Emerging Applications of Carbon Nanotube Wires in Electromagnetic Machines

Sumeet Chaudhary, Shweta Avinash Nair, Francois Tchondou Nyamsi, Mark Schulz, Massoud Maxwell Rabiee and Marc Cahay

Abstract**—** Currently, there is a strong need for improving the efficiency of electromagnetic machines as they have become an increasing part of our daily lives. The field of electric machines has seen steady growth in the last decade. However, no recent significant breakthrough has been made in the design of electric machines. To bring about a noteworthy change in this field, it is likely that new materials must be used. The recent advances made in the synthesis of carbon nanotube (CNT) materials have opened new doors of opportunity for the macroscopic application of CNT fibers. It has been found that CNT based wires have advantages over copper wires in terms of stability at extreme conditions, such as working at high temperatures, and the ability to withstand harsh chemical treatments. It has been shown that CNTs, owing to their "one dimensional" and symmetrical structure, can move charge carriers along the tube without scattering. If this behavior could be scaled-up to macroscale wires, carbon nanotube wire would replace the currently used copper wires. Due to the absence of scattering, the resistivity of individual CNTs have been found to be in the order of 10^{-8} Ωm. However, in macroscale carbon nanotube wire, the resistivity is about 100 times greater than the resistivity of individual nanotubes. The positive aspect is the density of carbon wire is about 1/5 the density of metal wire. In this paper, an extensive study is described on the state-of-the-art advances made in the synthesis of CNT based continuous fibers and the possibility of using CNT wires as an alternative to the traditionally used copper (Cu) and aluminum (Al) conductors in electromagnetic devices. As shown from the results of the CNT based electromagnetic machines investigated, a significant amount of research is still required to improve the performance of CNT macrostructures such as yarns and sheets in hope of replacing metal conductors.

Keywords**—**Electrical machines, electromagnetic devices, CNT yarn.

I. Introduction

The most widely used conductor material in electrical machines is Cu. At room temperature, the conductivity of Cu is 59.6 MS/m, and its resistivity temperature coefficient is 3.886 x 10^{-3}. In spite of high conductivity, a significant share of conductivity losses occurs in the Cu windings of electrical machines. This phenomenon is called Cu loss or joule loss. Figure 1 shows the power balance of a typically enclosed 4kW IE3 induction motor, wherein 12% of the electrical energy is converted into heat at the rated power of the machine. The proportion of the Cu losses in the machine is high, around 62.5% of the total losses and 7.5% of the rated power. [1]

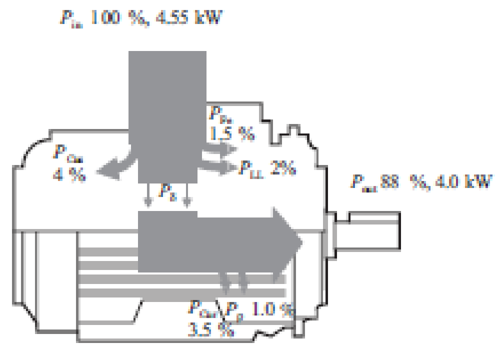

Figure 1. Sankey diagram of a 4 kW two-pole induction motor. P_{Fe}, iron losses; P_{Cus}, resistive losses of the stator; P_{ad}, additional losses; P_{δ}, air-gap power; resistive losses of the rotor; Pρ, friction losses[1][image reproduced by permission of John Wiley & sons]

Because the demand for valuable metals such as Cu is likely to increase tenfold as developing economies surge ahead and because the production of Cu requires energy-intensive extraction from its ore, Cu is becoming energy-expensive and a carbon-intensive material for use in rotating electrical machinery. Cu has high density (8.96 g/cc), which means that Cu products are heavier than other products of the same size. Cu wires also have a skin effect, a phenomenon which occurs when operated at higher frequencies. Moreover, the operating winding temperature of electrical machines is currently in the range of 120˚C. At that temperature, Cu conductivity usually decreases to the level of 42.9 MS/m. This is 72% of the conductivity at room temperature. Hence, to improve the efficiency of electric machines and to make them operable at high frequencies and temperatures, it is imperative to investigate the possibility of replacing Cu with an alternative material.

