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Selection of copper against aluminium windings for distribution transformers

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Abstract: Copper and aluminium are the two conductors most commonly used in transformer windings. This study presents a comprehensive comparison of distribution transformers built either with copper or with aluminium windings. The comparison is based on winding material conductivity, density, cost, connectivity, oxidation, machinability and behaviour under short-circuit. Additionally, a parametric analysis of transformer designs as a function of the cost of copper against aluminium is presented. The study establishes the winding material cost range that indicates when it is more economical to build the transformer windings with copper or with aluminium. All comparisons are carried out with cost of optimised transformer designs that fulfil all specifications together with manufacturing and operating constraints.

1 Introduction

Transformers are designed and built with copper or aluminium windings. In distribution transformers, aluminium–aluminium windings have been successful. For large power transformers, a copper–copper design is more common. To select the right material, the designer has to take into consideration several factors such as weight, maximum size, transformer total cost, availability and cost of the material. This study presents an analysis and comparison of the physical properties of these two materials that can influence their selection for the construction of transformer windings. Copper and aluminium are compared on the basis of conductivity, mass density, cost, connectivity, oxidation, machinability and behaviour under short-circuit.

The choice of the adequate material for a given transformer design could save large amounts of money and prevent transformer failures. This topic has not only been of interest to transformer designers, but the advantages and disadvantages of selecting copper against aluminium have been discussed for induction motors [1–4] and transmission lines [5]. One of the co-authors of this paper has used a non-parametric learning technique [6] and an artificial neural network [7] for the selection of the winding material in transformers.

The first transformers were built with copper conductors, since copper was more accessible at that time. During the Second World War, some industries began to manufacture transformers with aluminium because copper became scarce [8, 9]. The little copper available was used for purposes of war in weapons and ammunition [10]. It was in the 1960s when the demand for copper caused a large increase in its price. Then, transformer manufacturers began using aluminium as strips [11, 12]. In 1958, it was reported in [6] that for the manufacturing of a transformer 71 MVA, 55°C temperature rise, water cooled, single phase, 60 Hz, with a high voltage of 301 400 grounded Y/173 990 volts and a low voltage of 13 200 volts using aluminium.

This paper provides valuable guidelines for the selection of winding material in distribution transformers. The importance of this research lies in the fact that the cost of windings in distribution transformers ranges from 16 to

Table 1 Cost of materials that are used for the manufacturing of distribution transformers

Transformer material	Cost, %
magnetic steel	32.5 ± 5.5
windings (copper or aluminium)	22 ± 6
insulation	14.1 ± 5.5
carbon steel	16.4 ± 8.5
fabricated parts	15 ± 9
total	100

28% of the total cost of transformer materials as shown in Table 1 [13].

2 Conductors used for windings

Varied conductor shapes are used in transformer windings. The selection of the shape depends on the required voltage and current [14]. The shapes are (a) round or elliptical conductors and (b) rectangular conductors (if thickness is less than 0.008 inch, then the conductors are called foils and above this thickness conductors are called strips [15]). Conductors of circular cross-section are used only when the currents are small as is the case of high-voltage windings of distribution transformers. Frequently, when the winding machine allows it, two or more conductors are pulled in parallel. Conductors of rectangular cross-sectional area can be used in a wide range of currents, from 40 to 500 A on low-voltage winding of distribution transformers. Foil can replace rectangular conductors in distribution transformers. Fig. 1 shows a coil with low–high–low configuration with round copper conductors in the high-voltage winding and aluminium foil in the low-voltage winding. Some commercially available magnet wire enamels for use in oil-filled transformers are (insulation-temperature class in °C) modified polyvinyl formal resin-105, epoxy-130, omega** polyester-amide-imide-200 and pyre-ML*** polyimide-220. The advantages and limitations of these magnet wire enamels can be found in [15].

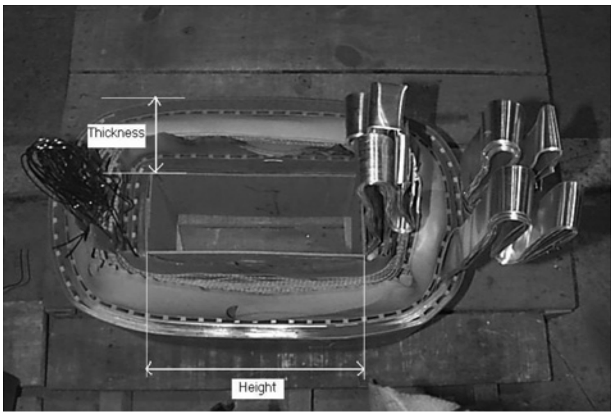

Figure 1 *Hybrid coil manufactured with circular copper conductor in the high-voltage winding and aluminium foil in the low-voltage winding*
This winding is called low–high–low (LHL)

Alloys are made in order to improve some of the properties of the conductor material. Copper is the material traditionally used in transformers because it is the second best conductor (after silver) of both electricity and heat. The most important alloys used in transformer design are those formed between copper and silver. Adding a small amount of silver (typically 0.01%) to copper produces a significant increase on the thermal conductivity with a minimal effect on the electrical conductivity. This also increases the mechanical strength [16, 17]. In [16], the impact of various chemical elements on the electrical resistivity of copper is presented. The copper content of copper alloys should be at least 99.9%. Tin, aluminium, manganese, chrome, silicon, cobalt, iron or phosphorus content of 0.1% and above causes a deterioration of electrical conductivity by more than 10% in copper alloys. Transformer windings are normally made from electrolytic tough pitch copper, C11000. Alloy designations used in this paper refer to the unified numbering system, which uses five digits code numbers preceded by the letter 'C' to identify copper alloys. New copper and copper alloys are incorporated into the listing as they come into use, and designations are placed in an inactive status when an alloy ceases to be used commercially. Nominal composition of C11000 alloys contains 99.95% Cu, 0.04% O_2 and less than 50 ppm metallic impurities.

