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Performance Comparison of Carbon Nanotubes with Copper and Aluminium as Winding Material in Transformer

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Abstract

Objectives: Transformers are used in almost every industry; therefore further improvement in their efficiency is always desirable. The objective of this work is to study the potential of Carbon Nanotubes to replace copper/aluminum in transformers. **Methods/Analysis:** In this work, FEM (Finite Element Method) technique based planar model of an aluminum-wound transformer is developed in FEMM software. The magnetic and steady state heat flow analysis of this transformer has been carried out. Then, the thermal and electrical properties of aluminum windings are replaced with that of new carbon based nanomaterial; Carbon Nanotubes (CNTs) and copper respectively to measure the effect on the performance of the transformer. Theoretical electrical conductivity of CNTs, which is much higher than that of macroscopic yarns till date, has been used. **Findings**: The comparison of maximum winding I2R losses and maximum winding temperature rise, when winding material is taken as aluminum, copper and CNT respectively, has been done. Also, weight of the conductor required has been compared. Maximum winding I2R losses and maximum winding temperature rise obtained in case of CNTs are lower than that in case of copper and aluminum. Weight of the conductor is also less than copper/aluminum. **Application/Improvement:** Previous work on use of CNT windings in transformer have demonstrated that it works in accordance with the classical theory of transformers. In this work, the effect on transformer winding losses and temperature rise has been analyzed when conventional winding materials are replaced by CNTs.

Keywords: CNT, Electrical Conductivity, FEMM, Losses, Temperature Rise, Transformer

1. Introduction

Carbon Nanotubes (CNTs) are basically one dimensional allotropes of carbon and belong to fullerene structural group. When one, two or more sheets of graphene are rolled into a cylinder, it is called SWCNT (Single Walled), DWCNT (Double Walled) and MWCNT (Multi Walled) respectively[1].

CNTs have already outperformed copper interconnects in integrated circuits[2]. CNT nanoelectrodes can be used to improve the performance of Lithium ion Batteries (LiB)[3]. A permanent magnet synchronous machine prototype made by replacing windings made of copper with carbon nanomaterial has been presented in[4]. A generating efficiency of 0.69 was obtained by using CNT yarn having electrical conductivity around 3.4 MS/m as winding

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material[4]. Also, a working prototype of standard high frequency transformer has been reported in[5]. In this prototype, copper wires were replaced with CNT wires and prototype was found to demonstrate agreement with the classical theory of transformers. However, losses are not discussed in this work.

2. Theoretical Properties of Carbon Nanotubes

CNT is also known as 'magic material' owing to its distinguished properties. These have shown high thermal conductivity, theoretically up to 6000 W/(K*m)[6,7]. A high thermal conductivity of 635 W/(K*m) has been reported even in macroscopic yarn available[8]. A very low density value of 1500 kg/m^3 for assembly of SWNTs has been reported[8,9]. Young Moduli variation was found between 0.25-0.95 TPa which indicates high tensile strength[10,11]. CNTs show "Ballistic transportation" i.e. charge carriers can travel without scattering. Therefore, individual SWCNT can carry maximum current densities as high as 100 MA/cm^2 theoretically[12]. Electrical conductivity of around 100 MS/m at room temperature has been reported for individual single walled armchair CNTs[13]. CNTs have also shown better structural stability than copper while they were submerged into different corrosive solutions[14]. The temperature coefficient of resistivity for CNT fibers was found to vary between -0.001 K^{-1} and 0.002 K^{-1}, which is lower than that of copper and aluminium[8,15]. A lower temperature coefficient of resistivity is desirable as the conductor will show lesser variation in resistivity.

3. Transformer Model

The three phase transformer under consideration has the rating of 100 KVA, 11/0.433 KV. The windings are made of aluminum and primary and secondary sides are connected in Delta-Star. The transformer geometry created in FEMM is shown in Figure 1.

The geometry is created in planar mode by determining the Cartesian coordinates for each point. The LV (Low Voltage) windings, placed near the core consists of one coil per phase. The HV (High Voltage) windings placed around LV winding consists of four coils per phase.

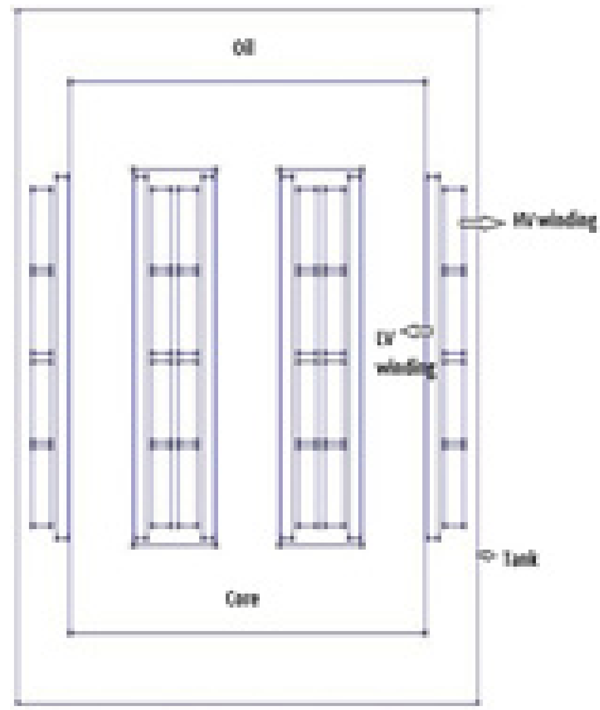

Figure 1. Transformer geometry created in planar mode.