II. CNT as an Alternative to Copper

While metals seem to have hit the pinnacle of their utility in electromagnetic devices, the emerging nanomaterials technology could be an alternative to copper. Even though theoretical physicists and experimentalists have been working on CNTs for over two decades, it is only recently that the use of CNTs in mainstream applications has emerged.

Structurally, armchair CNTs are highly conductive [2]. Owing to the "one-dimensional" and symmetric structure of a CNT, charge carriers can travel along the nanotubes almost without scattering, which is a phenomenon commonly referred to as "ballistic transportation". The negligible amount of scattering allows the CNT to carry very high current, typically on the order of 100 MA/cm^2. Individual single-walled armchair CNTs at room temperature have resistivity values in the range of 1x10^-8Ωm [3], and the resistivity temperature coefficient is negative(-0.2x10^-3K) [4]. This is discussed in more detail in section III.

The electrical properties of CNT macrostructures such as yarns and sheets have been found to be much lower than those of individual CNT [5]. However, the electrical properties of CNT yarn are improving and is predicted that the conductivity of CNT will someday catch up with the conductivity of Cu.

CNT materials have been used previously in electronic devices [6,7]. Nanostructured carbon materials have been evaluated for applications such as energy storages [8,9] and solar cells [10]. The results show that nanomaterials have the potential to be used as electrode materials, e.g., as a cathode for wearable and lightweight energy storage devices [11,12,13].

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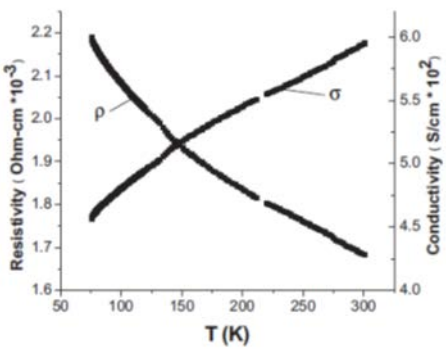


Figure. 2. Temperature dependence of the resistivity (ρ) and conductivity(σ) of a spun CNT fiber [14] [Image reproduced by permission of John Wiley & Sons].

III. PROPERTIES OF CNT

CNTs are allotropes of carbon. Their structure is illustrated by rolling a one atom thick sheet of carbon called graphene at specific and discrete angles. Nanotube actually grow by precipitating a tube out of a catalyst particle and the tube increases in length with time. The combination of the radius and the rolling angle determines the properties of the nanotube. Typically, CNTs are categorized into two types: single-walled CNT (SWCNT) or Multi-walled CNT (MWCNT).

A. SWCNT:

The majority of SWCNTs have a diameter close to 1nm. There are three basic types of CNT structures, depending on how the graphene sheet is rolled: (i) zigzag: where the hexagonal lattice forms a zigzag pattern on the circumference of the nanotube, (ii) armchair: where the lattice is turned around by 90˚ with respect to the zigzag and (iii) chiral: is when any other pattern appears along the circumference.

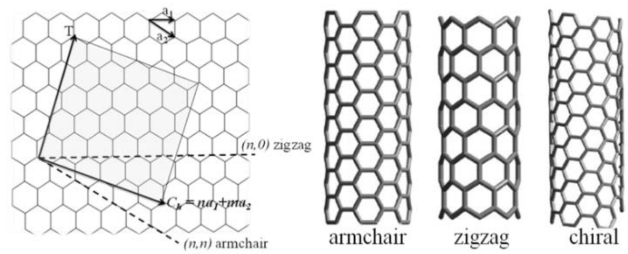


Figure. 3 A sheet of graphene rolled to illustrate different types of SWCNTs [© 2010 Choudhary V, Gupta A. Published in [15] under CC BY-NC-SA 3.0 license. Available from: http://dx.doi.org/10.5772/18423].

B. MWCNT:

MWCNTs are typically comprised of multiple concentric carbon nanotubes. The structure of the multi-walled nanotubes can be defined using two models: (1) Russian Doll Model or (2) Parchment model. In the Russian Doll model, sheets of graphene are arranged in concentric layers while in the Parchment model, a single sheet of graphene is rolled in around itself, resembling a scroll of parchment or a rolled newspaper.

