Replacing Copper with New Carbon Nanomaterials in Electrical MachineWindings

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Abstract

Primilary,the objective is to find the higher conductivity wires for the winding rather than the traditional way of using copper wire to upgrade the performance of the machine.Thus the first electrical motor applying a textile material; carbon nanotubeyarn(CNT'S). The test motor output power as 40 Watts, it rotates at 15000 rpm, and has almost a 70 % efficiency.It can be replaced and operated in both alernating current and direct current motor .Thus in future windings made of CNTs may have a double conductivity compared with the present-day copper windings.cnt's will spin to form multifiberyarn hence it is possible to reduce the Joule losses(copper losses) in the windings to half of the present-day machine losses. Carbon nanotube yarns are eco friendly. The motors could also be operated in different dimensions and masses that could reduce the higher temperatures significantly . We expect that in the future, the conductivity of carbon nanotube yarns could be even three times the practical conductivity of copper in electrical machines . carbon nanoyarn tube significantly increses the potential to success.

Keywords: Electrical machine, winding material, carbon nanotube yarn, machine design, efficiency improvement, multifiber yarn.

1.Introduction

Since 2009, with the European Commission Regulation (EC) No 640/2009 continuous incremental improvement in electrical machines has contributed effectively to the low-carbon economy targets set by the European Union. Nonetheless, electrical machines are considered a fairly mature technology. This can be observed from the fact that radical innovations, which are usually pioneered in niches, seem to have a hard time to break out. Still, electrical machines hold the potential for significant improvement.Radical advances that would substantially affect the cost, efficiencies and performance of electrical machines call for the introduction of new elements. In particular, new coducuctive materials are needed to replace the traditionally used metals.

Many of the significant efficiency improvements in electrical machines have been initiated by an emergence of enabling new materials technology. Such emerging technologies have been the development of low loss magnetic circuit steel materials and high energy density Nevertheless, considering material physics, traditional materials are reaching their limits; they do not offer clear perspectives for disruptive development of magnetic circuits. Copper and aluminium have been Used as conductor materials in rotating machines ever since their introduction by electrical engineering pioneers of the nineteenth century. Substituting copper and aluminium for other metals does not provide a reasonable solution. Silver has only higher conductivity than copper. Moreover, it is an expensive metal. In principle, superconductivity could take the development of machines a giant step further while enabling also considerably higher flux densities than those observed with steel-core machines. Yet so far, no such materials could be developed that remain superconductive in temperatures where rotating electrical machines operate.

2.EMERGING NEW ALTERNATIVES IN NANAOTECHNOLOGY

Where metals seem to have hit a ceiling, the new nanomaterials may offer a case for more powerful improvement of electrical machines Armchair CNTs are, by structure, highly conductive . Because of the "one-dimensional" and symmetric structure of CNT fibre, the charge carriers can travel along the nanotubes almost without "scattering", which is a phenomenon that is commonly referred to as "ballistic transportation". Copper is the most commonly used conductor material in electrical machines. For comparison, the conductivity values for copper and other metals are the following. At room temperature copper has a conductivity of 59.6 MS/m and its resistivity temperature coefficient is $3.886\cdot10^{-3}$/K For silver, the respective values are63MS/m and$3.8\cdot10^{-3}$/K

3.ADVANTAGES OF CARBON OVER COPPER

It is Ta/Ia is the electrical characteristic Whereas N/Ta is the mechanical characteristic The speed is determined by the N/Ia SWNT's its a sheet of graphite introduced in a unicircular manner The heat losses of the copper is comparitively high The extraction of copper from ore,cradle to gate expence is very high compared with carbon The temprature of copper,alluminium,silver is low thus it increses the negative co-efficient of current flow Carbon space occupancy is 0.15% It increses the flow of positive conduction of current It is an electrochemical,quasi material in nature Thus the efficiency of carbon is high

