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Magnetoelectric Alternator

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Abstract: The article is devoted to researching the practical application of the magnetoelectric effect for the development of energy harvesting devices, in particular for the design of magnetoelectric synchronous generator. The energy harvesting devices are designed to provide by the energy of remote or nonvolatile electronic devices that don't require the high power consumption. General dimensions of the generator were as follows: diameter of 12 cm, thickness of 2.4 cm. The model of generator comprising eight ME elements with dimensions of one element of $40 \times 10 \times 0.5$ mm at the frequency of the alternating magnetic field of 38 Hz provides the output constant voltage of 1.12 V and current of 3.82 microamps. Variable voltage before the rectifier was of 1.7 V. Total generated power was of 4.28 μW. The studies of resonant and non-resonant mode of ME element were carried out. Resonance mode of ME element provides a much greater output power. Designed generator can be applied in the construction of wind power sets, hydrogenerators, turbogenerators and other power generation equipment.

Keywords: energy harvesting system, magnetoelectric effect, magnetoelectric alternator

Introduction

The design of renewable energy assumes ever greater importance in the modern world. The energy harvesting devices if don't solve this problem, but at least help to forward the facilitation of energy regimes. Our study focuses on a new device that integrates the well-known design of a synchronous generator and magnetoelectric (ME) effect. Such generator can be applied, for example, in wind-turbine electric plants, hydrogenerators, turbogenerators, and the electrical equipment intended for converting the mechanical energy of the primary engines in electric one.

The use of ME effect in devices for energy harvesting and a description of the general principles of operation of such devices was given in one of the first articles on the topic (Dong et al. 2008). Since then, many papers describing various devices have been devoted to this subject (Bichurin et al. 2009; Priya et al. 2009; Tadesse, Zhang, and Priya 2009). The basis of these devices are ME elements made of special materials (Magnetoelectric Materials 2006) which use the ME effect (Bichurin and Petrov 2010) that is, the appearance in the material of the electric polarization under the action of external magnetic field. Structurally, these devices are made mainly on the effect of oscillatory processes. It is known that oscillations or vibrations contribute to the intense release of energy in ME element. Then the resulting energy is converted to the desired level and accumulated. The energy generated by the ME element at action of vibration and magnetic field, in the general case consists of two components: the energy due to piezoelectric effect, and to the ME effect (Bedekar et al. 2011; Petrov and Ivanov 2010).

The idea using the circular motion to generate energy is widely applied in practice. The energy produced by the wind and water mills and then by electromagnetic generators has became as the standard. However, still the designs using ME elements in a rotating magnetic field for energy harvesting system have not been developed. This idea can make the next step in technical progress of the energy harvesting devices. Rotational motion of ME elements around point sources of magnetic field, or Vice versa, the movement of the magnet around ME elements which are fixed, will inevitably lead to the induction of an alternating electric potential across the electrodes of the device. Such device may be implemented in the form of a compact generator, in different variants of designs.

The generator proposed in this paper in comparison with other energy harvesting devices has several advantages. For example, as to the solar cells panels the ME generator is more compact in size and does not require of big surface for operation. Electromagnetic generator can be characterized by a large weight and materials consumption, in contrast, ME element is lighter and doesn't use in its composition expensive copper for the windings.

According to the data presented in (Rödig, Schönecker, and Gerlach 2010) the overall efficiency of a piezoelectric generator is estimated to be 25 %, the efficiency of commercial solar cell <20 %, thermal electric generator <10 %. In the review (Caliòet et al. 2014) it is reported that for the

