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Research Article

Cost Analysis of Aluminum Winding Transformer for Electrical Distribution Network of Pakistan

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Abstract: Aluminum winding transformers have not yet been introduced in the distribution network of Pakistan. This paper evaluates the use of electrolytic aluminum in oil immersed distribution transformers to be used by electric utilities of Pakistan. Specifications for distribution transformers in terms of size and losses are examined. A particular rating from the specification is selected for transformer design with copper and aluminum winding separately. The cost of aluminum winding transformer was compared with the conventional copper winding transformer for the same technical performance parameters. Feasibility of aluminum winding transformer in the distribution network is presented and its viability is established through analyzing a practical unit.

Keywords: AC utilities, aluminum winding transformer, distribution transformer

1. INTRODUCTION

Globally, rise in cost of copper has affected the total transformer cost considerably. The design and manufacture of aluminum transformers is inadequate in Pakistan. Consequently, the relevant utilities in the country are purchasing bulk quantity of distribution transformers from local manufacturers with copper windings only. In June 2010, WAPDA revised the iron and copper losses for distribution transformers which are now about 20% less than the previously defined losses (Amendment # 5 of WAPDA Specs. DDS 84:2007) [1]. This reduction in losses has caused considerable increase in the price of transformer as the transformers procured are still of copper winding. Many researchers of the power engineering field have recommended the use of aluminum winding transformers instead [2]. In addition, many transformers manufacturing companies abroad have commenced aluminum winding transformer manufacturing [3]. Up till now local utilities have shown little interest for the procurement of aluminum winding transformers. Also, none of the Pakistani transformer manufacturers have worked out on this option.

In order to get approval as per standards for the distribution transformers, individual transformer manufacturer has to go through the type testing of that particular rating transformer. These type tests include impulse, temperature rise and short circuit test from an independent laboratory, such as WAPDA's High Voltage and Short Circuit Laboratory at Rawat in Punjab province, Pakistan. The short circuit test has to be repeated every year on an approved prototype transformer [2]. After the short circuit test, average temperature of winding should not exceed 200ºC for aluminum winding transformer, and 250ºC for copper winding transformer. In addition, no physical deformation in the core-coil assembly of the transformer should be observed [4]. In this scenario, the risk of failure for an aluminum winding transformer is higher as the thermal conductivity and tensile strength of aluminum is less than copper (thermal conductivity – 210 vs 398 W/mK and tensile strength – 46.5 Vs. 124 MPa).

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2. COST ANALYSIS

For medium range distribution transformers, i.e., up to 3000kVA, the tensile strength of aluminum can withstand the forces arising due to short circuit. For power transformers, where the short circuit forces are high, use of aluminum causes problems [5].

The percentage cost of materials in a transformer depends upon the losses and dimensions of the transformer required by the customer. The cost of materials in percentage for optimum defined losses is given in Table 1 [6].

The high voltage (HV) winding of a transformer can be constructed using either enameled aluminum wire or paper insulated aluminum conductor. For low voltage (LV) winding, due to high current, aluminum foil is required which is imported. Paper insulated aluminum wire can also be used in the LV of transformer; however, the use of foil eliminates the axial short circuit forces during a short circuit condition [7]. The failure rate of aluminum wound distribution transformers is greater in haphazardly expanded network where frequent switching and external short circuits occur [8]. To avoid this problem, the winding should be manufactured with interlayer varnish in both LV and HV windings. This will bond the winding together to minimize the risk of failure in the field short circuit. Also the pressure blocks should be seated properly on the windings to keep them rigidly within the clamping structure.

AA1050 is the aluminum grade to be used in transformer winding. It consists of 99.15% of Al and the remaining 0.85% includes Cu, Mg, Si, Fe, Mn, Zn and Ti [9]. In an aluminum winding transformer, the winding resistance calculation to convert it to a reference temperature (θ_r) for winding losses evaluation is different from a copper winding transformer. In the case of copper or aluminum, the winding losses R_r is calculated with the aid of a reference temperature θ_r. For copper winding, R_r is expressed as,

$$R_r = R_1\left(\frac{235+\theta_r}{235+\theta_1}\right), \quad (1)$$

Whereas for aluminum, R_r is expressed as,

$$R_r = R_1\left(\frac{225+\theta_r}{225+\theta_1}\right) \quad (2)$$

Where, both eq. (1) and (2), resistance of winding R_1 is taken at a temperature θ_1 [10].

A comparison of copper and aluminum temperature graph for distribution transformers during short circuit test for 4s is displayed in Fig. 1 [10]. Normally, the resistivity of aluminum is about 1.8 times greater than the resistivity of copper. Therefore, higher cross-sectional area of aluminum conductor is required to achieve the same winding losses to that of copper winding transformer. The greater volume of aluminum winding transformer would require more core, insulation, oil and a larger tank size. However, there is a considerable cost difference between the prices of copper and aluminum and winding is the most expensive part of the transformer. As per current (Sept., 2013) LME (London Metal Exchange) prices, the cost of copper is US $/Ton 7,170.50 and that of aluminum US $/Ton 1,780.50 [11]. Mass density of Aluminum is approximately 3.3 times less than the mass density of copper; therefore, less mass of aluminum is consumed to achieve the same winding losses to that of copper winding transformer.

