INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2020, VOL. 66, NO. 4, PP. 787-792
Manuscript received October 1, 2020; revised October, 2020. DOI: 10.24425/ijet.2020.135193

Analysis of the Magnetoelectric Sensor's Usability for the Energy Harvesting

Karol Kuczynski, Adrian Bilski, Piotr Bilski, and Jerzy Szymanski

***Abstract*—The paper presents the analysis of the magnetic sensor's applicability to the energy harvesting operations. The general scheme and technical advancement of the energy extraction from the electric vehicle (such as a tram or a train) is presented. The proposed methodology of applying the magnetic sensor to the energy harvesting is provided. The experimental scheme for the sensor characteristics and measurement results is discussed. Conclusions and future prospects regarding the practical implementation of the energy harvesting system are provided.**

***Keywords*—magnetoelectric sensor, current sensor, magnetostriction, amorphous metal ribbon, piezoelectric materials, energy harvesting**

I. INTRODUCTION

CONTEMPORARY transport systems (such as automotive or railways) are characterized by the increasing energy saving solutions. Their importance is growing, therefore new methods are constantly introduced. One of them is the Energy Harvesting (EH) [1, 2], preferred in railway systems (though also used in modern cars, for instance to extract energy from wheels while the vehicle is not accelerating). The implementation of the similar solution requires the application of specific devices, such as magnetoelectric sensors operating as magnetic field sensors. They can detect presence of the changing magnetic field in the vicinity of the transmission line and allow for the current flow induced by the field changes. This way the electrical charge can be collected and used later.

The following paper proposes the usage of the magnetic field sensor for the EH applications. The proposed solution and experiments with the selected sensor show the potential of the approach. It was proven that the prototype of the sensor is capable of collecting energy by generating the current in the presence of the changing magnetic field. The prototype of the complete device will be tested in the operational conditions, i.e. in the actual railway track system.

The content of the paper is as follows: in Section II the EH problem is presented. Section III contains the proposed approach using the designed prototype of the sensor. In Section IV the experimental procedure of determining characteristics of the device for EH is presented. The paper is concluded with the summary of future prospects of the proposed solution.
Experiments were conducted in the three axial circuit of inductances (so-called Helmholtz cage) located in the AGH University of Science and Technology in Krakow. They allow to determine the usefulness of the magnetoelectric sensors for the EH, for instance, from the railway cables with reduction earth magnetic field.

II. ENERGY HARVESTING METHODOLOGY

For many years the EH methods have been investigated [1, 2, 3, 4, 5, 6]. The magnetic field in the vicinity of the electrical lines can be exploited through the Magneto-Mechano-Electric mechanism (MME) [2]. When the composite material is located in the changing magnetic field, its magnetostrictive layer reacts to mechanical vibrations (magneto-mechanical coupling). It then influences the piezoelectric layer, which generates the output voltage on the electrodes through the piezoelectric effect (mechano-electric coupling). Because of the piezoelectric phase in the composite material [9] all mechanical vibrations related to it generate voltage on the output of the piezoelectric. Therefore, the MME generator can be used to harvest energy from the magnetic field and external vibrations at the same time [2]. Illustration of the operation (for the changing fields around the energetic cables) is presented in Fig. 1.

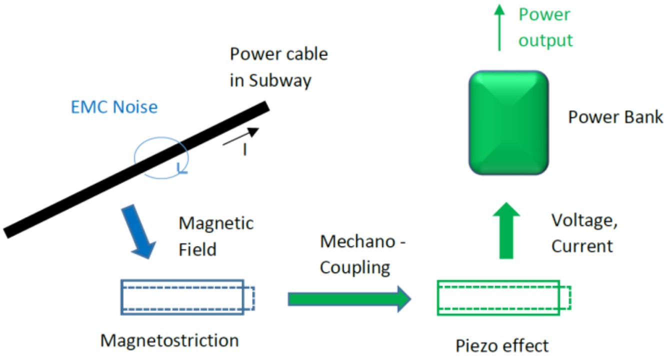

Fig. 1. Example of the Energy Harvesting from the magnetic noise in the Subway [2].

