables bounds

The upper and lower bounds of the design variables can be categorized as optimization constraints. In fact, they represent the physical limitations of these variables such as availability, and fabricability. Such constraints are known as *geometric* or *side constraints*. Upper and lower bounds of the design variables are listed in Table 4.2.

Table 4.2 Upper and lower bounds of different design variables

Design variables	Upper bound	Lower bound
Secondary Number of turns	55	7
Core radius (mm)	300	40
Primary wire diameter (mm)	5	0.3
Secondary foil width (mm)	750	130
Secondary foil thickness (mm)	3	0.3
Secondary No. of cooling ducts	4	1
Primary No. of cooling ducts	4	1
Primary No. of layers	27	5
Number of turns per HV layer	350	60

CHAPTER 5

5 Implementation of the Nonlinear (NL) and Genetic Algorithm (GA) to the transformer design problem

In this chapter, an overview of the NL programming and GA algorithm will be presented. Implementation of these two optimization algorithm to transformer design problem will also be described.

5.1 Overview of NL programming

Optimization is fairly a large branch of mathematics with major specialized subdivisions such as linear programming, unconstrained optimization, and linear or non-linear equality and / or inequality constrained optimization. Transformer design optimization falls into the most general category of such methods, namely non-linear equality and / or inequality constrained multivariable optimization. This is due to the nature of the objective function and design variables encountered in the transformer design problem. The general optimization mathematical formula can be stated as follows.

$$\text{Find } \mathbf{X} = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{Bmatrix} \text{ which minimizes } f(\mathbf{X}) \tag{5-1}$$

subject to

$$G_i(\mathbf{X}) \leq 0, \qquad i = 1, 2, \ldots, m$$

$$\begin{Bmatrix} lb_1 \\ lb_2 \\ \vdots \\ lb_n \end{Bmatrix} \leq \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{Bmatrix} \leq \begin{Bmatrix} ub_1 \\ ub_2 \\ \vdots \\ ub_n \end{Bmatrix}$$

where **X** is an n design variables, $f(\mathbf{X})$ is the *objective function*, $G_i(\mathbf{X})$ is known as *inequality constraints*, and *lb* & *ub* are the set of lower and upper bounds of design variables, respectively.

The function $f(\mathbf{X})$ can be classified as linear, nonlinear, integer, zero one, depending on the terms of it. Also, the constraints could be linear or nonlinear. In our mathematical formulation of the transformer design problem, it is very clear that we have a nonlinear objective function and nonlinear constraints.

The target of transformer optimization problem is to find the minimum cost of transformer which also must satisfy the design variables constrains and be within the practical bounds of design variables.

In constrained optimization, the general aim is to transform the problem into an easier sub-problem that can then be solved and used as the basis of an iterative process. A characteristic of early methods is the translation of the constrained problem to a basic unconstrained problem by using a penalty function for constraints that are near or beyond the constraint boundary. In this way the constrained problem is solved using a sequence of parameterized unconstrained optimizations, which in the limit (of the sequence) converge to the constrained problem. These methods are now considered relatively inefficient and have been replaced by methods that have focused on the solution of the Kuhn-Tucker (KT) equations. The KT equations are necessary conditions for optimality for a constrained optimization problem.

If the problem is a so-called convex programming problem, that is, $f(\mathbf{X})$ and $G_i(\mathbf{X})$, are convex functions, then the KT equations are both necessary and sufficient for global solution point.

Referring to general formula (Eq. 5-1), the Kuhn-Tucker equations can be stated as

$$\nabla f(x) + \sum_{i=1}^{m} \lambda_i \cdot \nabla G_i(x) = 0 \tag{5-2}$$

$$\lambda_i \cdot \nabla G_i(x) = 0 \qquad i = 1,\ldots,m$$

$$\lambda_i \geq 0 \qquad i = 1,\ldots,m$$

The first equation describes a canceling of the gradients between the objective function and the active constraints at the solution point. For the gradients to be canceled, Lagrange multipliers (λ_i) are necessary to balance the deviations in magnitude of the objective function and constraint gradients.

Because only active constraints are included in this canceling operation, constraints that are not active must not be included in this operation and so are given Lagrange multipliers equal to zero. This is stated implicitly in the last two sub-equations of Eq. 5-2.

Constrained quasi-Newton methods guarantee superlinear convergence by accumulating second order information regarding the KT equations using a quasi-Newton updating procedure. These methods are commonly referred to as Sequential Quadratic Programming (SQP) methods, since a Quadratic Programming (QP) sub-problem is solved at each major iteration (also known as Iterative Quadratic

Programming, Recursive Quadratic Programming, and Constrained Variable Metric methods).

Given the problem description in Eq. 5-1 the principal idea is the formulation of a QP sub-problem based on a quadratic approximation of the Lagrangian function.

$$L(x,\lambda) = f(x) + \sum_{i=1}^{m} \lambda_i \cdot G_i(x) \tag{5-3}$$

The general formula (Eq. 5-1) can be simplified by assuming that bound constraints have been expressed as inequality constraints. The QP subproblem can be obtained by linearizing the nonlinear constraints.

The SQP implementation consists of three main stages as follows:

- Updating the Hessian matrix of the Lagrangian function
- Quadratic programming problem solution
- Line search and merit function calculation

Updating the Hessian Matrix

At each major iteration a positive definite quasi-Newton approximation of the Hessian of the Lagrangian function, *H*, is calculated using the BFGS (Broyden, Fletcher, Goldfarb, and Shanno) method, where (λ_i) is an estimate of the Lagrange multipliers.

$$H_{k+1} = H_k + \frac{q_k q_k^T}{q_k^T s_k} - \frac{H_k^T H_k}{s_k^T H_k s_k} \tag{5-4}$$

where

$$s_k = x_{k+1} - x_k$$

$$q_k = \nabla f(x_{k+1}) + \sum_{i=1}^{n} \lambda_i \cdot \nabla G_i(x_{k+1}) - \left(\nabla f(x_k) + \sum_{i=1}^{n} \lambda_i \cdot \nabla G_i(x_k) \right)$$

Quadratic Programming Solution

At each major iteration of the SQP method, a QP problem of the following form is solved, where A_i refers to the ith row of the *m*-by-*n* matrix *A*.

$$\min_{d \in \Re^n} \; q(d) = \frac{1}{2} d^T H d + c^T d \tag{5-5}$$

$$A_i d \le b_i \qquad i = 1, \ldots, m$$

The solution procedure involves two phases. The first phase involves the calculation of a feasible point (if one exists). The second phase involves the generation of an iterative sequence of feasible points that converge to the solution. In this method an active set, $\overline{A}_k$, is maintained that is an estimate of the active constraints (i.e., those that are on the constraint boundaries) at the solution point..