Individual nanotubes belong to the class of quantum wires. They are long, hollow and extremely narrow, with diameters in the range of several atomic distances. The electron wavevectors are quantized along the circumference of the nanotubes and the charge carriers are free to travel along the axial direction. Experiments have confirmed that similar to other quantum wires, CNTs show ballistic electron transport [16,17]. Theoretical calculations have shown that at room temperatures, electrons in CNT can travel micrometer range distances without experiencing scattering at room temperature. The maximum mean free path was experimentally measured to be 1 µm [16], which is high when compared to copper, where the maximum mean free path is 40 nm [18].

In quantum wires, the classical formula of resistance, R=ρ*l/A* (ρ is the resistivity, *l* is the length and *A* is the area of the conductor) does not hold true. If the diameter of the wire is extremely small, then quantum confinement is experienced by the electrons in the transverse direction. Quantum confinement always leads to a finite conductance which is a multiple of G=2e^2/h (where e is the electron charge and h is the Planck's constant) and the value of conductance tends to increase with the number of quantum channels. This holds true even for cases of fully ballistic transport, implying that the non-zero resistance is due to the contact resistance and not the scattering within the quantum wire. The maximum conductance of an individual SWCNT is around G =4e^2/h~ 0.15mS [17,19]. Based on this value and the experimentally obtained ballistic transport length scales, the resistivity of individual SWCNT at room temperature has been found to be as low as 10^{-6} Ω/cm[16]. So far, the lowest resistivity reported for MWCNT is around 5 x 10^{-6} Ω/cm [20].

Diffusive transport is usually observed in CNTs where the length is larger than the ballistic regime [21]. High temperatures or electric fields could also lead to the suppression of ballistic transport. However, the maximum current density of an individual SWCNT at room temperature has been experimentally determined to be around 10^{-9}-10^{-10} A/cm^{-2}, which is still higher than the critical current density of superconductors [22-24].

Disorders such as structural defects formed during the synthesis process [25] or the physical distortions evoked by strong mechanical forces [26] may deteriorate the electrical performance of CNTs by bringing about a change in the electron transport in CNTs. It has been established that semiconducting nanotubes are the most sensitive to disorder [27]. The presence of a single vacancy defect in the channel of a small diameter metallic carbon nanotube can decrease its conductivity by a factor of 2. The presence of more than one vacancy in the channel can further drastically decrease the conductivity [28].

In addition to the unique electrical properties, CNTs are blessed with excellent mechanical properties. The experimentally obtained values of tensile moduli, tensile strength and tensile strains have been found to be approximately 0.3-0.95 TPa, 10-100 GPa and 6-12% respectively [29-31].

The thermal conductivity of CNTs in the axial direction has surpassed some of the best-known heat conductors such as diamond. The thermal conductivity of isolated SWCNT and MWCNT in the axial direction has been determined to be 3500 and 3000 W/Mk respectively.

All the above-presented data show that CNTs have all the characteristics of a perfect electrical conductor: very high electrical conductivity, high current carrying capacity, good strength and good thermal conductivity. Hence, CNT may be suitable materials for electrical engineering applications.

IV. Fabrication of CNT Yarn

Typically, there are three methods for CNT synthesis. One is the arc discharge method, which uses high voltage and discharge between the anode and the cathode to make CNTs. The quality of the CNTs produced using this method is high but the quantity produced is low. The second method is the laser ablation method, which is a very expensive method as it uses a laser and a high-quality graphite target. The third and the most sought-after method is the chemical vapor deposition (CVD) method. This method uses catalyst particles as seeds. CNT growth is a result of hydrocarbon decomposition, diffusion and adsorption on catalysts. However, this method which produces vertically aligned CNTs is very expensive as there are many steps involved in this CNT process. It begins with a Si wafer process followed by coating a catalyst layer on the Si and finally putting the wafer into a high-temperature furnace (750 to 900 ºC) for CNT synthesis. This process typically takes several hours taking into consideration the time required for cooling and cleaning the quartz tube. Nevertheless, there is another CVD method which can produce CNTs in large quantities. This is called the Floating Catalyst CVD.