The EH is possible thanks to the advancement in the material production and technologies allowing the acquisition of the energy from the background (i.e. from known, but so far neglected sources). The reason for ignoring them is the low harvesting efficiency and high cost of the devices used for this purpose (so-called harvesters) [1,3]. The key factor is the decreasing power consumption of the microsystems (such as Micro-Electro-Mechanical Systems – MEMS [7]). This increases attractiveness of devices consuming power of micro- and milliwatts, making them significant for the EH. They can eliminate traditional power circuits using batteries or accumulators [3].

The ability to acquire energy through EH is the way of increasing the energy available in vehicles (such as cars or railways) [3]. So far the kinetic energy, heat, light, electromagnetic field and other sources have been transformed.

Karol Kuczynski, Jerzy Szymanski are with Kazimierz Pulaski University of Technology and Humanities in Radom, Faculty of Transport, Electrical Engineering and Informatics, (e-mail: k.kuczynski@uthrad.pl)
Adrian Bilski is with University of Social Sciences in Lodz, Poland.
Piotr Bilski is with Warsaw University of Technology, Faculty of Electronics and Information Technology, Poland

Energy can be used in many ways depending on the obtained power [3, 6, 8]:

- single milliwatts range – for wireless power supply of sensors and actuators
- watts range – for self-sufficient supply of selected elements in external lighting systems. In case of energy storage (e.g. in supercapacitors), it may also be used to power air conditioning and selected components,
- kilowatts range – for charging traction batteries or supercapacitors (in case of electric or hybrid vehicles), supplying electricity to electric traction motors.

Examples of applications and obtainable electric energy are presented in [4, 5]. Usage of magnetoelectric sensors for EH was considered in [6]. Magnetoelectric sensors (through the transformation of the magnetic field strength into voltage) can be used do drive low-power communication systems. This is particularly useful to harvest energy from the nearby power lines, used in railways.

III. APPLICATION OF THE MAGNETOELECTRIC SENSORS TO THE ENERGY HARVESTING

Many uses of the so-called Giant Magnetostrictive Materials (GMM) result from the possibility of converting magnetic energy into the mechanical one (actuator-type operation) and the other way around (sensor-type operation), with a high efficiency factor. These materials also play a key role in Energy Harvesting (EH) from vibrations. GMM harvesters usually also contain neodymium magnets for economic reasons. Examples of GMM applications in the field of EH include aviation, road transport, stationary mechanical and medical constructions, sports and tourism equipment and many others. The aim of the research is mainly to increase the efficiency of converting mechanical energy into electricity, the miniaturization of harvesters and the reduction of their price [3].

The material, the form which the sensor is made of, plays a crucial role in EH. The most popular is solid Terfenol-D. Its major drawback for EH is high fragility associated with low tensile strength. Another issue is large value of eddy currents, limiting the effective operating frequency of the devices to a few kHz. Its price is high due to the low availability. These restrictions are the reason for seeking new solutions. One of them is the utilization of magnetostrictive composites based on, among others, the magnetoelectric effect, which can be used in the construction of harvesters. An important limitation of magnetic core harvesters is their size and weight. Installing piezoelectric harvesters is much simpler than doing so with the magnetic core that requires a complex mechanical structure and pre-magnetization and prestress. The current-voltage performance of magnetostrictive harvesters is higher than that for other types of harvesters [3]. This is also the reason for conducting research on the use of new harvester designs built of magnetic materials with high magnetostrictive strain and deformation-sensitive PZT ceramics.

Conventional current sensors measure the magnetic field strength present around the current conducting material. If the proportional relation between the field value and the current amplitude is known, the sensor can be used to measure the current in the power line (exploiting the Hall effect). Unfortunately, the so-called hallotrons must be powered by the extremely stable DC source. Their naturally low Hall voltage is between 5 and 40μV/Oe ($1\mathrm{Oe}=10^3/4\pi$ A/m) and requires the signal amplification [9].

