Technology to increase energy density of electric car batteries

V. I. ZUBTSOV
Department of Construction Industry
Polotsk State University
Novopolotsk, BELARUS

Abstract: The article deals with a small-sized unit developed using ferro-piezoelectric ceramics for electric power generation. The use of an electrochemical generator in the unit makes it possible to increase the efficiency of electricity generation by controlling the polarization of ferro-piezoelectric ceramics. At the consumption of 1 joule of electricity, using mechanical energy, 3, 5...5 joules of output electrical energy are generated. The increase in the energy density of the batteries occurs in two stages: the first stage is to increase the degree of polarization of the segmentelectric, the second stage is to increase the electrical power to the load.
The power plant efficiency is about 55...60 percent and depends on the ceramic modification and the electric circuit.

Keywords: Energy, power, voltage, polarization, technology, vehicle batteries
Received: September 8, 2021. Revised: June 21, 2022. Accepted: July 11, 2022. Published: September 2, 2022.

1. Introduction

Most countries are focused on achieving carbon neutrality. That is why electric cars are now being rapidly adopted. The mass transition to electric cars will require a large amount of additional electricity and the creation of networks of chargers and charging stations.

The range of an electric car on a single charge is much less than consumer demand. Its energy source (batteries) weighs a lot and costs a lot . The reason is that the energy density of modern batteries is too low. Although the energy density of batteries has recently almost doubled, they still have a large weight, size and cost. Known simple ways to increase the energy density of batteries are almost exhausted. In order for batteries to replace traditionally used internal combustion engines, their energy density should be increased approximately 10-15 times. The use of solar and wind energy is still inefficient. In addition, the national interests of hydrocarbon-producing countries are a deterrent to the development of electric vehicles. Thus, the problem of battery energy requires a solution.
Toyota's solid-state batteries, which promise to greatly increase energy density, are still under development. And it could be a decade or more before these batteries become mass-produced.

2. Brief description of the design and operation of the power plant. Mathematical justification of polarization and electrical voltage increase of an electrochemical generator

In connection with the above, a small-sized power unit (EU) of an alternative innovative technology using an electrochemical generator (ECG) based on ferro-piezoelectric ceramics was developed. Such an EU simultaneously increases the specific power and specific energy (energy density) of the batteries. Currently, there are opportunities to obtain significant electric currents (bias currents) in dielectrics by improving the electrical characteristics of ferro-piezoelectric ceramics and physical-technical solutions (technologies) [1]. In experimental dependences of output electric voltage on mechanical load of ferro-piezoceramic elements of various modifications and connection circuits are given [2].

Efficient use of ferroelectrics requires the development of a system that allows, compared to the electric drive devices currently used, to spend less energy from batteries and to increase the efficiency of converting mechanical energy into electrical energy due to the electrical characteristics of ferro-piezoelectric ceramics and physical-technical solutions (technologies). An increase in the energy density of batteries by

3.5...5 times is achieved by modifying ferro-piezoelectric ceramics, electric circuit, mechanical loading conditions, second-order ferroelectric transition, and interlayer and dipole polarization [2]. EU (interacting electromechanical transducer, device for mechanical energy generation and ECG), figure 1, increases the energy density of the battery in two stages: in the first stage there is an increase in the degree of polarization of ECG, in the second - an increase in the electrical power P_H at the output of EU, that is at the load.

In brief, the principle of operation of ECG, which is the main unit of the plant for increasing the energy density of batteries, is to release "frozen" energy of chemical reaction of oxidant and a ferro-piezoelectric ceramic element, which is a multi-component system of solid solution. Structurally ECG is ferro-piezoelectric ceramic element of a certain size and shape with metal contacts and attached leads for its connection to an electric circuit. Taking into account the use of mechanical energy, the power plant efficiency is 50 ... 55%. Consumption of 1 J of battery energy using mechanical energy makes it possible to obtain the output of 3.5...5 J of electrical energy at the output of the power plant. Used mechanical energy is generated by a device of simple construction [1, 3].

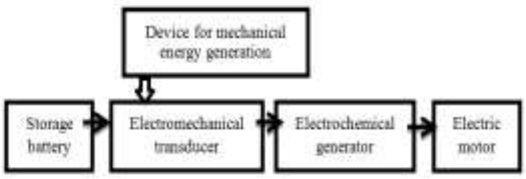

Figure 1**.** Functional diagram EU.

An increase in the degree of polarization of ferro-piezoelectric ceramic elements is achieved by controlling their compressibility and energy elasticity [2, 4].

The constructions of the electromechanical transducer and ECG, in addition to ferro-piezo electric elements, which can be represented as a resonant circuit, have other secondary elements. Therefore, in dynamics, these spring-mass structures have a complex spectrum of their own frequencies and in an electric circuit represent a series-parallel circuit [2, 5], which has two frequency constants: two resonances – a series one with frequency f_r and a parallel one (the so-called antiresonance) with frequency f_a.

