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A Hybrid Multi-Pole $Fe_{78}Si_{13}B_9$+$FeSi_3$ Soft Magnetic Core for Application in the Stators of Low-Power PM BLDC Motors

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Abstract: This paper presents results of a research work intended to develop production technology of the hybrid multi-pole $Fe_{78}Si_{13}B_9$+$FeSi_3$ soft magnetic cores suitable for application in the stators of low-power PM BLDC motors, and methods for testing its functional properties and performance. The hybrid core is made from the $FeSi_3$ support ring, onto which another core of the same dimensions, fitted with nine trapezoidal holes, is mounted. Both cores are firmly connected to each other by suitable glue. Next, the trapezoidal soft magnetic amorphous teeth are cut out from the cuboid-shaped packages of the 0.025 mm thick $Fe_{78}Si_{13}B_9$ amorphous ribbons, consolidated and glued-together by an epoxy resin, and then they are mounted on the carrier rings. Under this work, properties of the hybrid cores fabricated by this technology were examined by three original methods: (a) measurement of teeth magnetization, (b) measurement of a voltage on the winding of cyclically magnetized tooth, and (c) measurement of hysteresis loops of the partial hybrid core circuits. The Remacomp C-1200 magnetic measurement system was used to determine hysteresis loops and magnetic properties of the materials used in a hybrid core, including properties of consolidated package of the $Fe_{78}Si_{13}B_9$ ribbons, hysteresis loop of the $Fe_{78}Si_{13}B_9$ core, and hysteresis loop of the $FeSi_3$ core. The measurements showed that application of the amorphous material in a hybrid core resulted in considerable reduction of power losses thus making it possible to keep operating temperature of the core at the acceptable level of 36°C. An experimental batch of these novel cores was made and used in the stators of low-power PMBLDC motors, which were then subjected to the performance tests. It was found that application of a hybrid core in the stator of the PM BLDC motor makes it possible to achieve relatively low level of power losses. It has been concluded that the results from this work are very promising and the novel hybrid core may be suitable for application in implantable blood pumps, serving as a heart-assist device.

Keywords: Amorphous Materials, Hybrid Soft Magnetic Core, Stator, PMBLDC Motor

1. Introduction

The amorphous soft magnetic materials have found practical application in the stator cores of the electric motors relatively recently, mainly in order to reduce core losses [1-10]. In a work of J. M. Silveyra et. al, the $Co_{77.2}Fe_{1.4}Mn_{1.4}Si_2B_{14}Nb_4$ alloy was selected from among three Fe-based and Co-rich alloys for application in a stator of the demonstrator machine having a 14-pole ferrite rotor, showing that at B = 0.9 T and f = 2 kHz, the stator core losses were three times lower than in the case of $FeSi_3$-based stator [1]. In a work of Z. Wang et al, the 200 W PM BLDC motor with a stator utilizing twelve $Fe_{78}Si_{13}B_9$ tape-wound trapezoidal cores, and with a gap aimed at eliminating eddy-currents related losses, has been described [6]. The suitably powered coils were placed on these cores so as to generate magnetic poles on them thus forcing rotary motion of a rotor comprising 4 pairs of neodymium magnet poles. It was found that power losses at 3 000 rpm were of an order of about 5 W.

Interesting design of the amorphous stator has been presented in a work [7]. The stator was made from the FeSiB toroidal core, in which 12 trapezoidal-shaped slots were cut by the abrasive waterjet technology, and after inserting of a winding the stator was used in an electric motor operating at 8 000 rpm with 20 W losses and 90% efficiency at the output power of 1400 W. A model-based theoretical studies of the high-speed PMBLDC motor incorporating an amorphous FeSiB stator core and operating at the speed up to 100 000 rpm have been described in a work [9]. Results of R. Kolano et. al studies into fabrication technology of the PMBLDC motors with a slotless stator made from the $Fe_{78}Si_{13}B_9$ toroidal core are presented in a paper [10]. The motor efficiency of 73% at the torque M >80 [mNm] was reached, while motor power was 1 kW and the maximum rotary speed – 70 000 rpm, but significantly higher efficiency of about 90% at the rotary speed of 50 000 rpm and the torque of 100 mNm was achieved for the high speed PM BLDC motor with half-open slots [11]. However, it should be noted that there are so far no literature reports on application of the amorphous soft magnetic materials in the stators of low-power electric motors (about 10 W), which can be attributed to the specific feature of these materials – worsened mechanical strength after heat treatment.