For this purpose the lock-in amplifiers are used. Their selective element is the phase-sensitive rectifier. It allows to isolate components from the noisy signal, which have the identical frequency to the one of the reference signal and are in-phase with it. The phase-sensitive detector enables isolating nV-magnitude voltage signals and pA currents from the noise [10]. On the other hand, current conditioners constructed from the Magentoelectric (ME) composites allow for the AC or DC measurement. The value of the current is evaluated from the vortex magnetic field (constant or changing), excited around the conducting material, according to the Ampere's law. The amplitude of the magnetic field strength H depends on the amplitude of the current in the wire and on the distance r from this wire.

$$H = I/2\cdot\pi\cdot r \tag{1}$$

Therefore, the ME ring laminates are used in the electrical current sensors.

The magnetoelectric sensors that can be used for the purpose of EH differ in sensitivity and materials of which they are made. Depending on their design, it is possible to increase the sensor's output power as the output current increases at direct voltage. The volume of the magnetic material is proportional to the output power. Also, the linearity of the relation between the magnetic field and the generated current must be determined. Below some common solutions and their parameters from the EH point of view are presented.

The ring sensor [9], which reacts on the vortex magnetic field, contains the axially polarized ceramic PZT ring, located between two layers of longitudinally magnetized composite rings. They are connected through the epoxy resin (Terfenol-D / NdFeB magnet), forming the ring circuit. Sensitivity of the sensor was evaluated experimentally. In [8] it was proven that the output voltage is linearly proportional to the measured current. The sensor's sensitivity beyond the resonance frequency (between 1Hz and 30kHz) was 12.6mV/A, while for the resonance frequency (67 kHz) it was 92.2 mV/A.

Similarly, linearity and current sensitivity of 114.2 mV/A can be observed in the Metglas/PZT laminate during the measurement of the changing magnetic field at the frequency of 50Hz [11]. The sensor is used to measure the current flow in the power grid line. By connecting the ME ring with the structure of the piezoelectric transformer, the high resonance sensitivity can be obtained (around 157 mV/A), along with the electromechanical resonance frequency of 62kHz [12]. In [13] the beam AC sensor was presented. It contains two layers of the longitudinally magnetized Terfenol-D and one layer of the cross-wise polarized PZT material. All layers were connected using the epoxy glue. The conducting wire is wound around the transducer. The output voltage is proportional to the current, measured at the two PZT pins.

The ring-shaped sensor is also used to detect vortex fields and DC or AC signals flowing through the wire. The current induces along the wire the vortex magnetic field with $H_{vort}=I/(\pi R)$, where R is the radius of the field. In this case the piezoelectric surface deformed by the magnetic material was small, which leads to the low sensitivity while detecting other fields than the vortex ones [14].

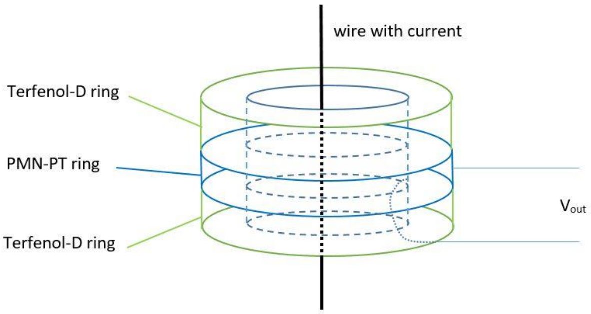

Fig. 2. The ring sensor for measuring currents flowing through wire [14]

In case of Terfenol-D/PZT, a piece of this material with dimensions 20×10×0.6 mm has the capability to collect 620µW of the output power [6].

Magnetic field sensors convert signals proportional to the induction or amplitude of the magnetic field in the air into the electrical signal: voltage, change of resistance, or frequency [15]. Due to the ability of using these signals to power devices used in the transportation, the most attractive are magnetoelectric field sensors with the output voltage proportional to the magnetic field, which can be up to the Volts range [16].

IV. EXPERIMENTAL SETUP

In the magnetic field, the microamperometer measures the current, which allows to determine the amount of energy that can be accumulated in the storage (such as capacitor). To evaluate efficiency of the process, characteristics of the device must be evaluated, especially its sensitivity, which determines the level of the detected signal and the amount of energy to store during the time period. This section covers experiments aimed at finding characteristics of the sensor and deciding whether it is suitable for EH.

