DISTRIBUTION TRANSFORMER WITH CIRCULAR SECTION OF AMORPHOUS-CORE

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ABSTRACT – In distribution transformer design, main stress is to reduce core losses. To reduce core losses in distribution transformer cold-rolled grain oriented (CRGO) steel is preferred by manufacturers. Amorphous material has very less core losses compared to CRGO steel, therefore it is being seen as a good substitute of CRGO steel. Now-a-days some manufacturers are using amorphous material in miniature and medium size transformers; however the cost of amorphous core transformer is higher than the cost of CRGO core transformer. In amorphous core transformers manufacturers are using square section of core. With square section of core, mean length of winding turn is more which causes more material cost and more copper losses. Here a comparison is being presented among CRGO core distribution transformer (CCDT), amorphous core distribution transformer with square section of core (AMDTS), and amorphous core distribution transformer with circular section of core (AMDTC), in terms of efficiency and cost. It is shown that the cost of amorphous core transformer reduces and efficiency improves, if a circular section of core is adopted in place of square section.

KEYWORDS- Amorphous core, CRGO steel, Transformer design, core losses.

1. INTRODUCTION

Transformer is a device that transfers electrical energy from one electrical circuit to another electrical circuit through the medium of magnetic field without a change in the frequency. They play vital role in transmission and distribution of electrical power by stepping up and stepping down the voltage levels [2]. Distribution transformers are used to distribute the electrical power in residential and industrial areas. Distribution transformers are energized for twenty four hours with wide variation in load, therefore they are designed to have low no-load losses. Under no-load condition only core losses occur in a transformer and copper losses are negligible; therefore no-load losses are also called core losses for a transformer. Core losses depend on peak value of flux density (Bm); they are proportional to square of peak value of flux density; therefore to reduce the core losses distribution transformers are designed with low value of Bm [3]. Now-a-days CRGO steel is being used in distribution transformers for which allowable limit of flux density is up to 1.55 Tesla [4]; however saturation limit for CRGO steel is 2.03 Tesla [9]. If a distribution transformer with CRGO core is designed above 1.55 Tesla then certainly the cost of the transformer reduces but performance deteriorates. The task of a designer is to make a proper compromise between cost and performance.

2. TRANSFORMER WITH AMORPHOUS CORE (AMDT)

Low loss Transformers are considered `More efficient transformers'[1a]. One of the prime components of losses is the core loss. This can be drastically reduced by proper design and using superior grades of electrical steel like CRGO. It can be further reduced in case conventional electrical steel is replaced by amorphous metal [1b]. There has been constant search for transformer core materials, which may have the least loss. Iron-Boron-Silicon Amorphous alloy has evolved as the low loss material for distribution transformers. Molten metal when cooled to solid state at a very high-speed rate, retains a random atomic structure which is non-crystalline. This metal is called amorphous. This resembles with glass and is also referred as `glass metal'. Need to achieve the required cooling rate restrict the thickness of the metal to 0.025 mm i.e. almost 1/10th of the thickness of conventional CRGO steel. Due to low saturation limit (1.5 Tesla) in amorphous core [1b], larger core and consequently larger coils and tank size are required as compared to CRGO core transformers. The problem has been overcome to some extent with the development of amorphous metal strips. This is achieved by compacting number of thin ribbons. This strip is commonly known as ‘POWER CORE’. Amorphous strips are four times harder than CRGO steel[5,6]. Amorphous metal core has some merits; the non-crystalline structure and random arrangement of atoms gives low field magnetization and high electrical resistivity. Due to low field magnetization, hysteresis loss is low and due to high electrical resistivity eddy current loss is suppressed. As such core losses
of amorphous metal alloys get reduced by 42 per cent and magnetizing current by 53 percent [6]. The most attractive characteristic of amorphous alloy is obviously its extremely low core loss and low magnetizing current. The amorphous metal saturates almost at 1.5 Tesla, whereas CRGO steel saturates at almost 2.03 Tesla. Overall cost of amorphous core transformer is approximately 20 to 30 percent higher than conventional core transformers [1a]. The initial cost of AMDT is more than the cost of conventional CRGO core transformer but in long run the running cost of transformer will be considerably reduced.