There is also a wide variety of alloys for aluminium. Aluminium is highly sensitive to impurities, and a drop in conductivity exceeding 10% is being caused by 0.4% magnesium, 0.1% titanium or 0.02% manganese or chrome [18]. Aluminium for power conductors is alloy 1350, which is 99.5% pure and has a minimum conductivity of 61.0%. Chemical composition of alloy 1350 is: 99.50 Al min, 0.10 Si max, 0.40 Fe max, 0.05 Cu max, 0.01 Mn max, 0.01 Cr max, 0.05 Zn max, 0.03 Ga max, 0.02 V max + Ti, 0.05 B max, 0.03 max other (each), 0.10 max other (total). Impurity elements in excess of limits degrade electrical conductivity. The tensile properties of aluminium of several purities are shown in Table 2. The effect of cold working on the tensile properties of five-nines (99.999%) purity aluminium is shown in Table 3 [19].

Most of the aluminium is produced from its ore, called bauxite, which is a mixture of hydroxides of aluminium, contaminated with iron, silicon and titanium oxides. First of all the bauxite is concentrated by separating the insoluble residue from it. The concentrated bauxite is then transformed into aluminium oxide (alumina). The alumina is now reduced to aluminium by electrolysis process. Originally, the name bauxite was given to a mineral found near the village of Baux in the South of France, which contained 52% Al_2O_3, 27.5% Fe_2O_3 and 20.5% H_2O [20].

Table 2 Mechanical properties of pure aluminium at room temperature

Purity, %	Tensile yield strength at 0.2% offset, MPa	Tensile strength, MPa	Elongation in 50 mm (2 in), %
99.90	10	45	50
99.8	20	60	45
99.6	30	70	43

99.50–99.79 (commercially purity), 99.80–99.949 (high purity), 99.950–99.9959 (super purity), 99.9960–99.990 (extreme purity) and >99.990 (ultra purity)

Table 3 Tensile properties of 99.999 + % Al

Amount of cold work	Tensile strength, MPa	Yield strength, MPa	Elongation, %
annealed	40–50	15–20	50–70
40%	80–90	50–60	15–20
70%	90–100	65–75	10–15
90%	120–140	100–120	8–12

It is impossible to predict future copper and aluminium prices, but we can obtain some conclusions by comparing reserves and production rates for copper and aluminium. World copper reserves are estimated to be 480×10^6 metric tons. Considering the 2006 consumption of 15.3×10^6 tons gives 31 years to reach full depletion. World bauxite reserves of 25×10^9 tons at the current annual production of 177×10^6 tons yields 141 years before reaching exhaustion. With these conclusions, we can expect that the cost advantage of aluminium will continue (or increase) in the long term [21].

3 Physical properties and cost of aluminium and copper windings

Table 4 compares some of the most important physical properties of copper and aluminium. Note that while the resistivity of copper is lower than that of aluminium, the mass density of copper is much higher than the mass density of aluminium. The expansion coefficient of copper is lower than that of aluminium, but the thermal conductivity is higher in copper than in aluminium. Also, note that the tensile strength of copper is superior.

In this section, the cost of copper winding is expressed as a function of the cost of aluminium winding for the same resistance. It is interesting to compare the prices of the materials when they have the same resistance. The length of an aluminium winding will be slightly larger than the length of a copper winding for same power. However, the effect of length is small when compared with the effects of area, price and mass density. Therefore in this analysis, it is assumed that the length of aluminium winding is equal to the length of copper winding. Since the windings must have the same resistance, this means that

$$\rho_{\mathrm{Cu}} \frac{L}{S_{\mathrm{Cu}}} = \rho_{\mathrm{Al}} \frac{L}{S_{\mathrm{Al}}} \qquad (1)$$

where $\rho_{\mathrm{Cu}}(\Omega\cdot\mathrm{m})$, $L_{\mathrm{Cu}}(\mathrm{m})$ and $S_{\mathrm{Cu}}(\mathrm{m}^2)$ are the resistivity, length and cross-sectional area of copper conductor, respectively, and where $\rho_{\mathrm{Al}}(\Omega\cdot\mathrm{m})$, $L_{\mathrm{Al}}(\mathrm{m})$ and $S_{\mathrm{Al}}(\mathrm{m}^2)$ are the resistivity, length and cross-sectional area of aluminium conductor, respectively. Using (1), the area of aluminium as a function of the area of copper becomes

$$S_{\mathrm{Al}} = \frac{\rho_{\mathrm{Al}}}{\rho_{\mathrm{Cu}}} S_{\mathrm{Cu}} \qquad (2)$$

Replacing in (2) the values from Table 4, we obtain

$$\begin{aligned} S_{\mathrm{Al}} &= \frac{\rho_{\mathrm{Al}}}{\rho_{\mathrm{Cu}}} S_{\mathrm{Cu}} \Rightarrow S_{\mathrm{Al}} = \frac{0.003}{0.016642} S_{\mathrm{Cu}} \Rightarrow S_{\mathrm{Al}} \\ &= 1.8027\, S_{\mathrm{Cu}} \end{aligned} \qquad (3)$$

Equation (3) shows that in order for an aluminium winding to have the same resistance as a copper winding, the cross-sectional area of the aluminium winding must be 1.8027 times larger. However, the prices cannot be compared directly from (3), since they depend on weight rather on area. Therefore it is necessary to use the mass density of each material from Table 4.

