Impact Factor (SJIF): 4.542

International Journal of Advance Research in Engineering, Science & Technology

e-ISSN: 2393-9877, p-ISSN: 2394-2444

Volume 4, Issue 4, April-2017

Performance Analysis and Design optimization of Distribution Transformer by using Genetic Algorithm

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Abstract: - Transformers are vital components of power system and its design requires reliable and rigorous solution methods. Optimal transformer design involves determination of design variables to optimize a particular objective, satisfying a set of constraints. The aim of transformer design is to obtain the dimensions of all parts of transformer in order to supply these data to the manufacturer. The transformer should be designed in a manner such that it is economically acceptable, has low cost, small size, good performance and at the same time it should satisfy all the constraints imposed by international standards. In this paper, Genetic Algorithm is used for minimization of the following four objective functions: Total active parts cost, Total losses, Percentage impedance and Transformer tank volume. A design example on a 100 KVA, three phase core type Distribution transformer is discussed further in this paper.

Keywords: MATLAB, Genetic Algorithm, Optimization, Total Losses, Active part cost, Efficiency, Percentage impedance, Tank volume

I. INTRODUCTION

The transformer is an electrical machine that allows the transmission and distribution of electrical energy simply and inexpensively, as its efficiency is from 95% to 99%, i.e., the transformer operates more efficiently than most of all other electrical devices. Transformer design is a complex task which requires the knowledge of magnetic circuits, electromagnetism, electric circuit analysis, loss calculations and heat transfer. The main aim of the design engineer is to optimize a particular objective function depending upon the user requirement. Transformer design consists of highly interrelated and heterogeneous design parameters. A design is developed after certain trials and errors and by experienced judgment. Whatever the chosen design optimization method is, the crux of the problem is to include how much detail in the problem description. Although, the main aim of design optimization is to find the lowest cost, the solution should be such that the actual design can be produced with little additional work. Further, one should also concentrate minimization of total losses, percentage impedance and transformer tank dimensions, overall efficiency, voltage regulation and available space respectively.

II. NEED OF TRANSFORMER DESIGN OPTIMIZATION

The problem of transformer design optimization is based on minimization or maximization of an objective function which is subjected to several constraints. Among various objective functions the commonly used objective functions are minimization of total mass, minimization of active part cost, minimization of main material cost, minimization of manufacturing cost , minimization of total owning cost or maximization of transformer rated power. Transformer Design Software package was developed providing a user friendly transformer design and visualization environment. In this paper Distribution transformer is optimized by using Genetic algorithm in MATLAB software.

III. TRANSFORMER DESIGN PROCEDURE

This section gives a brief outline of the design methodology of a 3-phase core type Distribution transformer. There are some assumptions made for design of Distribution transformer as mentioned below: Both Transformer windings are wound with aluminium conductors, as aluminium is more economical than the copper for transformers having rating of less than 190KVA. The core material is assumed to be of M4 grade, with a stacking factor of 0.97, and lamination thickness of 0.27 mm. Operating frequency is 50Hz.

A. Equations for calculation of Number of turns for LV and HV

Voltage per turn can be calculated using the equation

$$E_t = K\sqrt{Q} \qquad (1)$$

Where E_t voltage per turn and K is constant whose value is given as follows,

The value of K for Aluminium-wound transformer is 0.32-0.35
The value of K for Copper-wound transformer is 0.37-0.44

The number of turns in LV (N_{LV}) and HV (N_{HV}) are calculated as follows.

$$N_{LV} = \frac{V_{LV}}{\sqrt{3} \times Et} \quad \ldots\ldots(3)$$

$$N_{HV} = \frac{\sqrt{3} \times V_{HV} \times N_{LV}}{V_{LV}} \quad \ldots\ldots(4)$$

B. Core Area and Diameter

Transformer core area can be calculated using the equation,

$$A_i = \frac{Et}{4.44 f Bm} \quad \ldots\ldots(5)$$

Gross Core area can be calculated using the equation,

$$A_g = \frac{Ai}{0.97} \quad \ldots\ldots(6)$$

The core diameter can be calculated as follow,

$$dc = \sqrt{\frac{Ai}{a}} \quad \ldots\ldots(7)$$

Where value of a is depending on number of stamping used in the core.

