A Project Report
on

Optimization Technique for Designing a Power Transformer

Major Project
Part-II

Submitted in partial fulfillment of the requirements

for the degree of

Master of Technology
In
Electrical Engineering
(Electrical Power Systems)

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Certificate

This is to certify that the Major Project Report entitled **Optimization Technique for Designing a Power Transformer** submitted by **Mr.Bhargav J Prajapati (17MEEE10)** towards the partial fulfillment of the requirements for Semester-IV of Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for the award of any degree or diploma.

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Abstract

Power transformer design is large variables multi-objective, time consuming design optimization problem. An optimization of Power transformer design is purposive by minimizing transformer cost, losses, temperature rise and its design making time, and maximizing its efficiency and lifespan by considering constraints imposed by IS specifications, customers application, and manufacturing constraints.

By setting proper geometry parameter of transformer designer can minimize the transformer manufacturing cost and to reduce it designer have to select optimal value of volt per turn, core diameter and number of turns while considering constraints limits.

In Proposed Methodology to do a Transformer design optimization I used a Cu-fill factor (winding space factor) and Ratio Factor (Height to Width Ratio of Transformer winding) concept by which designer can get Height, Width of different Winding and volt per turn, core diameter and selected number of turns while considering constraints limits.After getting geometric dimension of transformer winding as height and width of winding designer can find a conductor dimension while considering conductor dimension constraint.

The main purpose of this work is to develop an optimization technique using successive iteration method to reach a global optimum design of a power transformer.

Dissertation Content

The Thesis is organized as Chapter01 presents problem definition and objective of work and contribution. Chapter02 Presents Basics of Transformer then detailed literature survey and breviary of literature survey. In Chapter03 Design process of transformer being addressed and Chapter04 presents the mathematical equation for Objective function methodology and constrains. in Chapter05 experimental work, results and discussion being addressed and Chapter06 concludes the thesis.

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Chapter 1

Introduction

1.1 Problem Formulation

- Power Transformers are one of the most expensive and essential parts of electricity transportation.Due to right now competitive market environment, the aim of a transformer manufacturing industry is to get better the efficiency and reliability of their machines while satisfying the high-quality standards(constrains limits) and minimizing their product prices in order to stay alive in the global economy.
- Therefore, the economic and efficient production of electrical apparatus is affected by the total ownership cost of the asset, which comprises the Active part material and production costs of the transformer and also the operational, capitalized cost of the losses.
- The design of power transformers is a complicated process. On the one hand, it follows the mathematical principles, but on the other hand, knowledge of these principles is often insufficient to produce a correct and economic design, and must be supplemented by considerable judgment, rules of thumb, and experience, which can be acquired only after intensive training and or great knowledge and experience on the job.
- Power transformer design is a very labor-intensive task that requires a lot of iterative design and time to find the optimum alternative.
- Thus, the research on the different calculation methods and the solution algorithms for transformer design has an important role from the beginnings of the industry.
- As i mentioned total ownership cost of transformer comprises the material and production costs of the transformer and also capitalized cost of transformer but this all mainly depends on active part material cost so the very first step to optimize transformer design is to take active part material cost as objective function while considering constraint limits of design variable, manufacturing constraint and customer constraint. Brief details about objective function and constraints limits are covered in chapter04.

1.2 Objective

The objective of this project is to develop Methodology in VBA to calculate transformer design variables while considering design constraints(limits). This method say ”successive iteration method” accurately determines the value of design variable at minimum cost of transformer active part while full-filling manufacturer constraint, design constraint, costumer constraint. The main aim of any transformer manufacturing industry is to minimize transformer manufacturing cost which can be given by sum of material costs, subject to constraints imposed by international standards, manufactures constraint and customer constraint. In this Proposed methodology to do a design optimization is to use a Cu-fill factor (winding space factor) and Ratio Factor (height to width Ratio of Transformer winding) concept to find out the dimension of winding and get a minimum cost of transformer Active part material.
Transformer Active part material cost can be represent as below:

$$\text{Transformer Active Part Material Cost} = \text{Min} \sum C_j \times W_j \tag{1.1}$$

Where, C_j and W_j are, respectively cost of material in Rupees/kg and weight of material in kg which includes winding material and core material cost .

1.3 What is an optimization?

“The process of determining the best design is called optimization.”
Engineering is a profession whereby the principles of nature and mathematics are applied to build useful logic to achieve optimization process.
To do an optimization its requires to define direction vector and initial point and these nature aspire methodology requires differentiation and integration on design variables.

1.3.1 Process flow for an optimization

First step in optimization process is something like, besides a model, we must have to know some variables which are free to be adjusted(say adjustable variables) whose values can be set, within the limit(say constraint), by the designer. We will refer to these variables as design variables. With having the knowledge of design variables, we must also have criteria we wish to optimize. These criteria take two forms

1. Objective Function: Objectives represent goals we wish to maximize or minimize.
2. Constraints: Constraints represent limits we must stay within, if inequality constraints, or, in the case of equality constraints, target values we must satisfy. Collectively we call the objectives and constraints of design functions.

The freedom we have to change the design variables leads to the concept of design space. If we have four design variables, then we have a four-dimensional design space we can search to find the best design. Although humans typically have difficulty comprehending spaces which are more than three dimensional,computers have no problem searching for higher order spaces.In some cases, problems with thousands of variables have been solved.

Once we have developed a good computer-based analysis model, we must link the model to optimization software. Optimization methods are somewhat generic in nature in that many methods work for a wide variety of problems. After the connection has been made such that the optimization software can ”talk” to the engineering model, we specify the set of design variables and objectives and constraints. Optimization can then star: The optimization software will call the model many times as it searches for an optimum design.

In the end, computer-based optimization refers to using computer algorithms to search the design space of a model. The design variables are adjusted by an algorithm in order to achieve objectives and satisfy constraints.

1.4 Contribution

The contribution of this work are as follows:

- Establishing a method in VBA to solve transformer design problem.Method starts by selecting core diameter and further it calculates volt per turn, number of turns and other design parameter based on equations.
- Establishing a method to calculate the core and winding Dimension.
- Taking winding dimension as reference and it will calculate conductor dimension.
- It consider all constraint limit and gives best possible solution among the all possible solution.

Some propitious attributes of the proposed method are as below

- It considers technical and consumer constraints as well as manufacturing constraints into account.
- It considers more design variables
- It divide the algorithm into some sub-algorithm and starts building solution space based on inputs.
- In this algorithm it allow to block improper design variable based on design constraints, and narrowing down the search space by simply not considering it into the solutions that do not meet design constraint.
- It can be use for No-Tap, Separate -Tap and Body-Tap Transformers.
- It can use for Helix and CD type winding.

Chapter 2

Literature survey

2.1 Basics of Transformer

2.1.1 Working Principle of Transformer

Transformer is device of two or more winding wound around a common core material which is made up of soft iron material. in that a voltage (VP) is applied to the primary winding, current flows through the winding which sets up a magnetic field around itself, called mutual inductance, and according to Law of electromagnetic induction say Faraday's law it will work.

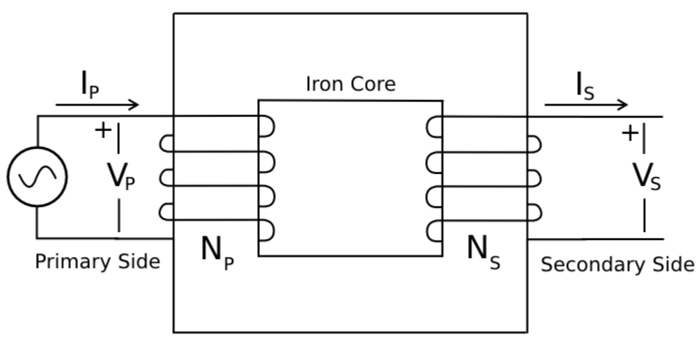

Figure 2.1: Simple Winding and Core arrangement of Transformer

Now, whenever magnetic flux stream around the magnetic core, they also go through the secondary winding turns,and cause a voltage to be induced into the secondary winding. The amount of voltage induced will be determined by low of electromagnetic induction ,as below

$$E = N \times \frac{d\phi_m}{dt} \tag{2.1}$$

where,
N = Number of Turns
ϕ = flux in Weber

2.1.2 Transformer Equivalent circuit

Transformer equivalent circuit can be represent as below with internal resistance and reactance.

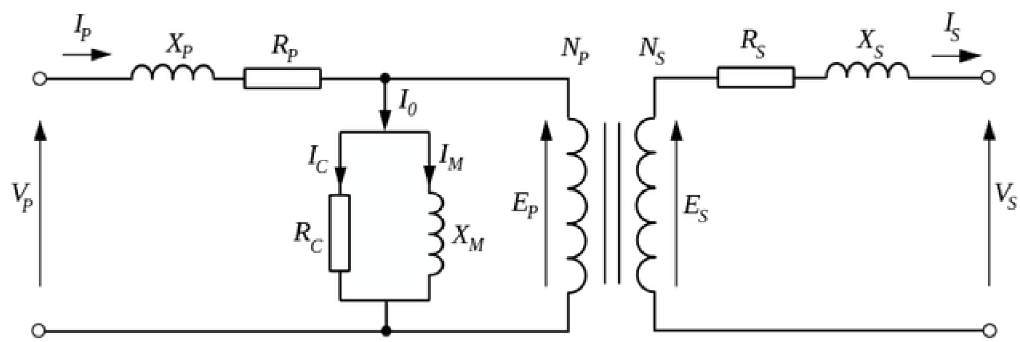

Figure 2.2: Transformer equivalent circuit

Where,
Ip = current of primary winding
Is = current of secondary winding
Vp = voltage at primary side
Vs = voltage at secondary side
Ep = induced voltage at primary
Es = induced voltage at secondary
Im,Xm = magnetizing current and reactance
Ic,Rc = current and resistance representing core loss
Rp = resistance at primary winding
Rs = resistance at secondary winding
Xp = leakage reactance at primary
Xs = leakage reactance at secondary
Io = no load current

Io is consist of magnetizing(Im) plus core loss(Ic) constituent for useful power consuming from the source to supply losses said to be eddy and hysteresis loss .

2.1.3 Various losses of Transformer

Transformer losses can be classified as below:

1. Constant losses (voltage-dependent losses)

   (a) Iron losses

      i. Hysteresis loss hysteresis loss is done in transformer because of magnetic reversal it can be given by below equation.

$$W_h = nB_{max}fv \tag{2.2}$$

Where, n = Steinmetz co-efficient. Bmax = maximum flux density. f = frequency. v = volume of core material.

ii. Eddy current loss it can be given by below equation.

$$W_e = k(B_{max})^2 f^2 t^2 \tag{2.3}$$

Where, k = constant f = frequency t = thickness of lamination Bmax = maximum flux density

(b) Dielectric loss
dielectric loss can be defined as its inherent dissipation of electromagnetic energy in surrounding material (in the form of heat)

2. Variable losses (current dependent losses)

(a) Copper loss : copper losses in transformer can be say as I2R losses which are depends on current .

$$W_c = I^2 R \tag{2.4}$$

Where,
I = current
R= resistance of winding .

(b) Stray load loss : This type of losses can be define as leakage flux that passes nearby/through such as the support structure of transformer or any conductive materials same for all machines this type of loss will give rise to eddy currents and be converted to heat.

2.1.4 Voltage regulation and efficiency

Transformer voltage regulation can be define as the change in secondary terminal voltage (Vs) from no-load to full load at temperature and constant primary voltage (Vp). It is articulated as a percentage of the secondary no-load voltage.

$$\%V.R = \frac{(Vp^2 - Vs^2)}{Vp^2} \times 100 \tag{2.5}$$

The ratio of output power to input power is nothing but the efficiency of transformer,and when the iron losses will be equal to copper losses in the transformer We get the maximum efficiency.(say NLL = FLL)

2.1.5 Impedance of Transformer

A transformer has an important parameter called leakage impedance and it has a significant effect on its overall design. impedance consists of two component say resistive component and reactive component. Which can be given by below equation

$$Z = \sqrt{R^2 + X^2} \tag{2.6}$$

%Z specified by the transformer user might be as low as 2% for a small transformer and 20% high for large transformer.

2.2 Research Paper survey on TDO

Traditionally the transformer design problem has been surrounded by much mathematical procedure and have lots many variable in it, in that designer has to rely on their experience and judgment in favor of mathematical relationship.Design problem defined as lowering the total mass (or cost) of the magnetic core and winding wire (copper) material while satisfying the transformer ratings and a number of design constraints. They proposed constraint limit on Efficiency, Voltage regulation, No-load current, Temperature rise, & winding fill factor while setting geometry parameters.They gets the solution by selecting the transformer geometry parameters and the relevant electrical and magnetic quantities while satisfying constrains they decided[1].

Taking SCI as sensitivity analysis by [2]milad Yadollahi & Hamid lesani. In their paper, they show a combination of three different techniques to judge the proper transformer design and its validation Heuristic and MINLP is used for optimization and FEM used for validation. They Proposed that to design transformer we have to divide their parameter to independent and dependent parameter (like depends on core dimension). They choose an impedance as sensitivity analysis and state the relation between impedance to volt per turns, height, and diameter. And by that they say that the impedance is directly proportional to the diameter so if we go on an increase in diameter it increases percentage impedance in winding and other is that percentage impedance is inversely related to height so if we go on increasing height then impedance reduced . and same for volt per turns also. So increase in impedance affects the performance of transformer-like if the impedance is high then it increases eddy current/stray loss and temperature of winding so it increases the requirement of cooling. And if the impedance is low then the short circuit forces are high and current density becomes low and it may damage the transformer[2].

A comparison of the use of one deterministic and three non-deterministic optimization algorithms to transformer design optimization has been proposed by E.I.Amorialis,A.Tsili & A.G.Kladas. In their paper one deterministic technique (Mixed Integer Nonlinear Programming),is compared with three non- deterministic approaches (Harmony Search, Differential Evolution and Genetic Algorithm) and stated that Deterministic approach always flows in one direction and non-deterministic are depends on roots value or previous value chosen as a reference to select the next point. In this they also show that MINLP method is more preferable than other methods[3]. Its results can be shown as in Figure 2.3

Eleftherios I.Amoiralis proposed A parallel mixed integer programming From their point of view design optimization is determined by minimizing the cost of transformer taking into consideration constraints imposed both by international standards and customer requirements. In this Finite element method is used as validation process in the end to get optimal transformer design validation process is done after optimization process. The proposed method can be build into software and its able to provide a global feasible solution for every given set of initial values for the design variables, for application in the transformer manufacturing industry[4].Its flow chart is shown in Figure 2.4 and its result can be shown as in Figure 2.5

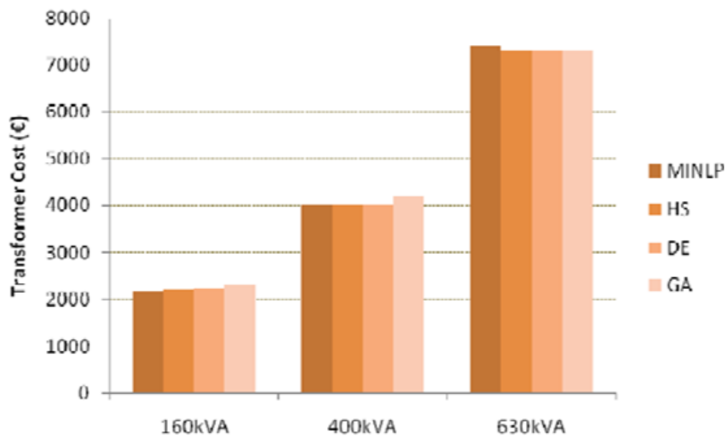

Figure 2.3: Comparison of Different Optimization Techniques

Dry type of transformer are used because they operate hazard less. But their application was limited to small rating in earlier days but now it can be use to in higher ratings also so here in this paper a cost optimal design of dry type transformer is given. In this paper a cost optimization design of dry type transformer is given by considering constraint of efficiency and V.R say voltage regulation. In this a selling cost is taken as objective function and two variables are taken to get optimal value that variables are as V/t and height: width ratio of the window which affects the transformer cost highly. And other parameter will be set on designers experience. For conductor material Copper has been used and for core material CRGOS as to achieve higher efficiency, lower running cost, and compressed design. The optimal solution has been obtained by the method of exhaustive search using nested loops.and after following loops procedure we can get an optimal solution based on constrained limits and variable values[7].

