ALUMINUM WOUND POWER TRANSFORMERS

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ABSTRACT

From technical view point there are two conductor materials that can be economically used in windings of power transformers (>10MVA) - copper and aluminum. In practice copper is widely used for this purpose. Historical background and reasons for popularity of copper are described in this paper. This paper highlights prospects and challenges in adopting aluminum as winding conductor in power transformers. It also covers various aspects of these conductors and discusses their viability and advantages for power transformer windings. Electrical, mechanical and other properties of aluminum conductors are compared with that of copper and it is suggested that with proper design and manufacturing a reliable power transformer with aluminum windings can be manufactured with similar performance parameters and quality as that of copper wound power transformers.

1 INTRODUCTION

When transformer technology was evolved, first transformers were built with copper conductors as it was second best available electric current carrying conductor after sliver, both in terms of electrical and thermal properties. Also copper was more easily available at that time. During the Second World War, some industries began to manufacture transformers with aluminum windings because copper became scarce due to increased demand of copper which was required to be used for weapons and ammunition.

During 1960s, when copper prices rose sharply, attempts were made to explore the possibilities offered by aluminum for its usage in many electrical equipment as it was much cheaper at that time. The use of aluminum in cables became widespread and has remained that way ever since. However, during that period, although some quite large power transformers were built using aluminum for windings, it could not gain much popularity.

From technical and economical point of view, both conductor materials can be used in transformers: Copper (Cu) or Aluminum (Al). The choice among these materials should depend mainly on price and availability. National and international standards on power transformers do not specifically mention which material to be used in winding conductors. Due to historical reasons, transformer users are following the same practice of specifying copper as a conductor material in their specifications. Many customers prescribe copper only, for different reasons, mainly conservatism, established customs and practices as well as perception of better quality.

2 ELECTRICAL, MECHANICAL AND THERMAL PROPERTIES

Generally used aluminum for electrical purpose is “E-Al F7” according to DIN 40501-4 with minimum aluminum content of 99.5%. Other commonly used material is called “alloy 1350, aluminum 1350 or EN-AW-1350” according to ASTM B230/B230M-07, EN 573-3, EN 755-2 or EN 14121. This material, with 99.5% aluminum content have a minimum volume conductivity of 61.2% IACS (International Annealed Copper Standard,) whereas copper has a volume conductivity of 100% IACS. Impurity elements in excess of limits degrade electrical conductivity of aluminum.

Comparison of various properties of copper and aluminum is provided in table-1. Resistivity of aluminum is higher than that of copper, however mass density of aluminum is less than that of copper. To estimate its net effect on transformer cost, we must compare the cost of copper and aluminum windings for the same load losses (I^2R losses for simplicity) i.e. for same resistance.

Resistance of aluminum winding $R_{al} = \rho_{al} \times l_{al} / A_{al}$

Resistance of copper winding $R_{cu} = \rho_{cu} \times l_{cu} / A_{cu}$

Where ρ_{al}, l_{al} and A_{al} are resistivity (Ω- mm^2/m), length (m) and cross sectional area (mm^2) of aluminum conductors used and p_{cu}, l_{cu} and A_{cu} are resistivity (Ω- mm^2/m), length (m) and cross sectional area (mm^2) of copper conductors used

If we consider both resistances to be equal:

$p_{al} \times l_{al} / A_{al} = p_{cu} \times l_{cu} / A_{cu}$ (1)

In practice length of aluminum winding will be slightly more in comparison to length of copper winding for same power, however for simplicity of analysis we can assume its effect to be negligible. With this assumption equation (1) will change to:

$A_{al} = p_{al} \times A_{cu} / p_{cu}$ (2)

If we replace the values of resistivity from table-1, we get the following equation:

$A_{al} = 0.028172 \times A_{cu} / 0.017241$

=> $A_{al} = 1.63 \times A_{cu}$ (3)

Above equation shows that for same losses, cross sectional area of aluminum conductors should be 1.63 times that of copper conductors. Since prices of aluminum and copper are compared in terms of weight, we need to convert above equation in terms of weight.

Length of aluminum winding $l_{al} = M_{al} / (d_{al} \times A_{al})$

Length of copper winding $l_{cu} = M_{cu} / (d_{cu} \times A_{cu})$

Where M_{al} & d_{al} are mass (kg) and density (kg/mxmm^2) of aluminum conductors respectively and M_{cu} & d_{cu} are mass (kg) and density (kg/mxmm^2) of copper conductors used.

We have assumed that lengths of both conductors are equal:

$M_{al} / (d_{al} \times A_{al}) = M_{cu} / (d_{cu} \times A_{cu})$

Substituting value of A_{al} from equation-3 and values of density from table-1 we get:

$M_{al}/(0.002703 \times 1.63 \times A_{cu}) = M_{cu}/(0.008890 \times A_{cu})$

=> $M_{cu} = 2.01\ M_{al}$ (4)

or

$M_{al} = 0.5\ M_{cu}$ (5)

This means, for same load losses we need 50% aluminum by weight in comparison to copper.

