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Amorphous-Core Transformer with Copper Winding Versus Aluminium Winding-A Comparative Study

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ABSTRACT

Amorphous core transformers are in developing stage; they are considered as energy efficient transformers. Cost of amorphous core transformer is about 20 to 30 per cent higher than that of a conventional transformer of same KVA rating. Among several parameters, cost of winding material is a parameter, on which cost of a transformer depends. In a transformer, the cost of winding material may be up to 28 per cent of overall cost of a transformer. Cost of a transformer may be reduced if aluminum winding is adopted in place of copper winding; aluminum is lighter in weight and cheaper in price, compared to copper winding. Here, a comparative study is presented for an amorphous core transformer with copper winding versus aluminum winding, in terms of cost efficiency and mechanical forces. It has been found that, if aluminum winding is adopted for 400KVA amorphous core transformer, the cost reduces, efficiency improves and mechanical forces also remain within limit.

Keyword: *Copper, aluminum, transformer winding*.

1.   INTRODUCTION

In amorphous core transformers, amorphous alloy is used as a core material. Amorphous alloy has significant advantages of low losses, low magnetizing current and less noise, over conventional cold rolled grain oriented silicon (CRGO) steel [1]. Amorphous core transformers are in developing stage; they are considered as energy efficient transformers [3]. Some of the limitations with amorphous alloy are more hardness and more cost; because of these limitations, there are limited number of manufacturers of amorphous core transformers. Cost of amorphous core transformer is about 20 to 30 per cent higher than that of a conventional transformer of same KVA rating [9]. Amorphous alloy is available in form of ribbons having thickness of 0.025 mm; which is used to develop C-core structure. The C-core structure is used to develop one phase and three phase core assembly. The cross-section of C-core is square or rectangular, for which shape of coil is square or rectangular [5,7]. For square or rectangular shape of coil, mean length of winding turn is comparatively more; it increases the load losses along with cost of winding. Thus, there are two main reasons for higher cost of amorphous core transformers- more price of amorphous alloy and more cost of winding. Manufacturing cost is also a factor which affects the overall cost of a transformer. As technology improves and production increases, the manufacturing cost reduces; therefore it is not a big problem for a designer or manufacturer. Some efforts have been made to reduce the cost of amorphous core transformers by adopting multi-stepped cross-section of amorphous-core and amorphous-CRGO core [6]. Cost of winding material is also a parameter, on which cost of a transformer depends. In a transformer, the cost of winding material may be up to 28 per cent of overall cost of a transformer [8]. Cost of a transformer

may be reduced if aluminum winding is adopted in place of copper winding; at present price per Kg of copper is about 1.5 times of price per Kg of aluminum. The task of a designer is not only limited to minimize the cost of a transformer, but to assess the performance also.

2.   COPPER VERSUS ALUMINIUM

Copper and aluminum are the primary materials used as conductors in transformer windings. Comparative features of copper and aluminum are shown in Table-1 [2, 10]. Copper has less resistivity, more tensile strength and higher melting point, while aluminum is lighter and generally less expensive than copper, a larger cross-section of aluminum conductor must be used to carry a current with similar performance as copper. Therefore, current density chosen for aluminum conductor is about one half of current density in copper conductor. For oil natural cooling in a transformer, the chosen current density is 1.25 A/mm^2 for aluminum conductor; however it is 2.5 A/mm^2 for copper conductor. It increases the physical size of aluminum winding and transformer both. Bigger size of aluminum winding does not increases the cost of winding, as aluminum is lighter in weight and cheaper than copper. On the other hand, copper has higher mechanical strength, and it is used almost exclusively in large power transformers, where extreme forces are encountered. The windings have to be strong enough to withstand the mechanical forces under short-circuit condition. Under short circuit condition, the current may be up to 20 times of rated current, and developed mechanical forces may be up to 400 times of forces under normal condition [4].