3.1 Magnetic Analysis

The coils and currents have been modeled using 'circuit' property. The LV winding turns on the left side of the core are assigned negative number and on the right side, positive number. An opposite convention is used for HV turns as suggested in[16]. The laminated CRGO core with non-linear magnetization characteristics has been used. The thickness of laminations is 0.27 mm and the fill factor is 0.97. The values of peak full load phase currents used to calculate maximum winding I^2R losses are 188.571 Amperes and 4.285 Amperes for LV and HV respectively. Assuming that the flux doesn't exist outside the transformer tank, the boundary condition has been taken as

$$A = 0 \tag{1}$$

Where A is vector potential.

Eddy current losses in winding occur due to current flowing perpendicular to load current[16]. As CNT is one dimensional in nature, it is conductive only in processed direction; therefore eddy current losses will be very less

Table 1. Losses obtained from magnetic analysis of the model with aluminum as winding material

Parameter	Design Value	Obtained from FEMM
Maximum LV I^2R losses at 75^0C (W)	612	595
Maximum HV I^2R losses at 75^0C (W)	967	969

than that generated in conventional materials. Since exact value of electrical conductivity of CNT in x and y direction is not known, only I^2R losses of each material can be compared.

3.2 Heat Flow Analysis

In the heat flow analysis of the same transformer, the losses obtained in different blocks in magnetic analysis above are converted to losses per cubic meter and used as source of heat generation in respective blocks. The stray losses in windings and structural steel have not been accounted for. The volumetric heat capacity is obtained by multiplying heat capacity with density for each block material. The density of core is 7650 Kg/m^3.

Oil properties i.e. specific capacity, thermal conductivity, density has been selected corresponding to top oil temperature rise of 40^0C for natural ester[17]. The ambient temperature is taken as reference and temperature rise is calculated by subtracting ambient temperature from output temperature. Ambient temperature is set to 20^0C.

Two types of convective heat flow boundary conditions are applied-solid to oil and oil to air. It is assumed that no convective heat transfer from oil to air occurs at the bottom boundary of transformer tank. The convective boundary condition in FEMM is given by Equation (2)[18].

$$k\frac{\partial T}{\partial n}+h(T-T_0)=0 \quad (2)$$

Where h is heat transfer coefficient, T_0 is temperature of ambient cooling fluid, k is thermal conductivity and T is output temperature.

4. Results and Discussion

This three phase transformer model is now simulated with the theoretical electrical and thermal properties of aluminum, copper and CNT respectively. The results obtained in case of aluminum are as given by Figure 2, Table 1 and Table 2.

Table 2. Results obtained from heat flow analysis of the model with aluminum as winding material

Parameter	Design Value	Obtained from FEMM
Maximum Winding Temperature Rise (in ^0C)	50	48.5

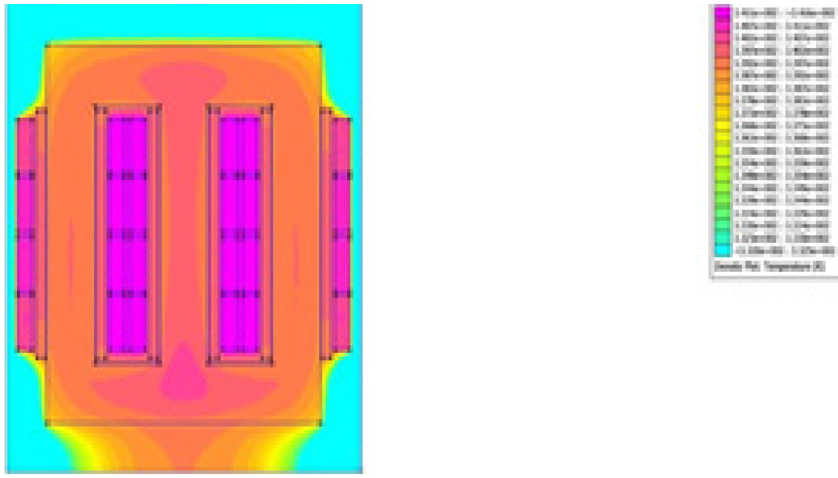

Figure 2. Heat flow simulation result with aluminum as winding material.