A comparison of copper and aluminum prices from the period from 2007 to 2013 is given in Fig. 2 [11-13]. As can be seen from the graph that at any point aluminum is about 3.5 times economical than copper over the period of past seven years.

There are nine types of ratings defined in the WAPDA specifications for distribution transformers. The ratings from 5kVA to 200kVA are pole mounted whereas 400 and 630kVA are platform mounted transformers. As per latest revision of WAPDA specifications [4] DDS 84:2007, the losses are defined as in Table 2.

There is no mandatory requirement in WAPDA specification that the winding of the transformer should be of copper only. The approval of prototype transformer from WAPDA involves physical verification of materials and its mass; therefore, any manufacturer cannot claim an aluminum winding transformer as copper winding transformer. Hence it is not possible to bid a transformer on copper price and manufacture aluminum winding transformers. 630kVA is the largest rating in the WAPDA distribution network. The material cost comparison of 630kVA transformer with both aluminum and

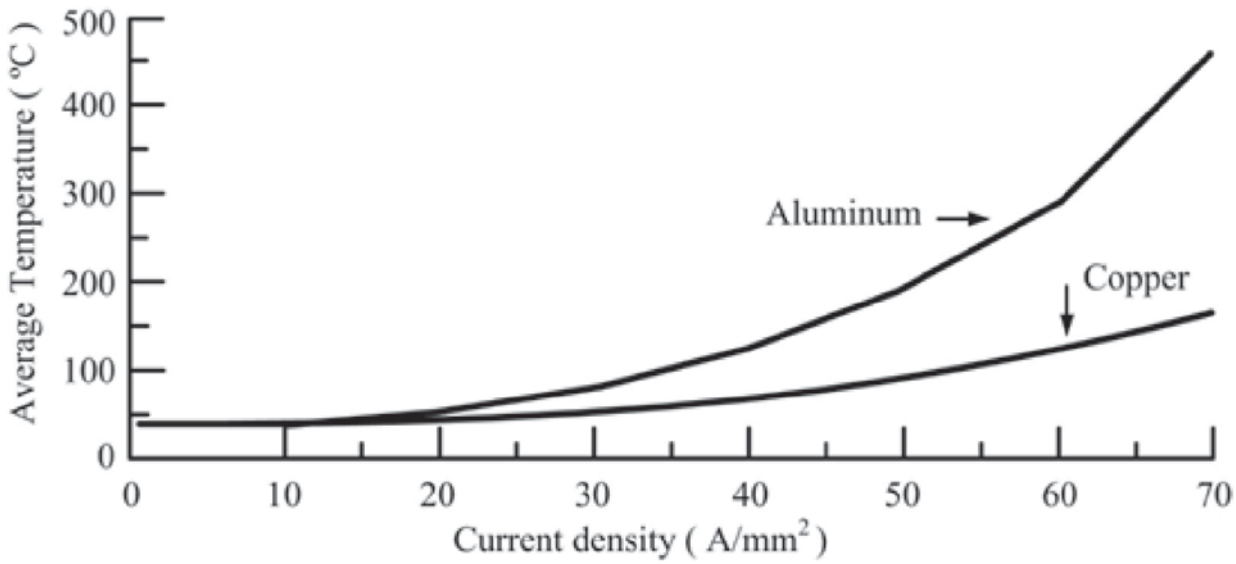

Fig. 1. Comparison of copper and aluminum temperature graph for distribution transformers during short circuit test for 4s [1].