A. Analyzed sensor

The designed sensor (Fig. 3), based on the utility model one od the authors [17], contains the piezoelectric ceramics ring (1). The applied ceramics is characterized by the large values of the dielectric and piezoelectric constant (d_{33}=425pC/N), and the piezoelectric voltage coefficient ($g_{33}=27\times10^{-3}$ Vm/N). Its breadth is equal to the half of the ring height. The amorphous metal ribbon has the thin hysteresis loop minimizing losses of energy required to magnetize the ring, which would have positive effect on the EH efficiency. The amorphous metal ribbon and the PZT ring are glued together. On the ring, the pick-up coil (3) is wound. It receives the control current Is, which induces the changing control field Hs driving the sensor's operation. The amorphous metal ribbon is influenced by the constant, measurable magnetic field strength H_{dc}, causing the magnetostrictive strain, transferred to the ring. As the result, on the electrodes located at the ring edges, the voltage U_{dc} (proportional to the field *Hdc*) is induced [17]. In the pick-up coil the amplitude of the magnetic field strength is obtained according to the relation:

$$I \cdot n = L_e \cdot H \tag{2}$$

where H is the magnetic field strength, I is the current flowing through the coils, Le is the effective length of the magnetic flux path and n is the number of turns in coils.

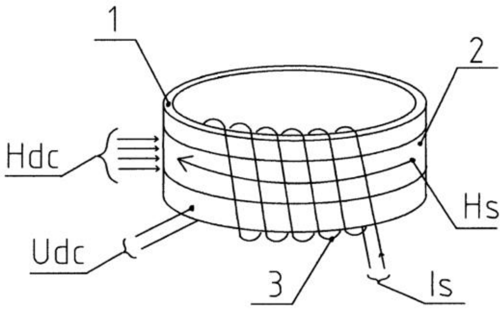

Fig. 3. The diagram of the proposed magnetic sensor prototype [17].

The sensor allows to measure weak, constant magnetic fields (ranging up to single A/m). The closed circuit decreases the noise influence in the desired signal and enables determining direction of the measured magnetic field (impossible in the open circuit sensors). The usage of the thin amorphous metal ribbon as the magnetic material allows to measure transient values of magnetic field strength. This also extends the frequency range of the device, which is important during the EH, as more energy can be extracted from additional harmonic components.

B. Test stand

Fig. 4 presents the scheme of the test stand, used to validate the sensor, i.e. measure the output voltage depending on the magnetic field. The system consists of the source of the field controlling the sensor's functions (H_S), the magnetic sensor under test and data acquisition system. The sensor output signal, which is a function of the measured constant magnetic field strength (H_{dc}), is processed in the measuring system. The use of a filter allows to focus on selected harmonics of the sensor's output signal. The acquired data are then visualized by the oscilloscope and can be also further processed by the computer. The measuring stand constructed based on the scheme from Fig. 4 is presented in Fig. 5. The most important elements of the pick-up magnetic field system are the arbitrary generator and the Kepco bipolar BOP power supply. It contains high speed power operational amplifiers that can be used to provide dynamically changing voltage or current with high precision for tests.

Evaluation of the magnetic field characteristics, especially of the low amplitude, requires isolating the experimental stand from the external sources of the electromagnetic field. Gradients and variations of this field are too large to be successfully compensated in urban areas. To perform measurements of the magnetic field strength resulting in the single A/m current values requires the specialized laboratory located far from other sources of the magnetic field strength and noise created by humans. This includes metal materials, moving vehicles, tramways, elevators and construction steel used inside the buildings. These elements create locally changing magnetic field. To increase the sensitivity of the measurement, it is crucial to remove all elements made from ferromagnetic materials from its immediate surroundings. Also, the active system of eliminating external disturbances must be used. It was implemented as the cage of Helmholtz coils with the diameter of 2 meters (Fig. 6). The measurement system was working in the feedback loop, where the measured magnetic field strength influenced the excitation currents from the power sources. In such a circuit signals acquired by the reference magnetometers are used to control the current flowing through the particular pairs of Helmholtz coils, suppressing the Earth field components in all axes [18]. The field disturbances inside the Helmholtz cage were: H_x=4.8mG, H_y=5.4mG and H_z=3.2mG, respectively. The amplitude of the magnetic field strength causing disturbances was 0.38; 0.43 and 0.29 A/m, respectively.