The aim of this work was to develop fabrication process and examination methods of a hybrid 9-pole $Fe_{78}Si_{13}B_9$+$FeSi_3$ soft magnetic core intended for application in the stators of low-power PM BLDC motors.

2. Experimental Methods

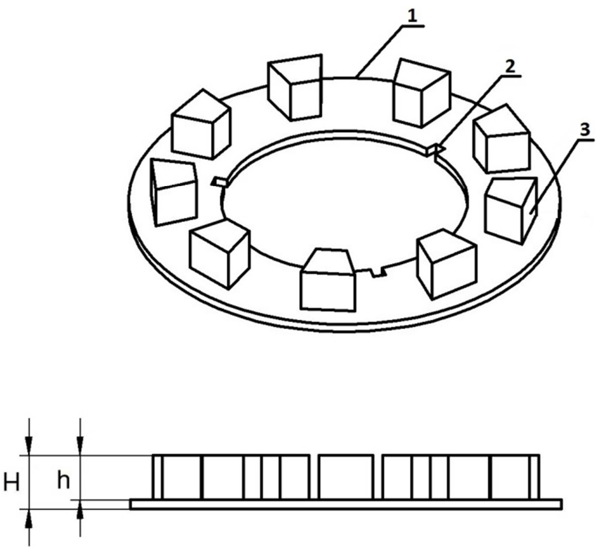


Figure 1. *A hybrid 9-pole amorphous soft magnetic core (1-carrier ring from $FeSi_3$, 2-positioning cut-outs, 3- amorphous poles from $Fe_{78}Si_{13}B_9$).*

The design of a soft magnetic core and its dimensions should always meet the requirements of its final application. The hybrid 9-pole $Fe_{78}Si_{13}B_9$+$FeSi_3$ core design developed under this work was to be used in a stator of the PM BLDC motor intended for application in implantable blood pump, serving as a heart-assist device. A ring-shaped rotor of this motor was to have six pairs of trapezoidal neodymium magnets. During motor operation, the surface of rotor magnets should be parallel to the surface of the core poles. Figure 1 shows sectional view of this hybrid core, consisting of a soft magnetic carrier ring (1) made from electrical steel $FeSi_3$, with rectangular positioning cut-outs (2), and nine soft magnetic poles (3) ("teeth") made from the 0.025 mm-thick $Fe_{78}Si_{13}B_9$ amorphous ribbons (*H* denotes the core height and *h* – pole height).

This hybrid soft magnetic core was fabricated in three stages, including:

(1) preparation of carrier rings from a soft magnetic material of the lowest possible power losses and suitably good stiffness,
(2) preparation of trapezoidal soft magnetic poles (teeth) from the $Fe_{78}Si_{13}B_9$ amorphous ribbons, and
(3) making stable connection between the teeth and the carrier ring, capable to withstand much greater disruption force than that acting on the core teeth during motor operation.

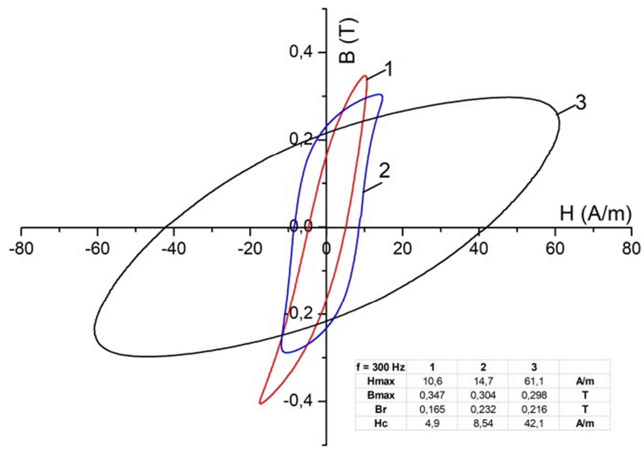


Figure 2. *Hysteresis loops and magnetic properties of the materials used in a hybrid core; 1 – hysteresis loop for consolidated package of the $Fe_{78}Si_{13}B_9$ ribbons, 2 - hysteresis loop of the $Fe_{78}Si_{13}B_9$ core, 3 - hysteresis loop of the $FeSi_3$ core.*