Now-a-days some manufacturers are using amorphous material in miniature and medium size transformers [6,7]. In amorphous core transformers manufacturers are using square section of core. With square section of core, mean length of winding-turn is more which causes more material cost and more copper losses. If a circular core is used for amorphous core transformer, then cost of the transformer may be reduced with improvement in efficiency. Here a comparison is being presented among CRGO core distribution transformer (CCDT), amorphous core distribution transformer with square section of core (AMDTS) and amorphous core distribution transformer with circular section of core (AMDTC) in terms of efficiency and cost.

3. CRGO DESIGN (CCDT)
Sectional view of core and winding are shown in Fig-1.
A. Core Design
Voltage per turn, \( E_t = K \sqrt{Q} \) volts
\( Q \) is KVA rating of transformer.
\( K \) = Output constant (according to problem)
\( E_t = 4.44 f \cdot \Phi_m \) volts
\( \Phi_m = E_t / (4.44 f) \)
We know that \( \Phi_m = B_m A_i \)
\( A_i = \) Net Iron Area of core \( = \Phi_m / B_m \)
\( B_m = 1.55 \) wb/m² (according to problem)
For cruciform core
\( d = \sqrt{(A_i/0.56)} \)
\( a = 0.85d \)
\( b = 0.53d \)
B. Window Dimensions
Window space factor \( Kw = 12/(30+K_V) \)
Rating\( Q = 3.33 f \cdot B_m A_i (K_w A_w \delta) \cdot 10^{-3} \) KVA,
\( A_i = \) Net Iron Area of core ; \( \delta \) is current density

4. AMORPHOUS DESIGN WITH SQUARE-SECTION OF CORE (AMDTS)
Sectional view of core and winding are shown in Fig-2.
A. Core Design
\( B_m = 1.5 \) wb/m²
Net Cross section of core area \( A_i = \Phi_m / B_m \)
Used square core having \( A_i = l^2 \times (\text{stacking factor}) \)
Here \( l \) is the side of square section
B. Window Dimensions
Window space factor \( Kw = 12/(30+K_V) \)
We have \( Q = 3.33 \cdot f \cdot B_m \cdot A_i \cdot (K_w \cdot A_w \cdot \delta) \cdot 10^{-3} \text{ KVA} \)

Generally \((H_w / W_w) = 2 \text{ to } 4\)

Window area, \(A_w = H_w \times W_w\)

Distance between adjacent core centers, \(D = W_w + 1\)

C. Yoke Design

The area of yoke is taken same as limb. So,

\(A_y = A_i\)

Flux density in yoke \(B_y = B_m\)

Taking section of yoke as square of yoke,

Depth of yoke, \(D_y = 1\)

Height of yoke, \(H_y = A_y / D_y\)

D. Overall Dimension Of Frame

Height of frame \(H = H_w + 2H_y\)

Length of frame \(W = 2D + d\)

Depth of frame \(= d\)

5. AMORPHOUS DESIGN WITH CIRCULAR SECTIONS OF CORE (AMDTC)

Amorphous alloy is available in form of ribbons having thickness of 0.025 mm. Therefore a core having cylindrical shape (with circular cross section) may be formed easily. Sectional view of core and winding are shown in Fig-3.

A. Core Design

Flux density in core \(B_m = 1.5 \text{ wb/m}^2\)

\(A_i = \text{Net Iron Area of core} = \Phi_m / B_m\)

For circular core the dia of the core \(d = \sqrt{A_i / (0.79 \times \text{stacking factor})}\).

B. Window Dimensions

\(H_w\) and \(W_w\) are same as in case of AMDTS.

Distance between adjacent core centers, \(D = W_w + d\)

C. Yoke Design

The area of yoke \(A_y = A_i\)

Flux density in yoke \(B_y = B_m\)

Taking section of yoke as rectangular,

Depth or thickness of yoke, \(D_y = d\)

Height of yoke, \(H_y = A_y / D_y\)

D. Overall Dimension Of Frame

Height of frame \(H = H_w + 2H_y\)

Length of frame \(W = 2D + d\)

Depth of frame \(= d\)

6. ESTIMATION OF LOSSES

Core losses = specific core loss in watt per Kg. \times\ mass of core

Copper losses = \(I^2R\), (here current = \(I\), winding resistance = \(R\))

7. ESTIMATION OF COST

Cost of CRGO = \text{rate in Rupees per Kg.} \times\ mass of CRGO in the frame

Cost of Amorphous = \text{rate in Rupees per Kg.} \times\ mass of amorphous material in frame

Cost of copper winding = \text{rate in Rupees per Kg.} \times\ mass of copper in windings.

