Hybrid magnetoelectric converter

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Abstract. The article is devoted to the study of a hybrid magnetoelectric voltage converter. The article deals with the magnetoelectric structure of the converter with its design features. The measuring stand with the calculation of the converter parameters is also described and the measurement results are given. In the manufacture of the ME element, materials such as piezoelectric PZT and magnetostrictive amorphous alloy Metglas were used. ME is a layered element, which consists of a PZT plate with electrodes applied to the lateral surfaces and one or more Metglas layers. The Metglas plates are connected to the piezoelectric using an adhesive bond. In experimental studies, the number of Metglas layers varied from one to three. The article discusses the design of the converter and the choice of the most optimal of the ones under study. As a result of the study, the lowest indicators were found for a converter without a core, the more Metglas layers, the better the characteristics of the converter. The ME element at the resonant frequency converts energy much better (the conversion power was about 130 μW) than the design of a conventional converter, and also a hybrid converter based on a series switching circuit gives an even greater gain in energy conversion (the conversion power was about 180 μW).

1. Introduction
Transformers and converters occupy a significant part of the electrical equipment market and despite the fact that a large number of different variants have been developed and produced, there are more and more interesting ideas for implementation. One such idea is to use the magnetoelectric (ME) effect as a transformation effect. ME materials have completely different structure and magnitude of the ME effect [1]. Among magnetoelectrics, a special, most effective class of materials for operation at frequencies of up to several megahertz is distinguished – these are layered composite ME materials, which include layers of piezoelectric and layers of magnetostrictive material [2]. Investigation of the properties of ME materials and the use of these materials for the development of new devices is an urgent work carried out by many research groups [3–5]. Magnetoelectric converters were previously also discussed in publications [6–11]. Unlike previous articles, a hybrid ME converter and transducer will be considered here. The aim of the work was to achieve better performance in terms of conversion efficiency than a conventional convertor.

2. ME structure
For the manufacture of the ME element, an ME layered material was used, which consists of piezoelectric PZT plate with dimensions of 20x8x0.45 mm with electrodes applied to the lateral surfaces and one or
several layers of the magnetostrictive Metglas alloy with dimensions of 18x8x0.023 mm. Such materials are commonly referred to as ME magnetostrictive-piezoelectric layered composites. To obtain the ME effect, from one to three Metglas layers were fixed to the piezoelectric from one of the sides using an adhesive bond. As a result, the resulting asymmetric design had a significant ME coefficient in the bending mode of electromechanical vibrations equal to more than 40 V / (cm-Oe) at a constant magnetizing field of 80 Oe. A constant magnetizing field of 80 Oe was chosen in such a way as to achieve the maximum ME coefficient at the resonant frequency. The measurement data of the ME coefficient are shown in Figure 1. For a converter with a single-layer Metglas, the electromechanical resonance (EMR) is at a frequency of about 3.8 kHz, with a two-layer Metglas the EMR is about 4.1 kHz, and with a three-layer Metglas the EMR is about 4.3 kHz.

The calculation of the ME voltage coefficient was carried out. Formula for theoretical calculation:

$$\alpha_v = \frac{2^{m^t} \rho \epsilon_1 t^2 \langle q_{11} \rangle \langle h_{31} \rangle \beta_{33}^S (r_r r_r r_r r_r - r_r r_r r_r r_r)}{t \langle c_{11} \rangle \kappa l^t \beta_{33}^S (1 - r_r r_r r_r - 2 \rho^t \langle h_{31} \rangle r_r r_r r_r r_r - r_r r_r r_r r_r - r_r r_r r_r r_r)}$$