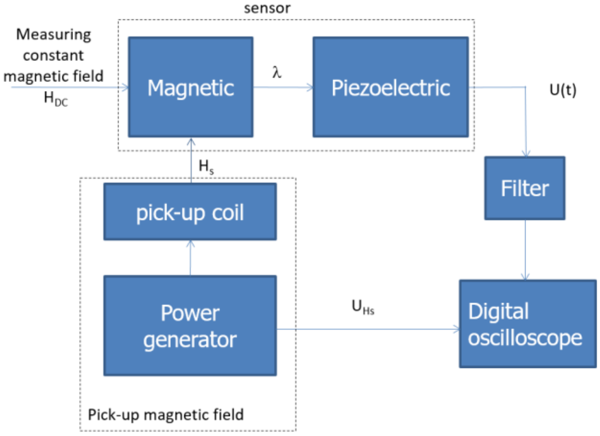

Fig. 4. The scheme of the measurement circuit.

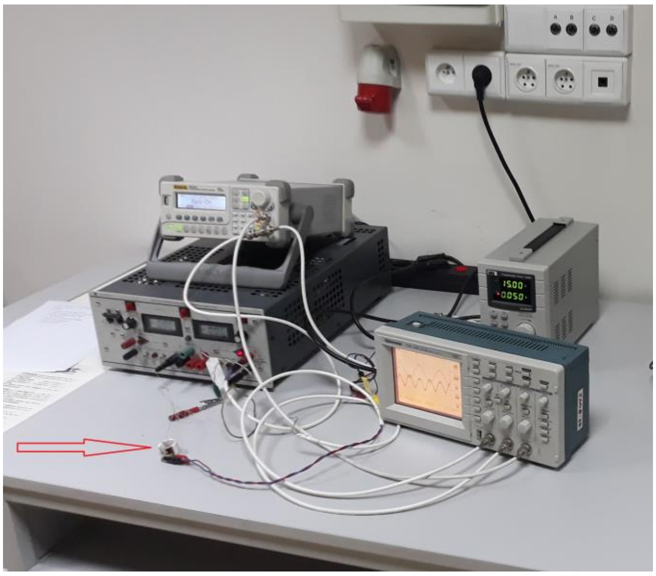

Fig. 5. Measuring stand constructed according to the Fig. 4 scheme with the prototype sensor.

C. *Experiments*

This section presents experiments performed with the sensor. The device is excited by the 5V sinusoidal voltage signal with 1kHz frequency. Based on the measured strength of the magnetic field it was determined if the sensor is able to detect Earth's constant component, which would confirm the sensitivity and ability to collect the specific amount of energy from the nearby magnetic field. The particular attention was also drawn to the harmonic components, of which the first two are the most important. The signal is proportional to the measured magnetic field. Its first and second harmonics carry the greatest amount of power, which ensures the maximum energy to be collected.

Fig. 6. The three-axial system of the Helmholtz coils eliminating the magnetic field.

The initial measurements were made in the laboratory conditions (Fig. 5). Fig. 7 shows changes in peak-to-peak voltage of the first harmonic as the function of the constant magnetic field H_{DC} generated in the pick-up coils. The asymmetry of the patterns is caused by the influence of the external magnetic fields (including Earth's field), which disturb the measurements. The Earth's field near Warsaw is directed at an angle of about 65° to the planet core. Its value is about 49 µT, with the horizontal component being only 19 µT [15]. To eliminate the influence of the Earth's field the three-axial circuit with Helmholtz coils is used.