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Table-1		
Physical property	**Copper**	**Aluminum**
Resistivity, Ω-mm^2/m	0.016642	0.03
Mass density, kg/dm^3	8.89	2.7
Tensile strength, MPa	124	46.5
Melting point, ^{0}C	1084.88	660.2
Price per Kg, INR	580	370

Apart from this, some other properties like-oxidation, connectivity and machine ability should also be considered. Oxidation is a process in which a metal reacts with oxygen in the air to form compounds called oxides. Both aluminum and copper oxidize when exposed to the weather. Aluminum is more prone to be oxidized, when it is exposed to air; it forms a layer of Al_2O_3. This layer protects the internal aluminum layers to react with air, but Al_2O_3 is an excellent insulation. This means that making satisfactory connections with aluminum is more complicated than with copper. Therefore, aluminum has poor connectivity than that of copper. When two pieces of aluminum are to be joined by fusion welding a certain amount of preparation is necessary. The edges to be joined should be cut square, degreased and cleaned by scratch brushing with a wire brush.

Machine ability is measured in power units; it is the power (HP) used by cubic inch over time necessary to process the material. For aluminum, the machine ability is 0.4 HP/in^3/min and for copper it is 0.8 HP/in^3/min. In this attribute, aluminum has an advantage over copper, since the energy needed to work with it is half the energy needed to do the same process with copper. A high machine ability factor is reflected in costs **[8]**.

3. DESIGN CONSIDERATIONS [2, 6, 10, 11]

Winding arrangement in a frame of transformer is shown in Figure-1a. The sectional view of 4-stepped core is shown in Figure-1b.
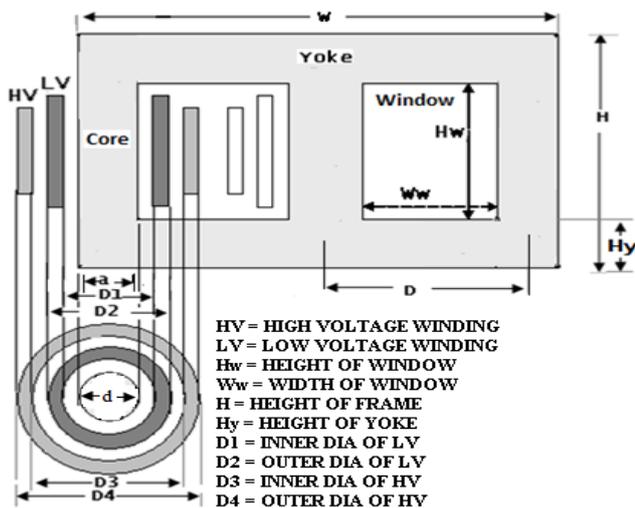

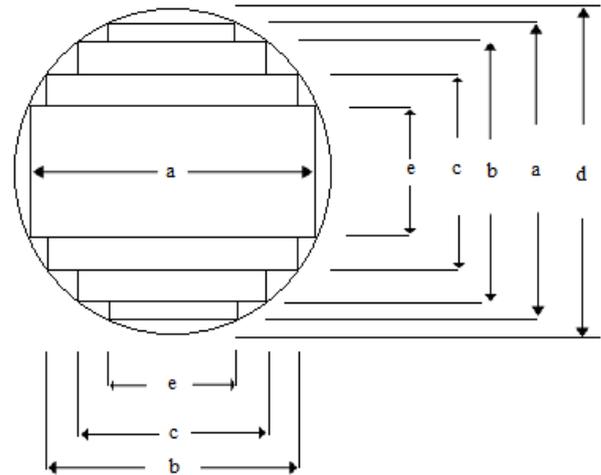FIGURE-1a : SECTIONAL VIEW OF FRAME AND WINDINGS

FIGURE-1b : CROSS-SECTIONAL VIEW OF 4-STEPPED CORE

a. Core Design

Voltage per turn, Et = $\sqrt{Q}$ volts   Q is KVA rating of transformer.
Constant= 0.45 for 400 KVA distribution transformer.
Et = 4.44 f.Φm volts
Φm = Et / (4.44 f)
Ai = Net Iron Area of core = Φm / Bm
Bm = 1.55 wb/m^2 (according to problem)
For 4-stepped core, Diameter of circumscribing circle d = $\sqrt{}$ (Ai/0.62);
Dimensions of different steps for 4-stepped core are:
a = 0.92d, b = 0.78d, c= 0.60d and e=0.36d.