(1)

where

$$\rho = \frac{\rho^t + m^t}{t}$$

– total composite thickness

$$\rho^t = \frac{\rho^t}{t}$$

– voluminous fractions of a piezoelectric and a magnetostrictive

Effective density of the composite

$$\rho = \frac{\rho^t \rho + m^t \rho}{t}$$

$$\bar{\epsilon}_{11} = \left( \rho_{s_{11}} - \frac{d_{31}^2}{e_{33}^T e_0} \right)^{-1}$$

$$\bar{F}_{31} = \frac{\rho_{s_{31}} d_{31}}{e_{33}^T e_0}$$

$$\bar{\beta}_{33}^S = \frac{1 + \bar{F}_{31} d_{31}}{e_{33}^T e_0}$$

$$\rho_{s_{11}}^E$$ – pliability of a piezoelectric at a constant electric field strength

$$d_{31}$$ – PZT piezoelectric coefficient

$$e_{33}^T$$ – relative dielectric constant of PZT at constant mechanical stress

$$\langle h_{31} \rangle = \frac{2 z_0 - \rho^t}{2 \rho^t}$$

$$\langle q_{11} \rangle = \frac{\bar{q}_{11} (2 z_0 + m^t)}{2 m^t}$$

$$\bar{q}_{11} = m^Y q_{11}$$
\[ \langle \beta_{33}^t \rangle = \frac{1}{\rho t} \int_{z_0}^{\hat{z}_0} \delta_{33}^t dz = \bar{\beta}_{33}^t \]

\[ z_0 = \frac{\tau_{11}^D \rho t^2 \bar{\beta}_{33}^S - mYB^m t^2 \bar{\beta}_{33}^S - \rho t^2 \bar{h}_{33}^S}{2 \left( \tau_{11}^D \rho t \bar{\beta}_{33}^S + mYB^m t \bar{\beta}_{33}^S - \rho \bar{h}_{33}^S \right)} \]

- the position of the interface between the piezoelectric and the Metglas relative to the centerline of the composite

\[ mYB = \frac{mY}{1 - mK_{11}^2} \]

\[ mK_{11}^2 = \frac{mY q_{11}^2}{\mu \mu_0} \]

- the square of the magneto-mechanical coupling coefficient

\[ mY, q_{11}, \mu \] - Young's modulus, pseudo-piezomagnetic coefficient, relative magnetic permeability of Metglas

\[ \langle c_{11} \rangle = \frac{1}{t^3} \left( D - \frac{\rho \bar{r}^t \langle h_{33}^s \rangle^2}{\bar{\beta}_{33}^t} \right) \]

\[ D = \rho D^m + mD^m \]

- full cylindrical stiffness of the composite beam

\[ mD = \frac{1}{3} \frac{mY}{t} \left( mY t^2 + 3m^2 t z_0 + 3z_0^2 \right) \]

\[ \rho D = \frac{1}{3} \tau_{11}^D \rho t \left( \rho t^2 - 3 \rho t z_0 + 3z_0^2 \right) \]

\[ k = \left( \frac{\rho}{t^2 \langle c_{11} \rangle} \omega^2 \right)^{1/3} \]

\[ r_1 = \cosh (kl) \]

\[ r_2 = \sinh (kl) \]

\[ r_3 = \cos (kl) \]

\[ r_4 = \sin (kl) \]

- sample length

The theoretical calculation data are shown in figure 1. When constructing the theoretical curves, the resonance Q-factor was used.
3. Construction design of the converter
To convert the magnitude of currents and voltages in electrical engineering, converters of various designs are used, with or without a core. For this study, the simplest converter design was chosen in order to qualitatively determine the degree of influence of the ME material on the conversion value. For measurements, the converter switching circuits shown in figure 2 were used. The design consisted of primary and secondary wire windings on a frame. The design and photo of the proposed converter is shown in Figure 3. Either the Metglas core or the ME element was placed inside the frame. Secondary winding II (blue wire in the photo) is wound over the primary I (red wire in the photo). The primary winding has 250 turns of wire with a diameter of 0.2 mm. The secondary winding has 10 turns of 0.6 mm diameter insulated copper wire. Spool frame is 18x18x10mm with 10x1mm inner hole. For the experiments, the following designs of converters were made: a converter without a core (figure 2a), a converter with a core made of Metglas or the ME element (figure 2b), the ME element located inside the coil of the primary I winding (figure 2c), hybrid series connection of the secondary winding of the converter and the element located inside the coil of the ME (figure 2d). The design of the converter (figure 2d) includes the primary winding of the converter and the ME element connected in series with it. By using a series resonant circuit in the secondary winding, in this case, it is possible to increase the converted power. The ME structure is involved in the following way. In the case of figure 2b, Metglas plates of the ME structure are used as the core. In the case of Figure 2c, the ME structure is used as an output element, just as the direct ME effect is measured.