The mass density $d_{\mathrm{Cu}}(\mathrm{kg/m^3})$ and $d_{\mathrm{Al}}(\mathrm{kg/m^3})$ of a copper and an aluminium winding are computed as follows

$$d_{\mathrm{Cu}} = \frac{m_{\mathrm{Cu}}}{v_{\mathrm{Cu}}} = \frac{m_{\mathrm{Cu}}}{LS_{\mathrm{Cu}}}, \quad d_{\mathrm{Al}} = \frac{m_{\mathrm{Al}}}{v_{\mathrm{Al}}} = \frac{m_{\mathrm{Al}}}{LS_{\mathrm{Al}}} \qquad (4)$$

Table 4 Physical properties of copper and aluminium (high-purity lab grade material) [22, 23]

Physical property	Copper	Aluminium
resistivity, Ω-mm^2/m	0.016642	0.03
mass density, kg/dm^3	8.89	2.7
expansion coefficient, μm/(m °C)	16.7	23.86
thermal conductivity, W/(m K)	398	210
tensile strength, MPa	124	46.5
melting point, °C	1084.88	660.2
specific heat, J/(kg K)	384.6	904

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where m_{Cu}(kg), m_{Al}(kg), v_{Al}(m^3) and v_{Cu}(m^3) is the mass and volume, respectively, of copper and aluminium conductor.

Combining (3) and (4) we obtain

$$m_{Cu} = \frac{1}{108\,027}\frac{d_{Cu}}{d_{Al}} m_{Al} \quad (5)$$

Substituting in (5) the values from Table 4, we obtain the mass of copper as a function of the mass of aluminium winding

$$m_{Cu} = 1.8265\, m_{Al} \quad (6)$$

For a winding with the same resistance, we need a volume of aluminium 1.8027 times larger than the volume of copper, as can be seen from (3), taking also into account that the length of the winding is the same. However, because aluminium is less dense than copper, we need a mass of copper 1.8265 times larger than the mass of aluminium for the same resistance and the same winding length, as can be seen from (6). That is, in order to have the same resistance, a larger volume of aluminium is needed; however, in terms of mass more copper is needed.

The total cost of aluminium and copper winding are P_{Al}(\$) and P_{Cu}(\$), respectively

$$P_{Al} = m_{Al} c_{Al}, \quad P_{Cu} = m_{Cu} c_{Cu} \quad (7)$$

where c_{Al}(\$/kg) and c_{Cu}(\$/kg) are the unit cost of aluminium copper winding, respectively. Combining (6) and (7), we obtain

$$w = 1.8265\, r \quad (8)$$

where

$$w = \frac{P_{Cu}}{P_{Al}}, \quad r = \frac{c_{Cu}}{c_{Al}} \quad (9)$$

w is the ratio of copper winding cost over aluminium winding cost and r is the ratio of copper unit cost over aluminium unit cost.

If copper unit cost is double the aluminium unit cost, that is, $r = 2$, it can be seen that a copper winding is 3.65 times more expensive than an aluminium winding for the same resistance [5]. Copper unit cost is double or more the aluminium unit cost after 2007, as can be seen in Fig. 2 [24].

4 Fluctuations of the price of winding materials over time

The price and availability of materials depend on the location. If a country does not produce a given material, there is a need to import it, consequently increasing its cost. The price also depends on the size of the reserves and energy required for processing. These factors become more important when there are material shortages, since more expensive processes may be required for their extraction.

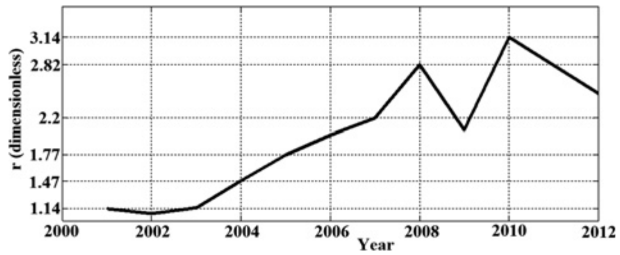

Figure 2 *Ratio of copper unit cost over aluminium unit cost, r, from 2001 to 2012*

Copper has had different trends over the years; in fact the price of copper is highly unstable. This is the main reason why aluminium transformers have been manufactured. As shown in Fig. 3, from 1900 to 2006, the price (US \$) of copper and aluminium have varied greatly. The main factors that have contributed to different price tendencies are [25, 26]: Second World War, the copper industry discovered and developed a large amount of deposits of copper (particularly in Chile), the US dollar was devalued in relation to the Chilean peso, producers of copper were very successful increasing their productivity and reducing their prices by introducing a series of innovations and new technologies, record production of aluminium, shortages of aluminium and collapse of the Soviet Union.

The price of aluminium is lower than the price of copper and it fluctuates, but not as much as copper. Just as the price of copper, the price of aluminium has a rising trend owing to the increased demand. Aluminium is not found in metallic form, but always found as mineral. Thus, the price of aluminium very much depends on the cost of electricity since it is obtained by electrolysis. Copper is also obtained by electrolysis.