C. Core weight and cost of core material

Transformer core weight can be calculated by using the equation

$$W_c = (4 \times Clc + 3 \times Hw) \times Ag \times Kf \times \rho c \ldots\ldots(8)$$

The core cost is then calculated by multiplying suitable cost co-efficient with the core weight

D. Conductor weight and cost of conductor material

The total conductor weight can be calculated by using mean diameter of LV and HV windings, total number of turns, cross section area and the density of winding material. It can be calculated by using,

$$W_{al} = 3 \times \rho al \times \pi \times (2 \times MD_{LV} \times N_{LV} \times A_{LV} + MD_{HV} \times N_{HV} \times A_{HV}) \times 10^{-6} \ldots\ldots(9)$$

Once the winding weight is obtain, its cost can be calculated by multiplying it with suitable cost co-efficient.

E. Losses in LV and HV winding

Copper losses in HV and LV winding are calculated using following equations,

$$LL_{LV} = 3 \times Is^2 \times \pi \times MD_{LV} \times N_{LV} \times \rho_R / A_{LV} \ldots\ldots(10)$$

$$LL_{HV} = 3 \times Ip^2 \times \pi \times MD_{HV} \times N_{HV} \times \rho_R / A_{HV} \ldots\ldots(11)$$

The total full load losses

$$W_{fl} = LL_{LV} + LL_{HV} \ldots\ldots(12)$$

F. No Load Loss and No Load Current Calculation

The core loss of specific core material can be obtain from its No-load loss curve. Equation for No-load loss can be obtain by using POLYFIT function in the MATLAB. Equation for no-load loss can be given as below which is fourth order function and depends on flux density.

$$W_{nlsp} = 1.5291{B_{max}}^4 - 5.9664{B_{max}}^3 + 8.6933{B_{max}}^2 - 4.9237B_{max} + 1.0388 \ldots\ldots(13)$$

Total no-loss can be obtain by using,

$W_{nl} = W_{nlsp} \times W_c$……………………………………..(14)

G. Percentage Reactance, Resistance and Impedance calculation

Following equations are used to calculate Percentage Reactance, Resistance and impedance calculation as shown below,

$$\%X = \frac{7.91 \times f \times Is \times N_{LV} 2 \times \pi \times DM \times}{V_{LV} \times AsI \times 106}\left(a + \frac{R_{BHV} + R_{BLV}}{3}\right) \quad .....(15)$$

$$\%R = (LL_{LV} + LL_{HV}) \times S \quad ....(16)$$

$$\%Z = \sqrt{\%X^2 + \%R^2} \quad ....(17)$$

H. Efficiency and Voltage Regulation

The efficiency at any load n for power factor of $cos\emptyset$ is given by

$$\eta = (S \times n \times cos\emptyset)/(S \times n \times cos\emptyset + W_{nl} + n^2 \times W_{fl}))..(18)$$

Voltage Regulation Vr at different power factor can be given by,

$V_r = \%R \times cos\emptyset + \%X \times sin\emptyset$……………………………(19)

IV. TRANSFORMER DESIGN VARIABLE

There are following four design variable which are as given below,

A. K:-

The value of K for Aluminium-wound transformer is 0.32-0.35

B. Bm:-

The usual values of maximum flux density Bm for transformers using **Hot Rolled Silicon steel** are:

Distribution transformer: - 1.1 to 1.35 Wb/m^2

Power transformer :- 1.25 to 1.45 Wb/m^2

For transformers using cold rolled grain oriented steel the following values may be used:

For transformer upto 132 kV:- 1.55 Wb/m^2

C. delp & dels:-

- Current density for distribution, small and medium power transformers are,

δ = 1.1 to 2.3 A/mm^2

- Current density for large power transformers, self oil cooled type or air blast is,

δ = 1.1 to 2.3 A/mm^2

- Current density for large power transformers, forced circulation of oil or with water cooling is,

δ = 5.4 to 6.2 A/mm^2

V. TRANSFORMER DESIGN OPTIMIZATION BY USING GENETIC ALGORITHM

Genetic Algorithms are based on random search method that can be used to optimize complex problems. Some fundamental ideas of genetics are borrowed and used artificially to construct search algorithms that are robust and require minimal problem information.
The main advantages of GA are,

- GA's do not need a good initial estimation for the sake of problem solution. In other words, if the initial estimates are weak, they can be corrected by an evolutionary process of fitness.
- GA's explore several areas of the search space simultaneously because of its population based approach, which reduces the probability of being trapped in local optimum
- GA's do not require any prior knowledge or properties of the function to be optimized such as convexity, smoothness, modality or existence of derivatives

This section describes the methods for optimal design of 100 kVA, 11/0.433 kV, distribution transformer using Genetic Algorithms. The main advantage of GA is that different objective functions can be optimized with little modification in the program. MATLAB program implements unconstrained GA technique to minimize any one of the four objectives namely,

(1) Active part cost
(2) Total losses
(3) Percentage impedance
(4) Transformer tank volume

The user can select any one of the above mentioned objective as per requirement.