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nanogenerator based on a zinc oxide nanowire array that works due to the piezoelectric effect the conversion efficiency lies between 17 % and 30 %. The steam (or gas) turbines (synchronous electric generators) in various configurations make use of practically all fossil fuels, from coal to natural gas and oil and nuclear fuel to geothermal energy inside the earth. Usually, their efficiency reaches 40 %, but in a combined cycle (producing heat and mechanical power), their efficiency recently reached from 55 to 60 % (Synchronous generators 2006). ME generator which considered in this paper incorporates the piezoelectric component and therefore has a similar efficiency of conversion of mechanical strain into electric potential as for piezoelectric generator. ME generator unlike piezoelectric generator uses a double power conversion, first the external mechanical energy is converted into the change of magnetic energy and as a result in the deformation of the magnetostrictive layer, and secondly, the deformation of the magnetostrictive layer causes deformation of the piezoelectric layer which causes the appearance of electric charge on the electrodes of ME structure. The first stage of energy conversion from mechanical to magnetic occurs efficiently and without significant losses, since there is almost no friction. Of course, such two-step conversion of mechanical energy less efficiently than in the case of piezoelectric generator, because at each stage of conversion we have the losses. However, the advantage of the ME generator can be a much more simple scheme of excitation of mechanical oscillations in ME structure which is carried out by means of magnetic field using the effect of magnetostriction. The use of ME effect in the device design allows to select the optimal mode of the generator operation, including in the resonance area. Also should be taken into account the fact that if the resonant mode of operation of ME elements is used, it can significantly increase power output.

Generator Design

The design of the generator is based on the use of ME elements. ME elements may be made of different materials, in our case we use magnetostrictively-piezoelectric layered material, which consists of piezoelectric material PZT and magnetostrictive material Metglas (Bichurin et al. 2012). Metglas layers were glued to piezoelectric material with two sides and used as electrodes for induced electrical voltage. Schematic drawing and photo of ME element is shown in Figure 1. The size of the ME element was of 40 × 10 × 0.5 mm.

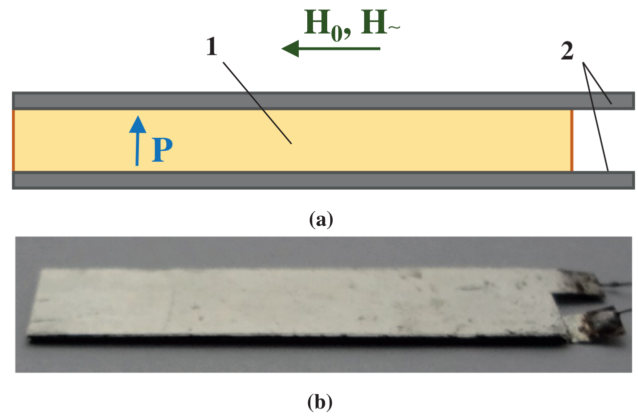

Figure 1: ME element. 1 is the piezoelectric PZT, 2 is the magnetostrictive material Metglas. (a) ME element structure, (b) The photo of ME element.

The ME element should be correctly positioned in the DC and AC magnetic fields for efficient operation of the device. Transverse direction of ME element magnetization is one of the structurally optimal variants of implementation of the design, when DC and AC magnetic fields are directed at the 90 deg angle to the direction of polarization, as shown in Figure 1. Deviations in the direction of the magnetic fields can significantly reduce ME effect and the value of the output voltage that should be considered at designing the generator.

The location of ME elements can be arbitrary, but for the best result, it needs to place the elements according to axes of symmetry with a maximum packing density. Consider two variants of this disposition with the forms of chamomile and the roll. Figure 2(a), (b) shows two variants of the designs. Figure 2(a) shows a longitudinal and cross section of three-phase synchronous ME generator in the form of the roll. Figure 2(b) shows the structure in the form of the chamomile.

The device consists of the stator and the rotor. The stator consists of the frame 1, in the plane which the ME elements 2 and the bias magnets 3 were located. The rotor consists of axis 4 mounted in the bearings of the stator 5, fixed on the axis by means of constructional holders 6, magnets 7. The electrical potential is induced at the electrodes 8.