4.THE DESIGN AND CONSTRUCTION OF SMALL PROTOTYPE WITH CNT'S YARN TUBE

Recently, Teijin Aramid BV, in collaboration with Rice University, has developed CNT yarn with conductivity in the range of 3.4 MS/m. At Lappeenranta University of Technology, we have launched a research project to investigate, understand and demonstrate the feasibility of using CNT yarn, in rotating machine windings. At Teijin Aramid, the CNT fibres are processed in a novel way and the fibres are used to assemble wire gauges, e.g. 26 and 39 AWG CNT based yarn. 39 AWG corresponds to 0.00632 mm^2 and has resistance of ca. 50 Ohm/m. The maximum allowable current in this wire is 0.7 A corresponding to 1100A/mm^2. In principle, it can operate at several hundreds of degrees Celsius. However, in our motor application a much lower current must be used because the present- day insulation materials should not be exposed to too high operating temperatures. The 26 AWG yarn type was selected for the test motor. This type has a cross- sectional surface of 0.1280 mm^2, an equivalent single wire diameter of 0.405 mm and corresponds to CNT yarn of approximately 2000 dtex. Each motor conductor is made of ten parallel 2000 dtex yarns. The motor coil conductors are 1.2 m long, and their measured resistance is 0.4 , yielding only 2.4 MS/m average conductivity whilst the predicted conductivity was 3.4 MS/m. The yarn has also a small positive temperature coefficient (0.0008/K) whilst we expected the yarn to have zero or a small negative temperature coefficient. The conductivity level of the sample conductors is thus very low. Therefore, the yarn can be used only for demonstration purposes; that is to show the potential of CNT yarn for application in an electrical machine.

Regarding the test motor manufacturing, we faced the problem that Teijin Aramid CNT-yarn is not provided with insulation. We solved the problem by preparing a tape of parallel conductors (with insulating Twaron yarns as side protection) on insulating aramid (Twaron) paper strip. The turn-to-turn insulation is thus made by using this kind of insulating paper. We recognized that, while having parallel conductors on a flat tape, this might increase the risk of circulating currents in the windings. However, as the winding material has high resistance we decided to ignore this problem for the test machine. Fig.1 illustrates the conductor material on an Aramid paper tape. For transport purposes the wires are wound on a large paper cylinder. The final conductor is spread on a 9 mm wide Aramid paper strip so that the surfaces of the flat conductor are insulated just on one side. The cross- sectional surface dimensions of the flat conductor with single-sided insulation are 0.59 mm

Fig.1. Ten parallel 26 AWG conductors (black ones) with aramid (Twaron) yellow yarns at the edges glued on aramid paper tape strips. In the Fig. the conductors are placed on a white paper cylinder for smooth transporting. The ends of the conductors have been treated by silver solution to allow for sleeve joints to external motor cables.

5.The Test Machine

The high resistance and complicated insulation system of the winding material dictates to a large degree the design of the machine. The winding should have only a few turns and the physical length of the winding must be low enough to minimize the resistive losses in the low- conductivity material. The machine must also be excited by means of permanent magnets to avoid excitation losses in the highly resistive conductors. For this purpose we decided to manufacture a very low voltage permanent magnet (PM) synchronous machine (U_{ph} = 7 V) with 15000 min^{-1} rotational speed. In high-speed machines, generally, only a very few winding turns are needed. The target was to have less than ten turns per phase winding. To keep the winding work as simple as possible we designed a tooth-coil permanent magnet machine with three stator teeth and two rotor poles which gives q = 0.5 slots per pole and phase. Table I gives the main design data of the machine.

Table I

CNT-YARN PERMANENT MAGNET SYNCHRONOUS MACHINE DESIGN PARAMETERS IN GENERATING

Parameter	Value
STATOR MAGNETIC CIRCUIT	
Stator stack length l_{sFe} [mm]	42
Stator lamination space factor k_{Fe}	0.96
Stator core material	SURA NO10
Stator inner diameter D_S [mm]	25
Stator stack outer electromagnetic diameter	75
Number of stator slots Q_S	3
ROTOR	
Rotor outer diameter D_r [mm]	23
PM cylinder diameter, D_{PM} [mm]	20
Rotor PM length, l_{rPM} [mm]	50
PM material (N38UH) remanence B_r @ 120 C [T]	1.15
PM relative permeability $_r$ at temperature of 120 degrees Celsius	1.05
PM material coercive field strength H_c [kA/m]	871
Rotor construction: Cylindrical PM is located inside a stainless steel tube with 1.5 mm wall thickness.	
STATOR WINDING	
Winding type	Fractional slot, concentrated, non-overlapping, single layer
Winding connection: star connected	0.5
Number of pole-pairs p	1
COOLING	
Cooling method	Air cooling
Number of slots per pole and phase q	0.5

A graph of the stator design with softened bending angels at the kinks is shown in Fig. 2, and Fig. 3 illustrates a single stator lamination laser-cut from SURA NO10 and the rotor of the machine.