8. RESULTS AND DISCUSSION

Transformer Rating: 250KVA, 11000/415 V, 50Hz, 3 Phase, Delta/Star, oil natural cooled, Distribution transformer and 5% tapping on HV side.

Calculated main dimensions of core and winding for CCDT, AMDTS and AMDTC are shown in Table-1. On basis
of physical dimensions, masses of core and winding are calculated; further on basis of the masses, losses and cost of the transformer are calculated. The calculated losses, efficiency and cost are shown in Table-2. Among CCDT, AMDTS and AMDTC, the CCDT has minimum efficiency with minimum cost. On the other hand the AMDTS has maximum cost with increased efficiency. For AMDTC the cost has been reduced with further increase in efficiency as compared to AMDTS. The cost of AMDTC is more than conventional CCDT. The increased cost of AMDTC may be recovered in few months in terms of energy saved, for this breakeven point (BEP) is determined. To determine breakeven point Total Owning Cost (TOC) of the transformer is calculated [8].

\[
\text{TOC} = \text{Initial cost} + \text{cost of energy loss during operation.}
\]

As time passes, cost of energy loss increases and the TOC increases with time. The calculated TOC for CCDT and AMDTC are shown in Table-3. Variation of TOC with months is shown in Fig 4. The rate of increase of TOC is higher for CCDT as compared to AMDTC. The BEP comes after 12 months; therefore AMDTC will be economical after 12 months.

### Table-3

<table>
<thead>
<tr>
<th>Time (Months)</th>
<th>TOC for CCDT (Rupees)</th>
<th>TOC for AMDTC (Rupees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>151721</td>
<td>193243</td>
</tr>
<tr>
<td>1</td>
<td>163010</td>
<td>200783</td>
</tr>
<tr>
<td>2</td>
<td>174300</td>
<td>208322</td>
</tr>
<tr>
<td>3</td>
<td>185590</td>
<td>215862</td>
</tr>
<tr>
<td>4</td>
<td>196879</td>
<td>223404</td>
</tr>
<tr>
<td>5</td>
<td>208169</td>
<td>230942</td>
</tr>
<tr>
<td>6</td>
<td>219458</td>
<td>238481</td>
</tr>
<tr>
<td>7</td>
<td>230748</td>
<td>246021</td>
</tr>
<tr>
<td>8</td>
<td>242038</td>
<td>253561</td>
</tr>
<tr>
<td>9</td>
<td>253327</td>
<td>261101</td>
</tr>
<tr>
<td>10</td>
<td>264617</td>
<td>268641</td>
</tr>
<tr>
<td>11</td>
<td>275906</td>
<td>276180</td>
</tr>
<tr>
<td><strong>12 BE.P.</strong></td>
<td><strong>287196</strong></td>
<td><strong>283721</strong></td>
</tr>
<tr>
<td>13</td>
<td>298486</td>
<td>291262</td>
</tr>
<tr>
<td>14</td>
<td>309776</td>
<td>298803</td>
</tr>
</tbody>
</table>

9. CONCLUSION

Among CCDT, AMDTS and AMDTC, the conventional CCDT has minimum efficiency with minimum cost. On the other hand the AMDTS has maximum cost with increased efficiency. For AMDTC the cost has been reduced with further increase in efficiency as compared to AMDTS. The cost of AMDTC is more than conventional CCDT. The increased cost of AMDTC will be recovered in 12 months for a 250 KVA transformer.

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   b) [www.metglas.com](http://www.metglas.com) (access on feb11, 2012).