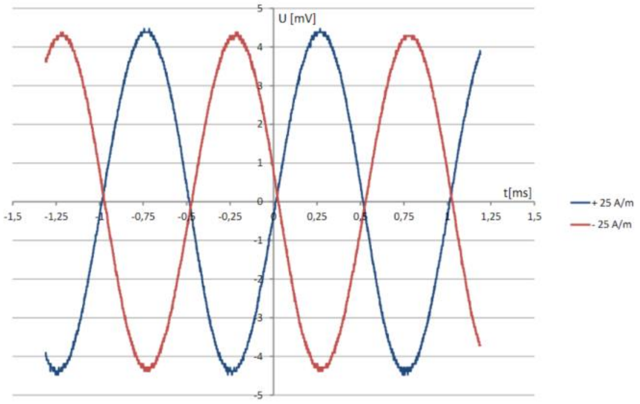

Fig. 7. Changes in the phase of the first harmonics for the sensor's output signal depending on the direction of the measured magnetic field strength for the field created in pick-up coils: H_{DC}=+25A/m and H_{DC}=-25 A/m.

Fig. 8 presents the output voltage patterns obtained from the examined sensor after putting it inside the Helmholtz cage (three-axial Helmholtz coils). The elimination of the Earth's magnetic field components causes the decrease of the pattern's symmetry. The current's amplitude is expected to be about 1mA, which should allow to charge the energy container (capacitor). This, in turn, opens the possibility of low-energy tasks execution (like sending text messages) in time of danger or energy deficiency.

The change of the phase allows to detect the change in the direction of the constant magnetic field. During experiments performed in the Earth's field the obtained power can be about 4µW amplitude. It will be then possible to obtain much higher voltage values for stronger fields [19].

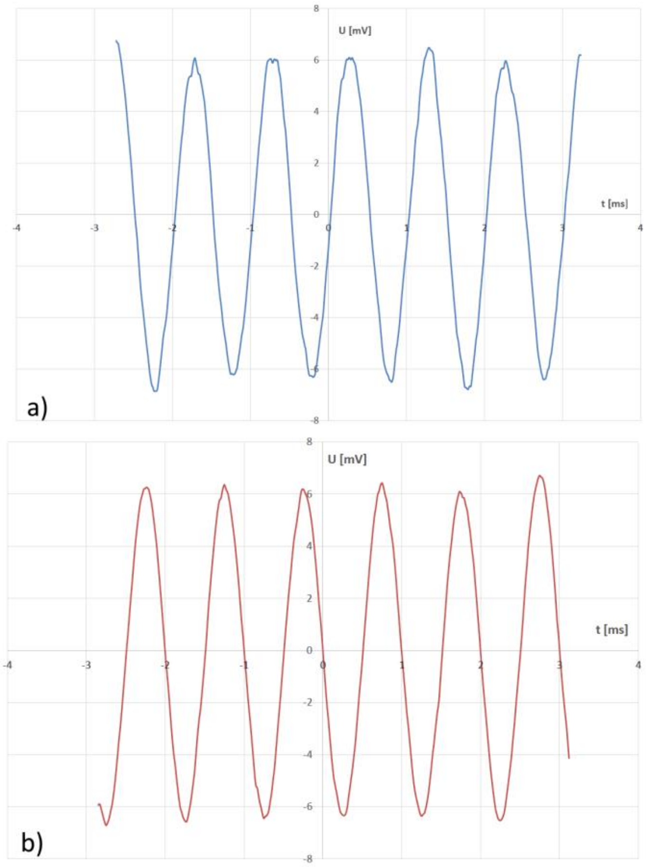

Fig. 8. Changes in the phase of the first harmonics for the sensor's output signal depending on the direction of the measured magnetic field for the field strength created in pick-up coil: a) H_{DC} =15 A/m and b) H_{DC} =-15 A/m.

D. *Discussion*

The conducted experiments prove that the sensitivity of the sensor is high enough to detect very low magnetic fields, comparable to the Earth's field. This makes the device a perfect harvester in situations where only small fields exist. An example of such a situation is compliant to the scheme presented in Fig. 1. For instance, in the subway platform the electroenergetic line, powering infrastructure appliances (such as lights) can be the source of the energy harvested by the sensor. The latter would be located near such a line and load the capacitor, which further could be used to power security systems, for example during the blackout.