We present the unknown expressions for f_r and f_a.

$$f_r = \frac{1}{4\cdot l}\cdot\sqrt{\frac{Y_{11}}{\rho}}\,kHz,\ f_a = f_r\left(\frac{K_c^2}{2.46}+1\right) = \frac{1}{4\,l}\left(\frac{K_c^2}{2.46}+1\right)\cdot\sqrt{Y_{11}/\rho},\,kHz \qquad (1)$$

Thus, it is possible to determine approximately the resonance and antiresonance frequencies, which is important for calculating the technical specifications for the EU.The increase in the degree of ECG polarization is explained as follows. Tthe equations of transformation for the plant of this construction and ferro-piezoelectric ceramics under active mechanical stress and closed output electrodes and E=0 is following:

$$S^E = s^E T$$
$$D^E = P^E = dT \qquad (2)$$

S^E goes for deformation under field strength of, E=0; s^E is compliance under E=0;

D goes for displacement when E=0; P means polarization when E=0.

The field with mechanical stress equal to E is used in case of open electrodes and the lack of strain (mechanical stresses T=0), when the element can be easily deformed. The equation is following:

$$S^T = dE$$
$$D^T = \varepsilon_a^T E \qquad (3)$$

S^T means deformation under T=0, different from S^E, D^T also differs from D^E.

If then decided that the electrodes are open and the field strain E and mechanical stress T influence simultaneously, and displacement D=0, then an interdependence between E and T can be found:

$$T = -\frac{\varepsilon_a^T}{d}E, \quad or$$
$$S^D = \left(S^E - \frac{d^2}{\varepsilon_a^T}\right)T = s^D T$$

Where D is less than S^E. It is clear that electric field E can be applied for changing elastic compliance s of ferroelectrics, i.e. for control of its rigidity (compressibility). An increase in compressibility is associated with an increase in deformation, and this is equivalent to the result of an increase in mechanical stress T, (2)

If E and T influences imultaneously, and deformation S=0, i.e. the element is pressed and does not deform, then an interdependence between mechanical stress T and electric field strain E is observed:

$$T = -\frac{d}{s^E}E$$

displacement D is found by the expression [4]:

$$D^T = \left(\varepsilon_a^T - \frac{d^2}{s^E}\right)E = \varepsilon_a^T \tag{4}$$

Absolute dielectric constants of the pressed element ε_a^S is obviously less than ε_a^T (3) and they are described in equation (5), K is an electromechanical coupling factor (a kind of efficiency of the material in the conversion of mechanical energy into electrical energy and vice versa):

$$\varepsilon_a^S = \varepsilon_a^T\left(1 - \frac{d^2}{\varepsilon_a^T s^E}\right) = \varepsilon_a^T(1 - K^2) \tag{5}$$

s^E goes for electric field strain compliance E=0

ε_a^T is an absolute dielectric constant under mechanical stress T=0. Controlling the compressibility and electroelasticity of ferro-piezoceramic elements in the installation makes it possible to increase the sensitivity of the output electrical voltage of these elements to the acting mechanical loads.

Thus, the control of compressibility and electrical elasticity of ferropoiezoelectric ceramic elements in the installation makes it possible to increase the electromechanical coupling coefficient K, i.e., their polarization [1, 4].

As already mentioned, the increase in battery energy density occurs in two stages. And the second stage is explained as follows. The degree of polarization depends on the magnitude of the charge on the surface of the ferroelectric. In a certain frequency range between resonance and antiresonance (1), where the strain will increase dramatically to a greater extent than it does due to mechanical loading, there is a sudden absorption of mechanical energy. This leads to a dramatic increase in the degree of polarization. A decrease in the electrical capacitance of the ECG segmentelectric leads to an increase in the electrical voltage U, and hence an increase in the electrical power P_H in the load.

At frequencies well below resonance, the equivalent circuit of the ECG [5, 6] is capacitive in nature and can be simplified as shown in Fig. 2. The electric charge is the natural output of the ECG. If it fluctuates according to the sinusoidal law, Fig. 2, we have [2]

$$q = Q_0 \cdot \sin(\omega t) = C \cdot U + \int i\,dt, \tag{6}$$

where Q is the amplitude value of the ECG charge, but $\dot{U} = \dot{I} \cdot R$, then

$$\frac{d\dot{I}}{dt} + \frac{1}{R_C}\dot{I} = \frac{\omega Q_0}{R_C}\cos\omega t \tag{7}$$