A design of transformer that full-fill certain requirements by various designs aspects including standards, manufacturer and customer constraint. The main motto of any manufacturers is to find the most low cost choice within the limitations imposed by the constraint functions, which are the combination of the design parameters resulting in the economic unit.The Geometric Programming to do optimization of power transformers is Proposed by Tamás Orosz (Doctoral student, Budapest University of Technology and Economics). They mentioned that the design optimization program seeks a minimum capitalized cost solution by optimally setting the transformer's geometrical and electrical parameters. The transformer's capitalized cost chosen for object function, because it takes into consideration the manufacturing and the operational costs. In their paper they considers the optimization for three winding, three phase,core-form power transformer & presents the transformer cost optimization model and the results of optimization[8].

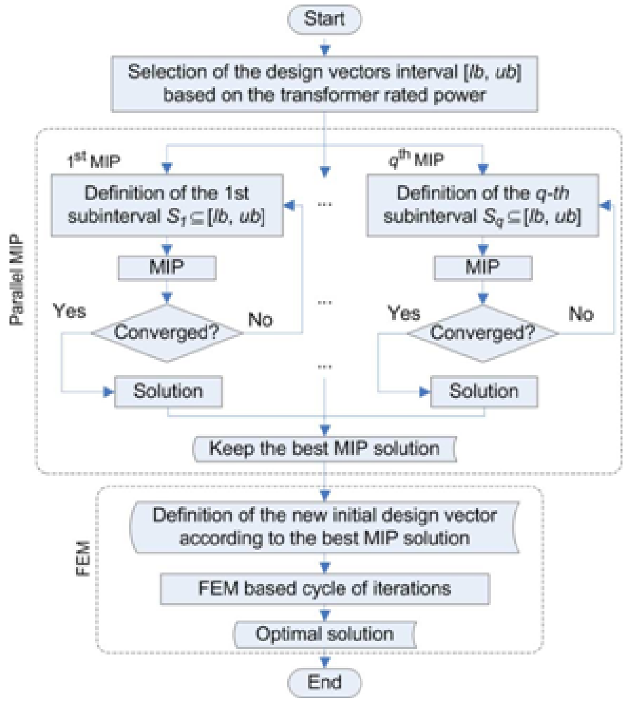

Figure 2.4: PMIP Technique flow chart

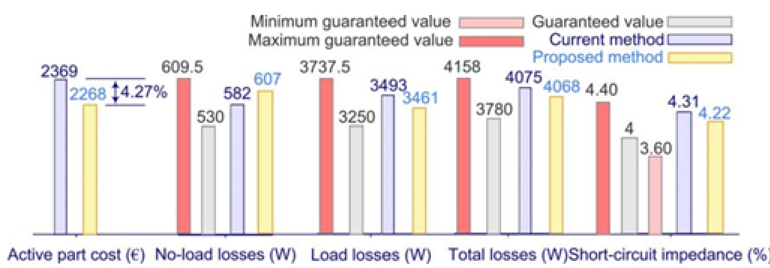

Figure 2.5: Output Result of PMIP

Genetic Algorithm and Simulated Annealing technique is proposed by Ajay Khatri & OP Rahi. Their objective function is similar to the first one like to minimize the total cost of the transformer. They simply show that after comparing conventional method, genetic algorithm, and simulated annealing algorithms. that the GA and SA have better and same results then CM technique. They conclude that GA and SA have been used as simple, robust and reliable tools for obtaining the optimal design of a transformer for minimum internal active part design cost[5].Results can be shown as in below Table 2.1

Design Variable	CM method	GA method	SA method
number of LV turns-x1	14	14	14
Max flux density-x2	1.7	1.8	1.8
width of core	215	250	250
Total Active cost	260168.328	256916.6154	256942.399
DNLL(W)	1130.22	1167.04	1160.21
DLL(W)	8823.90	9256.34	9250.34
Total Loss (W)	9954.12	10423.38	10410.55

Table 2.1: Comparison between CM,GA,SA Technique

Load loss and No-Load loss as sensitivity Analysis is proposed by - and their aim is to design a transformer by obtaining all dimensions of all the parts based on the given specification, with the use of available material economically in order to achieve minimum cost, minimum weight, and better operating condition In their paper, they take LL and NLL as sensitivity analysis with respect to flux density and by this, they show that NLL is increasing with an increase in flux density and LL are decreasing with increase in flux density[6].They set nloops, and its being calculated from the following equation:

$$n_{loops} = nLV \times csLV \times csHV \times nD \times nFD \times nG \tag{2.7}$$

(say a loop for number of turns, cross section area of LV , cross section Area of HV, core diameter, flux density, height) So, by this they solved the optimization problem of transformer design but its limitation is it's going through too many loops and might take more time to solve the problem It can be seen as in below Figure 2.6 & Figure 2.7

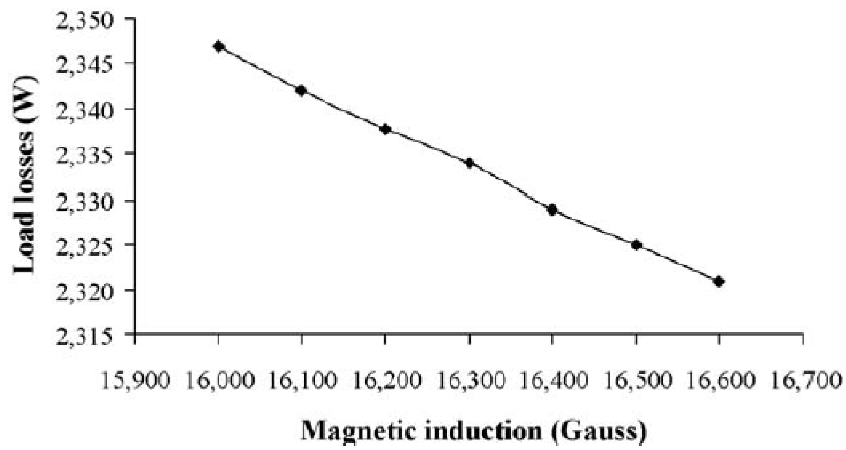

Figure 2.6: Load Loss vs Bm

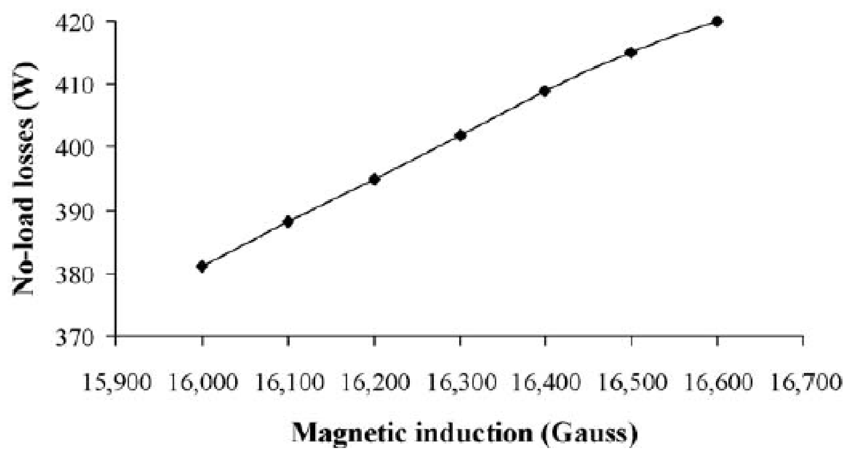

Figure 2.7: No Load Loss vs Bm

2.3 LINGO optimization software

To be continued in Optimization of Transformer Design I worked on different software and toolboxes to know which one is user-friendly and by which software optimization can be done. So I first started with someone Equation and by setting limits (constraint) on it I tried to find its Optimal solution (say minimum or maximum solution)

LINGO is available with a comprehensive set of fast, built-in solvers for Linear, Nonlinear (convex and non-convex/Global), Quadratic, Quadratically Constrained, Second Order Cone, Stochastic, and Integer optimization. we never have to specify or load a separate solver, because LINGO reads our formulation and automatically selects the appropriate one.

2.3.1 LINGO Examples

Example 01:

Here in this example I take,below equation as objective function

$$y = 1000 \times x1 + 1500 \times x2 \tag{2.8}$$

in that X1 and X2 are two variables, in which constraint I set as
a) $4 \times x1 + 2 \times x2$ ¡= 80;
b) $2 \times x1 + 5 \times x2$ ¡= 60;
c) $4 \times x1 + 4 \times x2$ ¡= 75;
d) $x1$ >= 0; $x2$ >= 0;

```
!sample equation solving;

max = y;
y = 1000*x1 + 1500*x2;

!constrains;
4*x1 + 2*x2 <= 80;
2*x1 + 5*x2 <= 60;
4*x1 + 4*x2 <= 75;
x1 >= 0;
x2 >= 0;

!this will find the solution ;
```

Figure 2.8: Lingo Code for example 01

```
Global optimal solution found.
Objective value:                              22500.00
Infeasibilities:                              0.000000
Total solver iterations:                             2
Elapsed runtime seconds:                          0.05

Model Class:                                        LP

Total variables:                      3
Nonlinear variables:                  0
Integer variables:                    0

Total constraints:                    7
Nonlinear constraints:                0

Total nonzeros:                      12
Nonlinear nonzeros:                   0


                        Variable           Value        Reduced Cost
                               Y        22500.00            0.000000
                              X1        11.25000            0.000000
                              X2        7.500000            0.000000

                             Row    Slack or Surplus      Dual Price
                               1        22500.00            1.000000
                               2        0.000000            1.000000
                               3        20.00000            0.000000
                               4        0.000000            166.6667
                               5        0.000000            166.6667
                               6        11.25000            0.000000
                               7        7.500000            0.000000
```

Figure 2.9: Solution of example 01

For this Maximizing problem, I get the solution as Y = 22500 when X1=11.25, X2=7..50 while satisfying constraint limits.

Example 02

In this example, I take simple equation and giving limits on variable,

$$Y = X^2 \tag{2.9}$$

And as we know that its min point is (0,0) on X-Y planes like when X=0, Y=0 and vice verse. So here I put this equation as the non-linear problem and tried to get its solution by optimization.

```
MODEL:
MIN = Y - X^2;
Y <= 25;
X <= 5;
Y -X^2 = 0;
END
```

Figure 2.10: Lingo Code for example 02

Result: so here is we expect in a result is that the minimum value of objective function says Y = 0 at X= 0, it works for a nonlinear equation.

```
Local optimal solution found.
Objective value:                              0.000000
Infeasibilities:                              0.000000
Total solver iterations:                            21
Elapsed runtime seconds:                          0.25

Model Class:                                        QP

Total variables:                   2
Nonlinear variables:               1
Integer variables:                 0

Total constraints:                 4
Nonlinear constraints:             2

Total nonzeros:                    6
Nonlinear nonzeros:                2


                     Variable           Value        Reduced Cost
                            Y        0.000000            0.000000
                            X    0.1275952E-05           0.000000

                          Row    Slack or Surplus      Dual Price
                            1        0.000000           -1.000000
                            2        25.00000            0.000000
                            3        4.999999            0.000000
                            4        0.000000           -1.000000
```

Figure 2.11: Solution of example 02

Example 03:

If we want to see the graphical representation of objective function and variable value and its minimum value and say we want to see how its behavior in a 2D system then in lingo a @chartpcurve named function we can use.

```
MODEL:

!let me plot graph of an equation say  Y = X^2 ;

PROCEDURE CURVE:
   Y = X^2;
ENDPROCEDURE

CALC:
   B = 20;

   @CHARTPCURVE(
     'Y = X^2',          !Title;
     'X','Y',            !Axis labels;
     CURVE,              !Procedure name;
     X, -B, B,           !var 1 and its bounds;
     'X^2',              !Legend;
     Y                   !Dependent var ;
   );
ENDCALC

END
```

Figure 2.12: Lingo Code for example 03

Results : So hear in below figure we can see the graph of the objective function in a 2D system

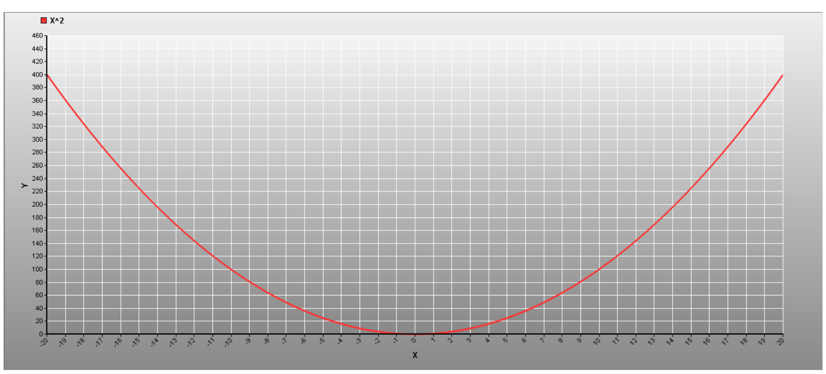

Figure 2.13: Graph of objective function example 03

```
Feasible solution found.
Infeasibilities:                                     0.000000
Total solver iterations:                                    0
Elapsed runtime seconds:                                 0.11

Model Class:                                               LP

Total variables:                      2
Nonlinear variables:                  0
Integer variables:                    0

Total constraints:                    0
Nonlinear constraints:                0

Total nonzeros:                       0
Nonlinear nonzeros:                   0



                                    Variable           Value
                                           Y        0.000000
                                           X        0.000000
                                           B        20.00000
```

Figure 2.14: Solution of example 03

Example 04:

Here an example of same objective function if we want to see in 3D then we have to add one more variable and our equation becomes Z= Y – X2, I do this just to know is it affect the output or not but the answer will be same just one dimension will be added whose value is zero .

```
MODEL:

!let me plot graph of an equation say z = X^2 - Y ;

PROCEDURE WAVE:
   Z = X^2 - Y;
ENDPROCEDURE

CALC:
   B = 200;
   @CHARTPSURFACE(
     'z = X^2 - Y', !Title;
     'X','Y','Z',  !Axis labels;
     WAVE,         !Procedure name;
     X, -B, B,     !var 1 and its bounds;
     Y, -B, B,     !var 2 and its bounds;
     'Z',          !Legend;
     Z            !Dependent var ;
   );
ENDCALC

END
```

Figure 2.15: Lingo Code for example 04

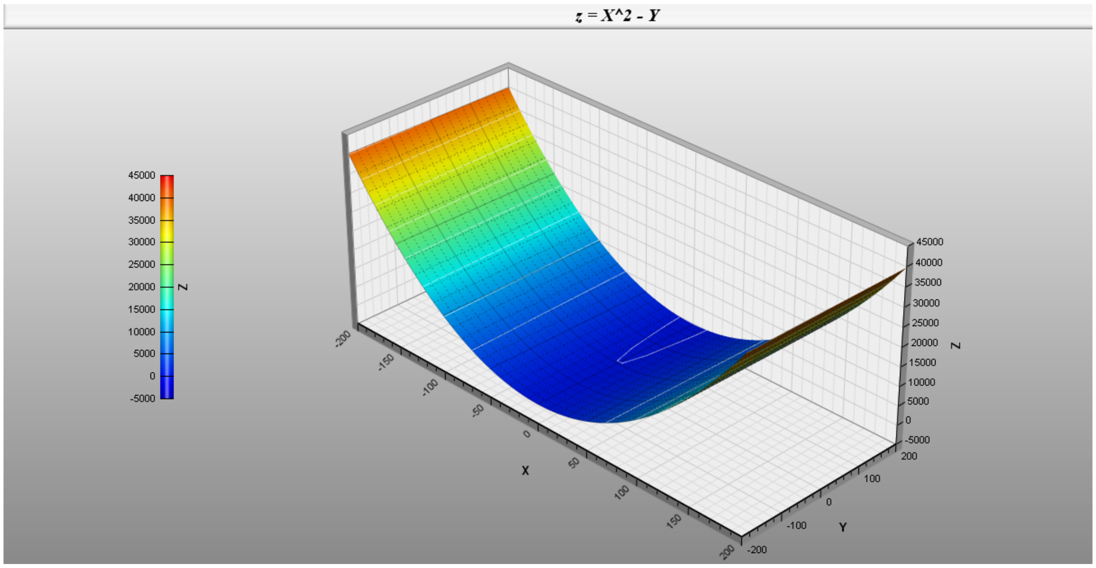

Figure 2.16: Graphical representation of example 04

```
Feasible solution found.
Infeasibilities:                           0.000000
Total solver iterations:                          0
Elapsed runtime seconds:                       0.14

Model Class:                                     LP

Total variables:                  3
Nonlinear variables:              0
Integer variables:                0

Total constraints:                0
Nonlinear constraints:            0

Total nonzeros:                   0
Nonlinear nonzeros:               0


                                  Variable           Value
                                         Z        0.000000
                                         X        0.000000
                                         Y        0.000000
                                         B        200.0000
```

Figure 2.17: Solution of example 04

we can use this logic to know behavior of error function like if I have some variable K and its limit is Klimit so while setting limits on some problem if I have to see the problem is converging or diverging then I can plot an of function say, Error= K - Klimit, and after plotting it we can say about it will converge or diverge.