The device operates as follows. On the axis 4 of rotor the torque is transmitted from an external source movement. The axis rotates the magnets 7 fixed by the holders 6. The magnets are designed for the creation of alternating magnetic fields at the rotation for ME elements of the stator 2. Permanent bias magnets 3 are installed in the stator to create

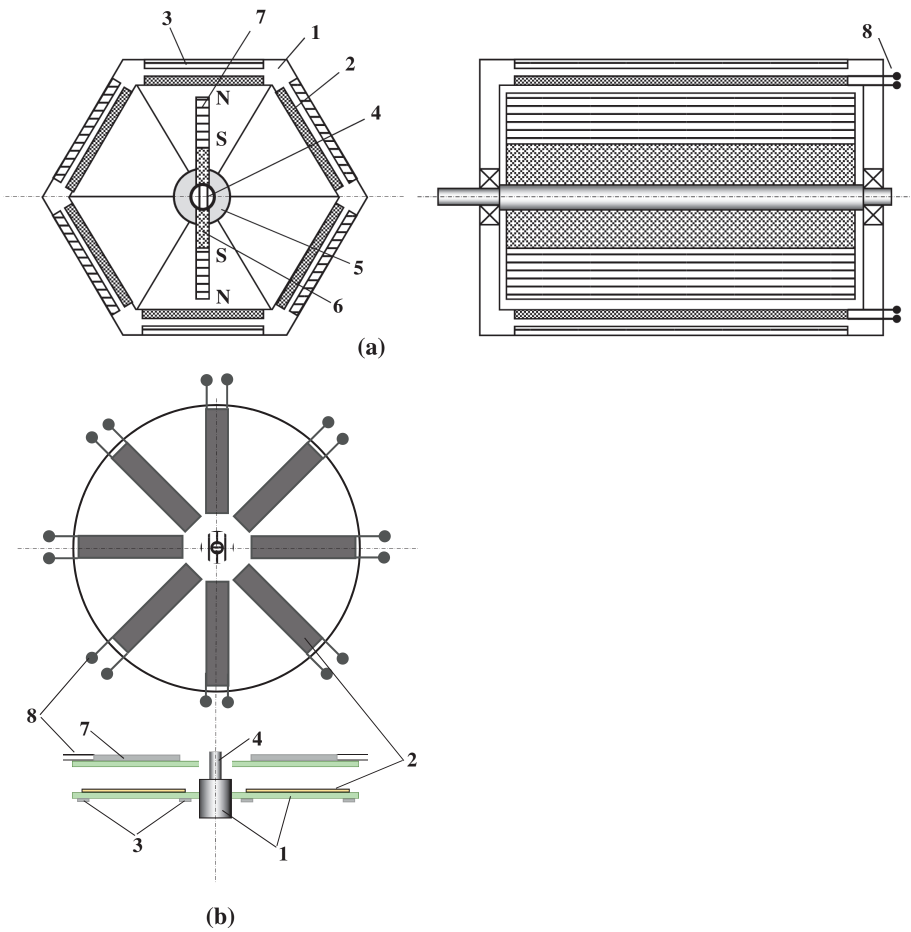

Figure 2: Examples of structures of ME generators. (a) Three-phase synchronous ME generator, (b) Single-phase synchronous ME generator.

the necessary offset in ME element. The alternating magnetic field induces an alternating electric potential on ME element via the ME effect: the alternating magnetic field acts on Metglas that in a result of the magnetostriction changes its dimensions, which lead to pressure on the piezoelectric phase of ME element, and this in turn induces the appearance of the electric potential on the electrodes of ME element due to the action of the piezoelectric effect. The ME elements may be interconnected, for example, as shown in Figure 3, or be used separately. If the polarized piezoelectric material is used for the manufacture of ME elements, it is necessary to consider the polarity of these elements. Finally, the electric potential is induced on the electrodes 8. In addition, the speed of the rotor at a constant frequency of magnetic field the stator is kept constant and does not depend on the output load on the shaft, i. e., the mode of operation of the generator is the synchronous.