Here the influence of the Earth's field must be considered, as its vector will change the amount of the energy collected (assuming the components have comparable amplitudes, i.e. tens of μT). Before the system is deployed, the information about the directions of magnetic vector components should be known to estimate the amount of energy that can be collected in the specific period of time.

Another application of this sensor for EH is its installation near the overhead power line of the electric train. The current flowing through the wire is between 400 and 1000A, which allows to collect large amounts of energy within the short period of time. However, in such an application the Earth's field is negligible because its strength is very small - comparable to the field created near the power wires.

In both scenarios the sensor should work in the passive mode, i.e. it will not be excited by the external voltage, but positioned in the varying magnetic field. The latter will induce the current, which would fill the capacitor.

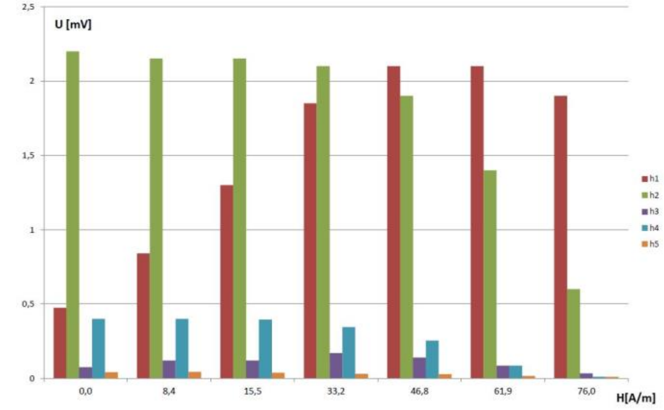

Fig. 9. Values of voltage components at subsequent harmonics for varying values of the magnetic field's strength.

An important aspect is the ability to collect energy from multiple harmonics, which is impossible in other magnetoelectric sensors, built from the GMM. This will increase the efficiency of the EH process by about 25% (see Fig. 9).

To confirm the applicability of the presented sensor in the EH scheme, experiments in the operational conditions have to performed. The harvesting efficiency has to be determined in both laboratory (Helmholtz coils) and during field tests.

V. CONCLUSION

The paper presented experiments with the prototype of the magnetic field sensor. The outcome was its processing characteristics. Experiments were performed in the three-axial circuit of the Helmholtz coils to eliminate influence of the Earth's magnetic field on the measurements. As the result, the increases in the pattern symmetry and signal amplification were obtained. The greater the volume of the GMM, the higher the output power. The ribbon's breadth is limited by the technological process of its manufacturing process.

Currently there are multiple research conducted on the application of magnetoelectric structures to construct the current sensors [9,11,12,13,14], especially for EH [2,6]. The interdisciplinary character of the domain covers physics, material sciences, mechanics and electronics. Despite numerous works, the topic of EH is still not fully explored. For instance, the energy created in the sensor could be enough to send the message about the vehicle location to the rescue teams if the primary power system was down.

Future works will cover creation of the mathematical model for the magnetoelectric sensor to better understand its characteristics. The prototype will be applied to the EH system and its abilities tested in the laboratory and real-world conditions.

ACKNOWLEDGEMENTS

The authors wish to thank dr Alberto Gallinia from the AGH University in Krakow for enabling them to make the experiments in the three-axial Helmholtz coils circuit.

REFERENCES

[1] S. Priya (Ed.), D. J. Inman, “Energy harvesting technologies”, Springer Science+Business Media, LLC, 2009.

[2] H. Palneedi, V. Annapureddy, S. Priya, J. Ryu, “Review: Status and perspectives of multiferroic magnetoelectric composite materials and applications”, Actuators, 5, 9, 2016, DOI:10.3390/act5010009.

[3] J. Kaleta, ”Smart magnetic materials. Structure, manufacturing, testing properties, application”, Wrocław University of Technology Publishing House, Wroclaw 2013 (in Polish).