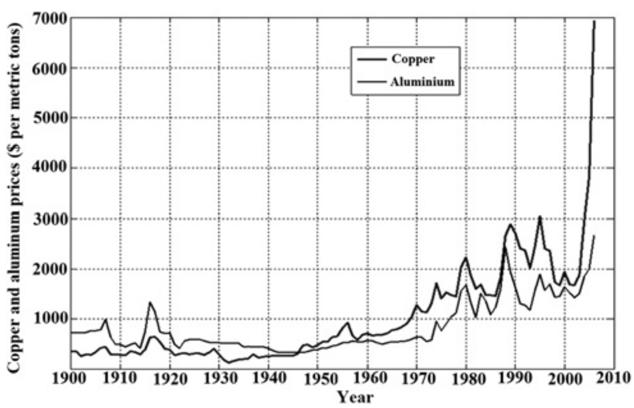

Figure 3 *Copper and aluminium prices in US dollars against time*

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5 Connectivity and oxidation

The term connectivity refers on how easy or difficult it is to make electrical connections. This is very important in a transformer, since the high efficiency of a winding can be lost if the connections are poor. Oxidation is a process in which a metal reacts with oxygen in the air to form compounds called oxides. Both aluminium and copper oxidise when exposed to the weather. Aluminium is more prone to oxidise because its valence is +3 whereas copper has a valence of +1. This explains why aluminium does not exist as a metal in nature.

Aluminium oxidises when it is exposed to air. It forms a layer of Al_2O_3. This layer protects the internal aluminium layers to react with air, but Al_2O_3 is an excellent insulation. This means that making satisfactory connections with aluminium is more complicated than with copper. Some methods of splicing aluminium wires includes soldering or crimping with special crimps that penetrate enamel and oxide coatings and seal out oxygen at the contact areas. Aluminium strap or strip conductor can be tungsten inert gas welded. Aluminium strip can also be cold-welded or crimped to other copper or aluminium connectors. Bolted connections can be made to soft aluminium if the joint area is properly cleaned. Aluminium joining problems are sometimes mitigated by using hard alloy tabs with tin plating to make bolted joints using standard hardware.

When two pieces of aluminium 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. The source of heat may be either an oxyacetylene flame or an electric arc [20]. The factors that affect the welding of aluminium include aluminium oxide coating, thermal conductivity, thermal expansion coefficient, melting characteristics and electrical conductivity [19]. A review of aluminium joining is given in [10, 19, 27, 28].

6 Machinability

Machinability is measured in power units; it is the power (HP) used by cubic inch over time necessary to process the material. For aluminium, the machinability is 0.4 $HP/in^3/min$ and for copper it is 0.8 $HP/in^3/min$ [29]. In this attribute, aluminium 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 machinability factor is reflected in costs; high machinability results in greater tool wear and more labour time.

The ease with which a metal can be machined is one of the principle factors affecting a product's utility, quality and cost. The usefulness of a means to predict machinability is obvious. Unfortunately, machinability is a so complex subject that it cannot be unambiguously defined. Depending on the application, machinability may be seen in terms of tool wear rate, total power consumption, attainable surface finish or several other benchmarks.

Machinability is strongly dependent on physical and mechanical properties of the workpiece: hard, brittle metals being generally more difficult to machine than soft, ductile ones. Machinability is also strongly dependent on the type and geometry of tool used, the cutting operation, the machine tool, metallurgical structure of the tool and workpiece, the cutting/cooling fluid and the machinist's skill and experience.

The main cause of machinability problems are always excessive heat. This may arise by frictional heating, and/or by insufficient cooling. All tools should be kept sharp and in good condition at all times (carbide tools retain sharp edges over a longer period between regrinds than carbon or high-speed steel tools). Tools geometry must be maintained within the established requirements for aluminium alloys. Cutter must have the optimum number of flutes and the optimum spiral configurations for each application. The cutting speed should be as high as is practical in order to save time and to minimise temperature rise in the part. As cutting speed is increased above 30–60 m/min, the probability of forming a built-up edge on the edge cutter is reduced, chips breaks more readily and finish is improved. In particular, a slow feed rate (dwelling) and high spindle speeds are especially troublesome. An adequate and continuous flow of cutting fluid directly at the cutting edges is essential. The flow of cutting fluid should begin before cutting and must continue until the cutter has been removed from the part.

7 Behaviour during short-circuit

During a short-circuit, the current increases sharply in the transformer windings. High currents generate an increase in temperature of the conductor. When the current is very high, the temperature rises rapidly. The melting point of aluminium is 660.2°C, while that of copper is 1084.88°C. However, it is more important to consider the speed at which the temperature of the conductor increases during the short-circuit than during the melting point.

Fig. 4 presents a curve of temperature rise against current density for a short-circuit of 4 s. The curve for copper was obtained from [30, 31]

$$\theta_1 = \theta_0 + \frac{2(\theta_0 + 235)}{(101\,000/J^2 t) - 1} \tag{10a}$$

while for aluminium

$$\theta_1 = \theta_0 + \frac{2(\theta_0 + 225)}{(43\,600/J^2 t) - 1} \tag{10b}$$

where θ_0 is the initial temperature (°C), J is the short-circuit current density (A/mm^2), t is the duration of short-circuit (s),