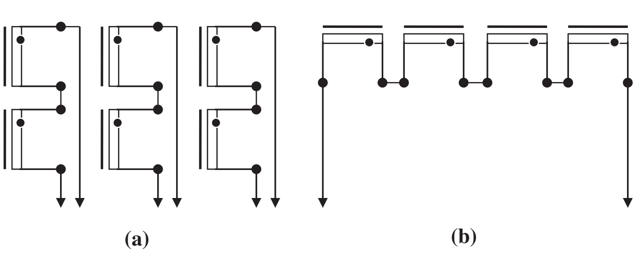

Figure 3: Diagram of connections. (a) Diagram of connections for the three-phase synchronous ME generator shown in Figure 2(a); (b) Diagram of connections for the single-phase synchronous ME generator shown in Figure 2(b).

Prototype of Generator

The designs shown in Figure 2 were manufactured in prototypes. The generator shown in Figure 2(b) is considered in more detail. In the design of the device shown in Figure 2(b) the ME elements are placed and fixed symmetrically on the stator in the form of a disk. General view of the prototype is shown in Figure 4. Permanent bias magnetic field acting on ME elements is created by the magnets fixed on the stator. The rotor in the form of the disc is rotated by an external source of motion from a small electric motor. Two niobium magnet with size $24 \times 12 \times 4$ mm were installed on the rotor.

Figure 4: Prototype of generator.

Permanent magnets create a variable magnetic field in the area of ME elements due to the rotation of the rotor, which leads to the emergence of the electric potential in them due to ME effect. The energy received from ME elements is rectified and then stored. General overall dimensions of the generator's prototype amounted to the diameter of 12 cm, thickness of 2.4 cm. Eight ME elements with size of $40 \times 10 \times 0.5$ mm of the composition of Metglas and PZT were presented in the structure of the prototype. All eight elements were combined into a single circuit through the rectifier bridges.

Measuring Stand

Figure 5 shows the schematic diagram of the measuring stand, photo of the stand is shown in Figure 6. Measuring stand consists of the ME generator, rectifier bridge, oscilloscope HMO722, multimeter HM8112-3, power supply

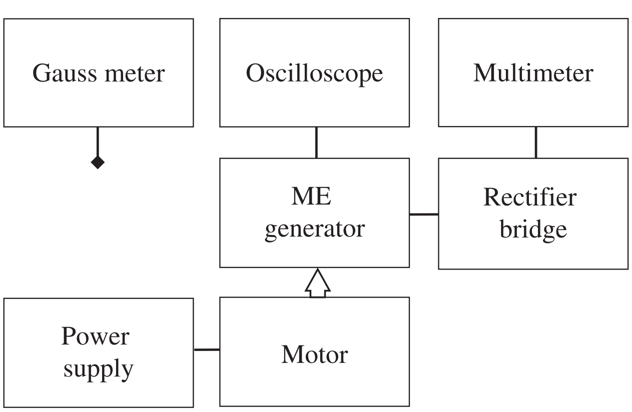

Figure 5: Diagram of ME generator measuring stand.

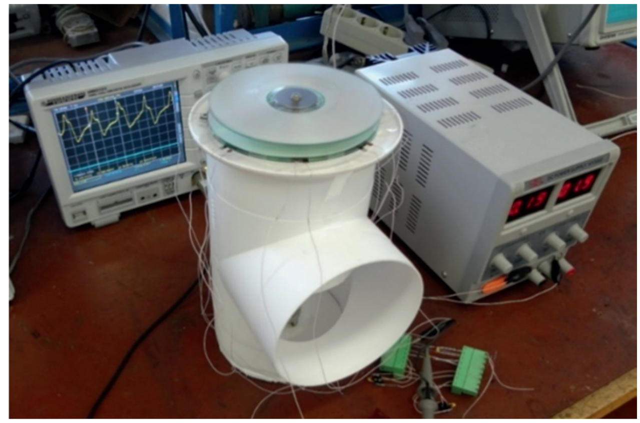

Figure 6: The measuring stand.