[4] B. Pozo, J. I. Garate, J. Á. Araujo, S. Ferreiro, “Energy Harvesting Technologies and Equivalent Electronic Structural Models – Review”, Electronics, 8, 486, 2019, DOI:10.3390/electronics8050486.

[5] F. Yang, L. Du, H. Yu, P. Huang, “Magnetic and Electric Energy Harvesting Technologies in Power Grids: A Review”, Sensors, 20, 1496, 2020, DOI:10.3390/s20051496.

[6] F. Narita, M. Fox, “A Review on Piezoelectric, Magnetostrictive, and Magnetoelectric Materials and Device Technologies for Energy Harvesting Applications”, Advanced Engineering Materials, vol. 20, 2018, DOI:10.1002/adem.201700743.

[7] Z.A. Ye, H. Kam, Tsu-Jae, K. Liu , “Negative stiffness structures for energy efficient MEM switches”, 2017 Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop (E3S), 19-20 Oct. 2017, Berkeley, CA, USA, DOI: 10.1109/E3S.2017.8246196.

[8] K. Kuczynski, G. Parzonko, “Possibilities of the energy recovery from the environment (energy harvesting) and other ways of powering electric vehicles”, “elektro.info”, 11, pp. 58-61, 2019, (in Polish).

[9] C.M. Leung, S.W. Or, S. Zhang, S.L. Ho, “Ring-type electric current sensor based on ring-shaped magnetoelectric laminate of epoxy-bonded Tb0.3Dy0.7Fe1.92 short-fiber/NdFeB magnet magnetostrictive composite and Pb(Zr, Ti) O3 piezoelectric ceramic”, Journal of Applied Physics, 107, 09D918, 2010, DOI: 10.1063/1.3360349.

[10] S. Tumański, “Measuring technique”, WNT , Warszawa 2007, (in Polish).

[11] C. Lu, P. Li, Y. Wen, A. Yang, C. Yang, D. Wang, W., He, J. Zhang, “Magnetoelectric composite Metglas/PZT-based current sensor”, IEEE Transactions on Magnetics, 50, pp.1–4, 2014, DOI: 10.1109/TMAG.2014.2326193.

[12] S. Zhang, C. M. Leung, W. Kuang, S. W. Or, S. L. Ho, “Concurrent operational modes and enhanced current sensitivity in heterostructure of magnetoelectric ring and piezoelectric transformer”, Journal of Applied Physics, 113, 17C733, 2013, DOI: 10.1063/1.4801390.

[13] X. Yu, G. Lou, H. Chen, C. Wen, S. Lu, “A slice-type magnetoelectric laminated current sensor”, IEEE Sensors Journal, 15, pp.5839–5850, 2015, DOI: 10.1109/JSEN.2015.2451551.

[14] S. Priya, R. Islam, S. Dong, D. Viehland, “Recent advancements in magnetoelectric particulate and laminate composites”, Journal of Electroceramics, 19, pp.147–164, 2007, DOI: 10.1007/s10832-007-9042-5.

[15] S. Tumanski, “Magnetic field sensors - the review”, Przeglad Elektrotechniczny, 2, pp.74-80, 2004, (in Polish).

[16] M. Bichurin, R. Petrov, V. Leontiev, G. Semenov, O. Sokolov, “Magnetoelectric Current Sensors”, Sensors, 2017, 17, 1271; DOI: 10.3390/s17061271.

[17] K. Kuczynski, „Magnetic field sensor”, utility model, PL 067861 (in Polish), [Online]. Available: https://pl.espacenet.com/publicationDetails/biblio?FT=D&date=20141027&DB=pl.espacenet.com&locale=pl_PL&CC=PL&NR=121952U1&KC=U1&ND=5#.

[18] A. Podgórni, “The importance of shielding in measurement of magnetic field”, Problems and progress in metrology PPM’18 – Conference Digest (in Polish).

[19] K. Kuczynski „Possibilities of the application of hybrid magneto-piezoelectric junction as the magnetic field sensor”, Przeglad Elektrotechniczny, 4, pp. 69-71, 2010, (in Polish).