Example 05 :

In this example, I take %reactance as an objective function and it can be defined as below,

$$\%X = 2\pi f \frac{uN^2}{Heq} \times \frac{I}{V} \times ATD \tag{2.10}$$

$$\%X = 2\pi f \frac{uN}{Heq} \times \frac{I}{V_t} \times \frac{1}{3} \times (T_1 D_1 + 3T_g D_g + T_2 D_2) \tag{2.11}$$

So, hear I represent it in a different way like
$\%X = (const \times x \times y)/z$,
I take this equation and relate it with the real reactance formula as,
x = IN say ampere-turn
y = ATD say ampere-turn diagram
$z = V/t \times Heq$,say volt per turn and equivalent height
and after relating this condition I put it in lingo optimization tool and tried to get minimum value of objective function.

```
!let me solve one equation a simplified equation of %impedance = ((2*pi^2*f*u)*NI*Eatd)/(H*Vt);
!where (2*pi^2*f*u) = constant value
           NI   = x  (Ampere turm)
           Eatd = y  (summation of ampere turn diagram)
           H*Vt = z  ( H  = equvalent height
                       Vt = volt per turn)
and relating this equation and assumption to cost function we get min cost after solving it ;

MODEL:
cost = (x*y)/z;
@BND(5,x,10);
@BND(10,y,20);
@BND(50,z,60);
min = cost;
END
```

Figure 2.18: Lingo Code for example 05

```
Local optimal solution found.
Objective value:                              0.8333333
Infeasibilities:                               0.000000
Extended solver steps:                                5
Best multistart solution found at step:               1
Total solver iterations:                             29
Elapsed runtime seconds:                           0.33

Model Class:                                        NLP

Total variables:                      4
Nonlinear variables:                  3
Integer variables:                    0

Total constraints:                    2
Nonlinear constraints:                1

Total nonzeros:                       5
Nonlinear nonzeros:                   3



                              Variable           Value        Reduced Cost
                                  COST       0.8333333            0.000000
                                     X        5.000000           0.1666667
                                     Y        10.00000         0.8333333E-01
                                     Z        60.00000        -0.1388889E-01

                                   Row    Slack or Surplus      Dual Price
                                     1        0.000000           -1.000000
                                     2       0.8333333           -1.000000
```

Figure 2.19: Solution of example 05

So from the above figure, we can see the results os objective function and its min value we got is 0.8333 by satisfying constraint I apply on it.
I have done this same activity in excel optimization toolbox and compared results of both tool boxes. So here in next, I explain how we can work with excel optimization (solver) toolbox in chapter05.

2.4 Breviary

All these methods are based on nature applied sciences which requires to define direction vector and initial point for optimization these methodologies require differentiation and integration on design variables.
Its important to note that several Design variables are integer and hence differentiation and integration are not possible on total space of transformer design variables.
This problem can be resolved using difference equation by scattering integer space and continuous variable space. The development efforts required to resolve using these methodology were crossing time limits hence,keeping time problem in mind the classical simplified methodology of "successive iteration method" was adopted to achieve optimized design. Using this method a optimize algorithm calculates the cost function by changing design variables within constrain space.
Change in value is define by step size size which defines in which numerical value they move forward and creates solution space and from the solution space it gives the most minimum value for user defined inputs within five minute and its user-friendly so any unknown person also can operate it and can get optimized value for design of transformer

Before optimizing transformer design the very first thing is to know the design process of transformer.While designing transformer design at some stage it requires to assume some variable and on the basis of assumption and judgment the transformer design being made.The design process is covered in chapter03

Afterwards in chapter04, I explained an objective function and constraint and proposed methodology and in chapter05 experimental work say results and discussion is explained.

Chapter 3

Design Process of Transformer

Transformer design is a multi-variable time-consuming process which can be done manually by following steps Before we start Designing Transformer its necessary to define or clear about for what purpose of product or service it should be designing. like to know what are the requirements of a customer. The first step of design is to select the number of turns in winding and proceed towards estimating the coil configuration up-to window height. Based on window height the design of secondary coil can be done.
Further core diameter, center limb, step width, core stake, core area, flux density are calculated with available design output.
Next step is to the formation of coils and center limb of core frame based on window height and center leg of the core frame detailed design of core up-to weight of the complete set of the core is estimated. Manufacturing details of low and high voltage winding tapping, placement of coils, internal clearance, the weight of conductor can be calculated. Now we have to know the performance parameter then we can calculate resistance, reactance, impedance, losses, no load current, ratio error, efficiency, regulation etc. After designing internal Active part the process of design continues with Tank design and different type of Radiators, conservator, calculation of oil volume required also. So by this above-mentioned steps/procedure we can find a solution of transformer design manually. Now we can further describe the above-mentioned step in details as below. A design procedure starts with data available(its specified by the customer, or it can be taken as per load requirement of customers workplace).

3.1 Data Available

1. Rating Q : kVA or MVA
2. Voltage ratio at No-Load : kV
3. Primary voltage /Secondary voltage
4. Frequency : Hz
5. Winding material : material type
6. Taps on HV : $\pm$ %t

7. No Load Loss : watt
8. Full Load Loss : watt
9. Impedance : %Z
10. Flux density Bm : Tesla(max)
11. Current density δ : Amp per sq.mm
12. Connection type : vector group
13. Temp. Rise : degree Celsius
14. Another specification as per IS standards

3.2 Design of Primary coil

1. Calculate V_{ph} Phase voltage of Primary and Secondary According to its Vector Group. From Data available for line voltages.
2. Calculate I_{ph} Phase Current of both According to its Vector Group
3. We have a current density (δ)
4. So we can calculate an approx conductor Area from it by = A= I_{ph}/δ sq.mm

3.2.1 Number of Turns

1. Firstly we have to find a Volt/Turns

$$\frac{V}{N} = K \pm \sqrt{Q} \tag{3.1}$$

2. After this, we can calculate Nlv , Nhv , Ntap

$$N_{lv} = \frac{V_{phlv}}{\frac{V}{N}} \tag{3.2}$$

$$N_{hv} = \frac{V_{phhv}}{\frac{V}{N}} \tag{3.3}$$

3. Adding percentage tapping to Nhv and we Can calculate HV tap turns.
4. And after this, we can calculate Ntap.

So up to now, we have Nlv , Nhv , Ntap and conductor area(if the area of conductor is more than 6 to 8 sq.mm then we should not go for the round conductor, so an alternative choice is to select a rectangular strip with the formation of continues disc coil and one coil per phase)
After this assume the "No of a disc" which include both Plain and Tap disc of HV winding.Separate plain and tap discs.

Calculate the size of strips for a plane disc. (we need to take approx window height of the core frame, 10percentage+- approx of Hw may not affect much on the performance figure.) This is where the designer has to prudently select a reasonable height based on his experience. And another thing is that various electrical clearance on the Basis of the voltage class is to be concaved as a part of design input. So a selection of proper clearance based on voltage class (say gaps) should be done by this. These gaps are maintained by paper insulations which shrink during ovening. It has been estimated that the blocks made out of pre-compressed pressboard shrinkage about 6percentage of its nominal thickness. Top to bottom yoke insulation is estimated as 30mm each for 11kv class and can be select on basis of kV class rating. A pressure Plate of 10mm thickness is provided at the top for pressing the coils.

3.3 Core Diameter

1. To estimate core diameter

   (a) To estimate the Core Diameter, we have first required to know the core area which is calculated on the basis of a volt per turn say (V/N) or V/t and Bm and f.

   (b)
   $$\frac{V}{t} = 4.44 \times f \times Bm \times A_g \times sf \tag{3.4}$$
   Where,
   Bm = Flux Density
   Ag = Gross Area of iron
   sf = Staking factor
   f = Frequncy
   So, now equation 3.4 can be modify to get gross area as below

   (c)
   $$A_g = \frac{\frac{V}{t}}{4.44 \times f \times Bm \times sf} \tag{3.5}$$

   (d) So from the above equation, we can find a gross area of the core and to find diameter we can follow a below equation.

   (e) Using circle Area equation we can find the diameter of core
   $$\frac{\pi \times d^2}{4} = A_g \tag{3.6}$$
   $$d = \pm\sqrt{\frac{4 \times A_g}{\pi}} \tag{3.7}$$

   (f) So from the above equation, we can find out a core diameter.

2. The width of the core step
   After the core diameter has been calculated we can calculate a width of core steps and while selecting the step width we should clear about that there must be at least a difference of 10 to 15,20mm between two consecutive steps and those should be in descending order.

3. Core Stack:

   It can be found as

$$K = \pm\sqrt{d^2 - L^2} \tag{3.8}$$

   Where,
   d = core diameter
   L = width of step

4. Core area

$$\text{Gross core area} = L \times K \tag{3.9}$$

$$\text{Net core area} = A_g \times sf \tag{3.10}$$

3.4 Flux Density

After calculating actual core area we can find actual working flux density by below equation.

$$B_m = \frac{\frac{V}{t}}{4.44 \times f \times A_g \times sf} \tag{3.11}$$

3.5 Coil Diameter and Limb center of a core

It can be found out from the following parameter

1. Core diameter
2. The radial build of a Secondary coil
3. The radial build of a Primary coil
4. Radial gap between Core to LV
5. Radial gap between LV to HV
6. The clearance between two limbs of HV coil

Clearances have been assumed on the basis of System voltage or can be said as selected on the basis of kV class of transformer
So from this, we get

1. ID, OD of LV winding
2. ID, OD of HV winding
3. Core limb center

3.6 Core Detail

Core details we have available up to now are as below:

1. Core diameter : d
2. Window height : H_w
3. Limb center : Cl
4. Gross core area : Ag
5. No of core steps : number
6. The width of core steps: L
7. The stack of each step : K
8. Grad of core : ρ_c

Approx weight calculation can be done by below equation

$$W_c = \rho_c \times (3 \times H_w + 4 \times C_l + 2d) \times sf \times Ag \tag{3.12}$$

3.7 Winding Detail

In this, I summarize the details of winding (for LV, HV, Tap)

1. Conductor material: specify
2. Type of coil: type of winding being in use
3. Type of connection : star/delta
4. Size of bare conductor : in mm
5. Covering: in mm
6. Size of insulated conductor : in mm
7. Disposition of conductor :
8. Transposition: specify location at where it is being applied
9. Turns per phase : in digit
10. No of coil per phase : in digit
11. Turns per coil : in digit
12. No of layer : in digit
13. Turns per layer : in digit

14. Interlayer insulation : in mm
15. Tapping: specify if tapping is available on winding
16. ID of coil : in mm
17. OD of coil : in mm
18. Winding axial height : in mm
19. End packing or gaps between winding: in mm
20. Overall height : in mm
21. The weight of the bare conductor: in kg
22. The weight of the covered conductor: in kg

A weight of conductor :
A simple formula to find the weight of winding is as below

$$\text{Weight of winding} = \text{density of conductor material} \times \text{length} \times \text{area of copper conductor} \tag{3.13}$$

So we can find the weight of HV, LV, and Tap winding from the above-mentioned formula.

1. Weight of LV winding

$$W_{lv} = \rho_{cu} \times (\pi \times D_{mlv} \times L_{lv}) \times A_{lv} \tag{3.14}$$

Where,
L_{lv}= mean turn length
D_{mlv} = mean diameter of LV
N_{lv} = turns of LV winding
A_{lv} = Area of LV conductor

2. Weight of HV winding

$$W_{hv} = \rho_{cu} \times (\pi \times D_{mhv} \times N_{hv}) \times A_{hv} \tag{3.15}$$

Where,
L_{hv} = mean turn length
D_{mhv} = mean diameter of HV
N_{hv} = turns of HV winding
A_{hv} = Area of HV conductor

3. weight of Tap winding

$$W_{tap} = \rho_{cu} \times (\pi \times D_{mhv} N_{tap}) \times A_{tap} \tag{3.16}$$

Where,
L_{hv} = mean turn length
D_{mhv} = mean diameter of HV

N_{tap} = turns of Tap winding
A_{tap} = Area of HV conductor

So the total copper weight can be write in terms of below equation

$$W_{cu} = W_{lv} + W_{hv} + W_{tap} \tag{3.17}$$

Where,
W_{cu} = total cu weight
W_{lv}=lv winding weight
W_{hv}=hv winding weight
W_{tap}=tap winding weigh

3.8 Winding resistance and Load Loss

The resistance of winding can be calculated by below equation

$$R = \frac{\rho_{ohm} \times L}{A} \tag{3.18}$$

Where,
ρ_{ohm} = resistivity of copper at reference degree Celsius temperature
L= $\pi \times D_m \times N$, length of the winding
A=cross section area

Now once we have the value of resistance we can calculate the load losses by it
As we know load losses are nothing but the I^2R losses and to calculate it we require I_{phase} current and resistance.
So we can calculate it for LV, HV and Tap winding by that equation. Here I^2R is for single phase so if we want to apply it on 3-phase then we have to simply multiply it with digit 3.

Now the other load loss is stray loss and its approx value can be calculated as 30percent of I^2R loss.
So that load loss can be given as Load Loss = I^2R + 30% I^2R

3.9 No Load Loss

No load loss depends on the grade of electrical steel being used and its magnetic characteristic at designed flux density.
The specific loss at working $B_m$taken from core characteristic curve available from the catalog.
On account of slitting, shearing, an air gap between joints and human error during an assembly process, the no-load loss tends to increase by approx 25percentage then the specified value.
So by this, we can calculate the no-load losses of the transformer

3.10 Performance Parameter

1. Percentage impedance : it can be written as

$$\%Z = \sqrt{\%R^2 + \%X^2} \tag{3.19}$$

so now,
% X can be given by below equation.

$$\%X = 2\pi f\mu \times \frac{NI}{\frac{V}{N} \times (H_{eq} + s)} \times r^2 \times \frac{1}{3} \times (T_1D_1 + 3T_gD_g + T_2D_2) \tag{3.20}$$

%R can be given by below equation as

$$\%R = \frac{\text{calculated load loss in kW}}{\text{Rated kVA}} \times 100 \tag{3.21}$$

Where,
$r = 1 - \frac{V_{lv}}{V_{hv}}$, Auto Factor
s = is a factor considered to correct for fringing at the winding ends, it has been found that a good Approximation is to increase Heq by some amount

2. Ratio error It can be represented in equation form as below

$$\text{Ratio error} = \frac{\frac{Vhv}{Vlv} - \frac{Nhv}{Nlv}}{\frac{Nhv}{Nlv}} \tag{3.22}$$

Its permissible tolerance as per IS-2026 is +-5%

3. Efficiency it can simply define by a ratio of output to the input.

$$Efficiency = \frac{Output}{Input} \tag{3.23}$$

$$Efficiency = \frac{Output}{Output + losses} \tag{3.24}$$

After this internal active part design, a design process proceeds towards tank design, radiator design, cooling arrangemnt etc.