The carrier rings were made from the 0.25 mm-thick $FeSi_3$ strip by electro-erosion cutting. The trapezoidal soft magnetic amorphous teeth were cut out from the cuboid-shaped $Fe_{78}Si_{13}B_9$ 0.025 mm-thick amorphous ribbons, consolidated and glued-together by an epoxy resin, and then they were mounted on the carrier rings. The hysteresis loops obtained by the measurements for the materials used in the hybrid core for the frequency of 300 Hz, i.e. operating frequency of the motor, are shown in Figure 2. The loops (2) and (3) were obtained for the cores from FeSiB and $FeSi_3$, respectively, having the same size. Moreover, in order to determine an effect of the epoxy resin on magnetic properties of consolidated FeSiB ribbons, a package of five 4.25 mm-wide resin-consolidated FeSiB ribbon sections was made and its hysteresis loop has been measured (loop 1). The measurements were made using the Remacomp C-1200 system. The loop (1) in Figure 2 was obtained for consolidated package of five FeSiB amorphous ribbons, 100 mm in length, subjected to heat treatment at the temperature of 633 K under longitudinal magnetic field. The loop (2) represents properties of the FeSiB rings after thermo-magnetic treatment at 633 K, while loop (3) was obtained for $FeSi_3$ cores.

A formed consolidated cuboid-shaped amorphous bar and the cuboids with trapezoidal base, cut out from this bar are presented in Figure 3.

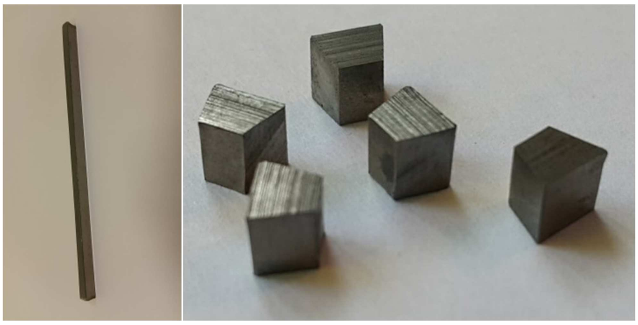


Figure 3. *Images of consolidated amorphous bar and trapezoidal teeth.*

Application of the amorphous material in a hybrid core resulted in considerable reduction of power losses thus making it possible to keep operating temperature of the core at the required level of 36°C. The next stage in fabrication of soft magnetic hybrid cores is mounting trapezoidal teeth on the carrier rings. Particular steps of this consolidation are as follows: *(a)* preparation of $FeSi_3$ rings, *(b)* precise positioning of the $Fe_{78}Si_{13}B_9$ teeth in a special matrix, *(c)* making durable connection of the $Fe_{78}Si_{13}B_9$ amorphous teeth with polycrystalline $FeSi_3$ ring.

Figure 4 shows examples of the hybrid $Fe_{78}Si_{13}B_9+FeSi_3$ soft magnetic cores fabricated according to the technology described above.