$\overline{A}_k$ is updated at each iteration *k*, and this is used to form a basis for a search direction d_k. Equality constraints always remain in the active set $\overline{A}_k$. The search direction d_k is calculated and minimizes the objective function while remaining on any active constraint boundaries.

Line Search and Merit Function

The solution of the QP subproblem produces a vector d_k, which is used to form new iteration

$$x_{k+1} = x_k + \alpha d_k \tag{5-6}$$

The step length parameter is α_k determined in order to produce a sufficient decrease in a merit function. The merit function of the following form can be used in this implementation.

$$\Psi(x) = f(x) + \sum_{i=1}^{m} r_i \cdot \max\{0, G_i(x)\} \tag{5-7}$$

where r_i is the penalty parameter and can be calculated as follows

$$r_i = (r_{k+1})_i = \max_i \left\{ \lambda_i, \frac{1}{2}((r_k)_i + \lambda_i) \right\} \qquad i = 1,\ldots,m \tag{5-8}$$

5.2 Overview of GA

Genetic Algorithms are powerful non-deterministic iterative search heuristics. GAs operates on a population, which consists of encoded strings where each string represents a solution. Crossover operator is used on these strings to obtain the new solutions that inherit good and bad properties of their parent solutions. Each solution has a fitness value and solutions having higher fitness values are most likely to survive for the next generation. Mutation operator is then applied to produce new characteristics, which are not present in the parent solutions.

The whole procedure is repeated until no further improvement is observed or run time exceeds to some threshold. The flowchart of a simple GA is presented in Figure 5.1 and the operation is explained as follows.

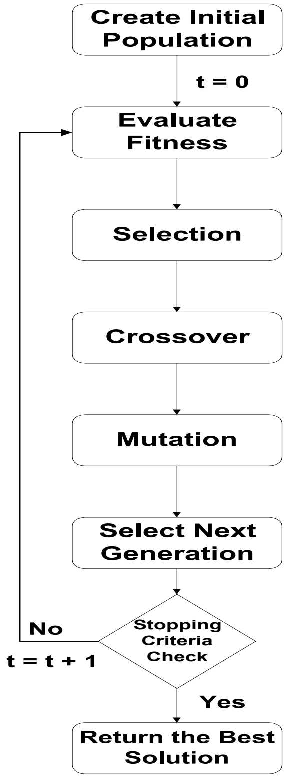


Figure 5.1 Flow chart of a simple genetic algorithm

To start the optimization, GA uses randomly produced initial solutions. This method is preferred when *a priori* knowledge about the problem is not available. After randomly generating the initial population of say *N* solutions, the GA uses the three genetic operators to yield *N* new solutions at each iteration. In the selection operation, each solution of the current population is evaluated by its fitness normally represented by the value of some objective function and individuals with higher fitness value are selected.

The crossover operator works on pairs of selected solutions with certain crossover rate. The crossover rate is defined as the probability of applying crossover to a pair of selected solutions. There are many ways of defining this operator such as single point crossover, double point crossover, multi-point crossover etc.

Mutation is a random alteration with small probability of the binary value of a string position. This operator prevents the GA from being trapped in local minima. The fitness evaluation unit in the GA acts as an interface between the GA and the optimization problem. Next the stopping criteria must be decided. This may be the case when there is no significant improvement in maximum fitness or the maximum allowable time (number of iterations) is passed. At the end of the algorithm, the best solution found so far is retained.

5.3 Proposed NL and GA optimal transformer design algorithms

In this section, the proposed NL and GA optimal transformer design algorithms are explained.

5.3.1 Proposed Nonlinear Optimization Program

A computer based program has been developed using the proposed mathematical formulation of the transformer design. This program used the built-in MATLAB nonlinear constrained optimization function.

A) Design variables initial values

As in most optimization methods, a set of design variables initial values must be specified at which optimization process will start. Choosing suitable initial design values based on experience will facilitate significantly reaching an optimum design.

Since the range of transformer primary voltage and transformer ratings of interest is large, it is extremely efficient to define different initial values for different ranges of transformer ratings. A good approach to categorize such ranges is based on primary voltage level such as

1) Transformers with primary voltage of 13.8 kV and less.
2) Transformers with primary voltage of 34.5 kV and less but higher than 13.8 kV.

Thereafter, each category is classified based on the transformer rating as follows:

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
9) 1250 kVA < Rating ≤ 1500 kVA

The proposed initial values are listed in Tables 5.1 & 5.2

Table 5.1 Design variables initial values for transformers with primary voltage equal or less than 13.8kV

Design variable	**Transformer rating**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Secondary No. of turns	27	20	18	15	13	11	10	9	8
Core radius	66	76	76	87	92	104	112	117	122
Primary wire diameter	0.71	1	1.4	1.7	2.2	2.7	3.2	3.5	3.85
Secondary foil width	160	190	300	350	400	420	470	530	545
Secondary foil depth	0.25	0.4	0.55	0.7	1	1.4	1.7	1.9	2.3
Secondary No. of cooling ducts	1	1	1	2	2	2	2	2	2
Primary No. of cooling ducts	1	1	1	2	2	2	2	2	2
Primary No. of layers	16	14	11	9	9	9	8	8	7
Primary No. of turns per layer	192	165	185	188	170	140	138	135	130

Table 5.2 Design variables initial values for transformers with primary voltage greater than 13.8 kV and less than or equal to 34.5 kV