HY3002, gauss meter DX-180 and the collector electric motor, the speed of which is controlled by the voltage from the power supply. Gauss meter DX-180 was used to measure the variable and constant magnetic fields. The frequency of rotation of the motor is regulated by means of a power supply. Electric motor rotated the rotor of ME generator. The measurement of the potential at ME elements was carried out using the oscilloscope. The multimeter provided accurate measurement of voltage and current both AC and DC rectified signal.

Characteristics of ME Element

Figure 7(a) shows the characteristics of ME element depending on the frequency when bias field near 40 Oe. The optimum mode of operation in which ME coefficient reaches maximum of 2.64 V/(cm·Oe) is about 50 Hz at the low frequency and 198 V/(cm·Oe) about 41 kHz at the resonance mode. The real designs of synchronous generators can't work at kilohertz frequency range. Therefore, the oscillator frequency tends to decrease to the optimum for the ME element. The decrease of the resonance frequency is possible by increasing the length of ME element and the excitation of oscillations at bending mode of resonance frequency, which can be below 1 kHz.

Figure 7(b) shows the characteristics of ME element depending on the applied DC magnetic field at the frequency about 50 Hz and the amplitude of AC magnetic field of 1 Oe. Figure 7(b) shows that ME coefficient strongly depends on the presence of the constant magnetic field and optimum field is about 65 Oe when ME coefficient reaches a value of 2.64 V/(cm·Oe).

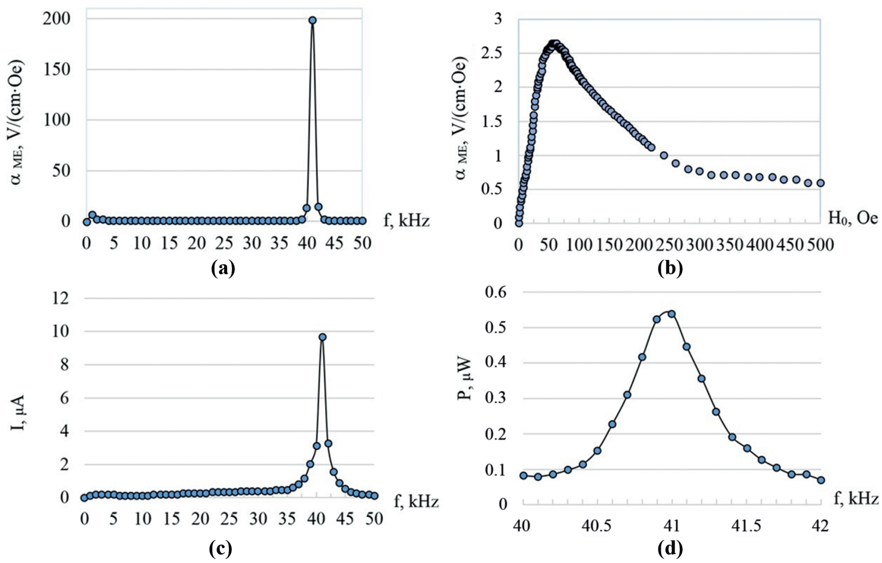

Figure 7: The characteristics of ME element. (a) Frequency characteristics of ME element. (b) DC magnetic field characteristics of ME element. (c) Frequency dependence of the output current. (d) Frequency dependence of the output power.

Figure 7(c) shows the frequency characteristic of output current of ME element in the range up to the frequency of 50 kHz. The current reaches the value of 0.01 μA at bias magnetic field of 65 Oe and the alternating magnetic field of 1 Oe at the frequency of 38 Hz. The current reached its maximum of 10 μA at the resonance frequency of 41 kHz.

The value of the output power is defined as the product of voltage and current. Figurer 7(d) shows the frequency dependence of output power in the resonance region. The maximum of output power was of 0.55 μW with bias magnetic field of 65 Oe and the alternating magnetic field of 1 Oe at the resonance frequency. At the same time, the value of the output power in the low frequency region amounted of 0.55 nW. Figure 8 shows the characteristic of the output current of ME element at the frequency of 38 Hz and the bias magnetic field of 65 Oe in the range of alternating magnetic fields from 0 to 20 Oe.