There are three stages involved in the Floating catalyst CVD method: (i) feedstock evaporation and decomposition, (ii) CNT growth, and (iii) sock formation. The feedstock mixture enters the high-temperature zone after injection. The high temperature induces feedstock decomposition into iron catalyst particles and a carbon source. CNTs then grow from the catalyst particles and aggregate into a sock near the outlet of the reactor tube. As mentioned earlier, the electrical properties of CNT macrostructures such as yarns and sheets have up until now been found to be lower than those of individual CNTs. However, due to the increased research and developmental efforts the properties of CNT yarns and sheets might approach the conductivity of Cu in the future.

V. Examples of CNT Based Electrical Wires

In order to prove that CNTs can be used as a conductor, researchers have used CNT as an ethernet cable [27] and a solenoid [27]. Figure 4(a) shows a CNT based ethernet cable which has been successful in transferring data at the rate of 10 MB/sec. Figure 4(b) shows a 10 turn CNT wire, which was wound onto a non-magnetic core. On applying a voltage of 9V at a frequency of 50 Hz, the magnetic field was found to be 150 µT. The results obtained from the CNT coil experiment can be improved by making changes in the number of turns, shape of the coil or introducing a magnetic core.

The work done on the development of a CNT based solenoid inspired researchers to develop the working prototype of an electrical machine-transformer. Substituting Cu with CNT can be beneficial for applications, where weight and/or high frequency is of importance because CNT is lighter than Cu and at the same time, since it is blessed with a structure that resembles a litz wire, the CNT yarn does not suffer from skin effect at higher frequencies. The details of a CNT based transformer is given in Section VI.

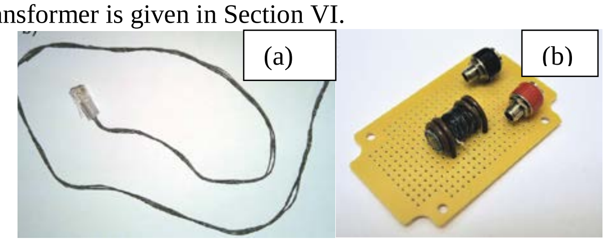


Figure 4(a) CNT based ethernet cable [27] (b) CNT wire wound on a non-magnetic core [27] [Image reproduced by permission of John Wiley & sons].

VI. Application of CNT Yarns in Electromagnetic Devices

A. *Prototype Transformer with CNT Windings*

Transformers are among the most common electrical devices along with motors. A transformer consists of a primary and a secondary winding. When a current is passed through the primary winding, a magnetic flux is induced in the core of the transformer. The induced magnetic flux is dependent on the amplitude of the current and the number of turns on the primary coil. The magnetic flux induces an electromotive force (EMF) on the secondary windings. The magnitude of the EMF depends on the number of turns on the primary and secondary coils.

The CNT based transformer was developed by L Kurzepa et.al [32]. It is comprised of CNT wires insulated with a silicone paste. The primary winding has 21 turns while the secondary winding has 12 turns. Both the primary and the secondary windings were placed next to each other on the central column of a core. The core was made by tightly joining two classical E-shaped elements with minimal air-gap, as shown in Figure 5 (a).

For comparative testing, an additional secondary coil of Cu wires, consisting of 12 turns was wound on top of the secondary CNT coil. A schematic of the transformer is shown in Figure 5(b). For the core used in this experiment, the optimum frequency range was found to be 25-500 kHz. A significant increase in the core losses was observed above 500 kHz. Since the real part of the complex magnetic permeability was constant up to 1 MHz, the device was tested up to 1 MHZ frequency.