A. DESIGN OPTIMIZATION FOR ACTIVE PART COST:

Active part cost includes cost of core material and cost of conductor material. Active part cost can be optimize by using GA as following, and equation for active part cost is (8) and (9).

- Take objective function of Active part cost
- Active Part cost includes cost of Core material and cost of conductor material.
- Then use it into GA optimization tool box for optimization.
- The total conductor weight in a transformer depends upon the mean diameter of LV and HV windings, total number of turns, cross sectional area and the density of winding material.
- GA toolbox finds minimum value of objective function by varying these four variables.
- After finding minimum value of Weight of core and conductor, cost can be find out by multiply with material cost per kg.
- Below given a graph between number iterations and fitness value of function at each iterations.
- Cost of conductor obtain by multiplying suitable cost with the optimize weight of core material.
- Now weight of conductor can be optimize as following, where after optimization we get different value of k, Bm, delp, and dels for a different function which needs to be optimize.

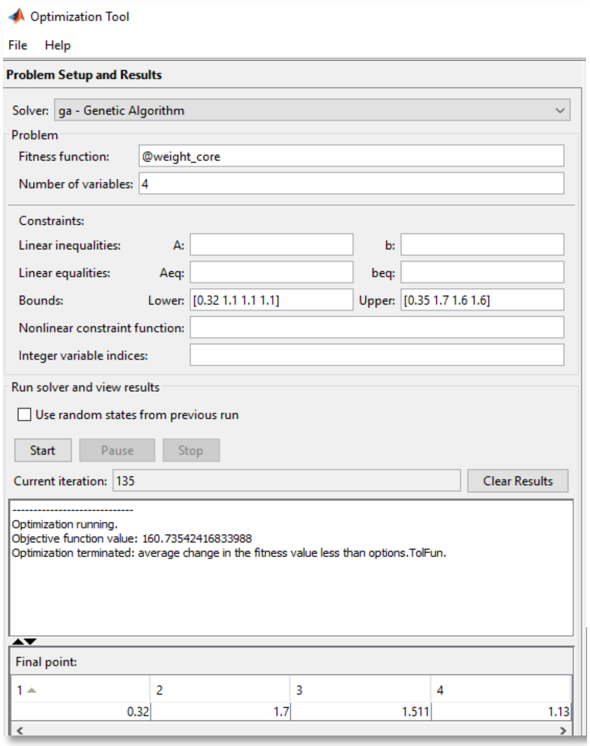

Fig 1.GA toolbox Optimization of Weight of Core