If we make direct comparison between properties of two metals, aluminum is a softer material and has a lower tensile strength in comparison to copper. However, in practice, when aluminum is used in transformer, windings are designed with about 63% more cross sectional area in comparison to copper for the same performance parameters. This increase in area works into advantage and as a result compressive (buckling) stress during short circuit is reduced for aluminum conductors such that it may remain within its allowed limits.

When we consider the critical force for tilting (allowed tilting force), it depends on modulus of elasticity of conductor and conductor strand dimensions (width and thickness). Even though copper has higher modulus of elasticity in comparison to aluminum, allowed tilting force for aluminum windings may remain within allowed limits as aluminum windings will generally have more strands in parallel with higher width and thickness to get more cross sectional area.

Short circuit strength needs to be carefully calculated and checked and generally it should be possible to achieve required short circuit strength with aluminum windings. In some cases, particularly for inner, low voltage windings, when compressive stresses are more and aluminum strip conductor may not offer required strength against these stresses, it is practical to go for inner LV windings with copper conductors and outer HV windings with aluminum conductors. In such cases it is also possible to design inner, low voltage windings, with aluminum continuously transposed conductors with epoxy bonding (CTCE) to achieve required strength against compressive stresses.

Heat capacity, or thermal capacity, is the measurable physical quantity that specifies the amount of heat required to change the temperature of an object or body by a given amount. Aluminum windings have more thermal capacity in comparison to copper windings, this can be derived as below:

$$\frac{Heat\_capacity\_Al}{Heat\_capacity\_Cu} = \frac{M_{Al}}{M_{Cu}} \times \frac{C_{Al}}{C_{Cu}} = (\frac{1}{2.01}) \times (\frac{0.000220}{0.000092}) = 1.189$$

Where M_{al} and C_{al} are mass (gm) and specific heat (cal/kg^{o}C) of aluminum conductors used M_{cu} and C_{cu} are mass (gm) and specific heat (cal/kg^{o}C) copper conductors used

Above equation indicates that for the same amount of losses and heat generated inside the windings, aluminum windings will have 1.189 times more heat capacity in comparison to copper windings. This means these windings need more heat to increase their temperature. Also higher resistivity of aluminum gives inherently lower additional losses (eddy current losses) in the windings. These two factors lower the risk for higher temperature rise and hot spots in aluminum windings.

Property	Copper	Aluminum
Volume conductivity (%IACS)	100	61.2
Resistivity (Ω- mm^2/m)	0.017241	0.028172
Density (kg/mxmm^2)	0.00889	0.002703
Coefficient of linear thermal expansion (meter x 10^{-6}/°C)	17	23
Thermal conductivity (W/mxk)	398	210
Melting point (°C)	1084.88	660.2
Specific heat (cal /kg° C)	0.000092	0.00022
Modulus of elasticity (MPa)	1.1 x 10^5	0.69 x 10^5

Tabel-1: Properties of copper and aluminum at 20°C

4 RELIABILITY CONSIDERATIONS

Many customers do not prefer to buy transformers with aluminum windings due to the misconception of poor quality and related unreliable performance. In fact, a well designed and manufactured transformer with aluminum windings can be as reliable as a copper wound transformer.

In transformers, temperature rise limits are specified mainly to limit the aging of paper coming in contact with conductor. Since same insulating material is used for aluminum wound transformers, same temperature rise limits are applicable and we should expect similar aging of insulating material as that of copper wound transformers.

ABB, worldwide has rich experience of supplying more than 1500 power transformers (>10MVA) with aluminum windings. Many of these transformers are in service since long time.

Sometimes aluminum wound transformers are considered to have more losses as conductivity of aluminum is less than that of copper. As explained in earlier section, in most of the cases, it is possible to design aluminum wound transformers with same losses as that of copper wound units by providing more cross sectional area.

5 ECONOMICAL CONSIDERATIONS

Copper had different trends over the years; in fact the price of copper has historically been highly unstable. It jumped from the 60-year low of 1320USD/t in June 1999 to 8270USD/t in May 2006. It dropped to 5290USD/t in Feb. 2007, and then rebounded to 7710USD/t in April 2007. In Feb. 2009, weakening global demand and a steep fall in commodity prices since the previous year's highs left copper prices at 3320USD/t. However, aluminum has been relatively stable.

Copper is currently much more expensive than aluminum in terms of USD/t. The price of copper has recently moved ahead much faster than the price of aluminum.