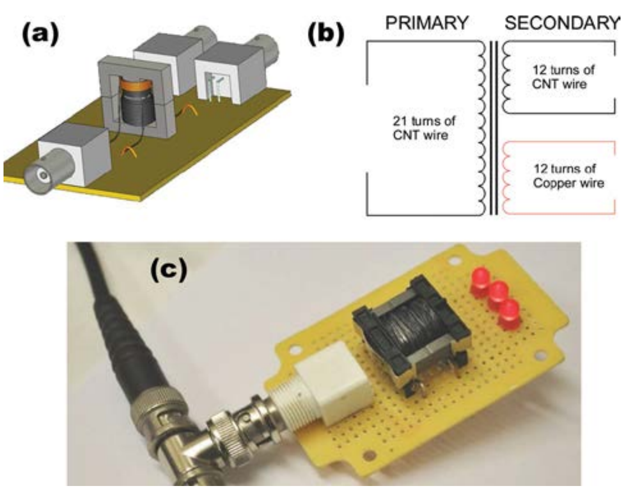
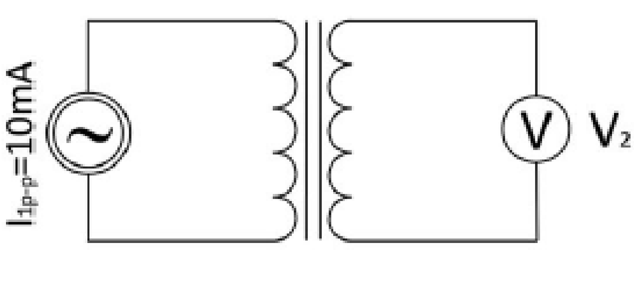


Figure 5(a) 3D schematic of the transformer [32] (b) Illustration of the windings [32] (c) Device in operation [32]. [Image reproduced by permission of John Wiley & Sons]

An open circuit test was performed on the device and the results obtained are shown in Figure 6. An output voltage was induced as a consequence to the excitation brought about by the application of an input current, having a peak-to-peak value of 10 mA and frequency ranging from 1-100 kHz, at the primary winding. The results obtained agreed with the classical theory of transformers and as expected the characteristics obtained were perfectly linear and were the same for both copper and CNT windings.



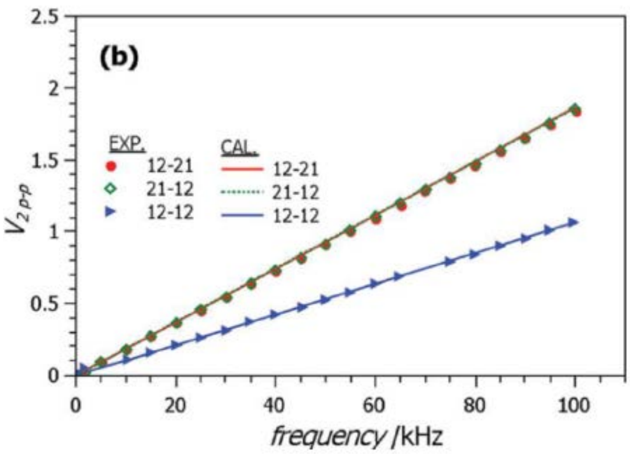


Figure 6(a) Illustration of the windings used for conducting the experiment (b) Output voltage across the secondary as a function of frequency. [32] [Image reproduced by permission of John Wiley & sons]

Another experiment was performed with Cu windings as the primary coil and the CNT coils as the secondary winding. A 150mV p-p was applied to the primary with frequency ranging from 1kHz – 1MHz and the output voltages across the secondary was recorded. It was seen that the output voltage does not depend on the frequency as in ordinary transformers. But when the same experiment was tested on 21 turns of CNT coil as primary and 12 turns of Cu and CNT as secondary, it was noted that at lower frequencies the output signal decays which indicates higher resistance in the CNT wires as compared to Cu. At higher frequencies, the losses due to high resistance of the primary windings is found to be negligible implying that the transformer operates in perfect agreement to the theory.The decrease in the resistance of the CNT windings will improve its performance.

B. *Prototype Motor with CNT Yarn Conductors*

CNT yarn with a conductivity of 3.4 MS/m was developed by Teijin Aramid at Rice University and researchers at Lappeenranta University of Technology used it to understand and demonstrate the use of CNT yarn in the stator windings of a motor[33].