Design variable	**Transformer rating**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Secondary No. of turns	21	16	15	14	11	9	8	7	7
Core radius	74	84	88	90	103	112	127	142	127
Primary wire diameter	0.45	0.65	0.9	1.1	1.5	1.8	2.1	2.3	2.5
Secondary foil width	160	190	300	350	400	420	470	530	545
Secondary foil depth	0.25	0.4	0.55	0.7	1	1.4	1.7	1.9	2.3
Secondary No. of cooling ducts	1	1	1	1	1	2	2	2	2
Primary No. of cooling ducts	1	1	1	1	1	2	2	2	2
Primary No. of layers	21	17	14	14	12	11	10	9	10
Primary No. of turns per layer	270	248	285	275	245	215	210	205	200

B) Steps of program

The steps of the program are as follows

I) Data Entry

Data entry consists of transformer characteristics data that are usually provided by user or vary from manufacturer to another. Input data are listed below

1. Transformer rating (kVA)
2. Primary and secondary voltages (Volts)
3. Rated frequency (Hz)
4. Maximum tapping range in percentage of primary voltage.
5. Primary and secondary connection (Delta or Star).
6. Core building factor
7. Guaranteed percentage impedance.
8. Applicable international standard (IEC or ANSI) to fix the reference temperature will be used for calculation of impedance and load loss.
9. Guaranteed winding temperature rise, top oil temperature rise and average yearly ambient temperature (^oC).

10. Core material grade, which will be a selection among six (6) grades.
11. Silicon steel and copper price (SR / kg).
12. Capitalization value of no load and load losses (SR / kW).
13. Maximum core and / or load losses, if available.

II) Initial values of design variables

Based on the entered transformer rating and primary voltage rating, initial values of design variables will be determined from Tables (6.1) and (6.2).

III) Upper and lower bounds

In this stage, upper and lower bounds of design variables are fixed.

IV) Optimization process

Optimization process commences using the predefined initial values, specified nonlinear inequality constraints, and upper and lower bounds.

V) Rounding the results

The optimized design variables values are not usually rounded and can not be used as they are. Therefore, the results are modified (rounded) to fit standard values.

VI) Calculation of total cost and final report

The rounded values (standard values) are used as input data for repeating again the design of the transformer. This final step includes also the calculation of other requirements such as:

1. Cooling fins design including arrangement, dimensions, and weight.
2. Oil volume and weight.
3. Transformer tank dimensions and weight
4. Transformer regulations and efficiencies

5.3.2 Proposed GA Optimization Program

The Genetic Algorithm has been used to determine the least cost design that meets the required transformer characteristics.

For this purpose, the genetic algorithm toolbox that was prepared by the department of Automatic Control and Systems Engineering at the University of Sheffield was used to work with the main proposed distribution transformer design algorithm. The flow chart of proposed GA algorithm is shown in Figure 5.2.

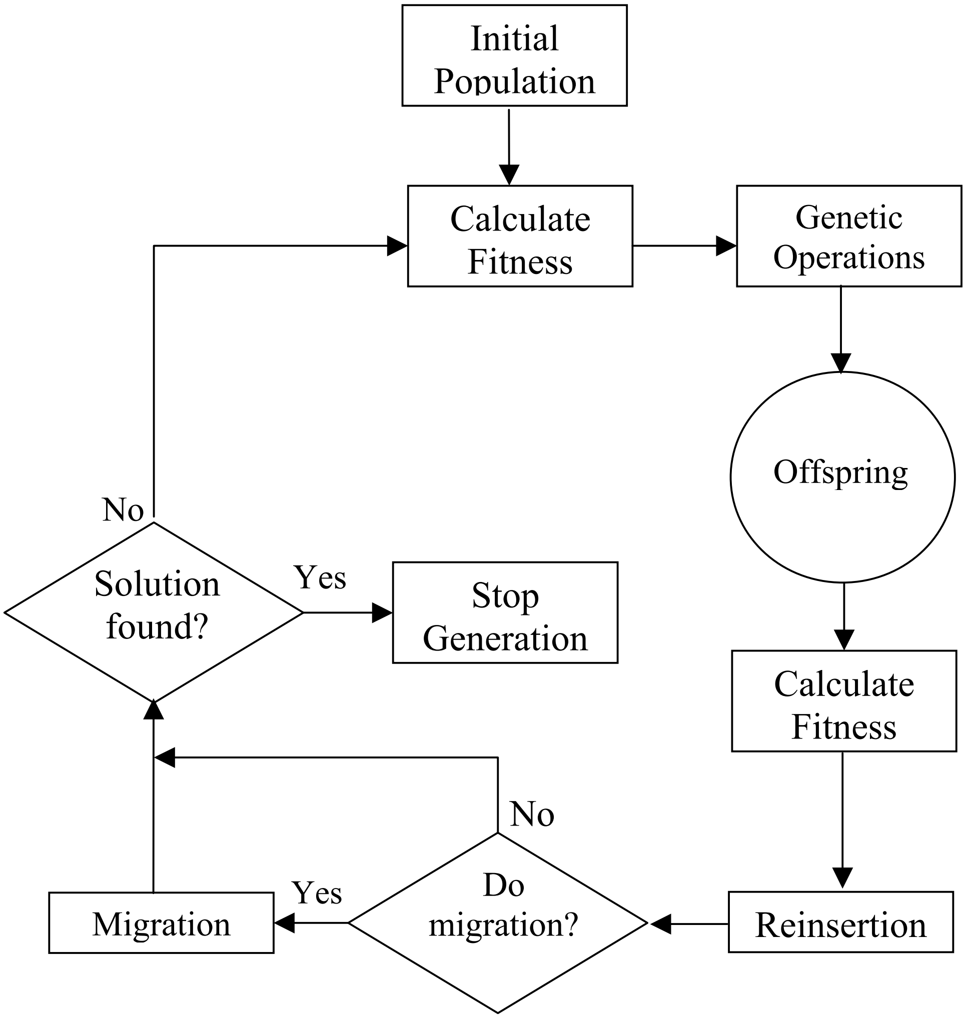


Figure 5.2 Flow chart of the proposed GA

The main GA parameters used in the algorithm are explained below:

1) Number of subpopulation: Each single population is divided into a number of subpopulation. The number of subpopulation used in the proposed algorithm is 12.
2) Number of individuals per subpopulation: Each subpopulation consists of 25 individuals.
3) Maximum No. of Generation: Because the GA is a stochastic search method, it is difficult to formally specify convergence criteria. A common practice is to terminate the GA after a pre-specified number of generations. From many trials of the proposed algorithm, it was found that the appropriate maximum no. of generation for termination criteria is 1000.
4) Mutation: Mutation is a random process where one allele of gene is replaced by another to produce a new genetic structure. Mutation is randomly applied with low probability, typically in the range of 0.001 and 0.01. In our algorithm, the mutation rate was set as 0.001.
5) Generation Gap: The fractional difference between the new and old subpopulation sizes is termed a generation gap. In other words, in case the generation gap is 0.8 and the number of individuals per subpopulation is 25 as in our algorithm, then 20 individuals are selected from each subpopulation.