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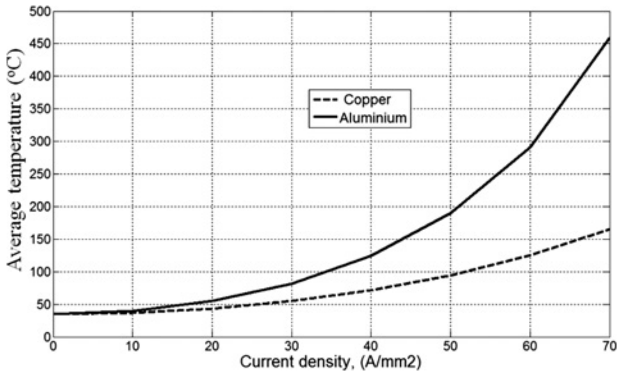

Figure 4 *Average temperature against current density for copper and aluminium under a short-circuit condition with duration of 4 s*

θ_1 is the highest average temperature attained by the windings after a short-circuit (°C), $E_2 = (J_r/J) \times 100\%$, where E_2 is the impedance voltage (%) and J_r is the rated current density (A/mm^2). Equations (10a) and (10b) were obtained assuming that the entire heat developed during the short-circuit is retained in the winding itself raising its temperature (adiabatic conditions) because of the short duration of the short-circuit (<10 s). The short-circuit current depends on percentage impedance between the transformer and fault point. If the faults occur at the transformer terminals, only the % impedance of the transformer should be taken into calculation of the fault current.

In Fig. 4 a curve of temperature rise against current density for copper and aluminium, for a short-circuit duration of 4 s is observed. Considering a short-circuit of 4 s with a current density of 30 A/mm^2, the temperature in an aluminium winding is 81.8°C, whereas in copper it is 54.95°C. The maximum allowed temperature for oil-immersed transformers with the insulation system temperature of 105°C (thermal class A) is 250°C for copper conductor, whereas the same is 200°C for an aluminium conductor without any detriment to mechanical properties. A maximum temperature of 250°C is allowed for aluminium alloys that have resistance to annealing properties at 250°C equivalent to electrical conductor (EC) aluminium at 200°C, or for applications of EC aluminium where the characteristics of the fully annealed material satisfy the mechanical requirements [32]. This limiting temperature is specified mainly to limit the ageing of paper insulation in contact with the conductor. It has been shown that high-conductivity copper would not be appreciably softened in the lifetime of a transformer by occasional excursions up to 250°C even if the copper is deliberately cold-worked to increase its strength. The same applies to the usual 99.5% aluminium alloys used as conductors [33]. The transformer insulation is burned long before the aluminium or copper is melted. The thermal expansion of conductors can break the insulation and then the failure is originated in the transformer.

Table 5 Simplified flowchart for TDO using TOC as the objective function

call routine of given variables
for $i = 1$ to N_{MFD} (number of options for the magnetic flux density)
for $j = 1$ to N_{CG} (number of options for high-voltage conductors)
for $k = 1$ to N_{LVT} (number of options for low-voltage turns)
for $l = 1$ to N_{LW} (number of options for laminations width)
for $m = 1$ to N_{LVA} (number of options for low-voltage conductors)
calculate dimensions of the core
calculate current densities for low voltage and high voltage
calculate coil dimensions and its insulation
calculate winding weight
calculate transformer impedance
calculate core weight and no-load losses
calculate load losses
calculate total losses
calculate efficiency
calculate tank dimensions and oil volume
calculate oil–copper gradient
calculate TOC
end
end
end
end
end
optimum transformer is the one with the minimum TOC that satisfies all the constraints

Copper and aluminium are the primary materials used as conductors in transformer windings. While aluminium is lighter and generally less expensive than copper, a larger cross-section of aluminium conductor must be used to carry a current with similar performance as copper. Copper has higher mechanical strength and it is used almost exclusively in large power transformers, where extreme forces are encountered, and materials such as silver-bearing copper can be used for even greater strength. The windings have to be strong enough to withstand the mechanical forces of short-circuit.

Table 6 TOC results for copper–copper transformers (copper cost = \$6.473/kg, LME officials, 2/November/2009; source: MetalPrices.com)

Parameters	Transformer rated power, kVA							
	5	10	15	25	37.5	50	100	167
no-load loss, W	26.7	39.8	52.65	71.62	99	120.94	201.5	279.5
load loss, W	56.7	107.3	130.55	219.85	274.33	370.42	603.9	876.5
HV winding cost (\$)	59.8	86.8	126.33	170.73	244.18	287.12	401.6	626.3
LV winding cost (\$)	128.4	93.7	158.02	180.85	278.17	245.98	382.58	836.98
core cost (\$)	97.3	147.6	195.47	270.85	367.56	440.70	846.16	1095.5
oil volume, l	25.2	36.9	44.06	48.23	61.36	81.12	100.45	112.29
other material cost (\$)	48.2	55.6	63.85	78.74	89.95	93.73	133.18	155.50
total material cost (\$)	333.6	383.7	543.67	701.17	979.85	1067.52	1763.5	2714.2
labour cost (\$)	33.4	38.4	54.37	70.12	97.99	106.75	176.35	271.4
manufacturing cost (\$)	367.0	422.1	598.03	771.29	1077.84	1174.27	1939.9	2985.7
bid price (\$)	564.6	649.3	920.05	1186.59	1658.21	1806.58	2984.4	4593.4
no-load loss cost (\$)	184.6	274.9	364.10	495.28	684.62	836.35	1393.4	1932.7
load loss cost (\$)	193.1	365.3	444.67	748.84	934.41	1261.71	2056.9	2985.4
efficiency (%) at unity power factor	98.39	98.6	98.81	98.85	99.02	99.04	99.18	99.31
TOC (\$)	942.4	1289.4	1728.82	2430.72	3277.24	3904.63	6434.7	9511.5

