Transformer’s Core Size Optimization Using Genetic Algorithm

Abstract—Exponential escalation in the energy requirements and depletion of mineral resources has forced scientists to recycle and find the most optimized way of using the mineral resources left on earth. Transformers are the most mineral consuming devices of the power distribution systems as the use of core and winding has a high mineral content. In this paper a solution has been proposed to solve this problem and provide with an optimization technique for the minimum volume used to develop transformers. The technique models the materials, using the dependence of material on the magnetization parameters and uses genetic algorithm to perform optimization.

Keywords—Transformer core; size optimization; genetic algorithm

I. INTRODUCTION

With the development seen in the 21st century, the energy requirements have exponentially escalated thus high energy demands are to be met. This has opened the gates for the scientists to find ways of getting maximum efficiency with minimum use of materials. Most of the material used in power distribution are copper and alloys of iron due to their high conductivity, while the discussion of material is quite irrelevant here, as it is a common knowledge that all mineral resources of earth are depleting. Thus which ever alloy or material used, it must be consumed in an optimized fashion so that minimum resources are utilized. The optimization will not only save a significant amount of material, but would also reduce the increasing cost of the products. Numerous optimization techniques have already been developed but with the advent of new algorithms in artificial intelligence, optimization has to be done in the most efficient manner to improve the outputs. This conclusion formed the basis of motivation to use optimization technique in order to implement algorithms which could be helpful in improving the efficiency of amount of material being used for the development of devices. Thus the genetic algorithm being one of the most favorite optimization technique of the present era, has been implemented in this paper to optimize the quantity of materials used in developing transformers [1][2].

II. LITERATURE REVIEW

The most common materials used for the production of transformers are iron and copper while zinc is also used as an alloy with iron for the production of cores. Specifically copper and zinc are under the threat of depletion in the next 10 years [3]. Transformers not only use extra electricity to energize their cores but they also have effect on the quantity of magnetization [4]. The cost function of transformer constitutes of two sectors 1) the initial cost 2) running cost, which has been modeled in various texts [5] The initial cost contains construction cost and the running cost function contains the losses which occur during the working of transformer.

III. MODELING

A. Creation of objective function

The main objective function, represented by ‘O’, depends on the total mass ‘M’, and the total volume ‘V’, as the local minima of both the quantities has to be found, of the material used in the development of the transformer.

\[ O = (V + M) \]  \hspace{1cm} (1)

The total volume of any transformer would include the volume of the core \( V_{core} \) and the volume of the winding \( V_{winding} \) used in its manufacturing. Similarly, the total mass of the transformer would include the mass of the core \( M_{core} \) and the mass of the conductor (winding) \( M_{copper} \) used in its winding.

\[ O = (V_{core} + V_{winding}) + (M_{copper} + M_{core}) \]  \hspace{1cm} (2)

Analyzing the volume of the winding, we find that it is composed of volume of the opening in the transformers core through which the winding is passed in addition to the volume of the winding which is utilized in its side.
lobe. Whereas the volume of the core is taken to be the portion of the core composed of all the three of its legs.

\[ O = (2(V_{w1} + V_{w2}) + (V_{c1} + V_{c2})) + \left(\frac{V_{copper}(D_{cu})}{1000} + \frac{V_{core}(D_{c})}{1000}\right) \]  

(3)

The mass of the copper includes the total mass of the conductor including the copper going through the window \( V_{w1} \) and the side lobes \( V_{w2} \) in addition to the total mass of the core.

\[ O = \frac{(2(V_{w1} + V_{w2}) + (V_{c1} + V_{c2})) + \left(\frac{K_{cu}.2(V_{w1}+V_{w2})D_{cu}}{1000} + \frac{2(V_{c1}+V_{c2})D_{c}}{1000}\right)}{1000} \]  

(4)

As by the basic law of science we know that mass of any object is the product of volume and density of that object. Similarly, mass of copper depends on the product of the total volume of copper \( V_{copper} \) used and the density of copper \( D_{cu} \). On the other hand we have the mass of transformers core to be the product of the total volume of core \( V_{core} \) and the density of the core material used \( D_{c} \).

\[ O = \frac{(2(V_{w1} + V_{w2}) + (V_{c1} + V_{c2})) + \left(\frac{K_{cu}.2(V_{w1}+V_{w2})D_{cu}+2(V_{c1}+V_{c2})D_{c}}{1000}\right)}{1000} \]  

(5)

The volume of the winding also depends on the copper fill factor \( K_{cu} \) which can alter the efficiency of the flow of current through them at different frequencies.

\[ O = 2000(V_{w1} + V_{w2}) + 2000(V_{c1} + V_{c2}) + K_{cu} + 2D_{cu}(V_{w1} + V_{w2}) + 2(V_{c1} + V_{c2}) + D \]  

(6)

The final simplified equation can be obtained as,

\[ O = 2002(V_{c1} + V_{c2}) + (V_{w1} + V_{w2})(2000 + 2D_{cu}) + K_{cu} + D_{c} \]  