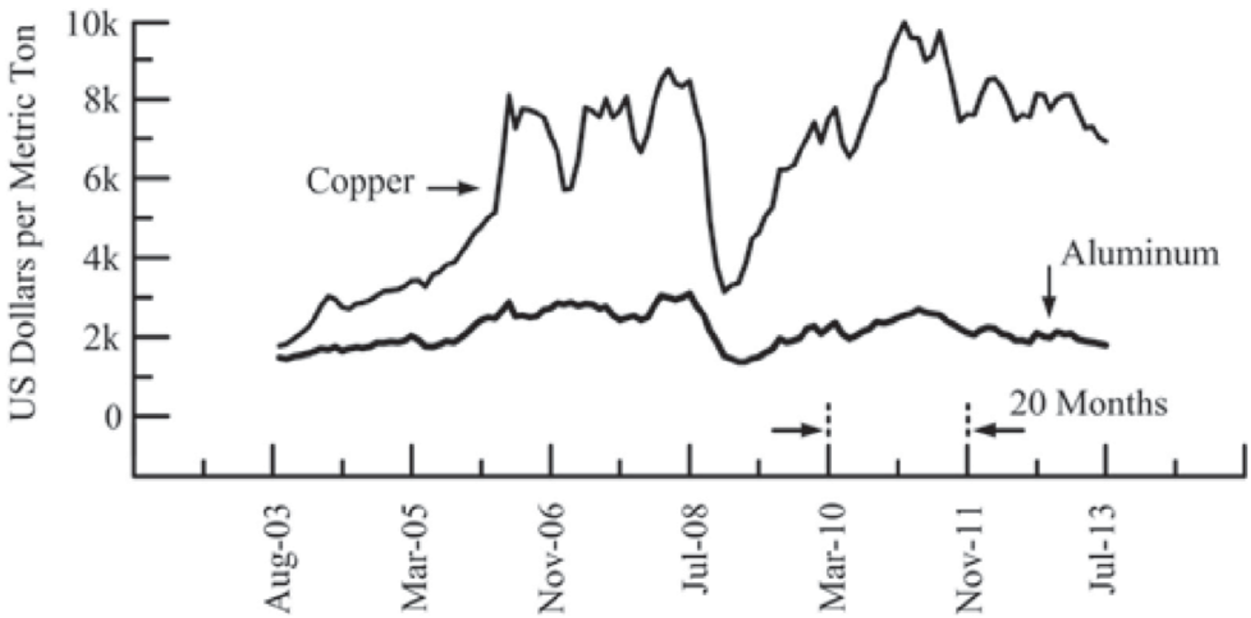

Fig. 2. Comparison of copper and aluminum per metric ton price from the period 2003 to 2013[10-12].

copper winding transformers are presented in Table 3, where the material cost is determined by keeping the performance parameters same for both copper and aluminum winding transformer as defined in WAPDA Specification DDS 84:2007 amended to date.

Table 1. Distribution transformer material costs in percentage.

Material	% Cost	Tolerance
Silicon Steel Sheet	22	±5
Windings	32.5	±6
Insulation	14.1	±5.5
Tank Structure	16.4	±8.5
Tap changer, bushings, etc.	15	±9

Table 2. Distribution transformer kVA rating with losses.

kVA	5	10	15	25	50	100	200	400	630
Fe Losses (W)	44	52	68	98	140	248	396	740	1080
Cu Losses (W)	140	256	348	512	936	1616	2728	4480	6520

Table 3. Assembled 630kVA distribution transformer cost comparison (as of Sept. 2013).

Material	Cost of Copper Winding Transformer	Cost of Aluminum Winding Transformer
Winding	Rs. 266801	Rs. 56792
Core	Rs. 167461	Rs. 177776
Oil	Rs. 87640	Rs. 105280
Steel Structure	Rs. 66159	Rs. 67280
Insulation & Accessories	Rs. 71769	Rs. 76052
Miscellaneous (4% of total cost)	Rs. 26393	Rs. 19276
Total Cost of Transformer	Rs. 686223	Rs. 502507
Total Cost of Transformer	US $ 6474	US $ 4741

3. DISCUSSION

Approximate comparison of copper winding and aluminum winding complete assembled 630 kVA distribution transformers is summarized in Table 4. The cost of aluminum winding transformer is 26.9% less than the cost of copper winding transformer based upon same performance parameters. The cost of core, coil, steel structure and Insulation is more in aluminum winding transformer as compared to copper winding transformer but there is a 78.7% reduction in the material cost of winding which is ultimately resulting in reduction in the overall material cost of aluminum winding transformer.

It is evident that the aluminum winding transformer is feasible for the distribution network of Pakistan as far as cost comparison with copper winding transformer is concerned. For Pakistani distribution network where utilities are spending enormous budget on purchasing a large quantity of transformers (approximately 40,000 to 45,000 transformers per year), this can be an attractive solution saving millions of rupees. Manufacturing issues such as brazing of aluminum wire with the tap changer pins, where aluminum being brittle material, may break easily at this point.

Frequent switching and short circuits occurring in electric distribution network may severely affect the aluminum winding transformer. Special care is to be taken during manufacturing of aluminum winding transformer. The winding has to be tightly wound with varnish used within each layer. The clamping structure should hold the windings tightly and aluminum conductor should be annealed before manufacturing the winding.

4. CONCLUSIONS

Winding being most expensive component of the transformer plays an important role in determining the total cost of the transformer. Replacing copper with aluminum in a transformer increases the overall volume of the transformer, however, still aluminum winding transformer turns out to be 26.9% less expensive than copper winding transformer for 630 kVA rating as per WAPDA specs. DDS 84:2007, amended to date.

For developing countries, like Pakistan, where capital cost of transformers matters, switching over to aluminum winding transformers is an optimized solution. By observing some precautions in manufacturing, these can suit the distribution network not only of Pakistan but in any developing country.

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