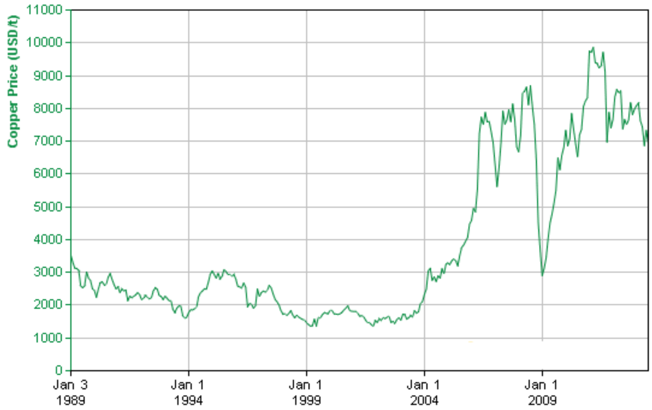

Fig-1: Movement of copper prices

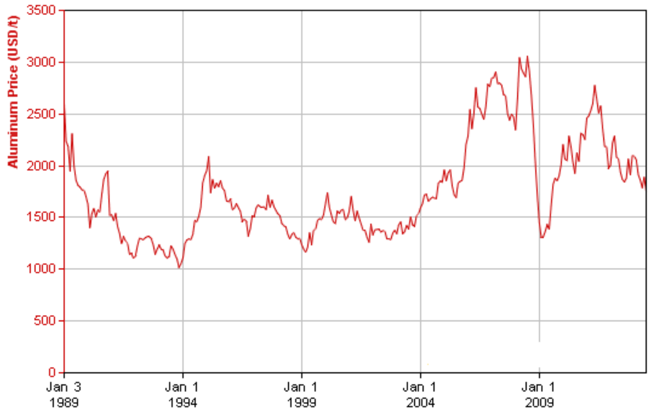

Fig-2: Movement of aluminum prices

Lower, per kg, cost of aluminum and lower weight of conductors used in these windings bring economic benefit in the transformer costs. On the other hand, increased volume and thus increased weight of core steel, insulation, tank and oil compensate partly these benefits. However as copper price increases and the price gap between aluminum and copper widens, aluminum wound transformers become economically more attractive.

6 MANUFACTURING LIMITATIONS

Transformer manufacturers may have to overcome some manufacturing limitations by having more experience with aluminum wound transformers. Wherever cross section area is more and strip conductors cannot be used due to manufacturing limitations, use of aluminum continuously transposed conductors (CTC) may be more practical. Aluminum foil windings with epoxy diamond dotted paper insulation between turns can be a good solution for low voltage windings of smaller ratings of power transformers.

Aluminum oxidizes when it is exposed to air. A hard transparent aluminum oxide coating quickly forms, which protects the internal layers to react with air. As Al_2O_3 (aluminum oxide) is a good insulation, making satisfactory connections with aluminum is more complicated than with copper. There are many methods used to mitigate aluminum joining problems, such as welding with tungsten inert gas, cold welding, crimping to other copper or aluminum connector, using hard alloy tabs with tin plating to make bolted joins using standard hardware etc. Thermal expansion coefficient for aluminum is 42% greater than that of copper. Issues from expansion and contraction of conductors in electrical connections, between copper and aluminum can be eliminated by proper and well-distributed forces in joints.

For practical reasons, even for aluminum wound transformers, manufacturers may like to use copper cables to join windings ends with bushings and tap changer. For this purpose special bi-metallic cable sleeves can be used which are having one end with aluminum and other end with copper. Aluminum end of the sleeve can be crimped with aluminum winding conductors and copper end can be crimped with copper cable. To reduce the quantity of such type of joints, it may also be practical to make only regulating windings with copper conductors, so that available standard solution of connecting them with copper cables and standard sleeves can be used. In such cases if LV and HV windings are made with aluminum conductors and they are connected with copper cables, there will be only 12 no. of special type of copper to aluminum joints in a standard, 3-phase transformer.

During testing, resistance of winding and load losses are measured at reference temperature and resistance is corrected to 75°C to calculate the losses at 75°C. When regulating winding is made with copper and main winding is made with aluminum, we can't apply the same correction factor for total winding resistance. We need to separately calculate the resistance of main and regulating windings after measuring the resistance of complete winding at maximum, minimum and normal voltage taps. After that separate correction factors to be applied for main winding made with copper and regulating winding made with aluminum. Following correction factors may be applied for copper and aluminum portions of winding respectively, in line with Annexure-E of IEC60076-1, "Power Transformers- General".

$$R_{cu} = R_{cu1} \times 310 / (235+\Theta_1)$$

$$R_{al} = R_{al1} \times 300 / (225+\Theta_1)$$

Where R_{cu} and R_{al} are corrected resistances at 75°C for copper main winding and aluminum regulating winding respectively. R_{cu1} and R_{al1} are measured resistances at Θ_1 °C for copper main winding and aluminum regulating winding respectively.

7 CONCLUSIONS

In this paper electrical, mechanical and thermal properties of aluminum and copper windings for power transformers are compared. Various aspects of aluminum conductors and advantages of using aluminum conductors for power transformer windings are also covered. Issues related to manufacturing are also discussed and some suggestions to overcome these limitations are given. It is possible to manufacture power transformers (above 10MVA) with aluminum windings. With proper care in design and manufacturing, required performance parameters like losses, temperature rises, shot circuit strength etc can be achieved with aluminum windings along with same quality & reliability as that of copper wound transformers.

Globally transformer industry has a lot of experience with power transformers manufactured with aluminum windings and same can be adopted by transformer manufacturers in India with economical advantage to the buyers.

8 REFERENCES

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