Chapter 4

Objective function, Methodology and Constraints

4.1 Mathematical formulas for Cost function of Transformer

Transformer cost can be given as,

1. Active Part Material Cost
2. Raw Material Cost
3. Capital Cost

Where,
Active part material cost includes the cost of require core material plus require copper material for different winding say LV, HV, And Tap. in equation form we can represent it as below,

$$\text{Active part material cost} = (C_c \times W_c) + (C_{cu} \times W_{lv}) + (C_{cu} \times W_{hv}) + (C_{cu} \times W_{tap}) \tag{4.1}$$

Raw Material cost is nothing but the cost we have to invest in the required material of the transformer. which includes core lamination's, copper required for (HV, LV, tap) winding and connections, oil, main tank radiators, pressed sheet, steel, insulation, and pressure ring.
In Equation Form, we can Write it as below,

$$\text{Raw Material Cost} = \text{Active part cost} + \text{cost of (radiator+oil+pressure ring+insulating material)} \tag{4.2}$$

And the Capital cost is which includes the Capitalized cost of annual no-load loss, load loss, and auxiliary losses to The raw Material cost of the transformer. Which can be written in equation form as below,

$$\text{Capital Cost of Transformer} = \text{Raw Material Cost} + (\frac{GNL \times RNL}{1000}) + (\frac{GFL \times RFL}{1000}) + (\frac{GAX \times RAX}{1000}) \tag{4.3}$$

4.2 Mathematical derivation of sensitivity analysis function

A two winding core type transformer and its geometric length and height and all dimensions are as shown in below figure. Where,
W = total width of the yoke
Heq = height of limb
Hw = window height
d = diameter of a core
Cl = center to center distance of yoke (center of the limb)
Ww = window width
D1 = diameter of L.V winding
D2 = diameter of H.V winding

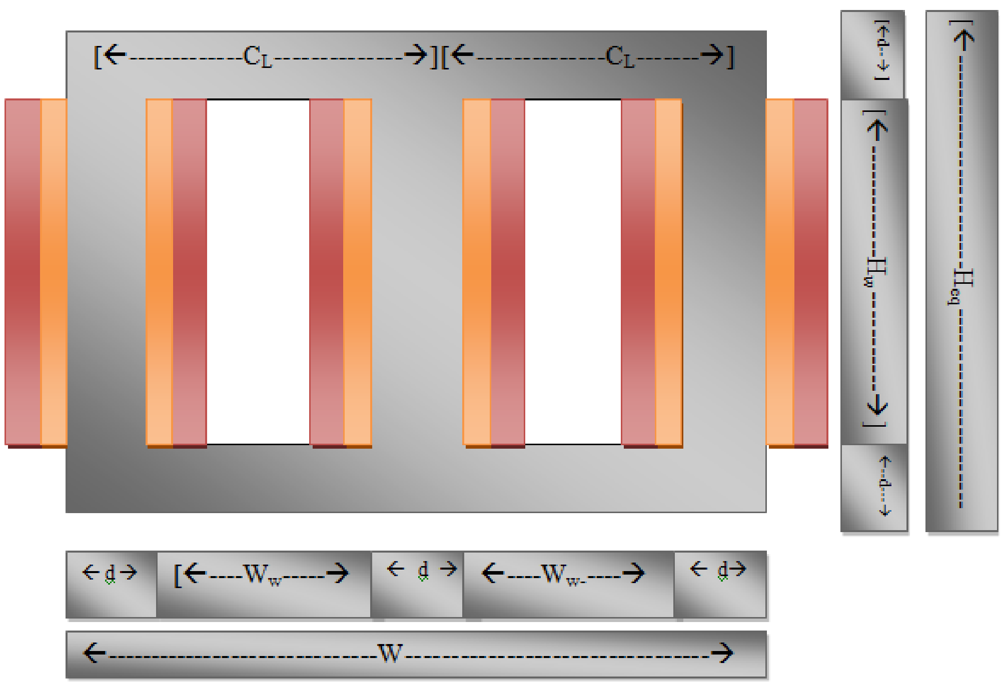

Figure 4.1: 3-phase 3limb core type transformer

Now a static induced EMF can be given as below and as explained in chapter 01 also

1. Statically induced EMF,

$$E = -N \times d\phi_m/dt \tag{4.4}$$

(rate of change of flux linkage) (-ve sign offers displacement of 90 degree apart)

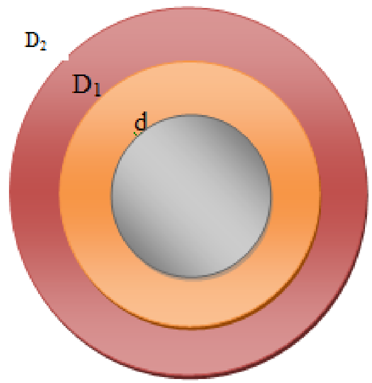

Figure 4.2: diameter (d), LV coil diameter (D1), and HV coil diameter(D2)

2. EMF Equation of transformer

$$E = 4.44 \times N \times Bm \times Ai \times f \tag{4.5}$$

3. Volt per Turn can be given by

$$\frac{E}{N} = 4.44 \times Bm \times Ai \times f \tag{4.6}$$

4. Transformation Ratio can be given as below

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} \tag{4.7}$$

So we can write from the above equation as,

$$N_1 \times I_1 = N_2 \times I_2 \tag{4.8}$$

that Primary ampere turns should be equal to secondary ampere-turns.

5. Now Ampere's Circuital law state that

$$\oint H \cdot dl = IN \tag{4.9}$$

$$\oint \frac{B}{\mu} \cdot dl = IN \tag{4.10}$$

4.2.1 Reactance calculation

Uniformly distributed AT(ampere turns NI) along LV and HV winding having the equal height the leakage field is mainly axial except at the end of winding, so a typical leakage flux pattern shown in below figure (4.3).

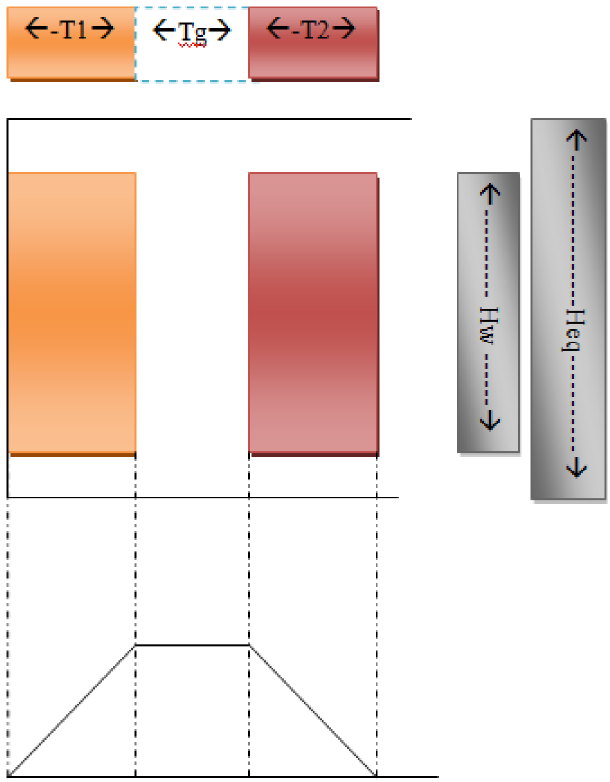

Figure 4.3: MMF or flux diagram

Where,
T1 = Radial depth of LV Winding
Tg = Radial depth of Gap
T2 = Radial depth of HV winding
Heq= Hw/Kr = equvivalent height
Heq = equivalent height of flux line Hw = window height
Kr = Rogowski factor (should be $\leq$ 1.0)

Now, MMF can be given by equation as below ,

So, it can write as,

$$\frac{B}{\mu} \times Heq = NI \tag{4.11}$$

or

$$B = \frac{\mu \times NI}{Heq} \tag{4.12}$$

So now as we know leakage inductance can be represented as below,

$$L = \frac{NBmAi}{I} \tag{4.13}$$

Where, Bm= μ NI/Heq So that

$$L = \frac{NAi \times \mu NI}{I \times Heq} \tag{4.14}$$

a	b	Winding	Radial depth	Mean diameter
0	1	LV	T1	D1
1	1	Gap	Tg	Dg
1	0	HV	T2	D2

Table 4.1: ATD table

$$L = \frac{\mu N^2}{Heq} \times \sum ATD \tag{4.15}$$

Where,
$\sum$ATD can be found by ampere-turn diagram

$$\sum ATD = \frac{R}{3} \times (a^2 + ab + b^2) \times D_m \tag{4.16}$$

R = Radial depth
D_m = mean diameter
So for the given diagram in figure $\sum$ ATD is as shown inn table 4.1,

So,

$$L_{leak} = \frac{\mu \times N^2}{Heq} \times ATD \tag{4.17}$$

$$L_{leak} = \frac{\mu \times N^2}{Heq} \times \frac{R}{3} \times (a^2 + ab + b^2) \times D_m \tag{4.18}$$

Then we can write an equation for "X" leakage Reactance As below

$$X = 2\pi f \frac{\mu N^2}{Heq} \times ATD \tag{4.19}$$

Now to calculate percentage reactance %X=X I/V

$$\%X = 2\pi f (\frac{\mu N}{Heq}) \times (\frac{I}{V/N}) \times \frac{1}{3} \times (T_1 D_1 + 3T_g D_g + T_2 D_2) \tag{4.20}$$

$$\%X = 2\pi f \mu (\frac{1}{Heq}) \times (\frac{NI}{V/N}) \times \frac{1}{3} \times (T_1 D_1 + 3T_g D_g + T_2 D_2) \tag{4.21}$$

So from the above last equation we can see that reactance is depends on :
N = Number of turns
Vt = volt per turn
Dm = mean diameter of windings
Heq = equivalent heignt of (flux lines) transformer core
NI = ampere turns
T = radial depths of winding

4.2.2 Core and Copper winding Weight formulas

Copper weight

weight of copprer can be given by below equation

$$W_{cu} = \rho_{cu} \times \text{volume of Cu material} \tag{4.22}$$

$$Wcu = \rho_{cu} \times A_{cu} \times L_{cu} \tag{4.23}$$

$$Wcu = \rho_{cu} \times \frac{I}{\delta} \times \pi D_m N \tag{4.24}$$

$$Wcu = \rho_{cu} \times \frac{I_{lv}}{\delta} \times \pi D_1 N_{lv} + \frac{I_h v}{\delta} \times \pi D_2 N_{hv} \tag{4.25}$$

Now as, $N_1 I_1 = N_2 I_2$ (Ampere turns should be same)

$$Wcu = \rho_{cu} \times \pi \frac{NI}{\delta} \times (D_1 + D_2) \tag{4.26}$$

So that above equation can be rewritten in terms of ampere-turns as below,

$$NI = \frac{\delta \times W_{cu}}{\rho_{cu} \times (D_1 + D_2) \times \pi} \tag{4.27}$$

here,
D1 = mean diameter of LV
D2 = mean diameter of HV

Core weight

It can be represent as below

$$Wc = \rho_c \times \text{volume of core} \tag{4.28}$$

$$Wc = \rho_c \times A_i \times L_i \tag{4.29}$$

Where,
$A_i = \frac{V_t}{4.44 \times f \times Bm}$

L_i=$(3 \times Hw + 4 \times C_l + 2 \times d)$

So that,

$$W_c = \rho_c \times \frac{V_t}{4.44 \times f \times Bm} \times (3Hw + 4C_l + 2d) \tag{4.30}$$

Where,
Hw = height of window
C_l = center to center distance between two limb
D = diameter of core

So now above equation can be represented in terms of a volt per turn.

$$V_t = \frac{Wc \times 4.44 \times f \times Bm}{\rho_c \times (3Hw + 4C_l + 2d)} \tag{4.31}$$

4.2.3 Short circuit impedance (SCI)

We know that %Z can be represent as below

$$\%Z = \sqrt{\%R^2 + \%X^2} \tag{4.32}$$

Where,

$$\%R = \frac{I}{V} \times R \times 100 \tag{4.33}$$

$$\%R = \frac{\rho_{ohm} \times \pi DmN}{A_{cu}} \times \frac{I}{V} \times 100 \tag{4.34}$$

Or

$$\%R = \frac{\text{Load loss}}{\text{Power Rating of transformer}} \times 100 \tag{4.35}$$

For Power Transformer considering %R is too small can be negligible
So that %Z can be represented as below

$$\%Z = \%X \tag{4.36}$$

such that,

$$\%Z = 2\pi f \frac{\mu N^2}{Heq} \times \frac{I}{V} \times \sum ATD \tag{4.37}$$

$$\%Z = 2\pi f \frac{\mu N}{Heq} \times \frac{I}{\frac{V}{N}} \times \frac{1}{3} \times (T_1D_1 + 3T_gD_g + T_2D_2) \tag{4.38}$$

so now its in the form of volt per turns and ampere turns

$$\%Z = 2\pi f \times \frac{\mu}{Heq} \times \frac{NI}{V_t} \times \frac{1}{3}(T_1D_1 + 3T_gD_g + T_2D_2) \tag{4.39}$$

Now we can rearrange above last one equation by putting NI and Vt from weight formula of core and copper.

As %Z =%X

$$\%Z = 2\pi f \times \frac{\mu}{Heq} \times \frac{\delta \times W_{cu}}{\rho_{cu} \times (D_1 + D_2) \times \pi} \times \frac{\rho_c \times (3Hw + 4Cl + 2d)}{Wc \times 4.44fBm} \times \frac{1}{3}(T_1D_1 + 3T_gD_g + T_2D_2) \tag{4.40}$$

so by the above equation we can relate how change in reactance or can be say change in impedance effect the require active part material we can relate that weight of copper material is directly proportional to impedance so for higher value of impedance require more copper material or else less core material and vice vers condition is true for core material.

4.3 Methodology

4.3.1 k_{cu} and RF of Winding

In Proposed methodology To do a design optimization I used a Cu-fill factor (winding space factor) and Ratio Factor (height to width Ratio of Transformer winding) concept Where , Cu-fill factor (winding space factor) can be define as ratio of Area occupied by copper to Area occupied by space can be say window space. By equation it can be represent as below

$$k_{cu} = \frac{A_{cu}}{A_w} \tag{4.41}$$

$$A_{cu} = \frac{AT}{\delta} \tag{4.42}$$

$$A_w = H_{wndg} \times W_{wndg} \tag{4.43}$$

Where,
A_{cu} = Area of copper
A_w = Area of winding window
AT = Ampere Turns
δ = Current Density
H_{wndg} = Height of Winding
W_{wndg} = Width of Winding

Now the Ratio Factor of winding can be define as below

$$RF = \frac{H_{wndg}}{W_{wndg}} \tag{4.44}$$

Now combining equation 4.42,4.43 and 4.44 Equation 4.41 can be represent in new way as below

$$k_{cu} = \frac{\frac{AT}{\delta}}{H_{wndg} \times W_{wndg}} \tag{4.45}$$

Such that, equation 4.45 can be rewritten as below

$$(H_{wndg} \times W_{wndg}) \times k_{cu} = \frac{AT}{\delta} \tag{4.46}$$

Now from the equation 4.44

$$H_{wndg} = RF \times W_{wndg} \tag{4.47}$$

Such that, equation 4.46 can be rewritten as below

$$RF \times W_{wndg}^2 = \frac{AT}{\delta} \tag{4.48}$$

Again equation 4.48 can be rewritten as below

$$W_{wndg} = \sqrt{\frac{AT}{\delta \times k_{cu} \times RF}} \tag{4.49}$$

and once we get W_{wndg} afterwards we get the Height dimension from below equation

$$H_{wndg} = RF \times W_{wndg} \tag{4.50}$$

So by this we can get a geometric design parameter of transformer design say width and height of LV , HV and Tap winding.

4.3.2 Calculation of ID,OD and Mean Diameter

Logic to find values of ID,OD and Mean diameter of LV,HV and Tap winding is as below

$$\text{LVID} = \text{DFE} + (2 \times \text{Core to LV Clearence}) \tag{4.51a}$$

$$\text{LVOD} = \text{LVID} + (2 \times W_{lvwndg}) \tag{4.51b}$$

$$\text{LVmean} = \frac{LVID + LVOD}{2} \tag{4.51c}$$

$$\text{HVID} = \text{LVOD} + (2 \times \text{HILO}) \tag{4.52a}$$

$$\text{HVOD} = \text{HVID} + (2 \times W_{hvwndg}) \tag{4.52b}$$

$$\text{HVmean} = \frac{HVID + HVOD}{2} \tag{4.52c}$$

$$\text{TAPID} = \text{HVOD} + (2 \times \text{Main to Tap Clearence}) \tag{4.53a}$$

$$\text{TAPOD} = \text{TAPID} + (2 \times W_{tapwndg}) \tag{4.53b}$$

$$\text{TAPmean} = \frac{TAPID + TAPOD}{2} \tag{4.53c}$$

Where clearance can be find out from BIL and its details are mentioned in Chapter05.

