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DISTRIBUTION TRANSFORMER WITH AMORPHOUS-CRGO CORE: AN EFFORT TO REDUCE THE COST OF AMORPHOUS CORE DISTRIBUTION TRANSFORMER

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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 in place of CRGO steel. The cost of amorphous core transformer is higher than the cost of CRGO core transformer. Here an effort is being made to reduce the cost of amorphous core distribution transformer by using a 'CRGO-Amorphous' core in place of amorphous core. A comparison is being presented here among 'CRGO core distribution transformer (CCDT)', 'amorphous core distribution transformer (AMDT)' and 'Amorphous-CRGO core distribution transformer (AMCCDT)', in terms of cost and efficiency.

Keywords: amorphous core, CRGO steel, distribution transformer, transformer design, core losses.

1. INTRODUCTION

Distribution transformers are used to distribute the electrical power in residential and industrial areas [1]. Distribution transformers are energized for twenty four hours with wide variation in load; therefore they are designed to have low no-load losses [2]. 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. Now-a-days CRGO steel is being used in distribution transformers for which allowable limit of flux density is up to 1.55 Tesla for low core losses [3]. If a distribution transformer with CRGO core is designed above 1.55 Tesla then certainly the cost of the transformer reduces but performance deteriorates in terms of efficiency.

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 [4b]. Molten metal when cooled to solid state at a very high 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, 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. Hardness along with reduced thickness makes slitting and shearing difficult. The brittleness property of amorphous metal has also made it un-friendly to the transformer manufacturers. Due to these limitations, the amorphous core technology has been limited at present to very few customers in India and abroad [4a]. 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. The most attractive characteristics of amorphous alloy are obviously its extremely low core loss and low magnetizing current. The amorphous metal saturates almost at 1.5 Tesla [5], whereas CRGO steel saturates at almost 2.03 Tesla. Overall cost of amorphous core transformer is approximately 20 to 30 percent higher than conventional CRGO core transformers [4a].

In past, some efforts have been made to reduce the cost of CRGO core transformer by preferring 'circular multi-stepped' cross-section of CRGO core in place of 'rectangular' cross-section [6]. For 'circular multi-stepped' cross-section of core, the mean length of winding turn reduces, so mass of copper used in winding reduces; therefore cost of transformer reduces because of reduction in the cost of winding. The manufacturers of amorphous core distribution transformers are very limited in the world because of two reasons, one is its high material cost and another is its brittleness property. Because of limitation of its brittleness property, in amorphous core transformers manufacturers are using square or rectangular cross-section of the core [7, 8, 9]. Over transformer design Amorialis *et al*., [10] have reported a huge literature survey of 425 papers. Till now no more work has been reported to reduce the cost of amorphous core distribution transformer. Here an effort is being made to reduce the cost of amorphous core distribution transformer by using a 'CRGO-Amorphous' core in place of amorphous core. A comparison is being presented here among 'CRGO core distribution transformer (CCDT)', 'amorphous core distribution transformer (AMDT)', and 'Amorphous-

CRGO core distribution transformer (AMCCDT)', in terms of efficiency and cost. The task of a designer is to make a proper compromise between cost and performance.

2. CRGO DESIGN (CCDT)

Sectional view of core and winding is shown in Figure-1.

A. Core design

Voltage per turn, $Et = K\sqrt{Q}$ volts
Q = KVA rating of transformer
K = Output constant (according to problem)
$Et = 4.44\, f.\Phi m$ volts
$\Phi m = Et / (4.44\, f)$
here f = supply frequency and Φm = flux in the core
We know that $\Phi m = Bm.Ai$
Ai = Net Iron Area of core = $\Phi m / Bm$
Flux density $Bm = 1.55\ wb/m^2$ (according to problem)
For cruciform core
$d = \sqrt{(Ai/0.56)}$
$a = 0.85d$
$b = 0.53d$