The motor coil conductors are 1.2m long, and their measured resistance is 0.4Ω, yielding only 2.4 MS/m average conductivity while the predicted conductivity was 3.4 MS/m. To overcome the issue of the Teijin Aramid yarn being without insulation, the researchers at Lappeenranta prepared insulation by using Twaron yarns on Twaron paper. This caused high resistance in the insulation system and thus a design modification was required for the machine. The winding needed to have only a few turns to minimize the resistive losses in the low conductivity material and the machine needed to be excited by permanent magnets to avoid excitation losses in the highly resistive conductors.

The winding was used as a winding for the stator of a 3 tooth 2 pole motor. The rotor is made of four parts, two shaft parts, a stainless-steel tube and a cylindrical magnet with 50 mm length and 20 mm diameter. The stator stack end finger plates were manufactured to have semi-circular cross-sectional areas which makes the end winding bends as smooth as possible. The stator designed is shown in Figure 7(a). The machine was tested by connecting it back to back with a commercial grinding machine as shown in Figure 7(b).

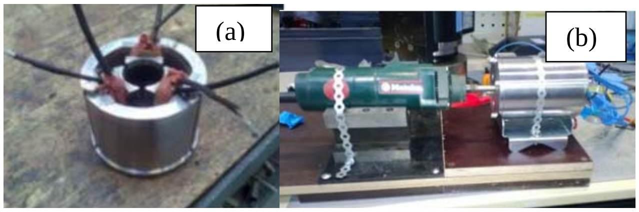


Figure 7(a) CNT windings used in the stator of a 3 tooth 2 pole motor (b) The motor is connected back to back with a commercially available commutator motor grinding machine to act as a generator.[33][Reproduced by permission of Praize Worthy Prize S.R.L]

The DC resistance of the stator assembly was measured at 3 different temperatures and was found to be 0.4Ω,0.416 Ω and 0.455Ω at 20˚C, 50˚C, 90˚C respectively. This shows that the CNT wires manufactured by Teijin Aramid have a slightly positive temperature coefficient for the resistivity and it amounts to approximately 40% of that of Cu. The no-load measurements yielded predictable behavior as the induced voltage increased linearly with speed until 10000 rpm. At higher speeds, the eddy current in the rotor magnet slowed down the increasing voltage slightly. Theoretically, the DC-resistivity of CNT yarns at higher temperature are significantly lower than that of Cu. The experimental results prove that more work needs to be done to be able to incorporate CNT materials into production lines.

VII. Conclusion

One of the key factors that can ensure the development of society is the ability to provide a reliable and highly efficient system for the delivery of electrical energy. The use of novel materials and technologies can bring about a radical improvement in the efficiency of energy transfer systems. One of the promising candidates that can fulfil this task is CNT.

For over a century, Cu has been used as an effective conductor in electrical machines. However, the need for improving the efficiency of machines has motivated researchers to find ways to decrease the losses of electrical machines. One of the most dominating losses suffered by most electrical machines is Cu loss. Hence, a slight improvement in the conductivity of the winding material can bring about a revolution in the development of electrical machines.

The ability to produce macroscopic assemblies of CNT has been the impetus to carry out research in replacing traditional metal wires. Recent developments in this field have made it possible to make CNTs with virtually no limit to their length and wide range of cross-sectional areas. The methods involved in the production of CNT are easy to scale up and cost effective. The materials obtained are usually of less density, making them useful for lightweight applications. Some of the properties of CNT has outperformed the traditional metal wires for example the fibers are capable of withstanding harsh chemical treatments where copper wires can be destroyed within hours or days. When strongly doped, the specific conductivity i.e. conductivity divided by density, of CNT may be higher than that of copper.

However, a significant amount of research is still required to be carried out to improve the performance CNT macrostructures such as yarns and sheets as evident from the results obtained by researchers who have attempted to use CNT yarns in electromagnetic devices. As previously mentioned, theory predicts that the conductivity of CNT is expected to increase with temperature. In addition, problems associated with skin effect at high frequencies is expected to be mitigated by use of CNTs and the use of which is more environmentally efficient. The continuous research and development efforts in this direction could bring in a new era in electric machine and device development.

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