A = \$8.16/W, B = \$4.02/W are October 2009 values, sales margin is 35% and labour cost is 10% of total material cost

8 Comparison of total owning cost (TOC) of transformers manufactured with copper and aluminium

Electrical engineers working in the design departments of transformer manufacturers use transformer TOC as an objective function when optimising transformer design [34–36]. The usefulness of TOC objective function is also very important when new transformer materials are being introduced [37]. The TOC takes into account not only the transformer bid price (BP) but also the transformer losses throughout the transformer lifetime. The TOC is computed as follows

$$\mathrm{TOC} = \mathrm{BP} + \mathrm{CL} = \mathrm{BP} + A\,\mathrm{NLL} + B\,\mathrm{LL} \qquad (11)$$

where

$$\mathrm{BP} = \frac{\mathrm{MC} + \mathrm{LC}}{1 - \mathrm{SM}} = \frac{\mathrm{TMC}}{1 - \mathrm{SM}} \qquad (12)$$

where TOC (\$) is the TOC throughout the transformer lifetime, BP (\$) is the transformer bid price, CL (\$) is the cost of transformer losses throughout the transformer lifetime, A (\$/W) is the no-load loss cost rate, NLL (W) is transformer no-load loss, B (\$/W) is the load loss cost rate, LL (W) is transformer load loss, MC (\$) is the cost of transformer materials, LC (\$) is the labour cost to manufacture the transformer, TMC (\$) is the transformer manufacturing cost, and SM (%) is the sales margin. Details on how A and B factors are determined can be found in [38–40]. For Mexican utilities current values (October 2009) for A and B factors ($A = 8.16$ \$/W, $B = 4.02$ \$/W) were calculated considering the following: discount rate = 6%, energy cost = \$0.065/kWh, duty cycle = 25 years. The readers interested in future energy prices can consult [41].

The objective of transformer design optimisation (TDO) is to design the transformer so as to minimise TOC subject to several constraints: (a) constructional constraints and (b) the following operating constraints: maximum no-load losses, maximum total losses (minimum efficiency), maximum and minimum impedance value and maximum limit on the magnetising current. The optimisation methodology is based on a multiple design method that assigns many alternative values to design parameters [34, 35]. The TDO results of this paper have been obtained with a field-validated TDO computer program that has been used for some years in a mid-size transformer factory [34, 35]. Table 5 shows the flowchart for minimising TOC. The other objective functions (e.g. bid price) can substitute TOC in line 19 and in line 25 of Table 5.

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Table 7 TOC results for aluminium–aluminium transformers (aluminium cost = \$1.869/kg, LME officials, 2/November/2009; source: MetalPrices.com)

Parameters	Transformer rated power, kVA							
	5	10	15	25	37.5	50	100	167
no-load loss, W	28.98	46.84	59.69	84.57	113.59	134.8	217.6	311.79
load loss, W	68.08	99.21	150.9	216.55	285.52	377.98	609.26	1083.1
HV winding cost (\$)	8.19	18.69	25.43	41.07	57.15	60.38	92.404	68.654
LV winding cost (\$)	11.04	24.57	21.21	51.69	71.74	60.62	95.815	106.14
core cost (\$)	109.6	173.91	225.71	313.98	421.72	500.46	929.32	1331.6
oil volume, l	33.47	50.53	56.89	76.09	92.57	99.42	158.25	174.95
other material cost (\$)	56.62	77.48	83.51	104.84	133.72	136.28	189.43	202.14
total material cost (\$)	185.4	294.65	355.86	511.58	684.33	757.74	1306.9	1708.5
labour cost (\$)	18.54	29.47	35.59	51.16	68.43	75.77	130.69	170.85
manufacturing cost (\$)	203.9	324.12	391.45	562.74	752.77	833.51	1437.7	1879.4
bid price (\$)	313.8	498.64	602.23	865.75	1158.10	1282.33	2211.8	2891.4
no-load loss cost (\$)	200.4	323.92	412.78	584.83	785.52	932.19	1504.8	2156.1
load loss cost (\$)	231.8	337.92	513.99	737.60	972.53	1287.46	2075.2	3689.0
efficiency (%) at unity power factor	98.11	98.58	98.62	98.82	98.96	98.99	99.16	99.15
TOC (\$)	746.1	1160.49	1529.00	2188.19	2916.15	3501.98	5791.8	8736.5

A = \$8.16/W, B = \$4.02/W are October 2009 values, sales margin is 35% and labour cost is 10% of total material cost

Tables 6 and 7 show TOC results for copper–copper windings and aluminium–aluminium windings in transformer ratings from 5 to 50 kVA. In Tables 6 and 7, the following parameter values are used: SM = 35%, $A = 8.16$ \$/W, $B = 4.02$ \$/W, $c_{Al} = 1.869$ \$/kg and $c_{Cu} = 6.473$ \$/kg. The experimental validation of the transformer characteristics presented in Tables 6 and 7 was done in a further work by the authors (currently under review).