B. Window dimensions

Window space factor $Kw = 12/ (30+KV)$
Rating $Q = 3.33\, f.\ Bm.\ Ai.\ (Kw.\ Aw\ .\delta).10^{-3}$ KVA
Ai = Net Iron Area of core; δ is current density
Generally, $(Hw / Ww) = 2$ to 4
Window area, $Aw = Hw \times Ww$
Distance between adjacent core centers, $D = Ww + d$

C. Yoke design

The area of yoke is taken as 1.2 times that of core or limb to reduce the iron losses on yoke.
$Ay = 1.2 \times Ai$
Flux density in yoke
$By = \Phi m / Ay$
$By = (Bm.\ Ai) / Ay$
Net area of yoke = stacking factor x gross area of yoke
Net area of yoke = 0.9 x gross area of yoke
Taking section of yoke as rectangular,
Depth of yoke, $Dy = a$
Height of yoke, Hy = gross area of yoke / Dy

D. Overall dimension of frame

Height of frame $H = Hw + 2Hy$
Length of frame $W = 2D + a$
Depth of frame = a

3. AMORPHOUS DESIGN (AMDT)

Sectional view of core and winding is shown in Figure-2.

A. Core design

Voltage per turn, $Et = K\sqrt{Q}$ volts
K = Output constant (according to problem)
$Et = 4.44\, f.\Phi m$ volts
$\Phi m = Et / (4.44\, f)$
We know that $\Phi m = Bm.\ Ai$
Ai = Net Iron Area of core = $\Phi m / Bm$
$Bm = 1.5\ wb/m^2$
Cross sectional area of core $Ai = \Phi m / Bm$
Used square core having $Ai = l^2$ x stacking factor
Here l is the side of square section,
Taking stacking factor = 0.9, $l = \sqrt{(Ai/0.9)}$

B. Window dimensions

Window space factor $Kw = 12/ (30+KV)$
We have $Q = 3.33\, f.\ Bm.\ Ai.\ (Kw.\ Aw\ .\delta).10^{-3}$ KVA
Ai = Net Iron Area, δ = current density in conductor.
Generally $(Hw / Ww) = 2$ to 4
Window area, $Aw = Hw \times Ww$
Distance between adjacent core centers, $D = Ww + l$

C. Yoke design

The area of yoke is taken same as limb. So,
$Ay = Ai$
Flux density in yoke $By = Bm$
Taking section of yoke as square of yoke,
Depth of yoke, $Dy = l$
Height of yoke, $Hy = Ay / Dy$

D. Overall dimension of frame

Height of frame $H = Hw + 2Hy$
Length of frame $W = 2D + l$
Depth of frame = l

4. AMORPHOUS-CRGO DESIGN (AMCCDT)

Sectional view of core and winding is shown in figure-3.For reduction in cost, taking-

- Cost of amorphous part in the core = cost of CRGO part in the core
- (volume x mass density x price per Kg)$_{amorphous}$ = (volume x mass density x price per Kg)$_{CRGO}$
- (area cross section of core x length x mass density x price per Kg)$_{amorphous}$ = (area cross section of core x length x mass density x price per Kg)$_{CRGO}$
- (area cross section of core x mass density x price per Kg)$_{amorphous}$ = (area cross section of core x mass density x price per Kg)$_{CRGO}$
- $(Ai)_{amorphous}$ x (mass density x price per Kg)$_{amorphous}$ = $(Ai)_{CRGO}$ x (mass density x price per Kg)$_{CRGO}$
- $(Ai)_{amorphous} = (Ai)_{CRGO}$ x [(mass density x price per Kg)$_{CRGO}$ / (mass density x price per Kg)$_{amorphous}$] (1)
- $Ai = (Ai)_{amorphous} + (Ai)_{CRGO}$ (2)

From equation (1) and (2) -

- $(Ai)_{amorphous}$ = Ai x (mass density x price per Kg)$_{CRGO}$ / [(mass density x price per Kg)$_{CRGO}$ + (mass density x price per Kg)$_{amorphous}$]
  = 0.2969 Ai

- $(Ai)_{CRGO}$ = Ai x (mass density x price per Kg) $_{amorphous}$ / [(mass density x price per Kg) $_{CRGO}$ + (mass density x price per Kg) $_{amorphous}$]
  = 0.7031 Ai

It means for minimum cost of core 29.69% area should be for amorphous part and 70.31% area should be for CRGO part in total cross sectional area of the core.

