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Comparitive Analysis of Copper and Carbon Nanotubes Winding Based Transformer

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Abstract — *Electrical transformers have been thoroughly studied and are considered to be a matured technology. Further significant improvement in their performance would require introducing new materials, with better properties, which can replace the conventional materials. Carbon Nanotube (CNT) fibers show amazing properties like high electrical conductivities, high strength and light weight. Although the value of electrical conductivity achieved in macroscopic yarn till date is less than that of copper, it is expected to improve significantly with more research. Therefore, CNT is considered as a promising candidate to replace copper as better winding material in near future. This paper presents comparative analysis of a transformer, in terms of resistive losses, when winding material is taken as copper and CNT respectively.*

Keywords- CNTs; copper; transformer; electrical conductivity; losses

I. INTRODUCTION

Carbon Nanotubes (CNTs), also called 'magic material', are one dimensional allotropes of carbon. It belongs to fullerene structural group. When graphene, a sheet of single layer of carbon atoms, is rolled to form a cylinder, it is called carbon nanotube. Depending on number of graphene sheets rolled, these are of three types. Single Walled carbon nanotube (SWCNT) is formed when one sheet of graphene is rolled in cylindrical form (Figure 1). Double walled carbon nanotube (DWCNT) comprises of two graphene sheets (Figure 2). When more than two graphene sheets are rolled, Multi walled carbon nanotube (MWCNT) is formed (Figure 3).

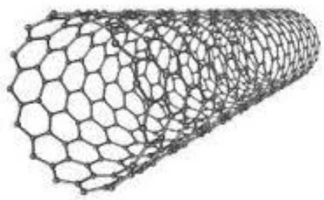

Figure 1. SWCNT

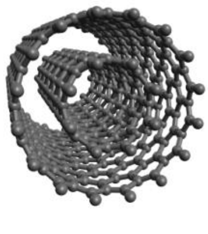

Figure 2. DWCNT

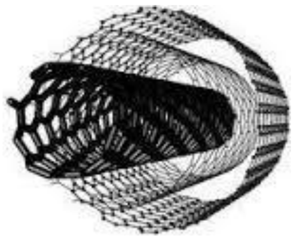

Figure 3. MWCNT

Due to its outstanding properties, CNTs can find various applications in electrical systems. Choi *et al.* has reported significant enhancement in thermal conductivity of insulating oil used in transformers by using dispersion of carbon nanotubes in ethylene glycol [1]. CNTs have already emerged as attractive alternative of copper interconnects in integrated circuits [2]. Performance of Lithium ion Batteries (LiB) can be improved by using CNT nanoelectrodes [3].

Transformers are widely used in industries, substations, generating stations, and transmission and distribution systems to increase/decrease the level of voltage or for just electrical isolation of two circuits. As the demand for energy is continuously increasing, it is desired to minimize the energy losses of all equipments and same is the case with transformers.

In this paper, results of a transformer model, if the windings were made of CNT, have been studied. Thus the potential future role of CNT in improving the performance of various electrical systems has been discussed.

II. CARBON NANOTUBES AS CONDUCTORS

CNTs have been found to exhibit distinguished properties like:-

- High thermal conductivity, theoretically up to 6000 W/(Km) [4][5].
- High tensile strength, variation of Young Moduli found between 0.25-0.95 TPa [6].
- Low density, theoretical value of 1500 kg/m^3 for assembly of SWNTs [7] [11]

But for this paper, we will limit our discussion to electrical conductivity. CNTs show “Ballistic transportation” i.e. charge carriers can travel without scattering. It allows individual SWCNT to carry maximum current densities of order of 100 MA/cm^2 theoretically, which is higher than most conventional metals including copper[8]. However, electron transport in CNTs greatly depends on synthesis process.

The conductivity of copper, at room temperature, is 58 MS/m [9].Individual single walled armchair CNTs, , have shown conductivity around 100 MS/m at room temperature [10]. However, preserving these conductivity levels while manifesting individual CNTs in form of macroscopic wires is a challenge. Rice University and Teijin Aramid BV, has prepared CNT yarn measured with conductivity approximately 3.4 MS/m. [11] This value increased to 5 MS/m upon doping with iodine [11]. Pyrhönen Juha et al have presented results of a prototype construction, made by replacing windings made of copper with Carbon Nanomaterials in Permanent magnet synchronous machine. CNT yarns with conductivity around 3.4 MS/m have been used. A generating efficiency of 0.69 was obtained with CNT as winding material as compared to 0.80 with copper as winding material [12]. A working prototype of standard high frequency transformer has been reported where copper wires were replaced with CNT wires [13]. It was found to demonstrate agreement with the classical theory of transformers indicating potential application of CNTs in transformer windings. With continuous research, the theoretical values of conductivity are likely to be achieved in macroscopic wires as well in near future. This requires development of better synthesis and spinning techniques.