We have compared the usage of aluminium windings in a broader range of distribution transformers up to 200 kVA with the current prices (November 2009) of copper (\$6.473/kg) and aluminium (\$1.869/kg) conductors and we observed that aluminium transformers are less expensive for small transformer rating, but as the transformer rating is increased the advantage of aluminium is reduced (see Fig. 5). The results of Fig. 5 show that for 190 kVA transformers and higher, copper is better than aluminium because TOC of copper transformers is lower (since copper allows the use of less

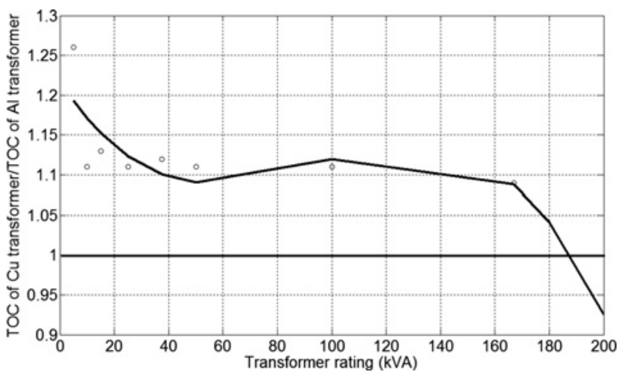

Figure 5 *Ratio of TOC (\$) of copper transformers over TOC (\$) of aluminium transformers as a function of transformer rating (kVA)*

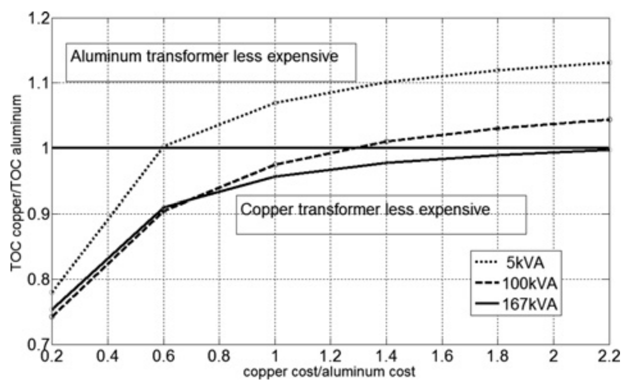

Figure 6 *Ratio of TOC (\$) of copper transformers over TOC (\$) of aluminium transformers as a function of the ratio of copper unit cost (\$/kg) over aluminium cost (\$/kg) for 5, 100 and 167 kVA single-phase transformers*

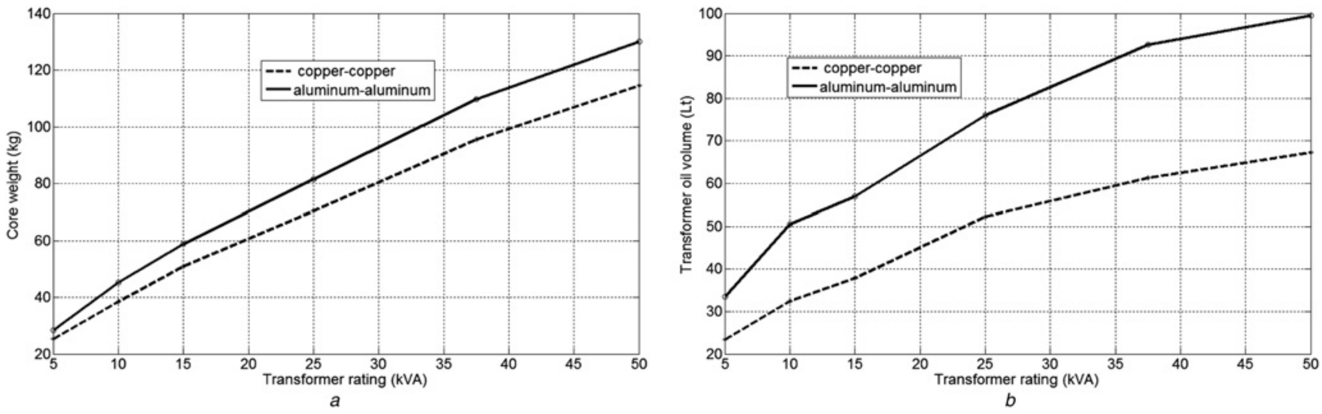

Figure 7 *Comparison of core weight and oil volume of copper versus aluminium transformers*

a Core weight against transformer rating for copper–copper transformers and aluminium–aluminium transformers
b Transformer oil volume against transformer rating for copper–copper transformers and aluminium–aluminium transformers

core material, less insulation, less structural steel for the oil tank and less oil).

Fig. 6 shows a parametric cost comparison of three single-phase transformers (with ratings of 5, 100 and 167 kVA) as a function of the copper/aluminium cost ratio with equivalent total losses. The copper/aluminium cost ratio is varied from 0.2 to 2.2 covering the entire historical range of cost variation. From Fig. 6, one can see that for each rating, there is a different point where the TOC of an aluminium transformer is less that the TOC of a copper transformer. The breaking point is when the TOC of a copper transformer is equal to the TOC of an aluminium transformer. This corresponds to the intersection of each of the curves of Fig. 6 with 1 (on the ordinate axis). Therefore the points with TOC copper/TOC aluminium below 1 correspond to the cases where the copper transformers are less expensive, while the points above 1 correspond to the cases where aluminium transformers are less expensive. Take for example, the curve corresponding to 5 kVA transformers (top line in Fig. 6). If the ratio of copper unit cost ($/kg) over aluminium unit cost ($/kg) is up to 0.6, that is, when aluminium costs 1.67 times as much as copper ($/kg), it is less expensive to use copper for the windings. Compare that with the 100 kVA transformer corresponding to the lower curve in Fig. 6. In this case, copper transformers are less expensive than aluminium transformers for a ratio of copper over aluminium unit cost of up to approximately 1.3. For 167 kVA transformer, it is better to build copper transformers when copper unit cost/aluminium unit cost is <2.2, as shown in Fig. 6. Transformers with ratings of 10, 15, 25, 37.5, 50 and 75 kVA have also been compared. The results (not shown in Fig. 6) give curves that lie in between those of Fig. 6.