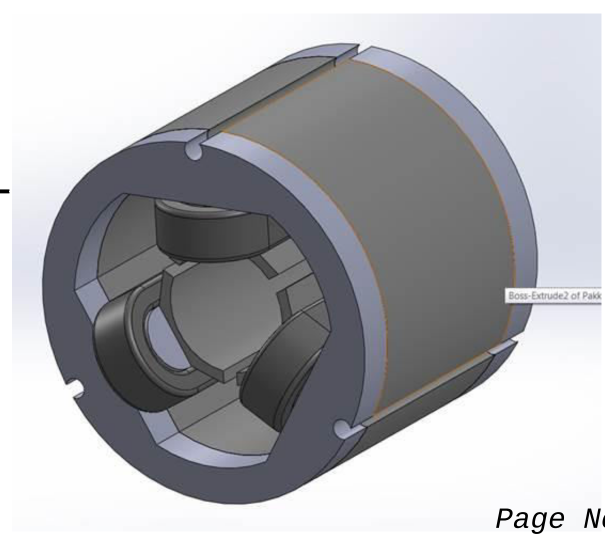


Fig. 2. A graph of the stator design with softened bending angels at the kinks

Fig. 3. Single stator lamination sheet on the left and the assembled PM rotor on the right. The magnetic circuit form is designed to reserve rectangular spaces for the cross-sections of the aramid-strip-insulated conductors.

A three-tooth two-pole machine is the simplest possible three-phase machine. It has the benefit that the winding procedure can be simplified when insulated conductors are used, as shown in Fig. 1. The slots are large and therefore the motor could take much more conducting material in the stator. The CNT-yarn space factor is now 15 % and could theoretically be increased to about 50 %. This should also significantly lower the carbon losses. However, the insulation system illustrated in Fig. 1, does not allow a better space factor for the conductors. To have a high space factor for the CNT yarn, the yarn should be insulated somehow similarly as enamelled copper wires nowadays are. The rotor of the machine has only one cylindrical NdFeB-magnet in a stainless steel tube which allows to keep the overall design of the machine as simple as possible. In a machine with such high resistance in the winding, PM excitation is, in practice, the only possible option. 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.

No load and load simulations

A finite element analysis (FEA) was performed with the CEDRAT Flux 2D software. A dynamic FEA with electric circuit was used to obtain the induced voltages at no-load. The generator load resistances were adjusted to get sufficient output power. Fig. 4 shows the machine air-gap flux density distribution.