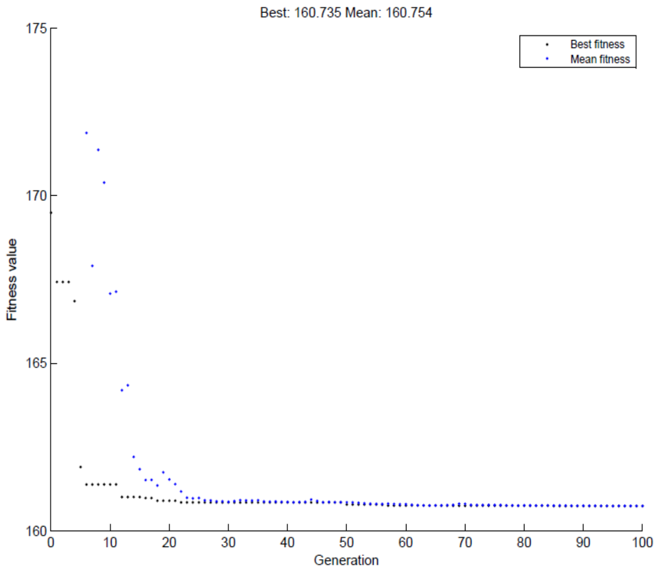

Fig 2.Graph for Optimization of Weight of Core

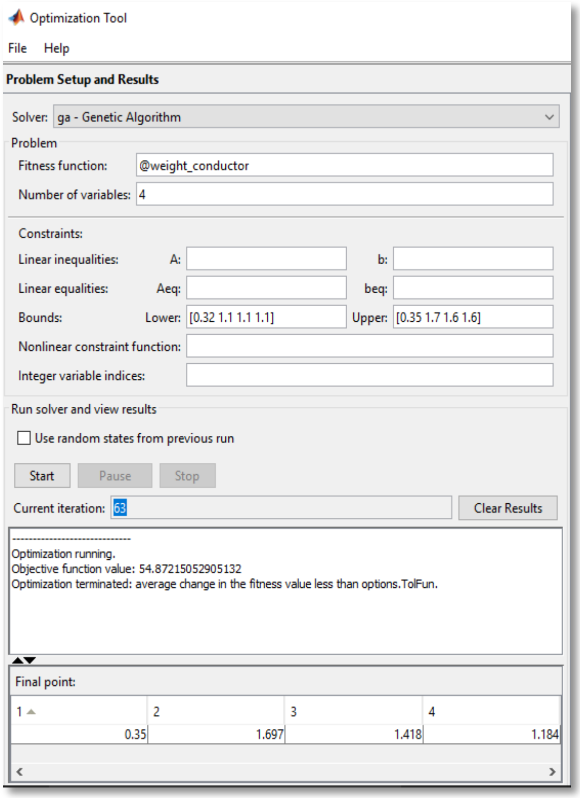

Fig 3.GA toolbox Optimization of Weight of Conductor

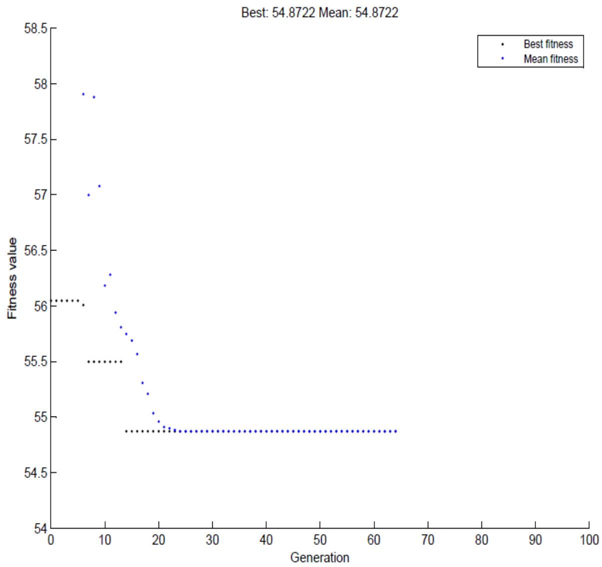

Fig 4.Graph for Optimization of Weight of Conductor

- So this is optimization of weight of conductor material and cost of conductor material can calculate by multiplying suitable cost coefficient

- Now total Active part cost can be expressed as sum of cost of core material and cost of conductor material. Here we take cost of CRGO material is 210 Rs and cost of Aluminium conductor material is 117 Rs

B. DESIGN OPTIMIZATION FOR TOTAL LOSSES

Total losses includes,

1. Winding copper losses
2. No load losses

- The load losses of LV and HV winding are calculated using the equations (10) and (11).
- Here No-load losses can be finding out by making function from no load losses curve of the CRGO core material. MATLAB polyfit function helps to make function from any given curve data. For a chosen core material No-load losses per Kg is provided by manufacturer, so we can calculate total No-load losses by multiplying No-load losses per Kg with total core weight which is also optimised with No-load loss optimization.