4.3.3 Calculate reactance

As i mentioned earlier in this chapter a reactance can be find out from below equation,

$$\%Z = 2\pi f \frac{\mu N}{Heq} \times \frac{I}{\frac{V}{N}} \times \sum ATD \tag{4.54a}$$

$$\sum ATD = \frac{R}{3} \times (a^2 + ab + b^2) \times D_m \tag{4.54b}$$

R = Radial depth
D_m = mean diameter

4.3.4 Calculation of Length, Area, Weight and Losses

After this a calculation of core length, length of LV HV and TAP winding pulse its Area and Weight can be find out using equation 3.12 to 3.17 and finding LL and NLL within tolerable limit design constraint or customer constraint if they have some special requirement then, a method will give a best optimal solution from all the Number of designs as its geometric design variables say Height and Width of Winding.

4.3.5 Condoctor Size Calculation

Afterwards once we get the outer geometric dimension we can find conductor size by doing back calculation for example H_{cond} = (H_{wndg} - Insulation), and same for conductor width also W_{cond} = (W_{wndg}- Insulation) .
Before calculating height and width of conductor we need to specify which type of winding is being in use for example Helix , CD , ext Afterwards it will calculate dimension of conductor based on winding type
By this we can get conductor size but there are many constraints to be considering while calculating conductor size.

4.4 Constraints

- Ratio Factor should be in between 5 to 50 (manufacturing constraint)
- DFE should be within some specified guaranteed value(manufacturing constraint)
- %Z should be <= some specified guaranteed value
- Ratio Error should be <= $\pm$0.5 According to IS
- Volt per Turn should be within specified value
- Area of conductor say ,$\frac{I}{\delta} \leq 50\ mm^2$
- H_{cond} in between 4 to 14 mm
- W_{cond} in between 1.3 to 4 mm
- $\frac{H_{cond}}{W_{cond}}$ in between 2 to 7
- No of Radially parallel conductor should be in between 1 to 35 (manufacturing constraint)
- No of Layers should be in between 1 to 2 (manufacturing constraint)
- No of Disc should be in between 1 to 200 (manufacturing constraint)
- δ <= specified δ value
- Conductor dimension should fit in window dimension
- Calculated area after getting conductor dimension >= $\frac{I}{\delta}$
- No Load Loss should be <= some specified guaranteed value
- Load Loss should be <= some specified guaranteed value

Chapter 5

Experimental Work

To be continued in Optimization of Transformer Design I worked on different software and toolboxes to know which one is user-friendly and by which software optimization can be done. So I first started with someone Equation and by setting limits (constraint) on it I tried to find its Optimal solution (say minimum or maximum solution)

Firstly I used Lingo Optimization tool to do Optimization. so to start learning it I started work on it by taking some equation as the objective function and applying limits say constraint on it and tried to get min/max Optimal value of the objective function by setting variable value.

5.1 Optimization Using Excel Solver

5.1.1 Define and solve a problem by using Solver

- A solver is an optimization toolbox in excel sometimes called what-if analysis tools.
- With Solver, we can find an optimal value for a formula say objective function in one cell called the target cell on a worksheet.
- Solver works with a group of cells that are related, either directly or indirectly, to the formula in the target cell.
- Solver adjusts the values in the changing cells(variable cells) that we specify called the adjustable cells (Variable cell) to produce the result that we specify from the target cell formula.
- we can apply constraints to restrict the values that Solver can use in the model, and the constraints can refer to other cells that affect the target cell formula.
- Using Solver we can determine the maximum or minimum value of one cell(objective function) by changing other cells(variable cell).

5.1.2 Steps to be follow

1. On the Data tab, in the Analysis group, click Solver. If the Solver command or the Analysis group is not available, we need to load the Solver from Add-in program. To load the Solver Add-in program

   (a) First Click the Microsoft Office Button, click Excel Options, and then click the Add-ins category.

   (b) In the Manage box, click Excel Add-ins, and then click Go.

   (c) In the Add-ins available box, select the Solver Add-in check box, and then click OK.

2. In the Set Target Cell box, enter a cell reference or name for the target cell. The target cell must contain a formula.

3. Do one of the following:

   - If we want the value of the target cell to be as large as possible, then we get it by clicking Max.
   - If we want the value of the target cell to be as small as possible, then we get it by clicking Min.
   - If we want the target cell to be a certain value, then click on Value of, and then type the value in the box.

   In the By Changing Cells box, we have to enter a name or reference for each adjustable cell say variable cell. Separate the nonadjacent references with commas. The adjustable cells must be related directly or indirectly to the target cell. we can specify up to 200 adjustable cells(which is the only limitation of excel).
   Now If we want a Solver to automatically propose the adjustable cells based on the target cell, click Guess. In the Subject to the Constraints box, enter any constraints that we want to apply.

5.1.3 Example 01

In this example, I take %reactance as an objective function and it can be defined as below,

$$\%X = 2\pi f\frac{\mu N^2}{Heq + s} \times r^2 \times \frac{I}{V} \times \sum ATD \tag{5.1}$$

$$\%X = 2\pi f\frac{\mu N}{Heq + s} \times \frac{I}{V_t} \times r^2 \times \frac{1}{3} \times \sum(T_1D_1 + 3T_gD_g + T_2D_2) \tag{5.2}$$

So, hear I represent it in a different way like
$\%X = (const \times x \times y)/z$,
I take this equation and relate it with the real reactance formula as,
x = IN say ampere-turn
y = ATD say ampere-turn diagram
$z = V/t \times Heq$,say volt per turn and equivalent height
and after relating this condition I put it in lingo optimization tool and tried to get minimum value of objective function.

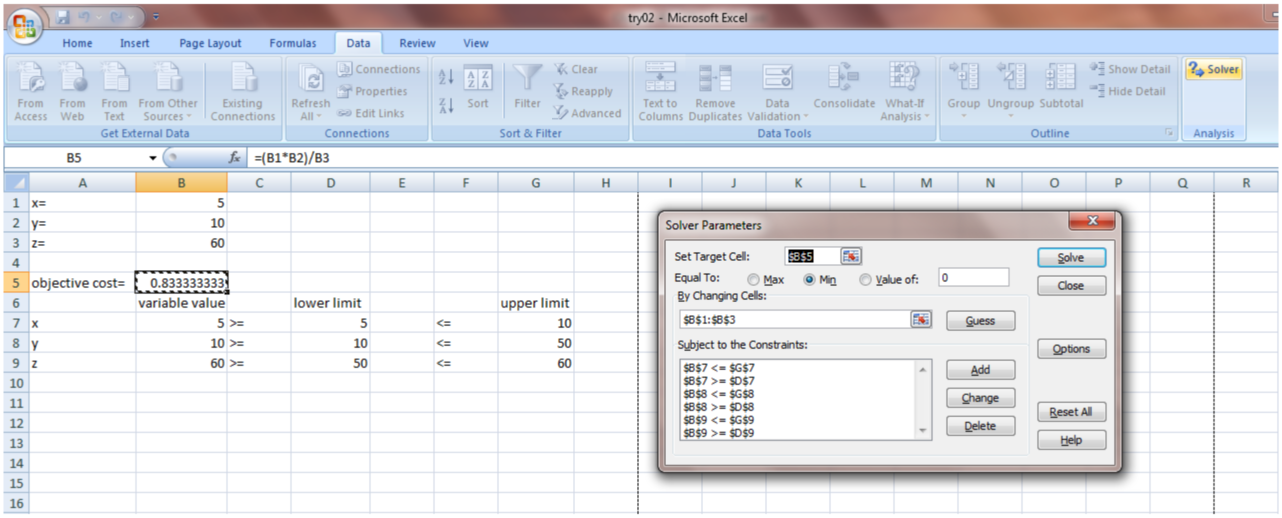

Figure 5.1: Excel Example 01

So from the above figure, we can see that I put all the variable in excel sheet and giving limit (constraint) to all variables. Initially, I assumed value = 01 for all variable and after solving this by excel solver I found the optimal value of those variables say x,y, and z equal to 5,10 and 60 respectively.
a constraint limit for a variable is as the limit for x is [5,10], the limit for y is [10,50] and the limit for z is [50,60]
So by this small activity, I can conclude that it works properly and giving as an optimal value of an objective function.
And the other technical conclusion came out from this activity was we get optimal value %X by setting a low value of IN(ampere-turn) and ATD(ampere-turn diagram) and higher value of V/t and Heq (volt per turn, equivalent height)
So if we increase the number of turns or diameter or hi-lo gap any of this then %X is going to be increased and vice versa. And if we decrease the V/t or Heq then %X is going to be increase means in inverse formation it works.

5.1.4 Example 02

In this example, I take an objective function as cost function and it can be defined as

$$Cost = C_c \times W_c + C_{cu}cu \times W_{cu}, \tag{5.3}$$

where Cc and Ccu are a price of core and copper respectively and Wc and Wcu is a weight of core and copper accordingly.
As the transformer cost mainly depends on core and copper I took this type of equation.
It can be seen in figure that solved equation for core weight is
Wc =density *length*area
Where,
density = const =1(assumed)

length = (3Hw+4Cl+2d)
area = (V/t)/4.44 f Bm
and equation for copper is as below
Wcu = density *length*area
Where,
density=const =1
length = pi*D*N
area = I/del
And constrain for this problem is as for Wcu is [40,45] ,for Lcu(X) is [10,20] , for Acu(Y) is [5,20] same for Wc is [80,85] ,for Lc(A) is [10,20] , for Ac(B) is [5,20] and for this objective and constrained function proble we get 220 cost as minimum cost under limitation on variables.

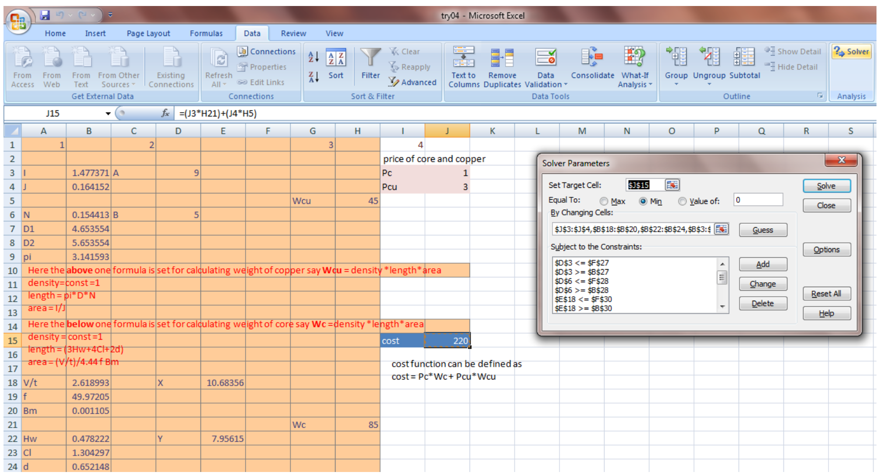

Figure 5.2: Excel Example 02A

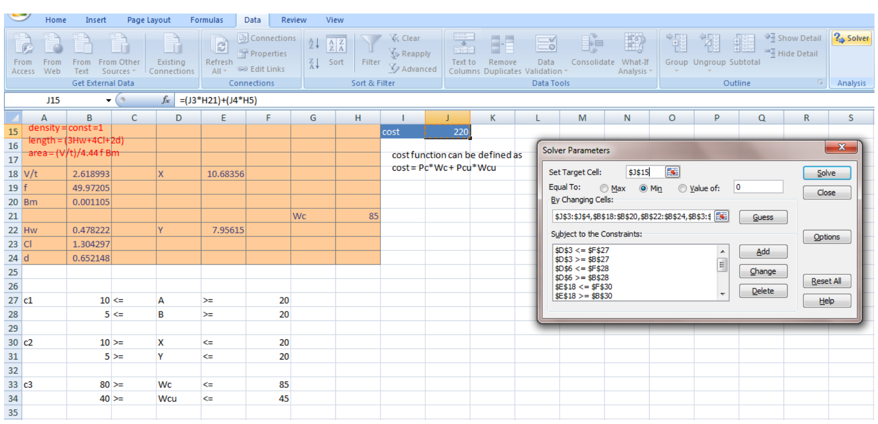

Figure 5.3: Excel Example 02B

In next 3rd and 4th example I worked on a design sheet of transformer which is already solved and having all the design variable in it interlinked but what I am doing new in it is that for same design I applied constraint on some of the variable say DFE(core diameter), H(height), %z (impedance), del(current density), Bm (flux density), NLL and LL and I set Raw material cost as an Objective function . so by changing above mentioned variable, I am able to get a different value of cost function (min cost). Now in following examples I used design sheet by which a design parameter can be decided so a transformer design of.

1. Rating Q: 42500 kVA
2. Voltage ratio at No-Load: 66/11 kV
3. Primary voltage /Secondary voltage
4. Frequency: 50 Hz
5. Winding material: Copper material type
6. Taps on HV: 10%
7. No Load Loss: 21200 watt
8. Full Load Loss: 212000 watt
9. Impedance :11.33 %Z
10. Flux density Bm :9 Tesla(max)
11. Current density (del) :9 A/sq.mm(max)
12. Connection type :Dyn11 vector group
13. Temp. Rise: 45 degree Celsius
14. Another specification as per IS standards

So hear by I attache an original value of variable and after solving a different report by applying different constraint limits on variables.

5.2 42500 kVA, 66/11kV Transformer Design

Particulars	Unit	Symbol	Calculations
Rating	KVA	S	42500
H.V. Voltage (line)	KV	VHL	66
L.V. Voltage (line)	KV	VLL	11
H.V. Connection	-	CH	DELTA
L.V. Connection	-	CL	STAR
Vector Group	-	VG	Dyn11
Max. Positive Tap	%	MPT	10
Max. Negative Tap	%	MNT	10
Tap Steps	%	TST	1.25
Winding Material	-	WM	CU
Core Material	-	CRM	MOH
Cooling Method	-	CM	ONAN
Avg. Wdg. temp rise	C	TW	45
Specified No load losses	W	WNL	21000
Specified Full load losses	W	WFL	210000
Specified impedance	%	ZSC	11.5
Max. Positive Tol. on ZSC	%	TZMP	7.5
Max. Negative Tol. on ZSC	%	TZMN	7.5
Max. flux density	T	BMmax	9
Max. current density	$\frac{A}{mm^2}$	CDmax	9
Rate of core	Rs./kg	RCR	178
Rate of Cu	Rs./kg	RCU	533

Table 5.1: Inputs for 42500kVA transformer Design

Sr.No	Variable	Intial value
1	DFE	577
2	Nlv	70
3	Volt per Turn	90.726
4	%Z	11.33
5	FLL	203430.14
6	NLL	19576.60
7	Bm	1.7

Table 5.2: Initial value of Variables

FLUX DENSITY / TURNS	T	1.7	70	655	145
	NO.		1	520	520
	NO.		1	11	11
BARE COND. HT / BARE DIA	MM	1.9	11.9	11	14
BARE COND. TH. / ACTUAL DIA	MM		2.1	1.45	2.1
CONDUCTOR HEIGHT-THICK RATIO	NO.		5.667	7.586	6.667
NO. OF RAD. PARALLEL COND.	NO.	TRY 1 RAD	25	4	2
NO. OF AXIALLY PARALLEL COND.	NO.		1	1	1
NO OF DISCS	NO.	108	76	76	32
TURNS/DISC	NO.	1	1	8.8	5
COMPENSATING/TRANSPOSE GAP	MM		52		50.00
AXIAL HT (ELECTRICAL)	MM		1163	1163	806
RADIAL THICKNESS	MM	TT= 800	67.5	77	28
CONDUCTOR COVERED WT	KG	MAX = 10	13132	3251	769
CURRENT DENSITY (MAX/ACTUAL)	A/mm²	8.898	3.623	3.409	3.696
'A' DIMENSION	MM	1355	LV= 6.2	HV= 7.9	B+C = 1095
CORE WEIGHT / TOTAL CU WT	KG	17771	17152	17770.03	0.958
DFE/STEPS/MIN TH/NET AREA		577	r=15/p=19	9.5	2405.459
FLL / NLL / % Z		203430.14	19576.60	11.05	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-4.04	-7.66	-2.58	BM =1.6990
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,163,238	1,821,242	15,613,082	18,423,437