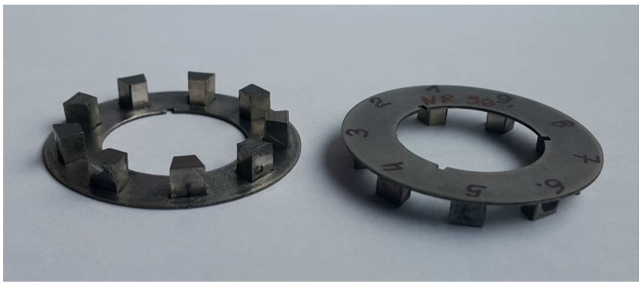


Figure 4. *Image of the hybrid $Fe_{78}Si_{13}B_9+FeSi_3$ soft magnetic cores.*

3. Results and Discussion

Application of a hybrid core in the stator of the PM BLDC motor makes it possible to achieve relatively low level of power losses. In case of a motor operating at the rotary speed of 3 000 rpm using a rotor with 6 pairs of neodymium magnets, re-magnetization frequency of the hybrid core will be 300 Hz ($f = n/10$; n – number of rotor revolutions per minute). During motor operation, a rotating magnetic field is generated over the core by the teeth, provided that they are equipped with suitable winding and suitably powered. As a consequence, the rotor starts to rotate over the teeth in a distance of about 1 mm from their surface. A cyclic re-magnetization of the teeth takes then place under the influence of the magnetic field produced by the windings and the magnetic field produced by rotor poles. This re-magnetization process taking pace in each tooth is accompanied by re-magnetization of a nearby $FeSi_3$ ring, which plays also a role of the magnetic shield.

Functional properties of the hybrid cores were evaluated by the following methods:

1. measurement of teeth magnetization,
2. measurement of a voltage on the winding of cyclically magnetized tooth,
3. measurement of hysteresis loops of the partial hybrid core circuits.

Ad.1. Measurement of teeth magnetization.

Cyclic re-magnetization of the teeth was forced by an alternating current, 300 Hz in frequency, flowing through a winding comprising 50 turns, mounted on a tooth. The magnitude of magnetization *B* on a tooth surface was measured using Lakeshore Model 450 Gaussometer. Dependence of the magnetic induction *B* on the current *I* obtained from the measurements is shown in Figure 5.

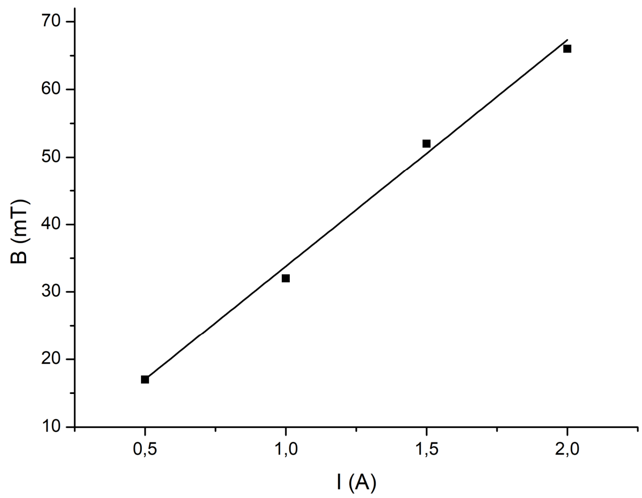


Figure 5. *Dependence of the dynamic induction B=f (I) measured on a surface of the hybrid core teeth.*

Ad.2. Measurement of a voltage on the winding of cyclically magnetized tooth. A setup for measuring voltage appearing on a tooth winding as a result of its cyclic magnetizing by the magnetic field produced by rotating disk with FeNdB magnets, is presented in Figure 6. It is composed of the following components:

(1) measuring head, which provides rotations of a disk with magnets and enables precise and parallel positioning of the hybrid core relative to the surface of that disk,
(2) electronic measuring instruments, including relevant meters and an oscilloscope.

Figure 6. *A setup for measuring voltage on a hybrid core tooth winding.*

Moreover, cross-sectional view of the measuring head and hybrid core assembling are shown in Figure 7.

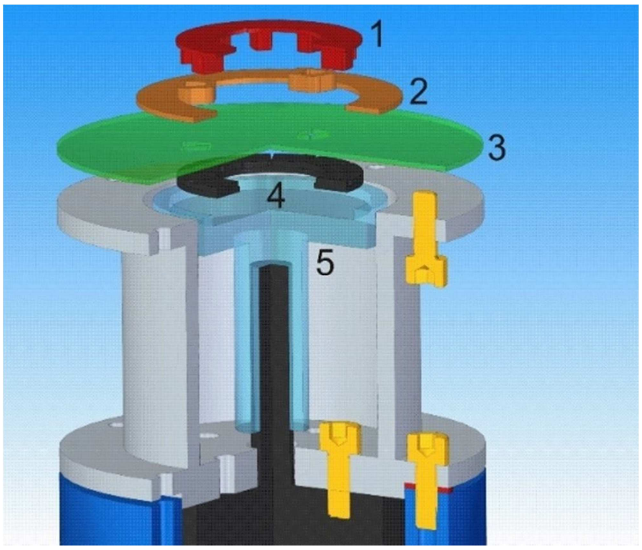


Figure 7. *Cross-sectional view of the measuring head: 1-hybrid core, 2-printed-circuit board, 3- carrier base of the core, 4- ring with magnets, 5-rotary axis of a disk with magnets.*