(7)

B. General equations

- \( N = \frac{1}{\frac{2\pi + \varepsilon - B_{m} + A + D}{2\pi + \varepsilon - B_{m} + A + D}} \)
- \( N_p = \frac{N}{V_p} \)
- \( N_s = \frac{N}{V_c} \)
- \( A_{cu} = (N_p \times A_{pc}) + (N_s \times A_{ps}) \)
- \( A_w = \frac{A_{cu}}{K_{cu}} \)
- \( A_w = \frac{A_{cu}}{K_{cu}} \)
- \( B_w = A_w \frac{h_w}{h_w} \)

- \( V_{c1} = A \times D(H_w + 0.4) \)
- \( V_{c2} = \frac{A}{2} \times D \times (2 \times A + 2 \times B_w + 0.6) \)
- \( V_{copper} = 2(V_{c1} + V_{c2}) \)
- \( V_{w1} = H_w \times B_w \times D \)
- \( V_{w2} = H_w \times B_w(A + 2B_w + 0.4) + \frac{1}{2}(\pi \times H_w \times B_w^2) \)
- \( V_{winding} = 2(V_{w1} + V_{w2}) \)
- \( V_{copper} = K_{cu} \times V_{winding} \)
- \( M_{copper} = \frac{V_{copper} \times D_{cu}}{1000} \)
- \( M_{core} = \frac{V_{core} \times D_{c}}{1000} \)

IV. Algorithm and Implementation

The genetic algorithm has been used to find the minima for the volume and mass of winding and core resultantly giving the most optimized values for the generations created. Basic algorithm begins after the setting of the basic parameters for the transformer which are as follows

A. Parameter for optimization

Frequency = 50 Hz
Maximum core flux = 1.3 wb/cm³
Primary voltage = 220v rms
Secondary voltage = 500v rms
Primary side wire gauge = 8.37/100 cm²
Secondary side wire gauge = 4.17/100 cm²
Copper fill factor = 0.4
Core material density = 7.85 gram/cm³
Winding material density = 8.96 gram/cm³

B. Process

1) The algorithms starts with the initialization of the basic values as sample values such as the sample values in A.

2) The base of the algorithm is then established by deciding the maximum values for all the width, depth and height of the E type core.

3) On the basis of the aforementioned local maximum values an array of random 1000 species is generated.

4) The program calculates; Number of turns per volt for given width and depth. Primary and secondary number of turns, copper cross sectional area and winding window width for all species.

5) Using the above values and the model described in detail we find out the final objective function values for every generation.

6) Selection of the generation is done on the knock out basis the one with the lower objective function value is kept while the others are rejected. The parameters are adjusted for the minimization of the objective function.

7) Local minima are found and curves are plotted according to it. If the local minima are very near to the maximum values provided the maximum values are again raised, the process is repeated until the values in output
are way below the maximum values such that local minima are absolutely perfect.

V. RESULTS & DISCUSSION

The process explained above after being simulated in Matlab was implemented to generate various values of each parameter, according to the genetic algorithm. Then these values were calculated to model for the best optimized value of the core’s volume, on the knock out basis. All the values of each parameter were calculated, as the optimization technique was implemented in four different steps accordingly. Firstly the values were calculated without applying optimization technique, and then the values were calculated by applying the algorithm only on the width of core. Then the algorithm was applied on both width of core and depth of core, and accordingly different values for each parameter was found. Lastly the algorithm was applied on all three, width of core, depth of core and height of core and accordingly different values of each parameter was again calculated. The values obtained for all parameters on each generation would result in different values of volume ‘V’ and Mass ‘M’ and as explained in modeling the final value, that best describes the optimized result is represented as the objective function ‘O’, which depends on volume and hence the total mass of material that would be used to make the transformer. Thus various values of ‘O’ are produced out of which the lowest, hence the most optimized value for ‘O’ is selected. The calculated values for each generation to obtain the optimized transformer design are given below.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>WITHOUT OPTIMIZATION</th>
<th>OPTIMIZING WIDTH OF E</th>
<th>OPTIMIZING DEPTH OF CORE AND WIDTH OF E</th>
<th>OPTIMIZING DEPTH OF WIDTH OF E AND HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS, KG</td>
<td>2.6086E+04</td>
<td>304.229</td>
<td>36.3994</td>
<td>31.2299</td>
</tr>
<tr>
<td>TOTAL VOLUME, CM$^3$</td>
<td>7.2770E+06</td>
<td>8.2991E+04</td>
<td>6.2895E+03</td>
<td>5.5389E+03</td>
</tr>
<tr>
<td>WIDTH OF E, CM</td>
<td>1</td>
<td>9.9337</td>
<td>7.8638</td>
<td>6.2855</td>
</tr>
<tr>
<td>DEPTH OF CORE, CM</td>
<td>1</td>
<td>1</td>
<td>9.603</td>
<td>9.074</td>
</tr>
<tr>
<td>HEIGHT OF WINDING WINDOW, CM</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>12.9416</td>
</tr>
<tr>
<td>WIDTH OF WINDING WINDOW, CM</td>
<td>679.80</td>
<td>68.434</td>
<td>9.0021</td>
<td>4.6049</td>
</tr>
<tr>
<td>TURNS PER VOLT</td>
<td>24.485/4</td>
<td>2.4649</td>
<td>0.3242</td>
<td>0.4293</td>
</tr>
<tr>
<td>PRIMARY SIDE TURNS</td>
<td>7.6181E+03</td>
<td>766.88</td>
<td>100.879</td>
<td>133.566</td>
</tr>
<tr>
<td>SECONDARY SIDE TURNS</td>
<td>1.7314E+04</td>
<td>1.7429E+03</td>
<td>229.272</td>
<td>303.559</td>
</tr>
<tr>
<td>BOBBIN AREA CM$^2$</td>
<td>1</td>
<td>9.9337</td>
<td>75.5163</td>
<td>57.0358</td>
</tr>
<tr>
<td>MASS OF COPPER, KG</td>
<td>2.6076E+04</td>
<td>291.452</td>
<td>10.3267</td>
<td>9.8221</td>
</tr>
</tbody>
</table>