Figure 5.4: Main Design Sheet

5.2.1 Example 03

Objective function = Raw material cost
Variables = DFE(core diameter), FLL(full load loss), NLL(no load loss), %Z(Impedance)

So after applying this constraints on such variable I got different answers as below and for this the solved results are as

1. In this for the values of
   DFE = 575
   FLL = 203430.14
   NLL = 19576.59
   %Z =11.048

   We get the transformer cost is = 15,581,370 Rps. This is 31,712Rps cheaper

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	[550,570]	576
2	Nlv	70	-	70
3	Volt per Turn	90.726	-	90.726
4	%Z	11.33	[10,11.5]	11.03
5	FLL	203430.14	[150000,200000]	203091.50
6	NLL	19576.60	[15000,20000]	19725.76
7	Bm	1.7	-	1.7

Table 5.3: For DFE=576

DFE/STEPS/MIN TH/NET AREA		576	r=15/p=19	9.5	2397.962
FLL / NLL / % Z		203091.50	19725.76	11.03	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-4.20	-6.95	-2.75	BM =1.7043
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,152,380	1,819,282	15,581,370	18,386,017
COND.COST/EX WORKS PRICE	Rs.	9,126,026		-2.13	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	COOL OK
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		MOR	
RAISE FOR RADIATORS	mm	300		SECTIONS	OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.725	ONAF	OK
	32.16	2100			
OTHER INPUTS	DFE&Turns			576	70
FLL / NLL / % Z as variable	solver	203430.14	19576.59519	11.04821626	

Figure 5.5: Result for DFE = 576

2. In this for the values of
   DFE = 575.25481
   FLL = 202974.12
   NLL = 19796.39
   %Z =11.02

   We get the transformer cost is = 15,569,416 Rps. Which is 43,666 Rps cheaper

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	[550,570]	575.25
2	Nlv	70	-	70
3	Volt per Turn	90.726	-	90.726
4	%Z	11.33	[10,11.5]	11.02
5	FLL	203430.14	[150000,200000]	202974.12
6	NLL	19576.60	[15000,20000]	19796.39
7	Bm	1.7	-	1.706

Table 5.4: For DFE=575.25

DFE/STEPS/MIN TH/NET AREA		575.253659	r=15/p=19	9.5	2394.483
FLL / NLL / % Z		202973.82	19796.39	11.02	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-4.26	-6.62	-2.81	BM =1.7067
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,147,574	1,819,562	15,569,416	18,371,911
COND.COST/EX WORKS PRICE	Rs.	9,119,630		-2.13	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	COOL OK
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		MOR	
RAISE FOR RADIATORS	mm	300		SECTIONS	OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.725	ONAF	OK
	32.15	2100			
OTHER INPUTS	DFE/Turns			575.2536589	70
FLL / NLL / % Z	Solver	203430.14	19576.59519	11.04821626	

Figure 5.6: Result for DFE =575.25

3. In this for the values of
   DFE = 574.24283
   FLL = 203430.14
   NLL = 19576.59519
   %Z =11.048
   We get the transformer cost is = 15,526,873 Rps. This is 86,209 Rps cheaper

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	[550,570]	574.25
2	Nlv	70	-	70
3	Volt per Turn	90.726	-	90.726
4	%Z	11.33	[10,11.5]	11.01
5	FLL	203430.14	[150000,200000]	202709.70
6	NLL	19576.60	[15000,20000]	19913.73
7	Bm	1.7	-	1.712

Table 5.5: For DFE=574.25

DFE/STEPS/MIN TH/NET AREA		574.24168	r=15/p=19	9.5	2386.594
FLL / NLL / % Z		202709.39	19913.73	11.01	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-4.38	-6.07	-2.94	BM =1.7124
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,129,952	1,814,167	15,526,873	18,321,710
COND.COST/EX WORKS PRICE	Rs.	9,107,371		-2.13	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	COOL OK
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		MOR	
RAISE FOR RADIATORS	mm	300		SECTIONS	OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.725	ONAF	OK
	32.14	2100			
OTHER INPUTS	DFE/Turns			574.2416802	70
FLL / NLL / % Z	Solver	203430.14	19576.59519	11.04821626	

Figure 5.7: Result for DFE =574.25

4. In this for the values of
   DFE = 574.017
   FLL = 202650.93
   NLL = 19985.24
   %Z =11.01
   We get the transformer cost is = 15,518,217 Rps. This is 94,865 Rps cheaper.

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	[550,570]	Approx574
2	Nlv	70	-	70
3	Volt per Turn	90.726	-	90.726
4	%Z	11.33	[10,11.5]	11.01
5	FLL	203430.14	[150000,200000]	202650.93
6	NLL	19576.60	[15000,20000]	19985.24
7	Bm	1.7	-	1.714

Table 5.6: For DFE=574.01

DFE/STEPS/MIN TH/NET AREA		574.016796	r=15/p=19	9.5	2383.115
FLL / NLL / % Z		202650.63	19985.24	11.01	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-4.41	-5.73	-2.97	BM =1.7149
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,125,324	1,814,167	15,518,217	18,311,496
COND.COST/EX WORKS PRICE	Rs.	9,103,640		-2.13	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	COOL OK
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		MOR	
RAISE FOR RADIATORS	mm	300		SECTIONS	OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.725	ONAF	OK
	32.15	2100			
OTHER INPUTS	DFE/Turns			574.0167961	70
FLL / NLL / % Z	Solver	203430.14	19576.59519	11.04821626	

Figure 5.8: Result for DFE =574.01

So I can conclude from this work is that by changing this variable I can get some optimal or say (feasible solution if some constraint is not satisfying).
In this I get low cost from the original one by changing its diameter as we decrease the diameter we get cheaper cost but in that looses may effect by changing this diameter variable. And another conclusion came out from this is I cant design diameter with a fractional number it requires integer number so in next I care about this things while solving it.

5.2.2 Example 04

Objective function = Raw material cost
Variables =
Nlv(Number of LV turns)
FLL(full load loss)
NLL(no load loss)
%Z(Impedance)

1. In this for this values of Nlv =66.5
   Vt =95.50
   Bm =1.78
   %Z=10.50
   NLL=23235.77
   FLL=194092.08

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	-	577
2	Nlv	70	[70,80]	66.5
3	Volt per Turn	90.726	[70,90]	95.50
4	%Z	11.33	[10,11.5]	10.50
5	FLL	203430.14	[150000,210000]	194092.08
6	NLL	19576.60	[15000,21000]	23235.77
7	Bm	1.7	[0,1.7]	1.78

Table 5.7: For Nlv=66.5

DFE/STEPS/MIN TH/NET AREA		577	r=15/p=19	9.5	2405.459
FLL / NLL / % Z		194092.08	23235.77	10.50	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-8.45	9.60	-7.94	BM =1.7884
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,109,126	1,813,047	15,062,680	17,773,962
COND.COST/EX WORKS PRICE	Rs.	8,687,900		-2.13	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	COOL OK
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		R	
RAISE FOR RADIATORS	mm	300		SECTIONS	OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.725	ONAF	OK
	31.52	2100			
OTHER INPUTS	DFE/Turns/ET		577	66.5	95.50154829
FLL / NLL / % Z		194092.08	23235.7703	10.4990107	

Figure 5.9: Result for Nlv=66.5

2. In this for this values of Nlv =68
   Vt = 93.394
   Bm =1.74
   %Z=10.70
   NLL=21417.06
   FLL=198149.26

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	-	577
2	Nlv	70	[70,80]	68
3	Volt per Turn	90.726	[70,90]	93.394
4	%Z	11.33	[10,11.5]	10.70
5	FLL	203430.14	[150000,210000]	198149.26
6	NLL	19576.60	[15000,21000]	21417.06
7	Bm	1.7	[0,1.7]	1.74

Table 5.8: For Nlv=68

DFE/STEPS/MIN TH/NET AREA		577	r=15/p=19	9.5	2405.459
FLL / NLL / % Z		198149.26	21417.06	10.70	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-6.53	1.02	-5.96	BM =1.7489
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,133,690	1,817,004	15,301,583	18,055,867
COND.COST/EX WORKS PRICE	Rs.	8,882,445		-2.13	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	COOL OK
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		MOR	
RAISE FOR RADIATORS	mm	300		SECTIONS	OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.725	ONAF	OK
	31.76	2100			
OTHER INPUTS	DFE/Turns/ET		577	68	93.39489649
FLL / NLL / % Z	Solver	198149.262	21417.0631	10.6959321	

Figure 5.10: Result for Nlv = 68

3. In this for this values of Nlv =72
   Vt = 88.2062
   Bm =1.65
   %Z=11.41
   NLL= 17811.50
   FLL= 208919.80

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	-	577
2	Nlv	70	[70,80]	72
3	Volt per Turn	90.726	[70,90]	88.2062
4	%Z	11.33	[10,11.5]	11.41
5	FLL	203430.14	[150000,210000]	208919.80
6	NLL	19576.60	[15000,21000]	17811.50
7	Bm	1.7	[0,1.7]	1.65

Table 5.9: For Nlv=72

DFE/STEPS/MIN TH/NET AREA		577	r=15/p=19	9.5	2405.459
FLL / NLL / % Z		208919.80	17811.50	11.41	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-1.45	-15.98	0.65	BM =1.6518
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,192,608	1,826,077	15,926,432	18,793,190
COND.COST/EX WORKS PRICE	Rs.	9,402,653		-2.13	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	COOL OK
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		MOR	
RAISE FOR RADIATORS	mm	300		SECTIONS	OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.725	ONAF	OK
	32.63	2100			
OTHER INPUTS	DFE/Turns/ET		577	72	88.20629113
FLL / NLL / % Z	Solver	208919.801	17811.50488	11.40678804	

Figure 5.11: Result for Nlv = 72

4. In this for this values of (non-optimal solution) Nlv =80
   Vt = 79.38
   Bm =1.48
   %Z=12.82
   NLL= 14428.94
   FLL= 230167.83
   In the last two example we get the transformer cost more than earlier one here because the

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	-	577
2	Nlv	70	[70,80]	80
3	Volt per Turn	90.726	[70,80]	79.38
4	%Z	11.33	[10,11.5]	12.82
5	FLL	203430.14	[150000,210000]	230167.83
6	NLL	19576.60	[15000,21000]	14428.94
7	Bm	1.7	[0,1.7]	1.486

Table 5.10: For Nlv=80

DFE/STEPS/MIN TH/NET AREA		577	r=15/p=19	9.5	2405.459
FLL / NLL / % Z		230167.83	14428.94	12.82	MAX GR =22
% VARIATION / ACTUAL FLUX DEN		8.57	-31.94	11.61	BM =1.4866
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,320,412	1,971,775	17,320,808	20,438,553
COND.COST/EX WORKS PRICE	Rs.	10,443,069		-2.14	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	CHK COOL
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		MOR	
RAISE FOR RADIATORS	mm	300		SECTIONS	NOT OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.65	ONAF	OK
	33.81	2300			
OTHER INPUTS	DFE/Turns/ET		577	80	79.38566201
FLL / NLL / % Z	Solver	230167.826	14428.93543	12.82145183	

Figure 5.12: Result for Nlv = 80

volts per turn was reduced that's why the number of turns increased and accordingly cost increases due to an increase in copper requirement.

So from this, I concluded that as the volt per turn increases the requirement of the number of turns will be less and accordingly required copper material also less and vice versa. So a choice of Volt per turn, DFE(core diameter) and, Nlv (number of LV turns) Affects the cost of the transformer so to get the optimal value of the transformer cost we have to adjust these main parameters such that all constraint can satisfy and give an optimal cost of the transformer.

5.2.3 Example 05

Objective function = Raw material cost
Variables =
Nlv(Number of LV turns)
FLL(full load loss)
NLL(no load loss)
%Z(Impedance)
DFE(core diameter)

Sr.No	Variable	Intial value	Constraints	New value
1	DFE	577	[560,570]	565
2	Nlv	70	[70,80]	72
3	Volt per Turn	90.726	[70,90]	88.2062
4	%Z	11.33	[10,11.5]	11.23
5	FLL	203430.14	[150000,210000]	205700.0
6	NLL	19576.60	[15000,21000]	19560.81
7	Bm	1.7	[0,1.7]	1.71

Table 5.11: For DFE=565, Nlv=72

DFE/STEPS/MIN TH/NET AREA		565	r=15/p=19	9.5	2313.633
FLL / NLL / % Z		205700.00	19560.81	11.23	MAX GR =21
% VARIATION / ACTUAL FLUX DEN		-2.97	-7.73	-0.90	BM =1.7173
CORE/COOLING/TOTAL/CAP. COST	Rs.	3,043,978	1,806,812	15,565,544	18,367,342
COND.COST/EX WORKS PRICE	Rs.	9,245,951		-2.13	NOT OK
GTD FLL / NLL / % Z / GRAD		212000	21200	11.333	COOL OK
% STEP FOR WHICH COOLING IS REQD.			PRINCIPAL TAP COOLING		
RATING FOR ONAN/ONAF COOLING	KVA	37500		MOR	
RAISE FOR RADIATORS	mm	300		SECTIONS	OK
NO SECTIONS PER RADIATOR	NO	33	HOT SPOT	RAISE	OK
NO OF RADIATORS	NO	16	85.725	ONAF	OK
	32.52	2100			
OTHER INPUTS	DFE/Nlv			565	72
FLL / NLL / % Z / Vt		203430.14	19576.59519	11.04821626	88.20629113

Figure 5.13: Result for DFE=565 ,Nlv = 72

So from the above figure we can see that by setting DFE and Nlv we can get optimal value of transformer design in this last figure we can see that a diameter will be reduced than the original one (from 577 to 565) and the number of turns increased (70 to 72) and the volt per turn reduced as Nlv increases , and the flux density changed but not that much it might be in 0.001or0.01 answer having value of 1.71 which was 1.7 earlier .

Hence by this, we can get solution of transformer design by optimization solver.

5.3 Optimization Using Programming in VBA

Up to Now I used Excel solver and Optimization Tool box to solve optimization problem.In excel solver I solved the transformer design by applying constraint limits on some specific variables to get optimal solution as Minimum Cost of transformer But in that it solves and gives us any random optimal solution from search space which might be local optimal or global optimal so for every iteration I got a different solution which might me same or different from previous Solution.