Figure 1. ME coefficient in the ME structure (solid lines – theoretical curves, dots – experimental data; black color – 1 layer of Metglas, red – 2 layers, blue – 3 layers).
In the case of Figure 2\(d\), a ME structure is used as the core, which is connected in series with the secondary winding II.

![Diagram](image_url)

**Figure 2.** Parameter measurement circuits: *a*) converter without a core, *b*) converter with a core made of Metglas or the ME element, *c*) ME element in a coil, *d*) hybrid series connection of the secondary winding of the transformer and the ME element.

![Photo](image_url)

**Figure 3.** Construction (left view) and photo (right view) of the ME converter. 1 is the ME structure, 2 is the primary winding I, 3 is the secondary winding II, 4 is the coil frame.

### 4. Measurement setup

The measurements were carried out using the measurement setup shown in figure 4. The setup included an HMF2550 generator, an HMO 722 oscilloscope, and an HM8112-3 multimeter. Current and voltage are measured in the frequency range up to 10 kHz. The full swing of the sinusoidal voltage at the generator output was 20 V.
5. Calculation of the converter parameters
To determine the ME coefficient of the curves shown in Figure 1, the following formula was used:

\[ a_{ME} = \frac{V}{d \cdot H} \]  

where \( V \) is the voltage at the output of the ME element; \( d \) is the thickness of the ME element, cm; \( H \) is the intensity of the alternating magnetic field acting on the ME element, Oersted.

The output power of the converter was calculated using the well-known formula

\[ P = V \cdot I. \]  

The current and voltage were found by direct measurements on an HM8112-3 multimeter.

6. Measurement data
The measurement data carried out according to the diagrams shown in figure 2 are shown in figure 5 and figure 6. Figure 5 shows the comparative characteristics that allow judging the influence of Metglas on the characteristics of the converter. The coreless converter has the lowest performance. The more Metglas layers, the better the converter performance (figure 5, lines 2,3,4). Comparing the characteristics of a converter with a core of 1 separate Metglas plate and a core in the form of the ME element, which includes a completely similar Metglas plate, it can be seen that they practically coincide (figure 5, lines 2,6). Thus, it is shown that the effect of the adhesive bond in the composition of the ME element on the characteristics of Metglas is minimal. It can also be seen that if a constant bias field of about 80 Oe is applied to the ME
element (or Metglas plate), then the characteristic of the converter becomes slightly higher than in the case of a converter without a core (figure 5, line 5).

Figure 6 shows the comparative characteristics for all cases of figure 6 and two additional ones: the case of measuring the actual characteristics of the ME element according to the diagram in figure 2c (figure 6, line 7) and the case of measuring the characteristics of a hybrid ME converter with a ME element with 1 Metglas plate and a magnetizing field $H_0 = 80$ Oe according to the diagram in figure 2d (figure 6, line 8). From the analysis of the measured data, it can be seen that the ME element at the resonant frequency converts energy much better (conversion power is about 130 $\mu$W) than the converter design shown in figure 2b, and the hybrid converter in figure 2d based on a series connection circuit gives an even greater gain in energy conversion (conversion power is about 180 $\mu$W).

**Figure 5.** Measurement data 1 – converter without a core (diagram in figure 2a), 2 – converter with a core of 1 Metglas plate (diagram in figure 2b), 3 – converter with a core of 2 Metglas plates (diagram in figure 2b), 4 – converter with a core of 3 Metglas plates (diagram in figure 2b), 5 – converter with a core of the ME element with 1 Metglas plate and a magnetizing field $H_0 = 0$ Oe (diagram in figure 2b), 6 – converter with a core of a ME element with 1 Metglas plate and a bias field $H_0 = 0$ Oe (diagram in figure 2b).