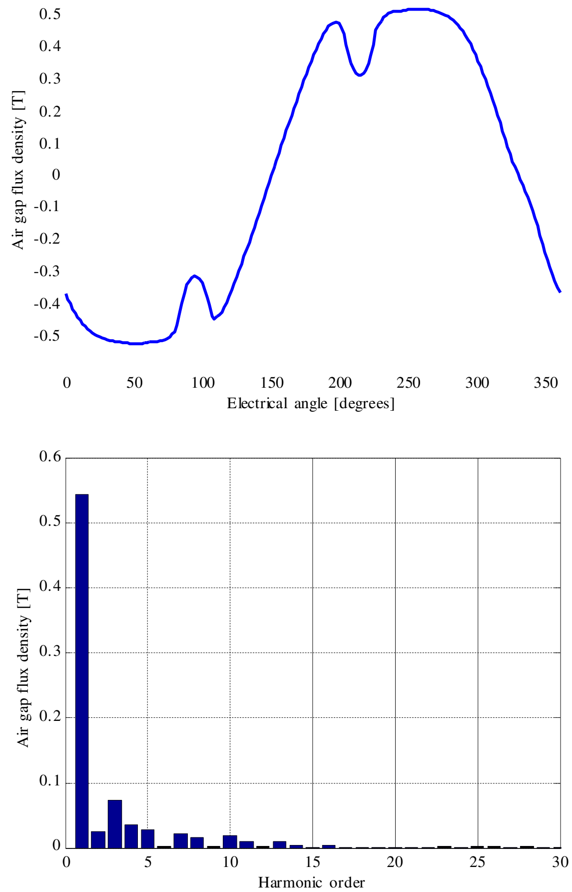
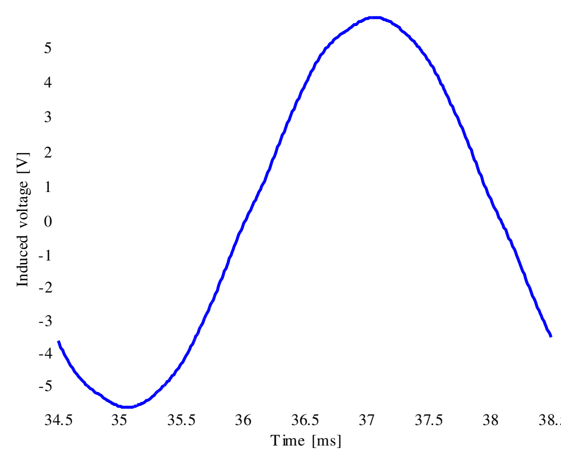


Fig. 4. Air gap flux density peak value 0.51 T and RMS value 0.361 T. The deep dips in the otherwise fairly sinusoidal waveform result from the permeance variation caused by the slot openings.

Fig. 5 shows the no-load induced voltage and its harmonic spectrum.



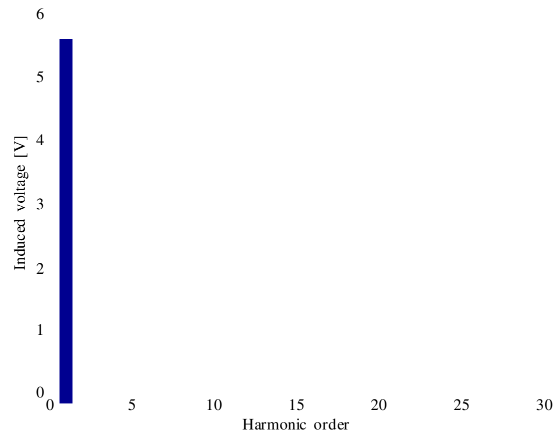


Fig 5. Induced voltage at no-load rated speed 15000 min^{-1}. In addition to the fundamental the voltage contains some fifth and seventh harmonic voltages. The fundamental RMS no-load voltage is E_{PM} = 3.96 V.

The peak value of the induced voltage per phase is 5.6 V. Induced no-load RMS phase voltage E_{PM} = 3.96 V. The machine was then simulated as a generator at its rated load. We used generator simulation instead of motoring because the FEA stabilizes much more easily in generating. The phase resistive loads were adjusted to c. 1.33 Ω. The voltage and the current curves over one of the load resistors are shown in Fig. 6 and Fig. 7, respectively.

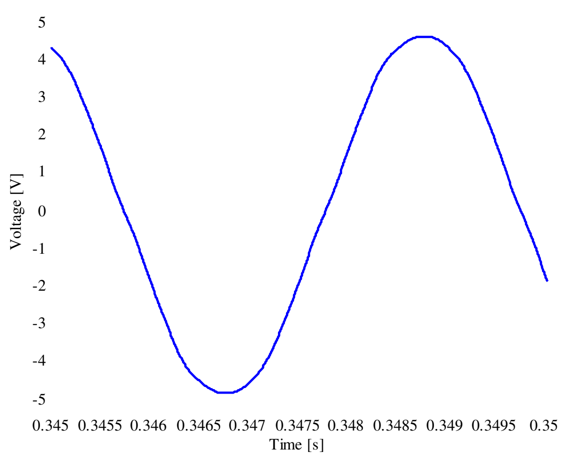


Fig. 6. Phase voltage under generating to 30 W resistive load.