Depth of amorphous part in frame = $(Ai)_{amorphous}$ / (0.9. l)

Depth of CRGO part in frame = $(Ai)_{CRGO}$ / (0.9. l)

All other dimensions are calculated as in case of AMDT.

5. ESTIMATION OF COST

Mass of CRGO in the frame = $[\text{mass of core} + \text{mass of yoke}]_{CRGO}$

Mass of amorphous material in the frame = $[\text{mass of core} + \text{mass of yoke}]_{amorphous}$

Mass of copper in winding = [(mean length of turn) x (number of turns) x (area cross section of conductor) x (mass density of copper)]

Cost of CRGO = Price per Kg. x mass of CRGO in the frame

Cost of Amorphous = Price per Kg. x mass of amorphous material in frame

Cost of copper windings = Price per Kg. x mass of copper in windings

6. ESTIMATION OF LOSSES

Core losses in CRGO = (specific core loss in watt per Kg.) CRGO x mass of CRGO in the frame

Core losses in amorphous = (specific core loss in watt per Kg.) Amorphous x mass of amorphous in the frame

Copper losses in windings = I^2 R, (here current = I, winding resistance = R).

7. RESULTS AND DISCUSSIONS

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, AMDT and AMCCDT 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, AMDT and AMCCDT, the CCDT has minimum cost with minimum efficiency. On the other hand the AMDT has maximum cost with increased efficiency. For AMCCDT the cost has been reduced with compromise in efficiency as compared to AMDT.

8. CONCLUSIONS

Amorphous core transformers are energy efficient transformers with increased cost. The cost of the transformer can be reduced by replacing the amorphous core with Amorphous-CRGO core.