Also, 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 [11]. A lower temperature coefficient of resistivity is desirable as the conductor will show lesser variation in resistivity.

III. TRANSFORMER MODEL

In this paper, the E-core transformer model in COMSOL Multiphysics software has been used for simulations. The transformer supply voltage used is 25 KV and supply frequency is 50 Hz. The primary winding consists of 300000 turns and the secondary winding consists of 300 turns. Both the primary and secondary side circuit resistance is 100 ohms. The transformer geometry is shown in Figure 4.

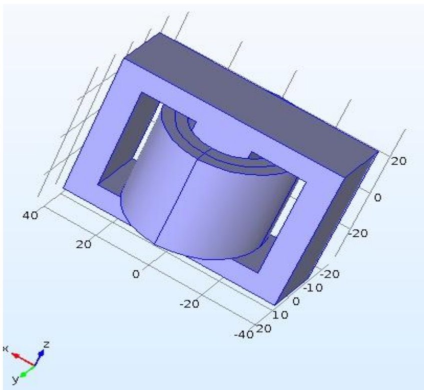

Figure 4. Transformer Geometry

Keeping electrical conductivity value of windings as 58 MS/m, the resistive losses with copper as winding material have been calculated. The graph obtained for Resistive losses in windings (W) vs. Time (seconds) has been shown in Figure 5. The peak resistive losses come out to be around 0.04 W.

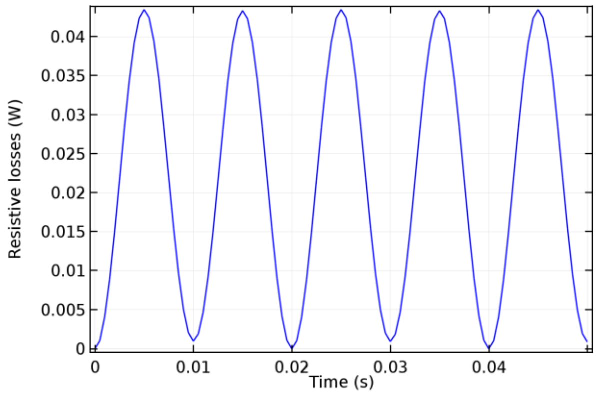

Figure 5. Variation of resistive losses in windings with time for copper

Keeping electrical conductivity value of windings as 100 MS/m (theoretical value), the resistive losses with CNTs as winding material has been calculated. The graph obtained for Resistive losses in windings (W) vs. Time (seconds) has been shown in Figure 6. The peak resistive loss comes out to be 0.024 W.

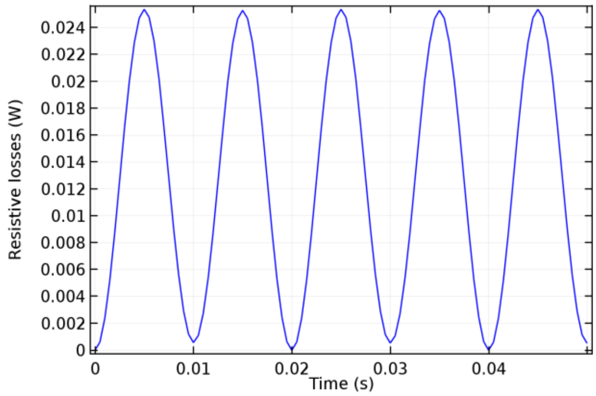

Figure 6. Variation of resistive losses in windings with time for CNT

The comparison of Figure 5 and Figure 6 shows lower resistive losses in windings in case of CNT, which is expected due to higher conductivity.

IV. CONCLUSION

A single phase, e-core transformer model have been simulated with the theoretical conductivity values of copper and CNTs. With CNT, 40% lesser resistive losses as compared to copper have been seen. As higher conductivity of individual CNT wires have already been established, CNTs can prove to be very good conducting material. It has been seen that with theoretical levels of conductivity reached in macroscopic CNT wires, the losses and thus the efficiency of electrical machines is likely to improve. In this work, effect of conductivity solely has been taken into account. Further work will include modifying the model to incorporate the effect of temperature coefficient of resistivity also and thus carrying out the heat analysis of the transformer.

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