b. Window Dimensions

Window space factor Kw = 10/(30+KV), here KV is voltage of high voltage (HV) winding in kilovolts.
Rating Q = 3.33 f.Bm.Ai.(Kw.Aw .δ).10^{-3} KVA,
δ is current density, f is the supply frequency.
δ =2.5 A/mm^2 for copper, and δ = 1.25A/mm^2 for aluminium .
Generally, (Hw / Ww) = 2 , here Hw and Ww are the height and width of window.
Window area, Aw = Hw x Ww
Distance between adjacent core centers, D = Ww + a

c. Yoke Design

The area of yoke, Ay = Ai Flux density in yoke
By = Bm =1.55wb/m^2
Depth of yoke, Dy = a
Height of yoke, Hy = a

d. Overall Dimension of Frame

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

e. Winding Design

Turns per phase (T) = voltage per phase / Et
Current per phase (I) = (KVA per phase. 1000)/ voltage per phase.
Cross sectional area of conductor = I / δ.
Clearance=5+0.9KV
D1=d+2**.**Clearance;   D2=D1 + 2**.**width of winding;
D3=D2+2**.**Clearance;   D4= D3 + 2**.**width of winding;
Mean length of turn for low voltage winding (Lmt) = π (D1+D2)/2;
Mean length of turn for high voltage winding $(Lmt)_{hv} = \pi$ (D3+D4)/2;
Height of winding (Lc) = Hw-2**.**Clearance;
Winding resistance=(specific resistance)**.**(Mean length of turn)**.**(Turns)/Cross sectional area of conductor.

f. Losses and Efficiency

Core losses in amorphous = (specific core loss for amorphous in watt per Kg.) x (mass of amorphous in the frame).
Copper losses in windings = I^2 R,   (here current = I, winding resistance = R).
Total losses = core losses + copper losses.
Full load efficiency= (KVA x power factor)/ {(KVA x power factor)+Total losses}.

g. Tank

Clearance between transformer assembly and tank wall may be taken100 mm.
Length Lt = W+2.clearance;
Width Wt = D4+2.clearance;
Height Ht = 1.5H;
Area of side walls St = 2(Lt +Wt) Ht.
Number of cooling tubes required Nt = (1/8.8 x l_t x 0.162). [(Total losses/ θ) – 12.5 x St].
Here, l_t =length of cooling tube,
average temperature rise $\theta = 0.8\theta_m$
θ_m is maximum permissible temperature rise (=50°C).

h. Radial forces and tensile stress

Average radial force on a transformer winding is given by
Fr = $(\mu_o/2)$**.**$(IT)^2$**.**(Lmt/Lc).
 area of conductor).

i. Cost

Mass of the frame = [mass of core + mass of yoke];

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 Frame = (Price per Kg. of amorphous) x mass of frame;

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

Cost of transformer oil = (Price/liter).Volume of oil.

Here, two amorphous-core transformers of same rating (400 KVA), one with copper winding and other with aluminum winding, are designed and compared in terms of losses, efficiency, cost, radial forces and tensile stress in winding.

4. RESULTS AND DISCUSSION

Transformer Rating: 400KVA, 11000/415 V, 50Hz, 3 Phase, Delta/Star, Amorphous-core Distribution transformer.
Option-1: Oil natural cooled (ON);   Option-2 : Dry Type (AF).

For the above transformer, physical dimensions of core, yoke, frame and windings are calculated. On basis of physical dimensions, masses of frame and windings are calculated; which are shown in Table-1. On basis of the masses, the losses, efficiency, cost of the Frame, windings and oil, radial forces and tensile-stresses are calculated. The calculated losses, efficiency, cost, radial forces and tensile-stress are shown in Table-2. For transformer with aluminum winding, tank size is larger with less number of cooling tubes, compared to copper winding transformer. Therefore, a transformer with aluminum winding needs more liters of oil for cooling. As shown in Table-2, the transformers with aluminum windings for option-1 and option-2, have higher efficiency with reduced cost, compared to transformer with copper winding. The efficiency of dry type transformer is less than that of oil natural-cooled transformer, because of power consumed in cooling fan. The developed tensile-stresses under short circuit condition are also within limit. The cost of dry type transformer is less than that of oil natural cooled transformer; the limitation with dry type transformer is that, it should not be installed in open space.