<table>
<thead>
<tr>
<th>Table-1: Main dimensions</th>
<th>(CCDT)</th>
<th>(AMDTS)</th>
<th>(AMDTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Window dimensions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width Ww</td>
<td>179 mm</td>
<td>178 mm</td>
<td>178 mm</td>
</tr>
<tr>
<td>Height Hw</td>
<td>358.3 mm</td>
<td>357.9 mm</td>
<td>357.9 mm</td>
</tr>
<tr>
<td><strong>Core or limb</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net iron area Ai</td>
<td>0.0206 m²</td>
<td>0.02133 m²</td>
<td>0.02133 m²</td>
</tr>
<tr>
<td>Laminations</td>
<td>d=191.8 mm, a=163 mm, b=101.6mm</td>
<td>l=146.05 mm, d= 164.8 mm</td>
<td></td>
</tr>
<tr>
<td>Mass of one limb</td>
<td>55.63 Kg</td>
<td>60.95 Kg</td>
<td>60.95 Kg</td>
</tr>
<tr>
<td><strong>Yoke</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth Dy</td>
<td>163 mm</td>
<td>146 mm</td>
<td>164.8 mm</td>
</tr>
<tr>
<td>Height Hy</td>
<td>168.1 mm</td>
<td>146 mm</td>
<td>129.2 mm</td>
</tr>
<tr>
<td>Net Yoke area Ay</td>
<td>0.0247 m²</td>
<td>0.02133 m²</td>
<td>0.02133 m²</td>
</tr>
<tr>
<td>Length W</td>
<td>847 mm</td>
<td>794 mm</td>
<td>794 mm</td>
</tr>
<tr>
<td>Mass of one yoke</td>
<td>160 Kg</td>
<td>112 Kg</td>
<td>112 Kg</td>
</tr>
<tr>
<td><strong>Total mass of frame</strong></td>
<td>486.88 Kg</td>
<td>453.92 Kg</td>
<td>453.92 Kg</td>
</tr>
<tr>
<td><strong>Winding details</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turns per phase LV, HV</td>
<td>34, 1639</td>
<td>34, 1639</td>
<td>34, 1639</td>
</tr>
<tr>
<td>Mean length of turn LV</td>
<td>644 mm</td>
<td>647 mm</td>
<td>573 mm</td>
</tr>
<tr>
<td>HV</td>
<td>853 mm</td>
<td>894 mm</td>
<td>792 mm</td>
</tr>
<tr>
<td>Conductor size LV</td>
<td>139 mm²</td>
<td>139 mm²</td>
<td>139 mm²</td>
</tr>
<tr>
<td>HV</td>
<td>3 mm²</td>
<td>3 mm²</td>
<td>3 mm²</td>
</tr>
<tr>
<td>Total mass of windings</td>
<td>194.43 Kg</td>
<td>199.41 Kg</td>
<td>176.65 Kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table-2: losses, efficiency and cost</th>
<th>(CCDT)</th>
<th>(AMDTS)</th>
<th>(AMDTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Core losses in watts</strong></td>
<td>898</td>
<td>83</td>
<td>83</td>
</tr>
<tr>
<td>Copper losses in watts</td>
<td>2862</td>
<td>2913</td>
<td>2581</td>
</tr>
<tr>
<td>Full load Efficiency at power factor 0.8 lag</td>
<td>98 %</td>
<td>98.5 %</td>
<td>98.7 %</td>
</tr>
<tr>
<td>Cost of core in Rupees</td>
<td>38952</td>
<td>90783</td>
<td>90783</td>
</tr>
<tr>
<td>Cost of winding in Rupees</td>
<td>1,12,769</td>
<td>1,15,658</td>
<td>1,02,460</td>
</tr>
<tr>
<td>Cost of core and winding in Rupees</td>
<td>151721</td>
<td>206442</td>
<td>193243</td>
</tr>
</tbody>
</table>

**APPENDIX**

- Mass density of CRGO steel: 7600 Kg / m³
- Mass density of Amorphous: 7200 Kg / m³
- Mass density of Copper: 8920 Kg / m³
- Price of CRGO steel: 80 INR/ Kg
- Price of Amorphous: 200 INR / Kg
- Price of Copper: 580 INR / Kg
- Current density (δ): 2.5 Amp./mm²
- (Specific core loss)_{CRGO}: 1.5 watt / Kg
- (Specific core loss)_{Amorphous}: 0.1 watt / Kg