6) Insertion rate: Insertion rate specifies the percentage of individuals produced at each rate that to be reinserted into the population. In other words, if insertion rate is 0.9 as in our case, then only 90% of the individuals produced at each generation are reinserted into the population.
7) Number of generations for migration: This number is specified as 20, i.e. migration of individuals will take place after 20 generations.

The algorithm starts with a creation of initial population where it consists of individuals equal to subpopulation multiplied with number of individuals per subpopulation with individual decision variable chosen uniformly at random in the range specified by upper and lower bounds of decision variables. Decision variables, lower and upper bounds are the same of those used in the nonlinear algorithm optimization. The objective function is calculated for each initial subpopulation by using the main distribution transformer design program. To satisfy the constraints of the design, the algorithm considers a penalty factor such that the objective function will be equal to 1×10^9 whenever a design constraint is violated. Initial subpopulation and corresponding objective values are created at this stage of algorithm.

The generational loop of the algorithm consists of the following steps:

- Fitness assignment of whole population.

- Selectivity of individuals from population where the total individuals to be selected are equal to number of subpopulation multiplied by generation gap multiplied by number of individuals per subpopulation, i.e. 12 × 0.8 × 25 = 240 individuals.
- Recombination of pairs of individuals within each subpopulation.
- Mutation routines with mutation rate of 0.001, considering the upper and lower bounds, so that the result of mutation process will not produce values outside the bounds of decision variables.
- Calculation of objective function value using the proposed main distribution transformer design algorithm.
- Insertion of best offspring as replacement of worst parents.
- Migration between subpopulation after 20 generations with most fit 20% of each subpopulation selected for migration.

The generational loop will continue until the number of generation reached the maximum number of generation specified as termination criteria which is 1000 generation.

CHAPTER 6

6 Application of the proposed algorithms to the transformer design problem

In this chapter, applications of the proposed mathematical formulation and optimization algorithms to the transformer design problem are presented. In addition, a comparison between different designs obtained using NL and GA algorithms is made.

6.1 Proposed distribution transformer design based on engineering experience

To examine the proposed mathematical formulation of the transformer design, a transformer was constructed and the tested as per applicable standards. Transformer rating values are presented in Table (6.1). Tables (6.2) and (6.3) show the design data and measured values of percentage impedance, no load loss, load loss, and total losses respectively.

Table 6.1 Transformer rating values

Parameter	**Value**
Transformer rating (kVA)	1000
Primary Voltage (V)	13800
Secondary voltage (V)	220
Frequency (Hz)	60
Primary connection	Delta
Secondary connection	Wye
Guaranteed %IZ	6
Applicable standard	IEC 60076

Table 6.2 Transformer design data

Design variables	**Value**
Secondary Number of turns	8
Core radius (mm)	222
Primary wire diameter (mm)	3
Secondary foil width (mm)	380
Secondary foil thickness (mm)	2
Secondary No. of cooling ducts	2
Primary No. of cooling ducts	2
Primary No. of layers	8
Number of turns per HV layer	115
%IZ	6.1
Copper weight (kg)	494
Steel core weight (kg)	1138
No Load Loss (W)	1298
Load Loss (W)	11825
Losses cost (SR.)	61,578
Materials cost (SR.)	14,657
Total Cost (SR.)	76,235

Table 6.3 Transformer measured values of No Load Loss, Load Loss, and impedance

Guaranteed parameter	Measured value	Standard tolerance
%IZ	5.92	± 10%
No Load Loss (W)	1232	+ 15%
Load Losses (W)	11730	+ 15%
Total Losses (W)	12962	+ 10%

The measured percentage impedance, no-load losses, load losses, and total losses of the constructed transformer were 5.92%, 1232 watts, 11730 watts, and 12962 watts, respectively compared to 6.1%, 1298 watts, 11825 watts, and 13123 watts obtained from the designed values. The differences between the designed and measured values are within the standard tolerances. This conforms that the proposed design mathematical formulation is reliable and satisfactory.

6.2 Application of NL programming algorithm

The proposed NL programming algorithm presented in chapter 6 has been applied to the design of 300 kVA, 13.8 kV primary voltage, 231 V secondary voltage with Delta / Wye winding connection, and 60 Hz. To test the effectiveness of the proposed NL programming algorithm, this design has been compared with a design made using *Random Walk* (RW) optimization method executed by a ready made program. This second design is based on varying the transformer design parameters, such as the maximum flux density, cross sectional area of the core and number of turns of the windings in a systematic way. In many cases, this design is considered for the construction of a quite good number of transformers as an optimum design.

No Load Loss and Load losses were evaluated at 11,000 SR/kW and 4,000 SR/kW respectively. Silicone steel and copper cost is 7.5 SR/kg & 14.5 SR/kg, respectively. Guaranteed impedance value is 4%. The data of both designs is shown in Table 6.4. A summary of the design report using the developed NL optimization program is presented below.

Results show a saving of 7.42% by using the present proposal design compared with the second design which can be considered as satisfactory saving taking into consideration the conventional consumption of distribution transformers and high competition between distribution transformers manufacturers.

Optimization program was terminated successfully after 91 iterations within 12 seconds using Pentium III processor with 696 MHz.