**Figure 6.** Measurement data 1 – converter without a core (diagram in figure 2a), 2 – converter with a core of 1 Metglas plate (diagram in figure 2b), 3 – converter with a core of 2 Metglas plates (diagram in figure 2b), 4 – converter with a core of 3 Metglas plates (diagram in figure 2b), 5 – converter with a core of the
ME element with 1 Metglas plate and a magnetizing field $H_0 = 80$ Oe (diagram in figure 2b), 6 – converter with a core of the ME element with 1 Metglas plate and bias field $H_0 = 0$ Oe (diagram in figure 2b), 7 – characteristic of the ME element with 1 Metglas plate and bias field $H_0 = 0$ Oe installed inside the coil (diagram in figure 2c), 8 – characteristic of the hybrid ME converter with ME element with 1 Metglas plate and bias field $H_0 = 80$ Oe (diagram in figure 2b).

Then the measurements of the hybrid ME converter were carried out according to the diagram in figure 2d. Such a switching circuit allows summing the converted power from the converter and from the ME element. The efficiency of the circuit is demonstrated by the data in figure 7. The power at the EMR frequency for a single ME element with 1 Metglas plate (figure 7, line 1), with 2 Metglas plates (figure 7, line 2), with 3 Metglas plates (figure 7, line 3), is compared with output power when the secondary winding of the converter and the ME element is connected in series (figure 7, line 2, 3, 4). It can be seen that series switching gives more power by an average of 20%. In the latter case, when 3 Metglas plates are used in an ME element, the power reaches a value of about 0.92 mW.

![Figure 7](image)

**Figure 7.** Measurement data of the hybrid magnetoelectric converter. 1 – characteristic of the ME element with 1 Metglas plate and the bias field $H_0 = 80$ Oe installed inside the coil (diagram in figure 2c), 2 – characteristic of the hybrid ME converter with the ME element with 1 Metglas plate and the magnetizing field $H_0 = 80$ Oe (diagram in figure 2d), 3 – characteristic of the ME element with 2 Metglas plates and a magnetizing field $H_0 = 80$ Oe installed inside the coil (diagram in figure 2c), 4 – characteristic of a hybrid ME converter with the ME element with 2 Metglas plates and a magnetizing field $H_0 = 80$ Oe (diagram in figure 2d), 5 – characteristic of the ME element with 3 Metglas plates and a magnetizing field $H_0 = 80$ Oe installed inside the coil (diagram in figure 2c), 6 – characteristic of the hybrid ME converter with the ME element with 3 Metglas plates and a bias field $H_0 = 80$ Oe (diagram in figure 2d).

The coefficient of efficiency (output-input ratio) of each of the investigated converters was equal to $2 \times 10^{-4}$% for the design of the converter without a core (figure 2a), for the design of the converter with a core made of Metglas/ME element (figure 2b) is 0.03%, for the ME element in the coil (figure 2c) is 0.08%, for the hybrid converter (figure 2d) is 0.09%.

### 7. Conclusion
The article studies the characteristics of a hybrid magnetoelectric (ME) voltage converter; for the manufacture of the ME element, the ME layered material was used, which consists of a plate of piezoelectric
PZT with dimensions of 20x8x0.45 mm with electrodes applied to the lateral surfaces and one or several layers of magnetostrictive amorphous Metglas alloy with dimensions of 18x8x0.023 mm. On one side, one to three layers of Metglas were fixed using an adhesive bond. For a converter with a single-layer Metglas, the electromechanical resonance is at a frequency of about 3.8 kHz, for one with a two-layer Metglas – 4.1 kHz, and one with a three-layer – 4.3 kHz. For this study, the simplest converter design was chosen in order to determine the degree of influence of the ME material on the conversion value. It is shown that the hybrid series connection of the secondary winding of the converter and the ME element gives more power by an average of 20%. In the latter case, when 3 Metglas plates are used in a ME element with dimensions of 20x8x0.52 mm, the power reaches a value of about 0.92 mW. The hybrid magnetoelectric voltage converter can under study be used to measure the current value in power current transformers, and also as a measuring element in DC and AC power circuits.

Acknowledgments
The study was carried out with the financial support of the Russian Foundation for Basic Research within the framework of scientific project no. 18-42-530001 r_a.

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