The hybrid core is placed over rotating disk with FeNdB magnets, in a distance of 1.4 mm from that disk. Measurements of a voltage on the winding can be performed simultaneously on three teeth of a core. The values of a voltage U, measured on 50-turn windings inserted on particular teeth numbered from 1 to 9, are given in Figure 8.

The lowest voltage value determining core usability for practical application is 240 mV.

Ad.3. Measurements of hysteresis loops of the partial hybrid core circuits. The hysteresis loop is determined for a closed circuit with 6 slots. This circuit (Figure 9a) consists of two $FeSi_3$ strips and four FeSiB amorphous teeth (ts1, ts2, t1, t2). A bottom part of the circuit is formed by the $FeSi_3$ strip and two teeth (ts1 and ts2), onto which windings C1 and C2 are inserted. This part of a circuit is permanently glued to the basis of a mounting assembly. On the teeth of the bottom part of the circuit, two neighbouring teeth of a hybrid core selected for measurements are placed. The Remacomp C-1200 instrument was used to determine hysteresis loops for the circuit shown in Figure 9a.

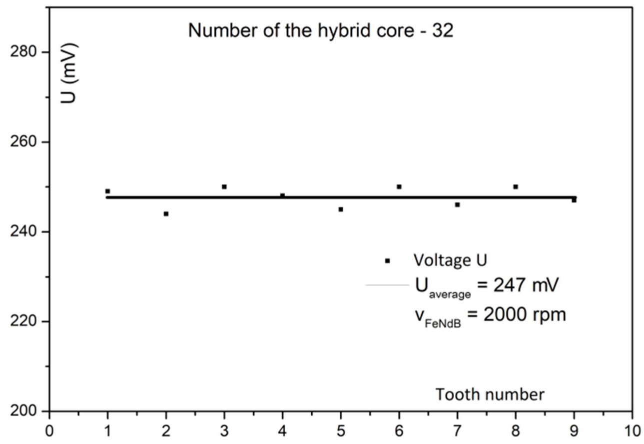
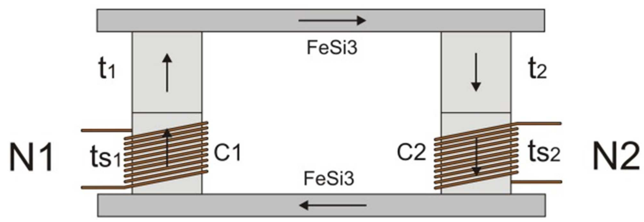
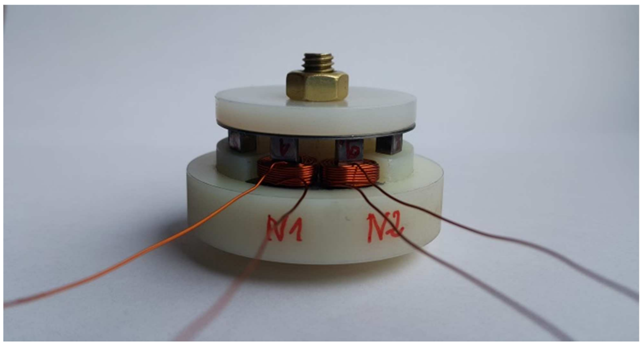


Figure 8. *The values of voltages induced on windings placed on the teeth 1-9 of the hybrid core.*

Assuming that the ratio between cross-sections of the FeSiB tooth and the $FeSi_3$ strip is 4:1, then the induction B in a strip will be four times higher than in a tooth. This means that if the induction B in a $FeSi_3$ strip is 0.3 T, then it will be 0.075 T in a tooth. View of the hybrid core subjected to the magnetic measurements is shown in Figure 9b.