Initial values, optimized values and final values of design variables are shown in Table 6.5

Table 6.4 Data of Nonlinear programming optimization and Random Walk 300 kVA designs

Design variables	**Proposed design**	**RW design**
Secondary Number of turns	17	15
Core radius (mm)	81	92
Primary wire diameter (mm)	2.4	1.91
Secondary foil width (mm)	458	279
Secondary foil thickness (mm)	0.9	0.9
Secondary No. of cooling ducts	1	2
Primary No. of cooling ducts	1	2
Primary No. of layers	11	12
Number of turns per HV layer	179	146
%IR	0.779	1.089
%IX	3.837	3.890
%IZ	3.916	4.04
Flux density (T)	1.69	1.65
Material grade	23M-0H	23M-0H
Core weight (kg)	418	442
Core Loss (W)	574	510
Total copper weight (kg)	306	169
Load Loss (W)	2338	3400
Losses cost (SR.)	15666	19210
Materials cost (SR.)	7572	5765
Total cost (SR.)	23238	24975

Table 6.5 Nonlinear optimization initial, optimized, and final design variables values

Design variables	Initial value	Optimized value	Final design value
Secondary Number of turns	15	17.1817	17
Core radius (mm)	87	80.7909	81
Primary wire diameter (mm)	1.7	2.3832	2.4
Secondary foil width (mm)	350	457.7553	458
Secondary foil thickness (mm)	0.7	0.9014	0.9
Secondary No. of cooling ducts	2	1.0000	1
Primary No. of cooling ducts	2	1.0000	1
Primary No. of layers	9	10.1676	11
Number of turns per HV layer	188	179.2427	179

The way the data is entered and the design report is given in parts A and B below:

A) Program data entry of nonlinear optimization example

```
Enter Transformer Rating in kVA OA: 300

Enter Primary Line to Line Voltage in (Volts): 13800

Enter Secondary Line to Line Voltage in (Volts): 231

Enter Frequency (Hz): 60

Enter the max taps in percentage (for example 5): 5

Enter Transformer Primary Connection (delta/star) d for delta & s for star: d

Enter Transformer Secondary Connection (delta/star) d for delta & s for star: s

Enter the Core Building Factor: 1.15

Enter voltage impedance: 4

Enter the temperature reference for resistance and Load Loss, 75 DegC as per

IEC and 85 DegC as per ANSI: 75

Enter the guaranteed average winding temperature rise in Deg. C: 55
```

```
Enter the guaranteed Top Oil temperature rise in Deg. C: 50

Enter the average yearly ambient temperature in Deg. C: 30

Enter the unit price per kilogram of Silicon Steel : SR/kg 7.5

Enter the unit price per kilogram of Copper : SR/kg 14.5

Enter the capitalization value for No Load Loss (SR./W): 11

Enter the capitalization value for Load Loss (SR./W): 4

Do you have a maximum No Load Loss requirement? (y or n) n

Do you have a maximum Load Loss requirement? (y or n) n
```

B) Design report of executed nonlinear optimization example

```
DESIGN VARIABLES ARE:
Primary Conductor size =  2.4 mm  Secondary Conductor size  =  458 X 0.90 mm
                                  Secondary No. of Turn     =  17 Turn
Primary No. of Layers  = 11 Layer
Primary Turns / Layer  =  179 T/L
Primary No. of Ducts   = 1        Secondary No. of Ducts    = 1
Core Circle rad.       =  81.0 mm

======================================================================
THE VALUE OF OBJECTIVE FUNCTION IS: SR.  23238
======================================================================

Rating                 =   300 kVA Frequency                = 60 Hz
Primary Voltage        = 13800 V   Secondary Voltage        = 231 V
Primary Phase Voltage  = 13800 V   Secondary Phase Voltage  = 133 V
Primary Current        = 12.55 A   Secondary Current        = 749.81 A
Primary Phase Current  = 7.25 A    Secondary Phase Current  = 749.81 A
Primary Conductor size =  2.4 mm   Secondary Conductor size = 458 X 0.90 mm
Pr. Cov Conductor size =  2.5 mm   Secondary Conductor size = 458 X 0.90 mm
Primary No. of Turns   = 1759 Turn Secondary No. of Turn    =  17 Turn
Primary No. of Layers  = 11 Layer  Secondary No. of Layers  = 17 Layer
Primary Turns / Layer  =  179 T/L  Secondary Turns / Layer  =  1 T/L
Primary Current Den.   = 1.63 A/mm2Secondary Current Den.   = 1.82 A/mm2
Primary Conductor Area =  4.45 mm2 Secondary Conductor Area = 412.20 mm2
Primary Coil Depth     = 39.75 mm  Secondary Coil Depth     = 21.81 mm
Primary Con. Mean Len. = 886.7 mm  Secondary Con. Mean Len. = 608.2 mm
Primary Con. Length    = 4726.7 M  Secondary Con. Length    =  31.0 M
Primary Con. Weight    = 192.5 kg  Secondary Con. Weight    = 114.2 kg
Primary Res. @ 75      = 22.050 OhmSecondary Res. @ 75      = 0.001577793Ohm
Primary Ele. Height    = 448.4 mm  Secondary Ele. Height    = 458.0 mm
Primary No. of Ducts   = 1         Secondary No. of Ducts   = 1
Primary I2R            = 1157.8 W  Secondary I2R            = 887.0 W
Primary Eddy Loss      = 115.8 W   Secondary Eddy Loss      =  44.4 W
```

```
                                   Secondary Lead Loss      =  98.6 W
Primary Misc. Loss     =  19.1 W   Secondary Misc. Loss     =  15.5 W
Primary Total Load Loss= 1292.7 W  Secondary Total Load Loss= 1045.5 W

======================================================================

Total Load Loss        =   2338
Guaranteed Load Loss   =

======================================================================

Percentage IR                     = 0.779
Percentage IX                     = 3.837
Percentage IZ                     = 3.916
Guaranteed Percentage IZ          = 4.000

======================================================================

Core Loss              = 574 W
Guaranteed Core Loss   =
Core weight            = 418 kg
Core Circle Dia        = 162.0 mm
Tesla                  = 1.69 T
Core Stacking Factor   = 0.970
Core Area              = 17949.2 mm2
Core W/kg              = 1.194 W/kg
Core Material          : M0H
Volt / Turn            = 7.845 V/T
Core No. of Steps      = 5
Core Steps Size
Width
 150.0  130.0  110.0   80.0   50.0
Height
  25.3   17.7   14.3   11.0    8.5

======================================================================

Efficiency
At 1 P.F
Percentage Load  25     50     75     100
                 99.05  99.23  99.17  99.04

At 0.8 P.F
Percentage Load  25     50     75     100
                 98.81  99.04  98.96  98.80

======================================================================

Average yearly ambient temperature     = 30.0 DEG. C
Top Oil Temperature Rise               = 50.0 DEG. C
Guaranteed Winding Temperature Rise    = 55.0 DEG. C
Calculated HV Winding Temperature Rise = 48.2 DEG. C
Calculated LV Winding Temperature Rise = 50.6 DEG. C
Calculated Mean Oil Temperature Rise   = 40.0 DEG. C
Calculated LV Gradient                 = 10.6
```

```
Calculated HV Gradient                 =  8.2

======================================================================

COOLING FINS
Primary Bushings are Top Mounted and Secondary Bushings are Side Mounted
Cooling Fins are on rear side only
Total No. of Cooling Fins                              =  21
Depth of Cooling Fin                                   =  200 mm
Height of Cooling Fin                                  =  900 mm
Weight of Cooling Fins CRC                             =  81 kg

======================================================================

Tank
Tank Width         =   391 mm
Tank Length        =  1053 mm
Tank Height        =  1042 mm
Oil Level          =   975 mm
Tank Steel Weight  =   104 kg
Oil Quantity       =   328 Liter
Oil Weight         =   292 kg
```