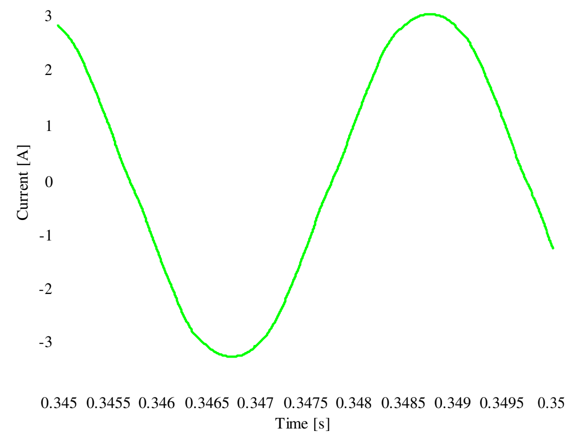


Fig. 7. Phase current under generating to 30 W resistive load.

The calculated iron losses of the machine at rated operating point are P_{Fe} = 6.34 W. The Joule losses in the stator – the carbon losses P_C are then $P_C = 3 \times 0.4 \times 2.3^2$ = 6.35 W. If we would have used copper instead of CNT yarn, the resistance with the same cross-sectional area would have been only R_{sCu} = 0.022 at 120 C operating temperature and the corresponding copper loss 0.35 W. The additional and mechanical losses will be in the range of P_{Mech} = 1 W. The total loss of the CNT-yarn machine under rated operating is thus about 13.7 W at generator 30 W output power. This yields a generating efficiency of about η_{CNT} = 0.69. With copper conductors the loss would be 7.7 W and the efficiency at the same operating point in generating η_{Cu} = 0.8.

Machine Design Summary and Prototype Manufacturing

Table II gives the design summary of the machine simulated as a generator.

TABLE II
SUMMARY OF THE MACHINE SIMULATED AS GENERATOR

Parameter	Absolute value
Rated Voltage, V	3.2/5.5
Rated Current, A	2.3
Apparent power, VA	33.8
Rated Input Mechanical Power, W	43.7
Rated output power, W	30
Rated speed, rpm	15000
Rated torque, Nm	0.019
Back-emf at 15000 rpm	3.96/6.86
Rated impedance,	1.66
Rated inductance, mH	1.057

Calculated synchronous inductance, mH	0.277
R_s, /pu measured	0.4/0.24

The stator laminations were laser-cut and the stack was glued to allow easy manufacturing. The stack was inserted in a steel tube housing and finally the winding material, illustrated in Fig. 1, was used to prepare the windings for the machine. Fig. 8 illustrates the wound stator before and after impregnation. We used normal electrical machine impregnation polyester varnish to mechanically fix the winding and to make sure that no earth faults should take place during the operation of the machine.

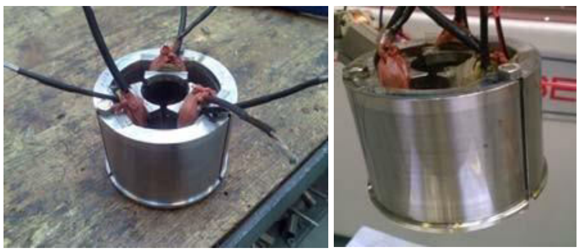


Fig. 8. Machine stator wound with 10 parallel 0.4 mm CNTF-wires after the winding manufacturing, left. On the right, the same stator after impregnating. The length of each phase winding is 1.2 m and the measured DC-resistance is ca. 0.4 at 20 C. These figures also show the sparse design of the machine to allow easy winding manufacturing. The CNT yarn space factor is in the range of 15 %.

The whole machine was assembled back-to-back with a commercial grinding machine to create a test bench for the generator. The test bench is shown in Fig. 9.

Fig. 9. The machine on the right ready to be tested as a generator. The CNT-yarn-winding machine is on the right and a high-speed commutator motor grinder machine on the left connected back to back.

Measurements

We first measured the DC-resistance for the stator assembly. The result of two tests show a higher stator resistance than what could have been expected. Table III summarizes the four-wire DC-resistance measurement results at three different temperatures.