a)



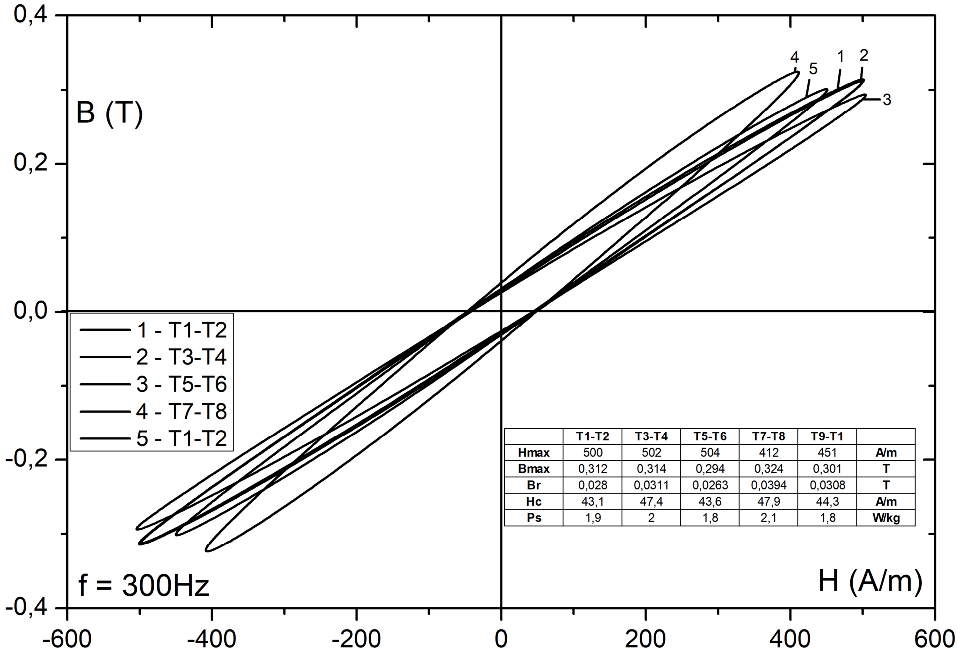
b)

Figure 9. *Illustration of a method for measuring hysteresis loops of the partial hybrid core circuits (a) and hybrid core subjected to the magnetic measurements (b).*

A special measuring system developed under this work, which is shown in Figure 9b, makes it possible to obtain a required good contact between the surface of selected pair of the hybrid core teeth and the surface of a pair of standard teeth. Figure 10 shows hysteresis loops obtained from measurements for five pairs of teeth of a hybrid core connected with a pair of standard teeth ts1 and ts2. It can be seen that coercivity H_c of a hybrid core and that of the $FeSi_3$ ring (see loop 3 in Figure 2) is about 40 A/m in both cases.

This implies that $FeSi_3$ has the greatest contribution in the hysteresis loops obtained from measurements. The need to use 10 times higher magnetic field in case of a hybrid core than in case of $FeSi_3$ ring to reach magnetization of 0.3 T results from the fact that the hybrid core has as much as 6 slots. The measuring method applied can be used to detect connection defects between the amorphous teeth and $FeSi_3$ ring.

The developed methods for quality control of magnetic properties of the hybrid cores FeSiB+ $FeSi_3$ make it possible to evaluate their usability in the stators of low-power PM BLDC motors. It is intended to use the stators incorporating these novel hybrid cores in a prototype implantable blood pump, serving as a heart-assist device.