6.3 Application of GA optimization technique

The proposed GA optimization algorithm has been applied to obtain the optimal design of the same 300 kVA, 13.8 kV primary voltage with delta connection, 231 V secondary voltage with star connection, and 60 Hz used in the NL programming algorithm example.

No Load Loss and Load losses were evaluated at the same capitalization values which are 11,000 SR/kW and 4,000 SR/kW respectively. Silicone steel and copper cost is 7.5 SR/kg & 14.5 SR/kg respectively. Guaranteed impedance value is 4%. The design data is shown in Table 6.6.

The optimization program was terminated successfully after 1000 generations and within 27 minuets using Pentium III processor with 696 MHz.

Table 6.6 Data of GA optimization design of 300 kVA transformer

Design variables	Design
Secondary Number of turns	11
Core radius (mm)	104
Primary wire diameter (mm)	2.6
Secondary foil width (mm)	269
Secondary foil thickness (mm)	1.59
Secondary No. of cooling ducts	1
Primary No. of cooling ducts	1
Primary No. of layers	14
Number of turns per HV layer	88
%IR	0.559
%IX	4.065
%IZ	4.104
Flux density (T)	1.58
Material grade	23M-0H
Core weight (kg)	646
Core Loss (W)	730
Total copper weight (kg)	273
Load Loss (W)	1676
Losses cost (SR.)	14,732
Materials cost (SR.)	8,804
Objective function value (SR.)	23,536

The program data entry and final design report are shown in parts A) and B) below

A) Program data entry for GA optimization example

```
Enter Transformer Rating in kVA OA: 300

Enter Primary Line to Line Voltage in (Volts): 13800

Enter Secondary Line to Line Voltage in (Volts): 231

Enter Frequency (Hz): 60

Enter the max taps in percentage (for example 5): 5

Enter Transformer Primary Connection (delta/star) d for delta & s for star: d

Enter Transformer Secondary Connection (delta/star) d for delta & s for star: s

Enter the Core Building Factor: 1.15

Enter voltage impedance: 4

Enter the temperature reference for resistance and Load Loss, 75 DegC as per

IEC and 85 DegC as per ANSI: 75

Enter the guaranteed average winding temperature rise in Deg. C: 55

Enter the guaranteed Top Oil temperature rise in Deg. C: 50

Enter the average yearly ambient temperature in Deg. C: 30

Enter the unit price per kilogram of Silicon Steel : SR/kg 7.5

Enter the unit price per kilogram of Copper : SR/kg 14.5

Enter the capitalization value for No Load Loss (SR./W): 11

Enter the capitalization value for Load Loss (SR./W): 4

Do you have a maximum No Load Loss requirement? (y or n) n

Do you have a maximum Load Loss requirement? (y or n) n
```