TABLE III
FOUR-WIRE MEASURED PHASE RESISTANCES OF THE TEST MACHINE

Phase, temperature	20 C	50 C	90 C U,
resistance,	0.400	0.416	0.455
V, resistance,	0.393	0.396	0.437
W, resistance,	0.388	0.390	0.430

No load Measurement

The no-load measurement yields promising voltage waveforms as they are purely sinusoidal (Fig. 10) and correspond well to the values calculated with the FEA. The voltage was measured by a Yokogawa power analyser.

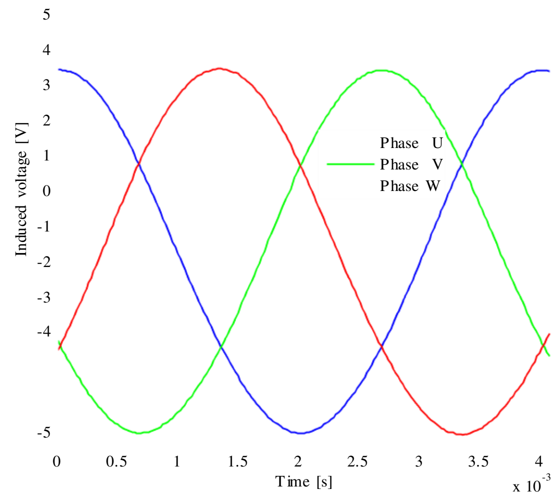


Fig. 10. Induced voltages at no load at 15000 min^{-1}.

Fig. 11 shows that the machine behaves as predicted and the induced voltage increases linearly with the speed until 10 000 rpm. At higher speed different eddy current phenomena (especially in the rotor magnet retaining stainless steel cylinder) slightly slow down the increasing of the voltage. The curve in Fig. 11 shows that small saturation starts to occur as the speed gets higher. The points indicate the measured values.

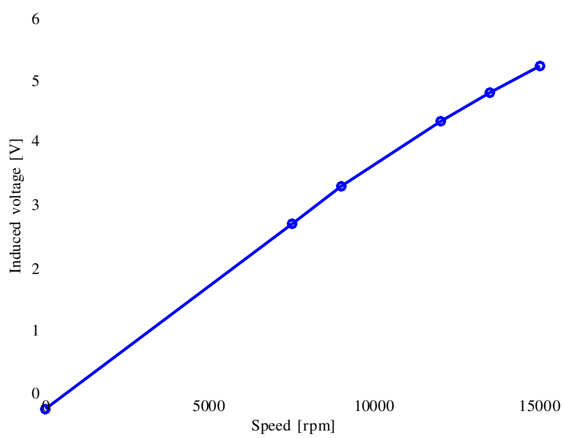


Fig. 11. Induced voltage RMS value as a function of rotational speed.

Load measurement as generator

In this test, the machine was rotated with external mechanical power supply and the machine was loaded as a generator supplying power to the 1 Ω load resistors which were connected to the machine phase terminals and in star at the other end. Fig. 12 shows the Yokogawa measured voltage and current over one of the load resistors the machine being at room temperature.

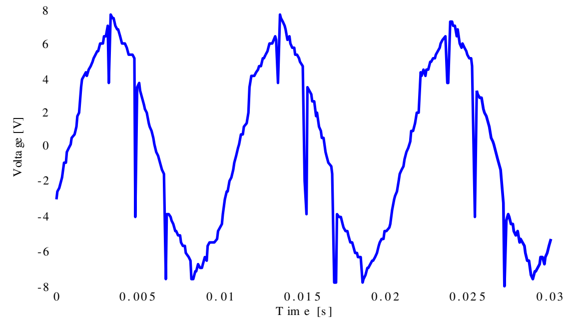
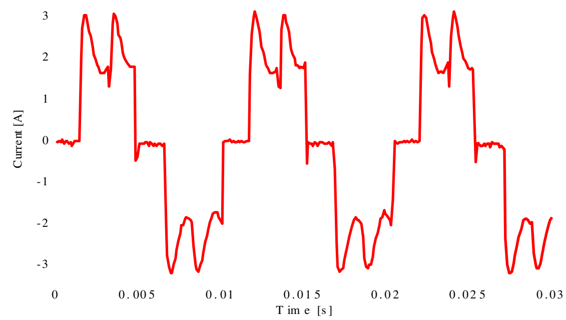


Fig. 13. Voltage of the motor at the speed 15000 min^{-1} at no-load in converter supply.