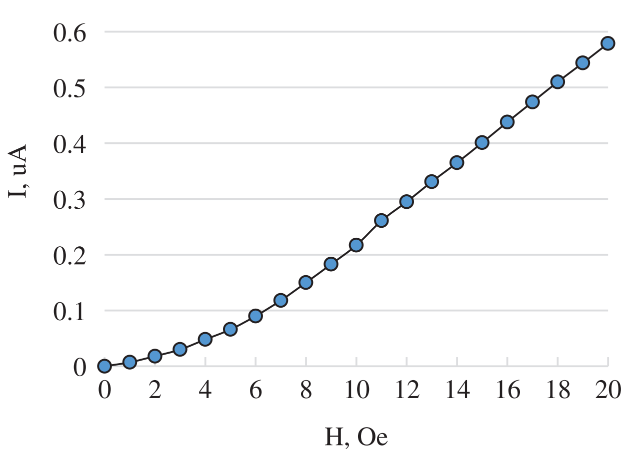

Figure 8: The output current dependence of the alternating magnetic field for ME element.

The nonresonant low-frequency ME effect was used in the generator's design. Resonance effect has the undoubted advantage of power output, but so far, the implementation of its design is planned in the future. For use of the resonance effect, it is necessary to reduce the resonant frequency of the element increasing the length of ME element to the required value or it is also possible to use bending vibrations (Petrov et al. 2012). However, in our opinion, the study of the design of the generator with the use of low-frequency ME effect is of considerable interest for the design of energy harvesting devices.

Characteristics of Generator

The prototype of generator contained eight of ME elements connected according to the scheme is shown in Figure 9. The elements were grouped by two for increase of the output voltage. At connecting of ME elements in pairs, it needs to take into account their polarization. Obtained four groups of elements then were connected to diode bridges. Further, the rectified voltage is summed and measured as the output characteristics of the generator.

Constant voltage of 1.12 V and the current of 3.82 μA was observed on the generator output when the frequency

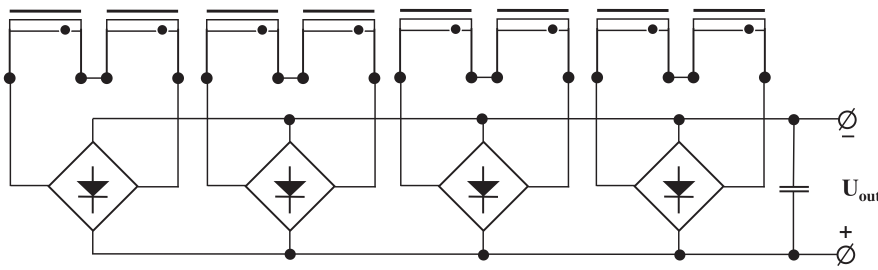

Figure 9: Schematic diagram of ME generator prototype.

rotation of the rotor and the alternating magnetic field was of 38 Hz. Alternating voltage until the rectifier was of 1.7 V. Total generator power amounted to 4.28 μW. The mode of operation of the generator was non-resonant. Figure 10 shows the waveform at the output of ME generator.

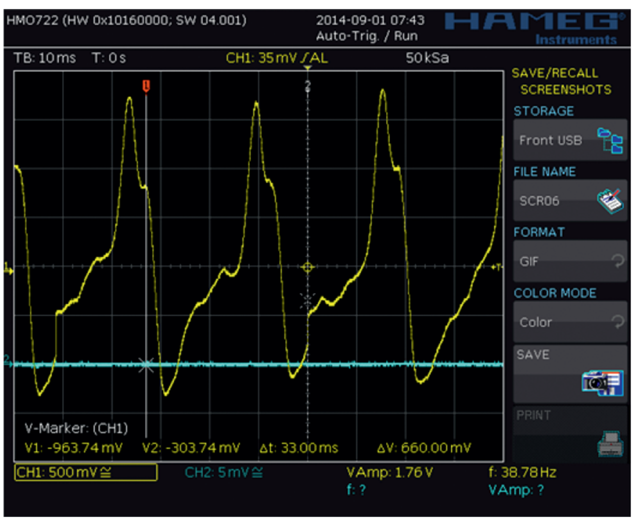

Figure 10: Oscillogram of the output voltage of ME generator.