It is important to emphasise that there may be occasions where it is not convenient to manufacture distribution transformers with aluminium windings; for example, when

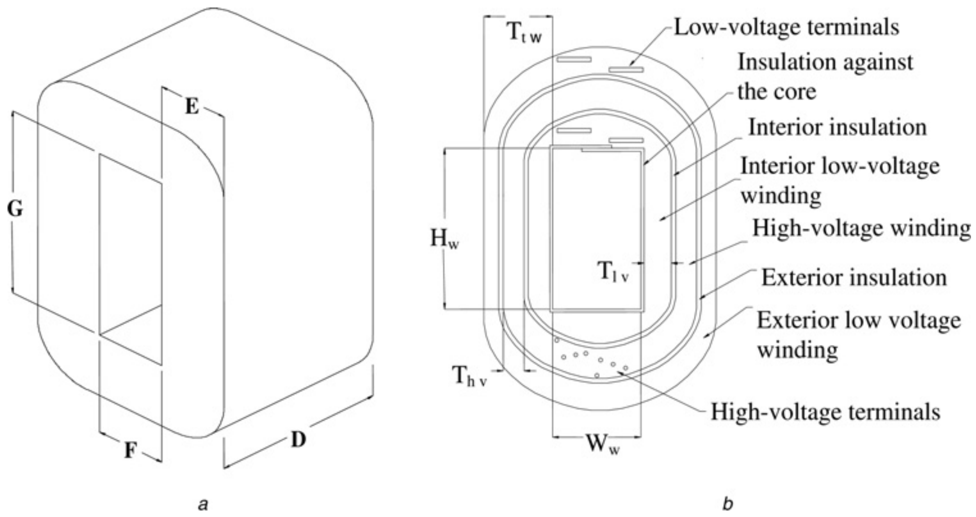

Figure 8 *Active part of single-phase shell-type transformer*

a Core dimensions
b Low–high–low winding dimensions

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such transformers exceed the maximum dimensions for the transportation and/or the maximum dimensions specified in the standards.

In addition to the already presented results, the following interesting conclusions have been drawn:

- The length of an aluminium winding is on average 15% larger than the length of a copper winding for same power.

- An aluminium transformer requires on average 20% more core weight; see Fig. 7*a*.

- The weight of the aluminium windings is on average 25% less than the weight of copper windings. To determine this average, the following expression for each transformer rating is used: (weight of Cu windings − weight of Al windings)/weight of Cu windings.

- An aluminium transformer requires 45% more oil than a copper transformer. This conclusion permitted the use of aluminium in winding for dry-type power transformer in 1955 [9]; see Fig. 7*b*.

The dimensions of core and low–high–low winding for a 25 kVA transformer are shown in Fig. 8. For a copper transformer, $E = 46$ mm, $D = 152.4$ mm, $F = 85$ mm, $G = 175$ mm, $T_{hv} = 37.98$ mm, $T_{lv} = 14.217$ mm, core weight = 70.42 kg, transformer weight = 140.04 kg, $H_w = 158.4$ mm, $W_w = 99$ mm, $J_{LV(Cu)} = 1.24$ A/mm^2 and $J_{HV(Cu)} = 1.32$ A/mm^2. For an aluminium transformer, $E = 35$ mm, $D = 190.5$ mm, $F = 125$ mm, $G = 225$ mm, $T_{hv} = 55.66$ mm, $T_{lv} = 25.17$ mm, core weight = 81.63, $H_w = 196.5$ mm, $W_w = 77$ mm, $J_{LV(Al)} = 0.58$ A/mm^2 and $J_{HV(Al)} = 0.62$ A/mm^2. We presented results in this section considering realistic and recent prices (November 2009) for copper and aluminium. The source of our prices for conductors is given in [24].

Today many distribution transformer manufacturers are moving towards the manufacturing of aluminium transformers. There are companies that manufacture distribution transformers with aluminium, for example, Cooper Power Systems [42], ABB, General Electric, Howard Industries, and so on. Almost all the large power transformers are manufactured with copper windings.

In the near future an extension of this study will be made, and we are planning to compare copper–copper transformers against aluminium–aluminium transformers in many aspects, such as current distribution in transformer windings [43], ferroresonance [44] and inrush current [45].

9 Conclusions

This paper has presented a comparison of distribution transformers with windings built with copper against aluminium. The advantages and disadvantages of the two materials have been analysed on the basis of conductivity, mass density, cost, connectivity, oxidation, machinability and behaviour under short-circuit. The selection between the use of copper or aluminium is not an easy task since many factors must be considered. In this paper, a parametric analysis of transformer designs as a function of the cost of copper against aluminium has been presented. The paper has established the winding material cost range, for different transformer ratings, indicating when it is more economical to build the transformer windings with copper or with aluminium. The study has been carried out with a field-validated TDO computer program, which minimises the TOC satisfying a set of construction and operating constraints. The analysis has shown that using current prices (November 2009) for copper and aluminium unit cost, aluminium is the best choice for transformer winding for transformers with rated power lower than 190 kVA. On the other hand, for 190 kVA transformers and higher, copper is better than aluminium because TOC of copper transformers is lower (since copper allows the use of less core material, less insulation, less structural steel for the oil tank and less oil).

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