So to get optimal Solution of Transformer cost while satisfying constraint limits I made one Program Using Excel VBA

5.3.1 Input for Program

To get the Optimal Solution through this Programming User first needs to specify Input Data in it

SPECIFICATION	**UNIT**	**VALUE**	**Nomenclature**
Power Rating	KVA	42500	S
HV No load Voltage	KV	66	VNLH
LV No load Voltage	KV	11	VNLL
Vector Group			
Flux Density	Tesla	1.68	BM
Current Density	A/mm2	3.	DEL
Stacking Factor		0.97	SF
Winding Insulation	GRD,UNI	UNI	WI
FREQ	Hz	50	F
MAX TAP	% Range(+ve)	10	MAXT
MIN TAP	% Range(-ve)	10	MINT
step for Tap	%	1.25	STEPST
TAP-Type	Type(1or2)	2	TYPET
tap	per unit value at min	0.1	
CONNECTION TYPE	LV	STAR	CL
	HV	DELTA	CHM
Core density	g/cm3	7.65	Drohc
CU density	g/cm3	8.96	Drohcu
Core Price	Rp/kg	178	Pc
Cu Price	Rp/kg	533	Pcu
DFE	mm	600	DFE
kwLV(Space Factor)		1	
kwHV(Space Factor)		1	
kwTAP(Space Factor)		1	
Tap Height Reduction	mm	100	
Resistivity of Material	ohm.cm	0.0215	
Core Material		MOH	

Table 5.12: Inputs for Program

5.3.2 Intermediate Calculation

Afterwards intermediate Calculation is done on the basis of Some specific selected input of DFE : The Volt per turn , Number of Turns for LV,HV & TAP, Ampere Turn , Conductor Cross section Area,Core area will be identify though mathematical equation As Below

- Specify DFE
- Volt per Turn = (DFE^2 * 4.44 * f * BM * SF * 0.72)/(1000000)
- N_{LV} = Phase Voltage of LV/Volt per Turn
- Update V/t = Phase Voltage of LV/N_{LV}
- N_{HV} = Phase Voltage of HV/Updated V/t
- $NTAP$ = Based on required%tap
- Ratio Error
- Ai = VT/(4.44*f*BM)
- A_{LV} = Phase Current of LV/ Del
- A_{HV} = Phase Current of HV/ Del
- $A_{Tap} = A_{HV}$
- Calculate AT= Phase current * Number of Turns

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Calculation of Clearances

Before deciding clearances designer needs to calculate power frequency and impulse level according to BIL of IS standard.
It can be calculate from Table 5.13

Core to LV clearance can be calculate from reference table 5.14 And 5.15

LV to HV clearance can be calculate from reference table 5.16 And 5.17

HV to TAP clearance can be calculate from reference table 5.18 And 5.17

V(kV)	IMPULSE(kVp)	POWER FREQ(Vrms)
0	0	3
1.2	40	10
3.7	60	20
7.3	75	28
12.1	95	38
17.6	125	50
24.1	170	70
36.1	250	95
52.1	325	140
72.1	450	185
100.1	550	230
123.1	650	275

Table 5.13: Impulse Level & Power Frequency Voltage

S	OFFSET
0	4
1601	3
2001	2

Table 5.14: Select Offset based on Power Rating for Core to LV Clearence

PFL	CLCL	3	4
0	14	12	10
3.01	25	25	25
20.01	28	28	28
50.01	32	32	32
70.01	38	38	38
140.01	75	75	75
275.01	VALUE	VALUE	VALUE

Table 5.15: Core to LV Clearance

Impulse	**OFFSET**
0	2
650	3

Table 5.16: Select Offset based on Impulse for Hilo Gap

PFHM	**CLLH**	**3**	**4 CLMT(UNI)**	**5 GRD**	**6 UNI**	**7 GRD**
0	13	13	NA	NA	NA	NA
28.01	15	15	NA	NA	NA	NA
50.01	18	18	NA	NA	NA	NA
70.01	30	30	30	28	30	28
140.01	48	55	48	46	55	52
275.01						

Table 5.17: HiLo Gap Clearance and MT Clearance

WI	**HVIMPH**	**HVIMPH**
	0	650
	2	3
UNI	4	6
GRD	5	7

Table 5.18: Select offset for Main to Tap clearance

SPECIFICATION	UNIT	OTHER	LV	HV	HV TAP
CONNECTION			STAR	DELTA	DELTA
LINE VOLTAGE	KV		11	66	66
PHASE VOLTAGE	V		6350.852	66000	66000
LINE CURRENT	A		2230.671	371.778	371.778
PHASE CURRENT	A		2230.671	214.646	214.646
DFE	mm	600			
VOLTS PER TURN		91.16634			
VOLTS PER TURN –UPDATED	V/TURN	90.72647			
Ai	m2	0.24444			
Number of Turns			70	655	146
Ratio Error		0.099609			
Area of CU	mm2		615.697	59.245	59.245
AT			156147.005	140593.434	31338.383
Kw			1	1	1
AT/(DEL*kw)			43098.814	38805.805	8649.8437
FOR CLEARENCE CALCULATION					
Implse Level	kVp		75	325	325
Power Frequency	KVrms		28	140	140
TOP WNDG INS	mm		20	60	60
BOTTOM WNDG INS	mm		20	60	60
CORE TO LV	mm		28	-	-
LV TO HV (HILO)	mm		-	30	-
HV TO TAP (MT)	mm		-	-	30
PH TO PH	mm		-	-	30
Bld Factor		1.15			
Specific Losses	watts/kg	0.92			

Table 5.19: Calculation Based on Input

5.3.3 Flow Chart

After the intermidiate calculation a solution of specified input will find by below one programming which i done Using VBA. A flow Chart for Programming Is as shown in Figures 5.14,5.15and5.16. In this i divide logic into some sub logic's and it will work according to below,

Logic 01:

1. In this Programming a Search Space for DFE (Core Diameter) is specified As DFEmin TO DFEmax (starts from j=0)
2. V/T Calculated
3. **If** V/T is within permissible limit then it **go to** next step or**else** takes another DFE
4. Calculate Number of Turns [N_{LV} ,N_{HV},N_{TAP}]
5. Calculate Ratio Error
6. **If** ratio error is within limit then it **go to** next step **else** take another DFE
7. (a) Search space **for** Ratio Factor of Height of LV/Width of LV , RFmin TO RFmax (starts from i=0)
   (b) find W_{LV} & H_{LV} (Width and Height of LV)
   (c) Find W_{HV} & H_{HV} (Width and Height of HV)
   (d) find W_{TAP} & H_{TAP} (Width and Height of Tap)
   (e) find ID,OD & MEAN of all Winding
   (f) select case to calculate ATD
   (g) Calculate %Z
   (h) if %Z is within limit **goto** next step **else** take another RF
   (i) Calculate Length of CORE & CU material
   (j) Calculate Weight of Core & CU material required
   (k) find Losses
   (l) Find Total Cost
   (m) i=i+1
   (n) Find Minimum Cost
8. Store Values of dimension and minimum cost for some specified DFE
9. j=j+1
10. find Global optimum value from a Solution Space of Different DFE
11. END

After executing this Logic it will give us a optimal valves for Geometric Parameter say Height and Width dimension of winding while considering constraint limits on it and after that we can calculate conductor dimension ,and also get the value of required No of Disc, Turns per Disc , OR No of Layers, Turns per Layers while considering constraint of conductor dimension .for that we have to activate Logic 02.

Logic 02:

1. FOR No of Radially Parallel Conductor k = NRPmin to NRPmax (1 to 35 which is manufacturer constraint)
2. **IF** $\frac{A_{cond}}{NRP \times NAP} <= 50mm^2$ **goto** next **else** k=k+1
3. Select Case For a Winding Type (Helix OR CD)
4. **IF** Winding Type = Helix **goto** Line 05 & **IF** Winding Type = CD **goto** Line 06
5. Helix
   (a) **For** No of Layers between l = NLAYERSmin to NLAYERSmax (1 to 2)
   (b) Calculate Turns per Layers = $\frac{NoofTurns}{NoofLayers}$
   (c) Calculate Height of Conductor(HT)
   (d) Calculate Thickness of Conductor(TH)
   (e) **IF** HT is within limit **goto** next **else** exist
   (f) **IF** TH is within limit **go** to next **else** exist
   (g) Calculate conductor area of based on HT and TH by = $HT \times TH$
   (h) select conductor deduction area based on its TH value
   (i) Calculate new Area of Conductor By considering Reduction in Area
   (j) Calculate δ in by $\frac{I_{ph}}{A}$
   (k) **IF** δ is within limit then **goto** next **else** exist
   (l) Calculate Resistance
   (m) Calculate $I^2 \times R$ losses
   (n) Calculate Eddy Current losses
   (o) Calculate weight
   (p) l = l+1
6. CD
   (a) **For** No of Disc between m = NDmin to NDmax (1 to 200)
   (b) Calculate Turns per Disc = $\frac{NoofTurns}{NoofDisc}$
   (c) Calculate Height of Conductor(HT)
   (d) Calculate Thickness of Conductor(TH)
   (e) **IF** HT is within limit **goto** next **else** exist
   (f) **IF** TH is within limit **go** to next **else** exist

(g) Calculate conductor area of based on HT and TH by = $HT \times TH$

(h) select conductor deduction area based on its TH value

(i) Calculate new Area of Conductor By considering Reduction in Area

(j) Calculate δ in by $\frac{I_{ph}}{A}$

(k) **IF** δ is within limit then **goto** next **else** exist

(l) Calculate Resistance

(m) Calculate $I^2 \times R$ losses

(n) Calculate Eddy Current losses

(o) Calculate weight

(p) m = m+1

7. Store calculated Values of Above mentioned variable to solution space of No of Radially parallel conductor.

8. k = k +1

Logic 03 : The same Logic 02 is use to find conductor dimension for LV, HV and Tap and a gives a solution space of conductor dimension at different No of radially Parallel Conductor and No of layers or No of Disc according to its Winding Type. So now a algorithm finds the best possible solution of conductor dimension while considering Load Losses as constraint with minimum cost.