B) Design report of executed GA optimization example

```
DESIGN VARIABLES ARE:
Primary Conductor size =  2.6 mm  Secondary Conductor size  =  269 X 1.59 mm
                                  Secondary No. of Turn     =  11 Turn
Primary No. of Layers  = 14 Layer
Primary Turns / Layer  =   88 T/L
Primary No. of Ducts   = 1         Secondary No. of Ducts    = 1
Core Circle rad.       = 104.0 mm

======================================================================
THE VALUE OF OBJECTIVE FUNCTION IS: SR.  23536
======================================================================

Rating                 = 300 kVA   Frequency                = 60 Hz
Primary Voltage        = 13800 V   Secondary Voltage        = 231 V
Primary Phase Voltage  = 13800 V   Secondary Phase Voltage  = 133 V
Primary Current        = 12.55 A   Secondary Current        = 749.81 A
Primary Phase Current  = 7.25 A    Secondary Phase Current  = 749.81 A
Primary Conductor size =  2.6 mm   Secondary Conductor size = 269 X 1.59 mm
Pr. Cov Conductor size =  2.7 mm   Secondary Conductor size = 269 X 1.59 mm
Primary No. of Turns   = 1138 Turn Secondary No. of Turn    =  11 Turn
Primary No. of Layers  = 14 Layer  Secondary No. of Layers  = 11 Layer
Primary Turns / Layer  =   88 T/L  Secondary Turns / Layer  =  1 T/L
Primary Current Den.   = 1.40 A/mm2Secondary Current Den.   = 1.75 A/mm2
Primary Conductor Area =  5.19 mm2 Secondary Conductor Area = 427.71 mm2
Primary Coil Depth     = 51.01 mm  Secondary Coil Depth     = 23.17 mm
Primary Con. Mean Len. = 1082.6 mm Secondary Con. Mean Len. = 760.0 mm
Primary Con. Length    = 3731.7 M  Secondary Con. Length    =  25.1 M
Primary Con. Weight    = 177.2 kg  Secondary Con. Weight    =  95.8 kg
Primary Res. @ 75      = 14.938 OhmSecondary Res. @ 75      = 0.001229366Ohm
Primary Ele. Height    = 237.3 mm  Secondary Ele. Height    = 269.0 mm
Primary No. of Ducts   = 1         Secondary No. of Ducts   = 1
Primary I2R            = 784.4 W   Secondary I2R            = 691.2 W
Primary Eddy Loss      =  78.4 W   Secondary Eddy Loss      =  34.6 W
                                   Secondary Lead Loss      =  63.1 W
Primary Misc. Loss     =  12.9 W   Secondary Misc. Loss     =  11.8 W
Primary Total Load Loss= 875.8 W   Secondary Total Load Loss= 800.6 W

======================================================================

Total Load Loss        =   1676
Guaranteed Load Loss   =

======================================================================

Percentage IR                     = 0.559
Percentage IX                     = 4.065
Percentage IZ                     = 4.104
Guaranteed Percentage IZ          = 4.000

======================================================================
```

```
Core Loss              =   730 W
Guaranteed Core Loss   =
Core weight            =   646 kg
Core Circle Dia        = 208.0 mm
Tesla                  = 1.58 T
Core Stacking Factor   = 0.970
Core Area              = 29651.6 mm2
Core W/kg              = 0.982 W/kg
Core Material          : M0H
Volt / Turn            = 12.124 V/T
Core No. of Steps      =  5
Core Steps Size
Width
 190.0  170.0  140.0  110.0   60.0
Height
  32.4   23.0   17.9   14.5   10.8

======================================================================

Efficiency
At 1 P.F
Percentage Load  25     50     75     100
                 98.90  99.24  99.26  99.20


At 0.8 P.F
Percentage Load  25     50     75     100
                 98.63  99.05  99.08  99.01

======================================================================

Average yearly ambient temperature     = 30.0 DEG. C
Top Oil Temperature Rise               = 50.0 DEG. C
Guaranteed Winding Temperature Rise    = 55.0 DEG. C
Calculated HV Winding Temperature Rise = 48.4 DEG. C
Calculated LV Winding Temperature Rise = 51.0 DEG. C
Calculated Mean Oil Temperature Rise   = 40.0 DEG. C
Calculated LV Gradient                 = 11.0
Calculated HV Gradient                 =  8.4

======================================================================

COOLING FINS
Primary Bushings are Top Mounted and Secondary Bushings are Side Mounted
Cooling Fins are on rear side only
Total No. of Cooling Fins                              =   26
Depth of Cooling Fin                                   =  150 mm
Height of Cooling Fin                                  =  750 mm
Weight of Cooling Fins CRC                             =   64 kg

======================================================================
```

```
Tank
Tank Width         =   462 mm
Tank Length        =  1267 mm
Tank Height        =   879 mm
Oil Level          =   825 mm
Tank Steel Weight  =   120 kg
Oil Quantity       =   375 Liter
Oil Weight         =   334 kg
```

6.4 NL and GA optimization comparison of different designs

In addition to the 300 kVA transformer example illustrated using the nonlinear and GA optimization algorithms, the results obtained from implementation of Nonlinear and GA optimization on different distribution transformer ratings, voltages, etc. and utilizing various core materials are shown in Table 6.7.

Table 6.7 Optimal Nonlinear and GA designs for different transformer ratings

	Ex. No. 1	**Ex. No. 2**	**Ex. No. 3**	**Ex. No. 4**
Rating (kVA)	150	300	650	1250
Primary Voltage (Volt)	13800	13800	33000	11000
Secondary Voltage (Volt)	208	231	400	480
Frequency	60	60	60	50
No. of taps	7	5	5	5
Primary / Secondary connection	D / S	D / S	D / S	D / S
Building Factor	1.1	1.15	1.2	1.2
% Z	4	4	5	6
Reference Temp.	85	75	75	85
Winding Temp. Rise	65	55	50	65
Oil temp. Rise	60	50	45	60
Average Ambient Temp.	30	30	30	30
Core Material	ZDKH	M0H	M4	M3
Core Price (SR./kg)	9	7.5	5.5	6.5
Copper Price (SR./kg)	15	14.5	16	13
No Load Loss Evaluation price (SR/W)	13	11	11	9
Load Loss Evaluation price (SR/W)	3	4	4	3

Results								
	Ex. No. 1		**Ex. No. 2**		**Ex. No. 3**		**Ex. No. 4**	
Optimization method	NL	GA	NL	GA	NL	GA	NL	GA
% Z	4.158	3.958	3.916	4.104	5.195	5.355	5.859	6.281
No Load Loss (W)	269	315	574	730	1394	1212	1506	1338
Load Loss (W)	2080	1218	2338	1676	3683	5077	9606	10974
Total cost (SR.)	14802	14449	23238	23536	43201	46516	63111	69583
Execution Time	10.2 Sec.	26.87 min.	12 sec.	26.7 min.	13.1 sec.	25.8 min.	39.2 sec.	26.3 min.

It can be seen that most of the designs obtained by NL programming algorithm are better that those obtained by GA. This can be attributed to the availability of constraints in the transformer design problem. Constraints are difficult to incorporate into the GA program as generally it is left to the fitness function to manage and quantify possible infeasibility. When comparing the execution time of each algorithm, it has been noticed that the NL programming algorithm has much less time than the GA. In general, genetic algorithms should not be regarded as a replacement for NL programming algorithm, but as another optimization approach that can be used.

CHAPTER 7

7 Conclusions and future work

According to the results obtained from this thesis, the following can be concluded.

- A new formulation of an oil-immersed distribution transformer has been proposed. A computer based design program was successfully developed. The proposed design formulation takes into consideration the practical constraints in the art of transformer design and manufacturing.
- Results of the constructed transformer using the proposed formulation were presented to illustrate and confirm the reliability and effectiveness of proposed design mathematical formulation.
- A nonlinear programming algorithm has been implemented and applied to the transformer design problem. The results obtained by using the NL programming algorithm were encouraging when compared to the design made by practical experience.