Configuration of the Magnetic Field Generator

The results of measuring the magnetic fields of the stator are shown in Figure 11. Magnetic field measurements were carried out on the model of the generator with the using magnetometer.

The results of measuring of the magnetic fields of the rotor are shown in Figure 12. The influence of the magnetic field of the rotor on ME elements fixed on the stator was measured. The magnitude of the field decreases with increasing distance from the magnet. Therefore, the magnetic field of the rotor was measured at the distance between the rotor and the stator equal of 2 cm.

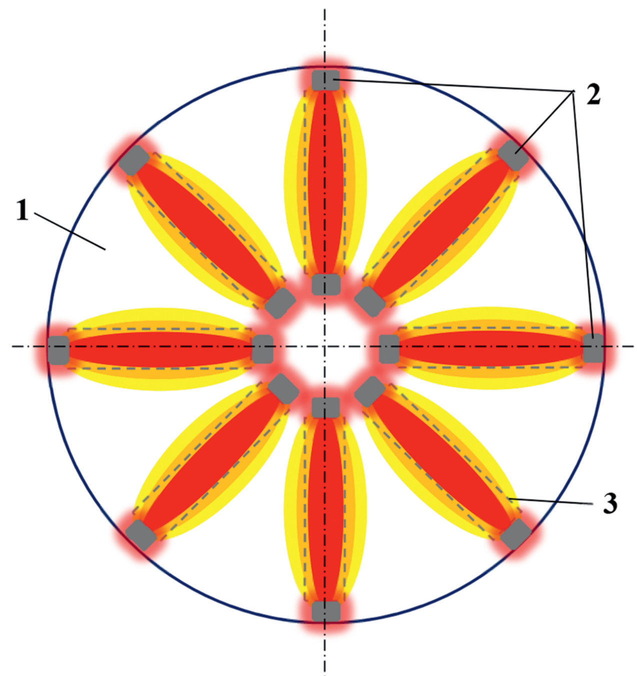

Figure 11: Configuration of the magnetic fields of the stator. Red zone between the magnets area is zone with field of 20 Oe. 1 is the stator, 2 is the permanent magnet, 3 is the contour of ME element.

The configuration of the magnetic field of the rotor was studied in order to determine the optimal location of ME elements and to find the best distance between the disks of the rotor and stator. The rotor was rotated with the frequency of 20 Hz, and because two magnets were installed on the rotor, the observed frequency of the output signal was of 40 Hz. If the bigger quantity of magnets is installed on the rotor, respectively, it will increase the frequency of the generated signal. The efficiency of the device work depends on the correct ratio of magnetic fields, which are applied to ME element. The field of the magnets on the stator forms the necessary bias for ME elements in linear mode, and variable magnetic field of