C. DESIGN OPTIMIZATION FOR EFFICIENCY AT DIFFERENT LOAD FOR DISTRIBUTION TRANSFORMER

- Distribution transformer should have maximum efficiency at 60-65% or 50-60% of full load, so we design transformer such that it has maximum efficiency at half of the full load. Here **we take 100Kva 11kv/433v aluminium wound transformer.**
- For distribution transformer we take following four variables,
  K = 0.32 to 0.37 (Aluminium wound transformer)
  Bm = 1.1 to 1.7 (1.6 Wb/m2 is maximum limit)
  delp = 1.1 to 1.6
  dels = 1.1 to1.6

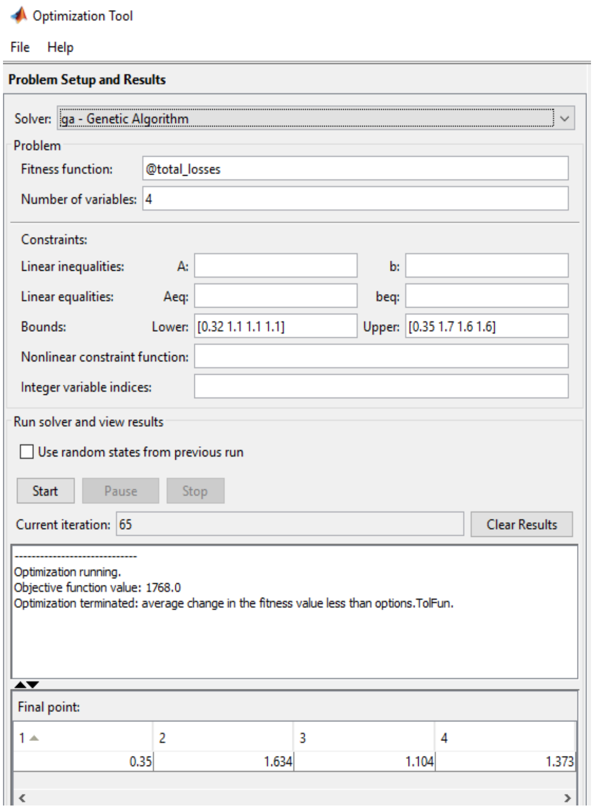

Fig 5.GA toolbox Optimization of total losses

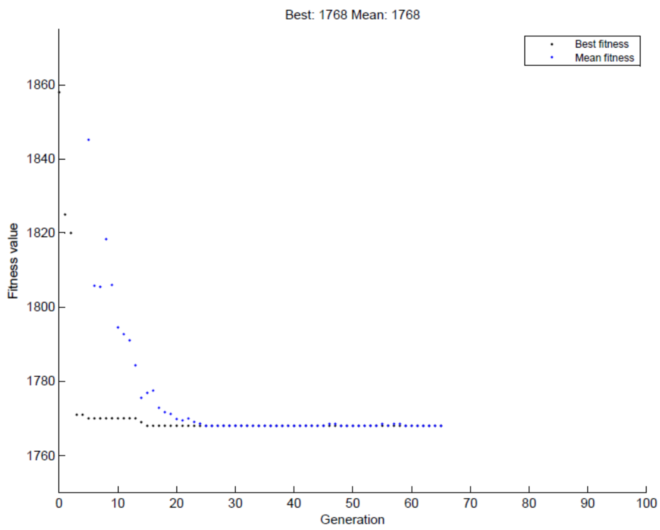

Fig 6.Graph for Optimization of total losses

- In distribution transformer core design is important because No-load loss is depends on the core material, so choose **core material** such that it has **high resistivity**. Due to high resistivity eddy current circulation becomes less so no load loss gets reduce and efficiency gets increase at half of full load or at 60-70% of load. **CRGO laminated core** is use **to**

reduce eddy current loss. As **flux density is higher less core material** require **but iron loss increase** too, so **flux density is set 1.6 Wb/m2 as a maximum**