Initially, minimum values were selected on the basis of numerical data. The optimization can be viewed in the following graphs of mass and volume.
Both mass and the volume of the transformer show a similar curve while the graph of the objective function decreases. The quantity of material as a total core’s volume and its mass being conserved in the manufacturing is quite evident. Moreover, the variation of core material was also practiced. The same simulation and a second simulation were done for the silicon steel and iron core, respectively. The initial changes were made to parameters $B_m$, which is 10, and density which is 7.85 g/cm$^3$, to that of a pure iron powder core. The results are as follows in the case for a complete height, width, and depth genetic algorithm implementation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Iron Powder</th>
<th>Silicon Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mass, Kg</td>
<td>37.8691</td>
<td>31.2299</td>
</tr>
<tr>
<td>Total Volume, cm$^3$</td>
<td>6.7622E+03</td>
<td>5.5389E+03</td>
</tr>
<tr>
<td>Width of E, cm</td>
<td>4.8172</td>
<td>6.2855</td>
</tr>
<tr>
<td>Depth of Core, cm</td>
<td>9.3255</td>
<td>9.074</td>
</tr>
<tr>
<td>Height of Winding Window, cm</td>
<td>14.5171</td>
<td>12.9416</td>
</tr>
<tr>
<td>Width of Winding Window, cm</td>
<td>5.0898</td>
<td>4.6049</td>
</tr>
<tr>
<td>Turns per Volt</td>
<td>0.5323</td>
<td>0.4293</td>
</tr>
<tr>
<td>Primary Side Turns</td>
<td>165.6025</td>
<td>133.5662</td>
</tr>
<tr>
<td>Secondary Side Turns</td>
<td>376.3694</td>
<td>303.5596</td>
</tr>
<tr>
<td>Bobbin Area Square cm</td>
<td>59.8027</td>
<td>57.0358</td>
</tr>
<tr>
<td>Mass of Copper, Kg</td>
<td>12.7818</td>
<td>9.8221</td>
</tr>
<tr>
<td>Mass of Core, Kg</td>
<td>25.0872</td>
<td>21.4078</td>
</tr>
</tbody>
</table>

The effect of $B_m$ and density is very visible in the core size and mass, according to the objective function but this has also effected the mass of copper which is to be used in the winding which is due to the change in number of turns.

VI. CONCLUSIONS

A new technique for the core size optimization has been introduced for transformer size optimization. A drastic decrease in the size of transformers has been observed in the optimization through genetic algorithm. This opens gates for the scholars to use other techniques like firefly algorithm, ant hill optimization and other advanced artificial intelligence based techniques for the optimization of transformer’s complete cost function.

The change of material has also been shown in the function and the difference of the size is visible, which adds to the decrease in the total cost of transformers manufacturing.
References


Nomenclature

- Frequency $f$
- Core flux $B_m$
- Primary winding peak voltage $V_p$
- Secondary winding peak voltage $V_s$
- Primary winding wire area $A_{pc}$
- Secondary winding wire area $A_{ps}$
- Copper fill factor $K_{cu}$
- Core material density $D_c$
- Copper density $D_{cu}$
- Width of E-type core $A$
- Depth of E-type core $D$
- Height of winding window $H_w$
- No. of turns/volt $N$
- Primary winding turn $N_p$
- Secondary winding turns $N_s$
- Copper cross sectional area $A_{cu}$
- Winding window area $A_w$
- Width of window $B_w$
- Center leg of E-Type core $V_{c1}$
- Top & bottom leg of E-type core $V_{c2}$
- Core volume $V_{core}$
- Window volume $V_{w1}$
- Side lobe of winding $V_{w2}$
- Winding volume $V_{winding}$
- Volume of copper $V_{copper}$
- Mass of copper $M_{copper}$
- Mass of core $M_{core}$
- Total Mass $M$
- Total Volume $V$
- Objective function $O$