5. CONCLUSION

Amorphous core transformer with aluminum winding has higher efficiency with reduced cost, compared to transformer with copper winding. The developed tensile stresses are also within limits. Therefore, for 400KVAamorphous core transformer,

aluminum winding is a suitable choice, for both options- oil natural cooled (ON) and dry type (AF).

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Table-1: Calculated Main dimensions of Frame and windings				
Description	Option-1 (copper winding)	Option-1 (Aluminium winding)	Option-2 (copper winding)	Option-2 (Aluminium winding)
Window-				
Height (Hw)	440.8 mm	623.4 mm	440.8 mm	623.4 mm
Width (Ww)	220.4 mm	311.7 mm	220.4 mm	311.7 mm
Core or limb-				
Net iron area (Ai)	0.02615 m^2	0.02615m^2	0.02615 m^2	0.02615 m^2
Laminations, (mm)	a=189,b=160 c=123, e=74	a=189,b=160 c=123, e=74	a=189,b=160 c=123, e=74	a=189,b=160 c=123, e=74
Mass of one limb	82.84Kg	117.34kg	82.84Kg	117.34kg
Yoke-				
Depth (Dy)	189mm	189mm	189mm	189mm
Height (Hy)	189mm	189mm	189mm	189mm
Yoke area (Ay)	0.02615m^2	0.02615m^2	0.02615m^2	0.02615m^2
Mass of one yoke	189.74Kg	224Kg	189.74Kg	224Kg
Frame-				
Length (W)	1007.8mm	1190.4mm	1007.8mm	1190.4mm
Height (H)	818.8mm	1001mm	818.8mm	1001mm
Total mass	628Kg	801kg	628Kg	801kg

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Windings-				
Turns per phase- (LV,HV)	27,1222	27,1222	27,1222	27,1222
D1,D2 (in mm) D3,D4 (in mm)	217.4, 247.2 275.2, 323.5	217.4,258.6 286.6,351.2	217.4, 247.2 275.2, 323.5	217.4,258.6 286.6,351.2
Mean length of turn- (LV,HV)	729mm, 940mm	942mm, 1001mm	729mm, 940mm	942mm, 1001mm
Conductor size (LV,HV)	222.6mm^2, 4.8mm^2	445.2 mm^2, 9.6mm^2	222.6mm^2, 4.8mm^2	445.2 mm^2, 9.6mm^2
Total mass of windings	264Kg	187Kg	264Kg	187Kg
Resistance per phase (LV,HV)	0.00186 Ω, 5.025Ω	0.00184 Ω, 4.091 Ω,	0.00186 Ω, 5.025Ω	0.00184 Ω, 4.091 Ω,
Tank-				
Lt,Wt,Ht, (meter)	1.53,0.52,1.02	**1.74,0.55,1.1**	nil	nil
Cooling tubes(Nt)	40	**21**	nil	nil
Vol.of Oil, (litre)	605	**795**	nil	nil

Table-2: losses, efficiency, cost, radial forces and tensile-stress on windings				
Description	Option-1 (copper winding)	Option-1 (Aluminium winding)	Option-2 (copper winding)	Option-2 (Aluminium winding)
No load loss, watts	63	80	63	80
load loss, watts	3939	3506	3939	3506
Efficiency at Full load (at pf= 0.8 lag)	98.7%	**98.9%**	98.6%	**98.8%**
Cost of Frame[C1], INR	125,603	160,200	125,603	160,200
Cost of windings [C2], INR	153,120	**69,190**	153,120	**69,190**
Cost of Oil [C3],INR	**102850**	135,150	nil	nil
Cost of cooling Fan etc.[C4], INR	nil	nil	10,000	10,000
C1+C2+C3+C4, INR	381,573	**364,549**	288,723	**239,390**
Average Radial Force (Fr),N	314	236	314	236
Developed tensile stress, (Under full load),MPa	0.00852	0.0032	0.00852	0.0032
Developed tensile-stress, (Under short-circuit),MPa	3.408	**1.28**	3.408	**1.28**
Natural Tensile strength of winding material,MPa	124	46.5	124	46.5