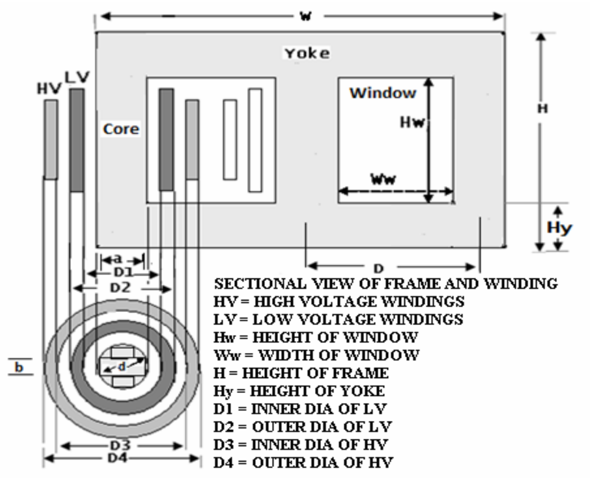

FIGURE 1 : CRGO CORE

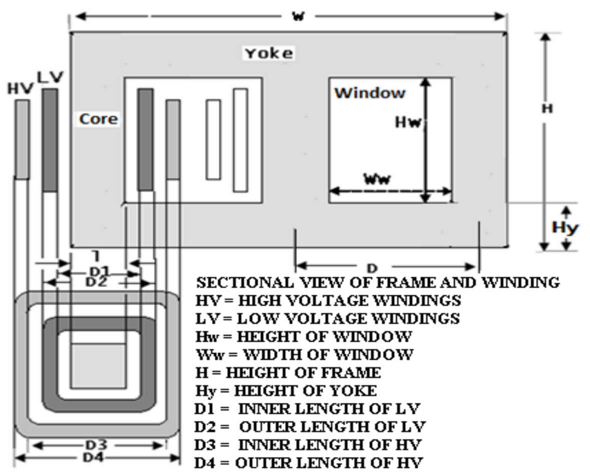

FIGURE 2 : AMORPHOUS CORE

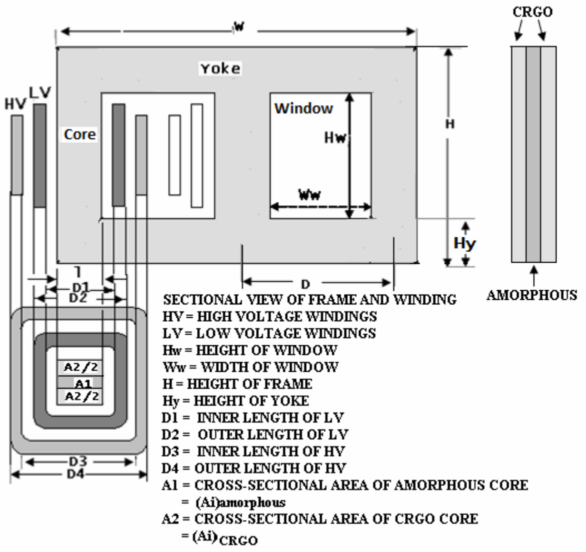

FIGURE 3 : AMORPHOUS - CRGO CORE

Table-1. Calculated main dimensions.

Description	**CRGO core distribution transformer** (CCDT)	**Amorphous core distribution transformer** (AMDT)	**Amorphous-CRGO core distribution transformer** (AMCCDT)
Window dimensions			
Width Ww	179 mm	178 mm	178 mm
Height Hw	358.3 mm	357.9 mm	357.9 mm
Core or limb			
Net iron area Ai	0.0206 m^2	0.02133 m^2	(0.00683+0.0145) m^2
Laminations	d=191.8 mm, (a=163 mm, b=101.6 mm)	l=154 mm depth = 154 mm	l=154 mm depth = (49.4+104.6) mm
Mass of one limb	55.63 Kg	58.02Kg	(17.6 +39.44)Kg
Yoke			
Depth Dy	163 mm	154 mm	(49.4+104.6) mm
Height Hy	168.1 mm	154 mm	154mm
Net Yoke area Ay	0.0247 m^2	0.02133 m^2	(0.00683+0.0145) m^2
Length W	847 mm	794 mm	794 mm
Mass of one yoke	160 Kg	128.71Kg	(39+87.5)Kg
Total mass of frame	486.88 Kg	431.48Kg	(130.8 +293.3)Kg
Winding details			
Turns per phase	34	1639	1639
Mean length of turn LV ,HV	644 mm,853mm	647 mm, 894 mm	647 mm,894 mm
Conductor size LV,HV	139 mm^2, 3 mm^2	139 mm^2, 3 mm^2	139 mm^2, 3 mm^2
Total mass of windings	194.43 Kg	199.41 Kg	199.41 Kg

Table-2. Losses, efficiency and cost.

Description	**CRGO core distribution transformer** (CCDT)	**Amorphous core distribution transformer** (AMDT)	**Amorphous-CRGO core distribution transformer** (AMCCDT)
Core losses in watts	1058	43.1	(13.8+586.6) = 600.4
Copper losses in watts	2862	2913	2913
Full load efficiency at power factor 0.8 lag	98 %	98.5 %	98.3 %
Cost of core in rupees	38,952	86,296	(26160+23464) = 49,624
Cost of winding in rupees	1,12,769	1,15,658	1,15,658
Cost of core and winding in Rupees	151,721	201,954	165,282

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Appendix

Mass density of CRGO steel = 7600 Kg / m^3
Mass density of amorphous = 7200 Kg / m^3
Mass density of copper = 8920 Kg / m^3
Price of CRGO steel = Rs. 80 / Kg
Price of amorphous = Rs. 200 / Kg
Price of copper = Rs. 580 / Kg
Current density (δ) = 2.5 Amp. /mm^2
(Specific core loss)$_{CRGO}$ = 1.5 watt / Kg
(Specific core loss)$_{amorphous}$ = 0.1 watt / Kg