	T1-T2	T3-T4	T5-T6	T7-T8	T9-T1	
Hmax	500	502	504	412	451	A/m
Bmax	0,312	0,314	0,294	0,324	0,301	T
Br	0,028	0,0311	0,0263	0,0394	0,0308	T
Hc	43,1	47,4	43,6	47,9	44,3	A/m
Ps	1,9	2	1,8	2,1	1,8	W/kg

Figure 10. *The hysteresis loops measured for partial magnetic circuits with a structure shown in Figure 9a.*

4. Conclusion

This work was focused on fabrication technology and examination of functional properties of a 9-pole hybrid soft magnetic core designed for application in low-power PM BLDC motors (about 10 W). The core consists of a carrier ring from soft magnetic $FeSi_3$ steel, 0.25 mm in thickness, onto which trapezoidal-shaped teeth are symmetrically attached. A unique technology for fabricating such cores, based on forming packages of FeSiB amorphous ribbons consolidated by gluing, has been developed. These packages have a form of cuboid-shaped bars, from which trapezoid prisms are cut off and mounted on a surface of the $FeSi_3$ carrier ring. Functional properties of the fabricated hybrid cores were examined by the measurements of teeth magnetization, measurements of a voltage on the winding of cyclically magnetized tooth, and measurements of hysteresis loops of the partial hybrid core circuits. Particularly useful in the hybrid cores fabrication process is the measurement of a voltage on a tooth winding, which is induced by the rotating neodymium magnets.

Acknowledgements

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References

[1] J. M. Silveyra, P. Xu, V. Keylin, V. DeGeorge, A. Leary, and M. E. McHenry, “Amorphous and nanocomposite materials for energy efficient electric motors,” J. Electron. Mater., vol. 45, no. 1, pp. 219–225, 2015.

[2] L. Wang, J. Li, S. Li, G. Zhang, and S. Huang, “Development of the new energy-efficient amorphous iron based electrical motor,” in Proc. Int. Conf. Comput. Distrib. Control Intell. Environ. Monitor., Feb. 2011, pp. 2059–2061.

[3] T. Fan, Q. Li, and X. Wen, “Development of a high power density motor made of amorphous alloy cores,” IEEE Trans. Ind. Electron., vol. 61, no. 9, pp. 4510–4518, Sep. 2014.

[4] M. Dems and K. Komeza, “Performance characteristics of a high-speed energy-saving induction motor with an amorphous stator core,” IEEE Trans. Ind. Electron., vol. 61, no. 6, pp. 3046–3055, Jun. 2014.

[5] Z. Wang, R. Masaki, S. Morinaga, Y. Enomoto, H. Itabashi, M. Ito and S. Tanigawa “Development of an axial gap motor with amorphous metal cores,” IEEE Trans. Ind. Appl., vol. 47, no. 3, pp. 1293–1299, May/Jun. 2011.

[6] Z. Wang, Y. Enomoto, M. Ito, R. Masaki, S. Morinaga, H. Itabashi and S. Tanigawa “Development of a permanent magnet motor utilizing amorphous wound cores,” IEEE Trans. Magn., vol. 46, no. 2, pp. 570–573, Feb. 2010.

[7] N. Ertugrul, R. Hasegawa, W. L. Soong, J. Gayler, S. Kloeden, and S. Kahourzade, "A novel tapered rotating electrical machine topology utilizing cut amorphous magnetic material," IEEE Trans. Magn., vol. 51, no. 7, Jul. 2015, Art. ID 8106006.

[8] S. R. Ning, J. Gao, and Y. G. Wang, "Review on applications of low loss amorphous metals in motors," Adv. Mater. Res., vols. 129–131, pp. 1365–1371, Aug. 2010.

[9] K. Krykowski, J. Hetmańczyk, Z. Gałuszkiewicz, and R. Miksiewicz, "Computer analysis of high-speed PM BLDC motor properties," COMPEL Int. J. Comput. Math. Elect. Electron. Eng., vol. 30, no. 3, pp. 941–956, 2011.

[10] R. Kolano, K. Krykowski, A. Kolano-Burian, M. Polak, J. Szynowski, and P. Zackiewicz, "Amorphous soft magnetic materials for the stator of a novel high-speed PMBLDC motor," IEEE Trans. Magn., vol. 49, no. 4, pp. 1367–1371, Apr. 2013.

[11] R. Kolano, A. Kolano-Burian, K. Krykowski, J. Hetmańczyk, M. Hreczka, M. Polak and J. Szynowski, „Amorphous soft magnetic core for the stator of the high-speed PMBLDC motor with half-open slots" IEEE Trans. Magn. vol. 52. No. 6. pp. 2003005 June 2016.