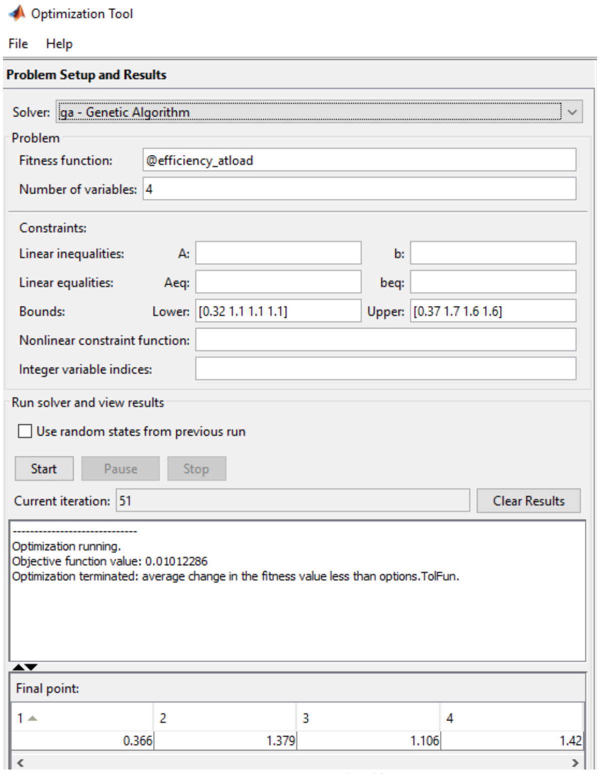

Fig 7.GA toolbox Optimization of efficiency at 60% at UPF

- So efficiency at full load unity power factor is $\frac{1}{0.0101732}$ = 98.29 %
- Efficiency can be calculated at different load at different power factor by using GA toolbox.
- Results of efficiency at different load and different power factor are shown in following table.
- Here we are optimized Distribution Transformer so efficiency should be maximum at 50-60 % load and this can be observed from table.

LEVEL OF LOAD	POWER FACTOR	EFFICIENCY
1	1	98.29%
1	0.9	98.11%
1	0.8	97.88%
0.75	1	98.60%
0.75	0.9	98.45%
0.75	0.8	98.27%
0.6	1	98.78%
0.6	0.9	98.65%
0.6	0.8	98.48%
0.5	1	98.89%
0.5	0.9	98.77%
0.5	0.8	98.62%

Table 1.Efficiency at different Load and at different Power factor

VI. OPTIMIZATION OF VARIOUS DESIGN FUNCTION OF TRANSFORMER USING GA

Genetic Algorithm can optimize various transformer design function which are listed below. Here **we take 100Kva 11kv/433v aluminium wound transformer.** In section (V) explain three Design function optimization and below in fig (8) given optimization of various function of transformer design.

Minimization Function	Function Value	k	Bm	dels	delp
Core Weight	160.4575	0.3226	1.7	1.4993	1.3001
Conductor Weight	55.3305	0.336	1.6993	1.4388	1.2276
Load losses at full load	1557	0.3498	1.6947	1.1069	1.4168
Load losses at 50% load	385	0.35	1.7	1.12	1.367
No load losses	114	0.32	1.1	1.5783	1.16
Total losses at full load	1768	0.3497	1.5931	1.1065	1.4791
Percentage impedance	4.0483%	0.3497	1.7	1.1221	1.4922
Efficiency at Full load 0.9 PF	98.039%	0.35	1.5934	1.1	1.5683
Voltage regulation at UPF	1.544%	0.3499	1.6935	1.1154	1.4219
Voltage regulation at 0.9 PF	3.0187%	0.3497	1.7	1.1167	1.4094
Tank Volume	247248	0.3226	1.7	1.5117	1.2781

VII. CONCLUSION

Here we conclude that the GA gives more minimized results as compared to the conventional approach. The proposed method is very effective as GA's are more likely find the global optimum because of their population based approach. The cost benefits obtained from GA based transformer design can be appreciated. Small transformer manufacturing companies and even inexperienced engineers can successfully use this software.

VIII. ACKNOWLEDGMENT

I would like to take this opportunity to best of my acknowledgement on all people who have directly or indirectly helped me in making project and turn it up into a Successful Piece of work.

It gives me a great pleasure electrical department for guidance and Suggestion. First I would like to thanks **Mr. Nilesh D. Rabara (Assistant professor at L.D college of Engineering)** for kind co-operation for the Completion of this paper.

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IX. APPENDIX

List of symbol

LV:	Low Voltage
HV:	High Voltage
N_{LV}:	Number of turn of HV winding
N_{HV}:	Number of turn of LV winding
Clc:	Core limb centre
Hw:	Height of window
Ag:	Gross area of core
Kf:	Space factor
ρ_c:	Density of core
ρ_{al}:	Density of conductor material
MD_{LV}:	Main diameter of LV
MD_{HV}:	Main diameter of HV
A_{LV}:	Cross section Area of LV winding
A_{HV}:	Cross section Area of HV winding
W_{nlsp}:	No-load losses per Kg
W_{nl}:	No-load losses
LL_{LV}:	Load losses in LV winding
LL_{HV}:	Load losses in HV winding
S:	Rating of Transformer
B_m:	Flux density
del_p:	Current Density in LV winding
del_s:	Current Density in HV winding
CRGO :	Cold Rolled grain oriented