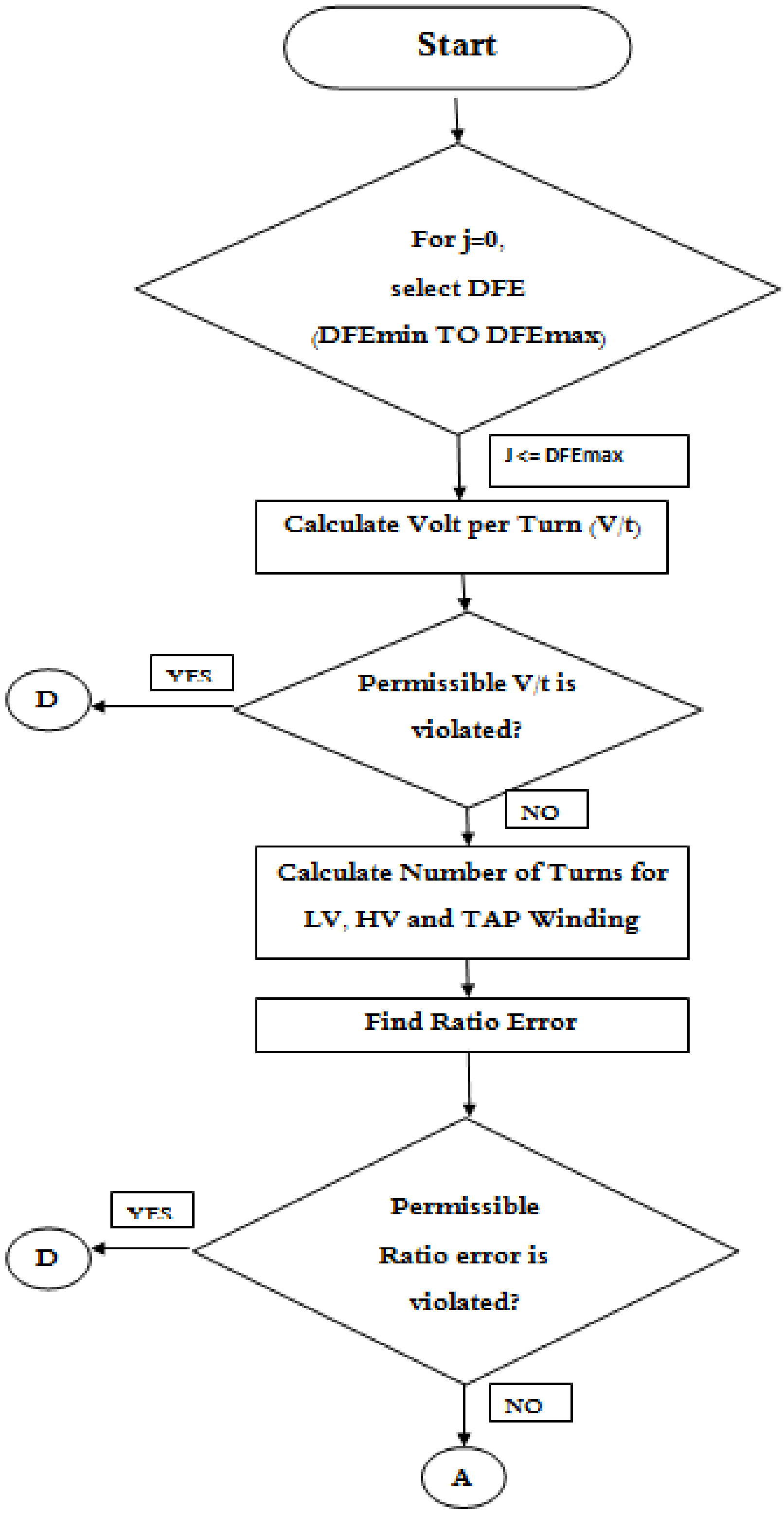

Figure 5.14: Flow chart 1

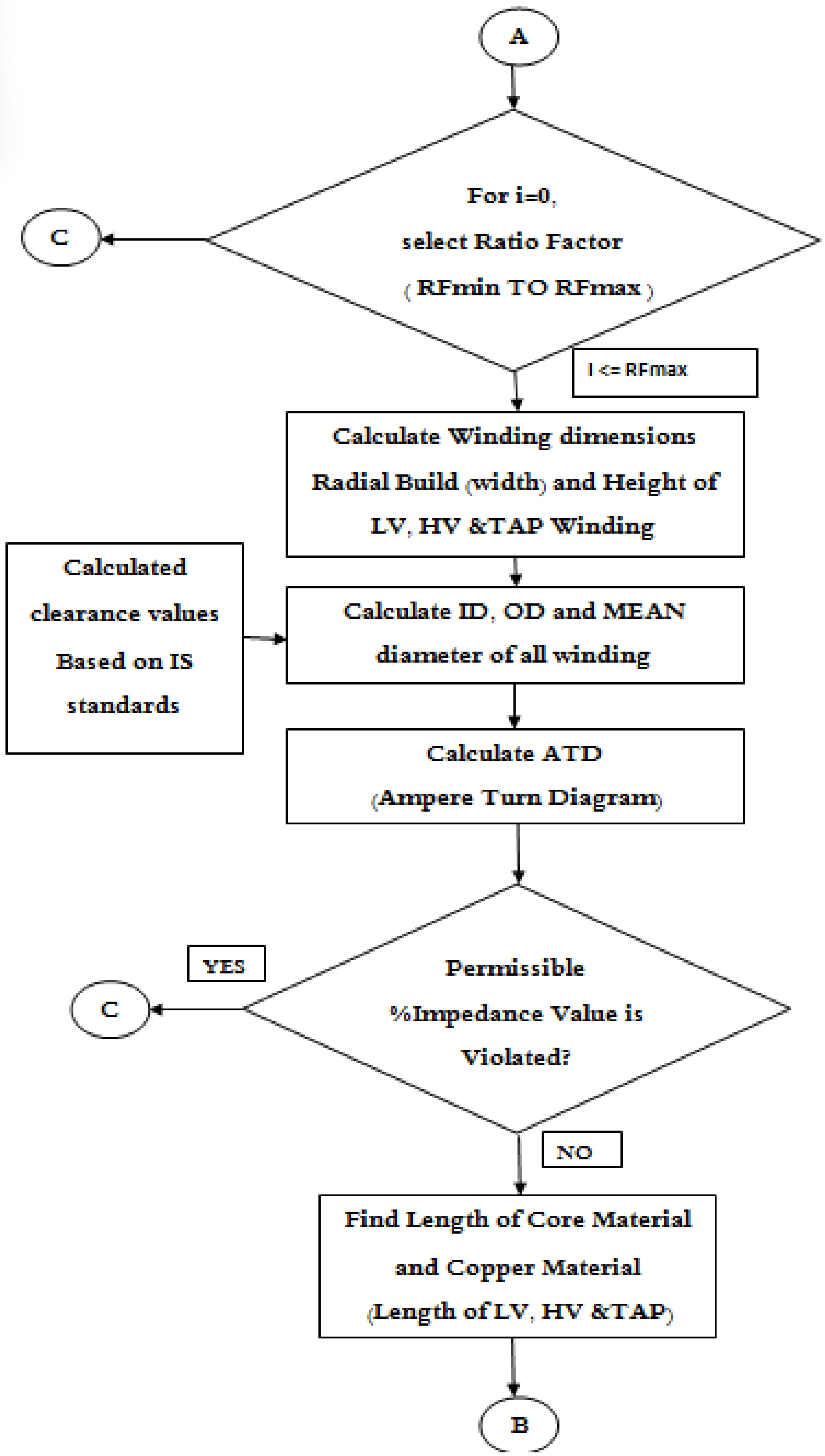

Figure 5.15: Flow chart 2

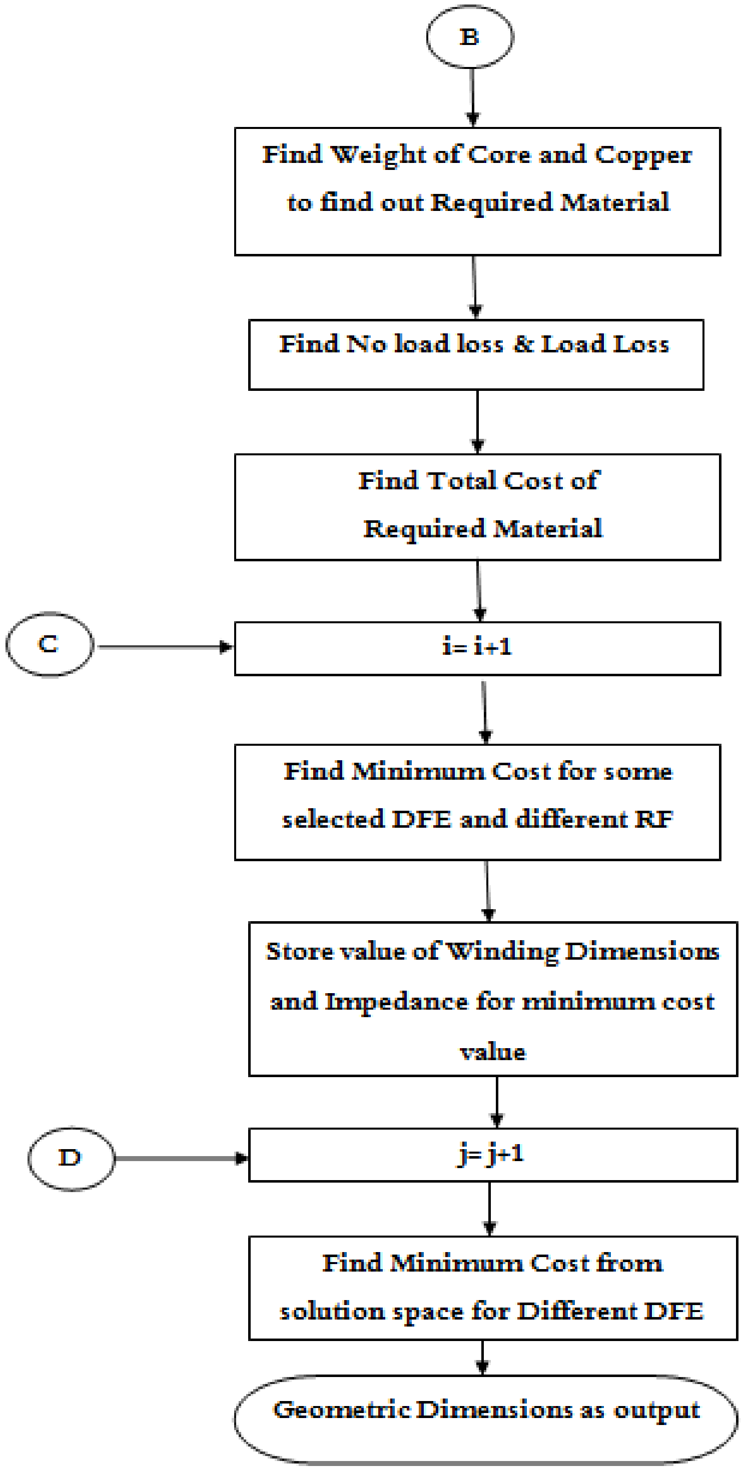

Figure 5.16: Flow chart 3

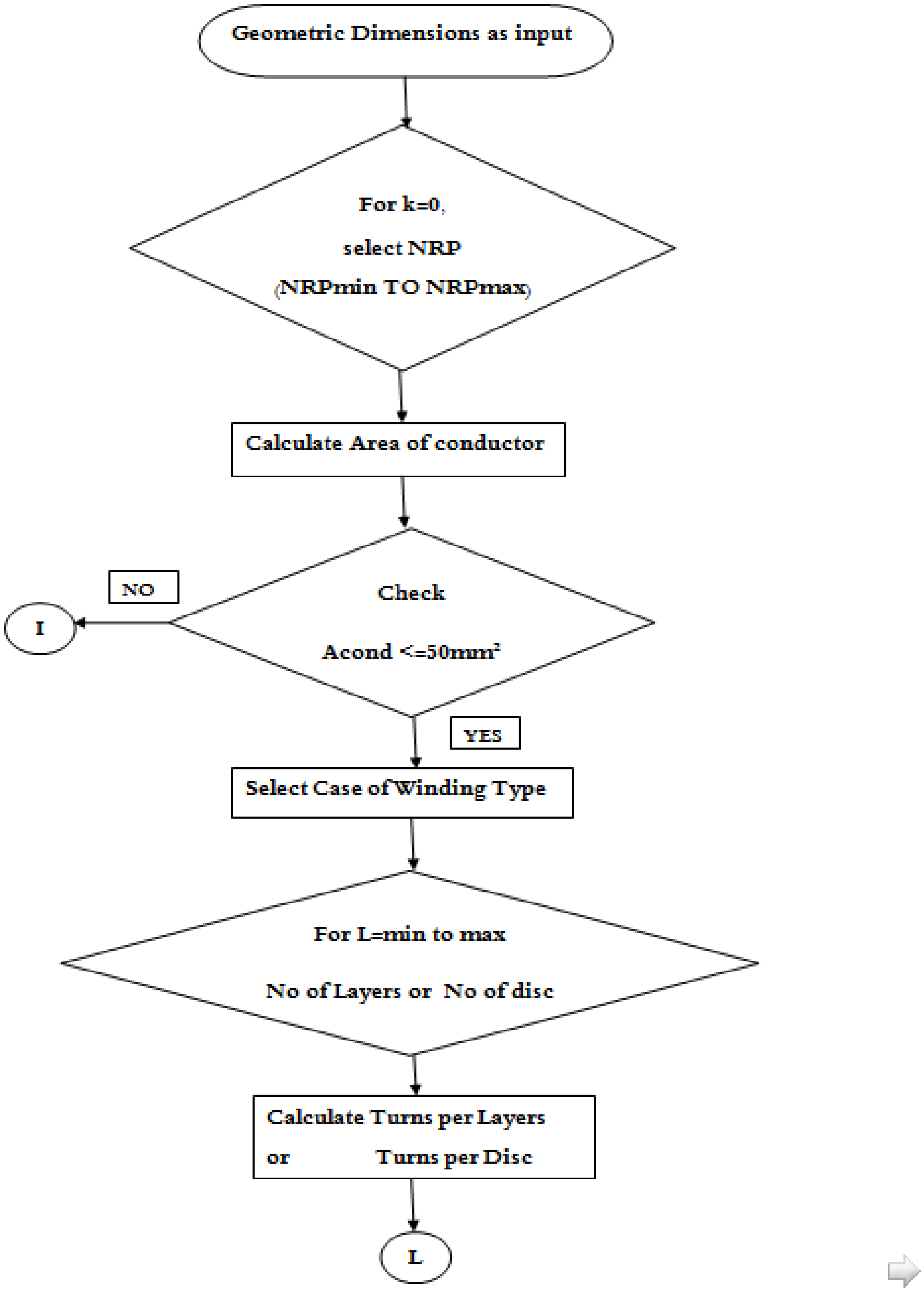

Figure 5.17: Flow chart 4

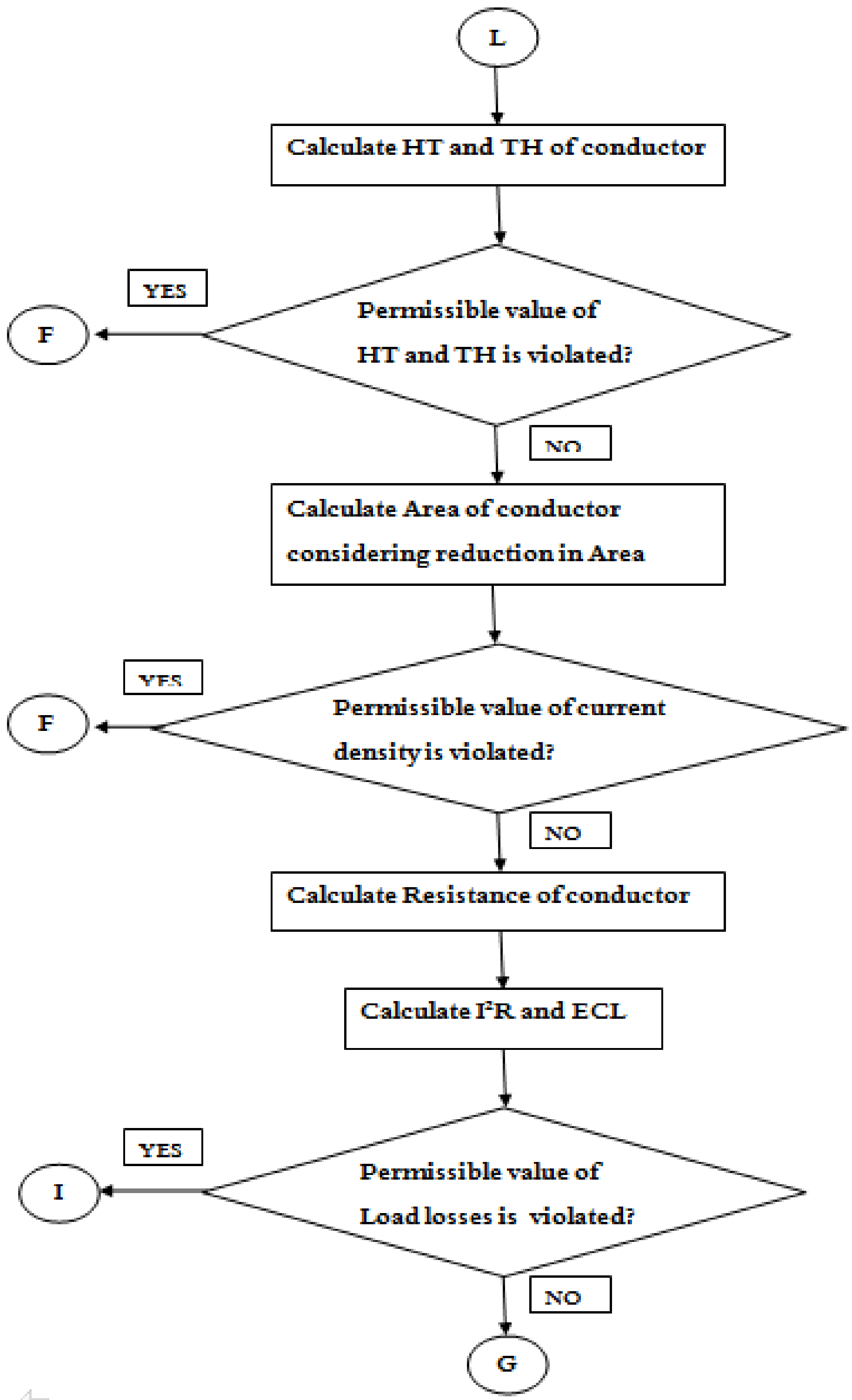

Figure 5.18: Flow chart 5

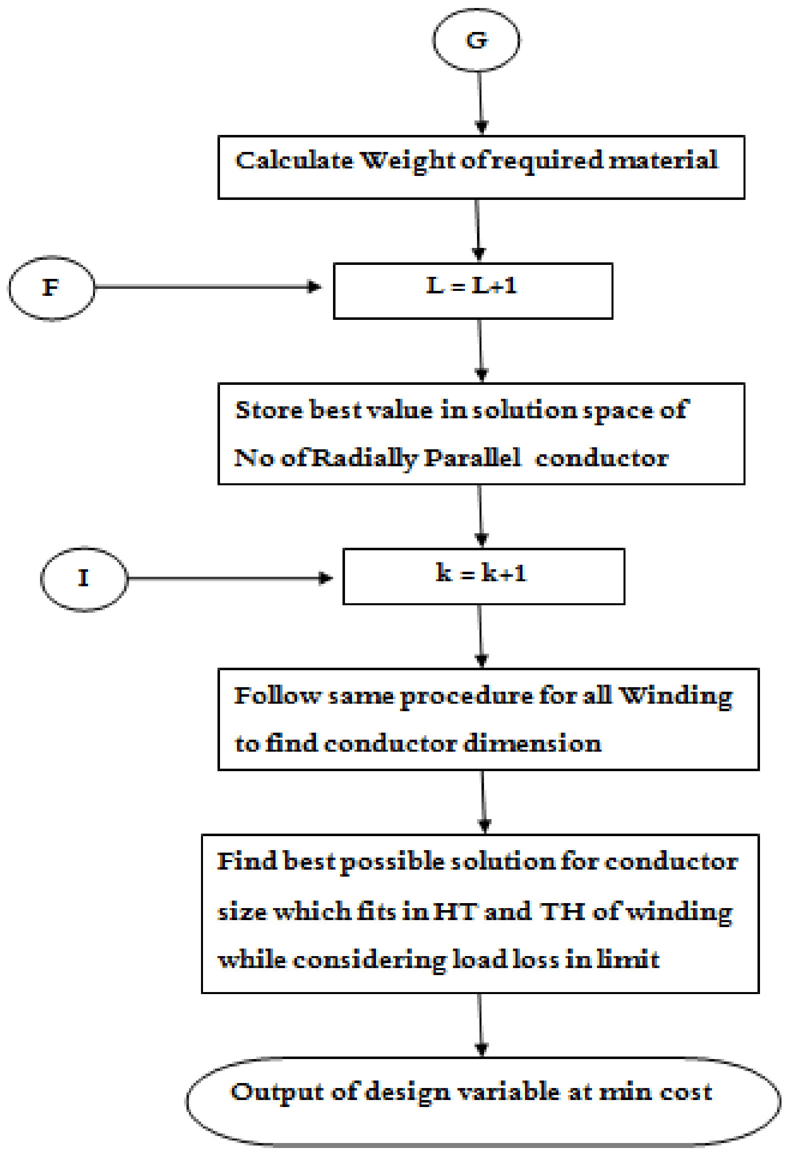

Figure 5.19: Flow chart 6

5.4 Outcome of Optimization Program

After this all procedure mentioned as above Designer can get the output based on inputs and applied constrains to get the answer. for 42500kVA 66/11 kV transformer design where designer's data has been compared with the obtained optimal design data using successive iterative method. It shows that the cost of the optimal machine is much less and most of the performance indices are better. An output of optimized design is compaired with designer method as shown in below table.

TERM	SIM	DM	Unit
DFE(core diameter)	594	577	mm
NL(LV turns)	68	70	
NHM(HV turns)	636	655	
NHT(Tap turns)	142	146	
V/T(Volt per turns)	93.39	90.72	
LVID	650	605	mm
LVMEAN	713	672	mm
LVOD	776	740	mm
HILOMEAN	806	770	mm
HVID	836	800	mm
HVMEAN	904	877	mm
HVOD	972	954	mm
HTMEAN	998	980	mm
TAPID	1024	1006	mm
TAPMEAN	1059	1034	mm
TAPOD	1094	1062	mm
Height-LV	1074	1163	mm
Height-HV	1074	1163	mm
Height-TAP	574	806	mm
%Z	10.15	11.03	
Height of Window	1234	1355	mm
Weight of CORE	17989	17771	kg
Weight of Copper	6012.25	6192.33	kg
NLL	19032.63	19576	watt
LL	204222	203430	watt
COST OF CORE	3208287	3163238	Rp
COST OF CU	3204529	3300513	Rp
TOTAL COST	6406617	6463751	Rp
EFFICIENCY	0.994	0.994	

Table 5.20: Optimum Output

Chapter 6

Conclusion

During this given period of time, I first understand the design process of the transformer and identified that on which parameter transformer cost depends the most and by changing that variable designer get a change in transformer cost.
Afterwards I formulate objective function, its constraints for optimization of power transformer design. I take a leakage impedance as sensitivity analysis to see the impact of it on transformer material cost.
I can say that the material cost of a transformer may vary with the change in a specified impedance value. And as the impedance is nothing but the function of DFE(core diameter) and N (number of turns) so as this variable may change a significant change can be seen in impedance.
It will be expensive to design a transformer below or above impedance specified value. In that, if the impedance is too low, short circuit current and forces are high which require low current density and accordingly a required material increases.
Same as if the impedance is high which increase loss(eddy loss) in winding and loss in body parts too which increase the temperature of the transformer which leads to an extra cooling arrangement and increase the cost of the transformer.
I done the optimization of transformer design using VBA and shown a comparison of performance and cost is given in tabular form (Table 5.20),for 42500kVA 66/11 kV transformer design where designer's data has been compared with the obtained optimal design data(SIM). It shows that the cost of the optimal machine is much less and most of the performance indices are better.

Future scope:

I done the optimization by "successive iteration method" using excel VBA Programming and getting optimized value of transformer cost function for specified inputs and constrains limits. Designer get the best possible solution of transformer design problem by specified inputs so its very useful for any designer to get optimal solution of active part design through it.In this further i can add mechanical design part also.

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