- Another optimization approach which is Genetic Algorithm was also implemented to optimize the distribution transformer design variables. The obtained results confirm the suitability of using GA as an optimization method for transformer design.
- A comparison of results obtained by using the two optimization techniques (Nonlinear & GA) and a ready made distribution transformer optimization program has been made. Both of the proposed methods (NL & GA) are providing better results than the ready made optimization program. NL programming showed better results in most of the application cases.

In addition to the achievement of thesis objectives, it is worthy mentioning that one important outcome is effectiveness and success rather than suitability of using both of optimization techniques (Nonlinear & GA) in the field of transformer design. Using such techniques in transformer area, with no doubt, is of a high value added from the point of view of saving money, effort and time.

Future work

Positive and encouraging results have been achieved using the NL programming or the GA optimization techniques. Future work with the NL and GA combined optimization technique might lead to another advanced step in the field of distribution transformer optimization. Such a new algorithm may starts with execution of GA subprogram which does not require any initial values for the designed variables and then feed the GA optimized values as initial values to the NL program.

In addition, a mathematical formulation of power transformers design problem could lead to more economical designs when optimized through Artificial Intelligence (AI) and NL techniques.

Nomenclature

B : Operating flux density

Vt : Volt per turn

V_{ps} : Secondary rated phase voltage

$Strn$: Secondary number of turns

f : Operating frequency

A_{net} : Core net area

$E_{impulse}$: Impulse breakdown in paper versus thickness (kV_{peak} / mm)

E_{ac} : AC breakdown in paper versus thickness (kV_{rms} / mm)

$\%Z$: Percentage impedance

I_{fl} : Transformer primary or secondary full load current

E : Transformer primary or secondary open circuit voltage

R : Coil resistance per phase

X : Coil reactance per phase

ρ : Copper conductor resistivity at the temperature of interest

L : Mean length of conductor turn

N : Number of turns

A : Cross section area of conductor

MLT_{LV} : Mean length of LV winding turn

ID_{LV} : LV winding inside diameter

RD_{LV} : LV winding radial depth

N_{LV} : LV number of turns

T_{foil} : Copper foil thickness

$N_{LV-duct}$: Number of cooling ducts

T_{duct} : Cooling duct thickness

$T_{LV-ins.}$: Thickness of insulation between LV turns

$Gap_{core-LV}$: LV coil to Core clearance

MLT_{HV} : Mean length of HV winding turn

ID_{HV} : HV winding inside diameter

OD_{LV} : LV winding outside diameter

RD_{HV} : HV winding radial depth

N_{HV} : HV number of layers

D_{wire} : Copper wire covered diameter

$N_{HV-duct}$: Number of cooling ducts

T_{duct} : Cooling duct thickness

$T_{HV-ins.}$: Thickness of insulation between HV layers

Gap_{HV-LV} : HV coil to LV coil clearance

μ_o : Magnetic space constant

$Eddy\ Loss_{LV}$: LV windings eddy loss

$Eddy\ Loss_{HV}$: HV windings eddy loss

β : Flux density in the space between the windings

l : Length of leakage flux path

H : Watts loss passing through the material.

A_{ins} : Area of insulation surface

L_{ins} : Insulation thickness

θ : Temperature difference

K : Thermal conductivity of insulation materials

θ_m : Mean tank oil temperature

θ_a : Average winding temperature

W_c : convective heat loss (watt/m^2)

K : constant = 2.17

n : exponential value depending on the shape and position of the surface being cooled

W_R : Radiant heat loss

σ : Stefan-Boltzmann constant

E : Emissivity factor

T_{amb} : Ambient temperature

M_C : Materials cost

M_L : Losses Cost

K_1 & K_2 : Optional weighting factors

$(SR/kg)_{wire}$: Copper wire cost per kilogram

$Weight_{wire}$: Copper wire weight

$T_{HV\text{-}ins.}$: Thickness of insulation between HV layers

NT_{HV} : HV number of turns

$(SR/kg)_{foil}$: Copper foil cost per kilogram

$Weight_{foil}$: Copper foil weight

$T_{LV\text{-}ins.}$: Thickness of insulation between LV turns

r : Core radius

W_{foil} : Secondary foil width

J : Current density

$\theta_{Gw\text{-}rise}$: Guaranteed average winding temperature rise

$\theta_{HV\text{-}W\text{-}rise}$: HV average winding temperature rise

$\theta_{LV\text{-}W\text{-}rise}$: LV average winding temperature rise

$\theta_{TG\text{-}oil\text{-}rise}$: Guaranteed top oil temperature rise

LL_{HV} : HV winding load loss

LL_{LV} : LV winding load loss

$L_{ins\text{-}THV}$: HV winding insulation thickness

$L_{ins\text{-}TLV}$: LV winding insulation thickness

$f(\mathbf{X})$: Objective function

$G_i(\mathbf{X})$: Inequality constraints

lb : Design variables Lower bounds

up : Design variables lower bounds

λ_i : Lagrange multipliers

H : Hessian of the Lagrangian function

d_k : Search direction

r_i : Penalty parameter

m : Number of inequality constraints

n : Number of optimization design variables

NL : Nonlinear Programming

GA : Genetic Algorithm

NLL : No Load Loss

LL : Load Loss

IGA : Improved Genetic Algorithm

SGA : Simple Genetic Algorithm

CRGO : Cold Rolled Grain-Oriented

SF : Stacking Factor

BF : Building Factor

DDP : Diamond Dotted Presspaper

ONAN : Oil Natural, Air Natural (As per IEC)

OA : Oil, Air (As per ANSI)

SQP : Sequential Quadratic Programming

QP : Quadratic Programming

RW : Random Walk optimization method

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Vita

Mohamed Y. Abu-Sada was born on September 17, 1975, in Al-Hasa, Saudi Arabia. He earned a Bachelor of electrical engineering degree from Al-Isra University in Amman, Jordan, in 1997. He was employed as an engineer with the Wahah Electric Supply Co. of Saudi Arabia (WESCOSA) in 1997. He joined King Fahd University of Petroleum and Minerals in 1999 as a part time student. He published few conference papers.