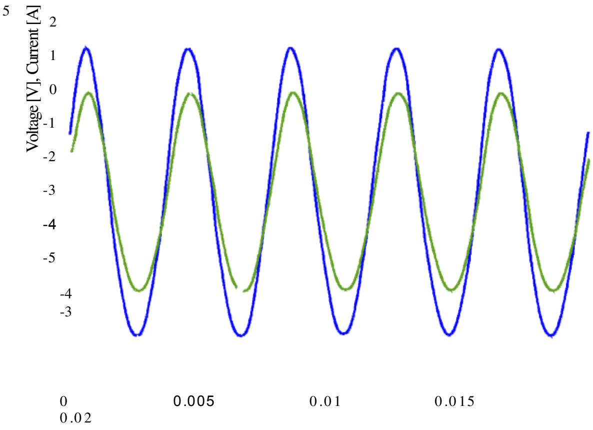


Fig. 14. Current of a motor phase at the speed 15000 min^{-1} at no-load.

Fig. 12. Measured voltage (peak value c. 4.2 V) and current (peak value c. 3 A) of the generator operation with resistive load at the electrical machine.

RESULT

The results indicate that the Teijin Aramid-manufactured CNT wires have a slightly positive temperature coefficient for the resistivity. The slightly positive temperature coefficient may be explained by a slight increase of electron-phonon scattering in the material. The temperature coefficient for the resistivity based on this measurement is in the range of +0.00155–0.00196/K which is about 40 % of the corresponding coefficient of copper.

6. CONCLUSION

This article is the first in its kind to introduce a break- through approach to the use of new carbon nanomaterials to enable the development of a new generation of rotating electrical machinery. The article scans the environment and indicates some future perspectives for potential applications of carbon nanotube yarn in electrical rotating machines where significant efficiency improvement can be achieved. The topicality of the proposed feature article lies in that is explains the potential for integration of new and greener carbon nanomaterials into electrical machine development and innovation of industrial production rotating machines that keep industry and society on the move while coupling such development to the important and topical issues of natural resource savings, carbon savings as well as cost savings issues for more sustainable and economic growth.

REFERNCE:

[1] Commission Regulation (EC) No 640/2009 of 22 July 2009.Available at eurlex.europa.eu/LexUriServ/LexUriServ.do?uri= OJ:L:2009:191: 0026:0034:EN:PDF

[2] F.W. Geels, “Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case- study”, Research Policy, vol. 3, 2002, pp. 1257–1274

[3] Z. Wenliang, T.A. Lipo, K. Byung-Il, “Material-Efficient Permanent-Magnet Shape for Torque Pulsation Minimization in SPM Motors for Automotive Applications”, IEEE Trans. on Industrial Electronics, vol. 61 n. 10, 2014. pp. 5779-5787.

[4] A.Boglietti, A.El-Refaie, O.Drubel, A.Omekanda, N.Bianchi, “Electrical Machine Topologies: Hottest Topics in the Electrical Machine Research Community”, IEEE Trans. on Industrial Electronics magazine, vol. 8 n. 2, 2014. pp. 18-30.

[5] A.Tenconi, S.Vaschetto, A.Vigliani, “Electrical Machines for High-Speed Applications: Design Considerations and Tradeoffs”, IEEE Trans. on Industrial Electronics, vol. 61 n. 6, 2014. pp. 3022-3029.

[6] G.-A. Capolino, A. Cavagnino, “New Trends in Electrical Machines Technology – Part I”, IEEE Trans. on Industrial Electronics, vol. 61 n. 8, 2014. pp. 4281-4285.

[7] G. -A. Capolino, A. Cavagnino, “New Trends in Electrical Machines Technology – Part II”, IEEE Trans. on Industrial Electronics, vol. 61 n. 8, 2014. pp. 4931-4936.

[8] Y. Alexandrova, R. S. Semken, J. Pyrhönen, “Permanent Magnet Synchronous Generator Design Solution for Large Direct-Drive Wind Turbines”, 2013, International Review of Electrical Engineering (IREE), 8 (6), pp. 1717-1738.