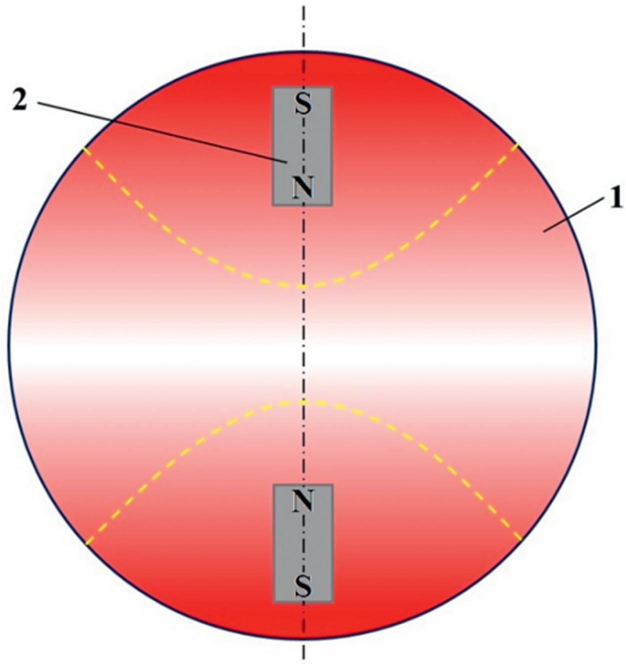

Figure 12: The configuration of the magnetic field at the distance of 2 cm from the rotor. Red zone is the zone of maximum magnetic field with the magnitude of 100 Oe, white is the zone of the field with the magnitude about 0 Oe. Yellow dotted lines are isomagnetic lines with the magnitude of the field of 30 Oe. 1 is the rotor disk, 2 is the permanent magnets.

the rotor causes alternating potential at the ME element. Correctly calculating and configuring the magnetic fields are possible to achieve better result, so this calculation should be given great attention as well as the choice and location of the magnets in the generator design.

Calculation of ME Coefficient

For successful analysis of the generator characteristics, it is sufficient to know the level of the output voltage obtained at each of ME elements. The method of calculation of the output voltage is reduced to obtaining expressions for ME coefficient (Bichurin, Petrov, and Priya 2011). The expression for the transverse ME coefficient at low frequencies is as follows:

$$\alpha_{E,\,31} = \frac{E_3}{H_1} = \frac{-V(1-V)({}^{m}q_{11} + {}^{m}q_{21}){}^{p}d_{31}}{{}^{p}\varepsilon_{33}({}^{m}s_{12} + {}^{m}s_{11})V + {}^{p}\varepsilon_{33}({}^{p}s_{12} + {}^{p}s_{11})(1-V) - 2{}^{p}d_{31}^{2}(1-V)}, \quad [1]$$

where E_3 and H_1 are the intensities of the electric and magnetic fields; ${}^{p}s_{11}$ and ${}^{p}s_{12}$ are the compliance coefficients of the piezoelectric material under constant electric field; ${}^{m}s_{11}$ and ${}^{m}s_{12}$ are the compliance coefficients of the magnetic phase with permanent magnet field; ${}^{p}\varepsilon_{33}$ is permittivity of piezoelectric material; ${}^{p}d_{31}$ is the piezoelectric coefficient of the piezoelectric phase; ${}^{m}q_{11}$ and ${}^{m}q_{21}$ are piezomagnetic coefficients of the magnetic phase; V is the volume fraction of piezoelectric material, $V = {}^{p}V/({}^{p}V + {}^{m}V)$; ${}^{p}V$ and ${}^{m}V$ are the volumes of piezoelectric and magnetic materials.

Output voltage for ME element can be calculated by known ME voltage coefficient of the material, which is determined by experimentally or theoretically, if the magnitude of the alternating magnetic field is known:

$$U_{out} = \alpha_{E,\,31} \cdot H_1 d, \quad [2]$$

where d is the thickness of ME element.

Outlook of Increasing Output Power of ME Generator

One ME element generates in the non-resonant mode very little power. The power of one ME element may be significantly higher by several orders in magnitude in the resonant range. In addition, the output power can be increased by increasing the density of the space-filling generator by ME elements. According to our estimates, generated power can be increased up to several watts with the same geometric dimensions of ME generator if to increase the density of the space-filling generator by ME elements and use a resonant mode. In this case, ME generator can be used as an effective energy harvesting device.

Conclusion

The paper presents experimental data of using the ME effect for the design of ME alternator. The generator can be used as the energy harvesting device. The prototype of ME generator including of eight ME elements with dimensions of one element $40 \times 10 \times 0.5$ mm and at the frequency of the alternating magnetic field of 38 Hz at the output of the device showed the constant voltage of 1.12 V and the current of 3.82 μA. Alternating voltage until the rectifier bridge was of 1.7 V. Total generator power amounted to 4.28 μW. Designed generator can be applied in the construction of wind power sets, hydro generators, turbogenerators and other power generation equipment.

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