Table 3. Material properties used in magnetic analysis of the model

Material	Electrical Resistivity (at 20 ^{0}C) [ohm m]	Temperature Coefficient of Resistivity [per^{0}C]	Electrical Conductivity (at 75^{0}C) [MS/ m]
Al	2.65 x 10^{-8}	0.00429	30
Cu	1.68 x 10^{-8}	0.00386	50
CNT	1 x 10^{-8}	0.002	90

Table 4. Material properties used in heat flow analysis of the model

Material	Thermal Conductivity [W/ (m*K)] (at 273 K)	Volumetric Heat Capacity [MJ/(m^3*K)]	Density [Kg/m^3]
Al	236	3	2760
Cu	401	3	8960
CNT	635	6.3	1500

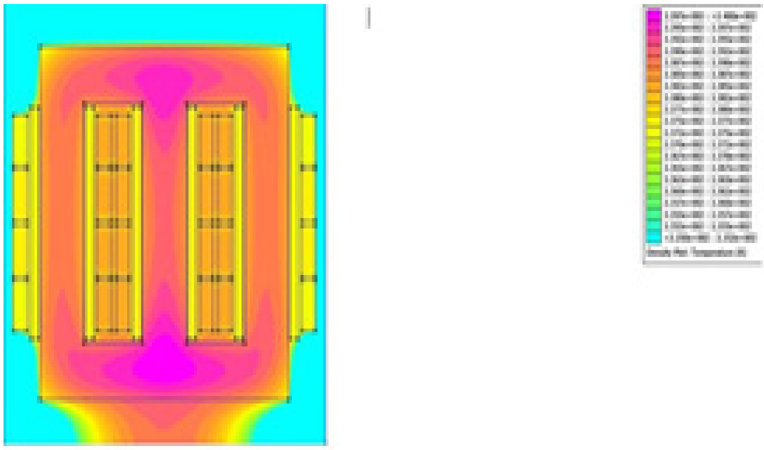

Figure 3. Heat flow simulation result with copper as winding material.

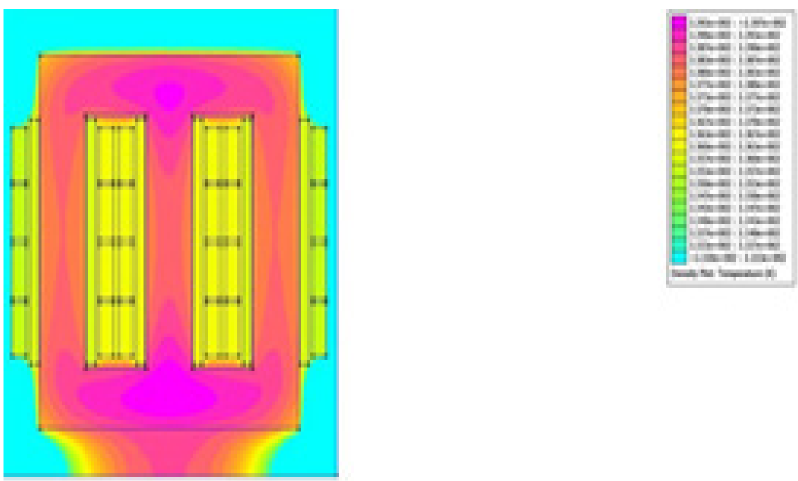

Figure 4. Heat flow simulation result with CNT as winding material.

The error obtained in Table 3 and Table 4 is small enough and we can say that the model can predict the resistive losses and internal temperature rise closely. The aluminum properties can now be replaced with copper and CNT properties given in Table 3 and Table 4. The simulation result for heat flow model with copper and CNT as winding material is shown in Figure 3 and Figure 4 respectively.

Also, the calculation of conductor weight required can be done analytically. Table 5 shows the summarized results obtained in above paragraphs.

Table 5. Results obtained from magnetic and heat flow analysis of the model for different winding materials

Winding Performance Parameter	Aluminum	Copper	CNT
Maximum I^2R Losses (W)	1564	937	519
Approximate Maximum Temperature Rise (^{0}C)	48.5	45	43
Weight (Kg) of uncovered conductor	72	234	40

It is found in the work, that the maximum winding I^2R losses are reduced by 45% and 67% when copper and aluminum respectively are replaced by CNT as the winding material. In addition to this, the maximum rise in winding temperature and weight of the transformer winding is also reduced.

5. Conclusion

With the dimensions of transformer remaining the same, CNT wound transformers will have lesser resistive losses than copper/aluminum wound transformers. Reduced loss will generate lesser heat and in turn lower temperature rise in windings. Also, the resultant transformer will be lighter. Thus, assuming macroscopic yarns will be able to reach theoretical values of electrical conductivity in future; CNTs can deliver more efficient transformers. This analysis has been performed by replacing material properties while keeping the dimensions of transformer same. However, optimization of transformer design in accordance with the high current carrying capability of CNTs will lead to even lighter transformers. The exact method of calculation of eddy current losses in case of CNTs also needs to be developed. However, due to one dimensionality of carbon nanotubes, eddy current losses will be minimal. It will further add to the efficiency of the transformers. The major challenge at present is the development of more efficient spinning and processing techniques which can preserve the properties of individual Carbon Nanotubes while forming macroscopic yarns.

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