The final solution of this equation will be of the form:

$$U = U_1 sin\left(\omega t + arctg\,\frac{1}{\omega R_C}\right) - U_2 \cdot e^{\frac{-t}{R_C}}, \tag{8}$$

where

$$U_1 = \frac{Q_0/C}{\sqrt{1+\left(\frac{1}{\omega RC}\right)^2}} \tag{9}$$

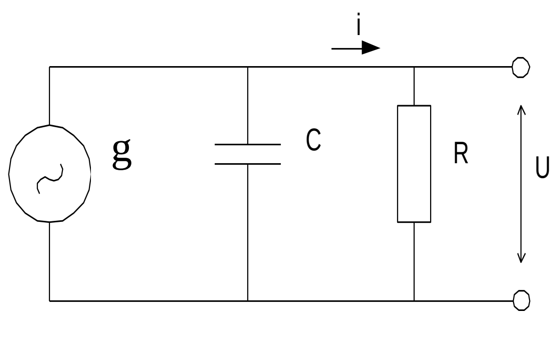

Fig. 2. Simplified equivalent diagram of the ECG, reflecting its capacitive nature of electrical resistance.

g - electric charge generated by the piezo effect;

C - capacitance of the ECG;

$$U_2 = \frac{Q_0 / C}{\frac{1}{\omega RC} + \omega RC} \quad (10)$$

Expression $\frac{Q_0}{C} = U_0$ - this is the amplitude value of the voltage that appeared on the capacitance C at $R \to \infty$. It follows from expression (8) that the output voltage U depends on the frequency ω, where the first term of equation (9) is proportional to the measured physical quantity, i.e. mechanical stress: an increase in mechanical load, as is known, is accompanied by an increase in the charge on the piezoelectric element, and an increase in the charge Q_0, as follows from equation (9), leads to an increase in voltage U_1; the second term characterizes the ECG in the transient mode, it disappears at large values RC, see equation (10). We transform expression (9) to such a form that it is possible to establish the dependence U_1, from ω:

$$U_1 / U_0 = \frac{\omega RC}{\sqrt{1 + (\omega RC)^2}}. \quad (11)$$

Using (11), we construct the dependence U_1 / U_0 from ωRC, fig. 3.

Curve in Fig. 3 is part of the experimental amplitude-frequency response of an electromechanical piezotransducer, see in [2] in fig. 4. 1 (curve 2), in the frequency range between anti-resonance and resonance. Piezoconverter is made of the segnelectric PZT-19, with a diameter of 10x1 mm with a mechanical load of 2.5 MPa.

From Fig. 3 it is obvious that increasing ω leads to increasing U_1 , and hence the output voltage U, see equation (8).

Thus, in a certain frequency range between resonance and antiresonance there is a sharp increase in the degree of polarization of the segmentelectric, which leads to an increase in the electrical voltage at the ECG output (increase of the charge g on its surface) and, consequently, the electrical powerMoreover, today there are

R - internal resistance of the battery, power plant load;

U - output electric resistance of the ECG. multicomponent ferro-piezoelectric ceramics of a considerably higher electromechanical coupling factor K than a PZT system.

Tests proved that 2 times increase (decrease) of a load electric power (Pн) causes 2√2 times, 3 times - 3√3 etc., increase (decrease) of ECG mass . All the changes follow the principles of geometric progression. More details about this are given in [1, 5, 7, 8].

The technology has no analogues. The main components of the EU are protected by copyright certificates and patents [2, 3], and the performance has been tested in experimental studies.

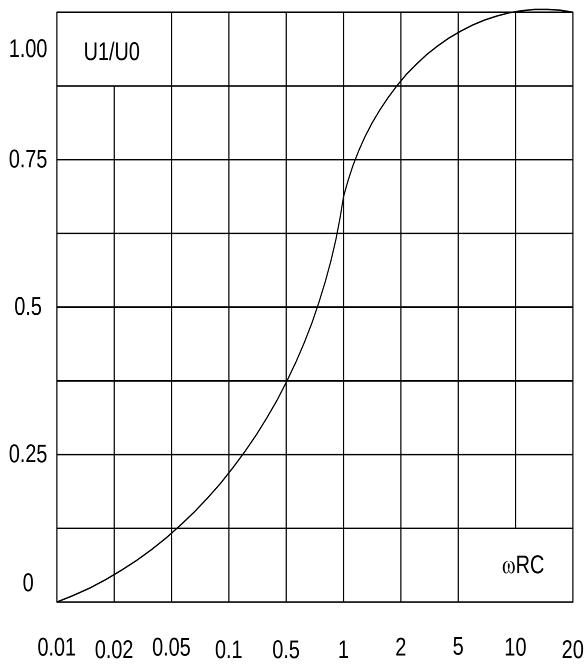

Fig. 3. Frequency response of ECG.

3. Conclusion

The proposed alternative innovative technology to increase the energy density of batteries compared to solar and wind energy has advantages: it does not depend on climatic conditions and time of day and has high efficiency. Segnetoelectrics are relatively cheap to produce [9, 10], while lithium ion batteries are very expensive to produce and only the more efficient batteries currently being designed will be even more expensive. The weight and cost of the electric car will increase slightly due to the presence of the EU. If you use an EU with the same range on a single charge, the weight and cost of the electric car will decrease, as the battery pack will be reduced by 3.5 times. Controlling the degree of polarization of ferroelectrics and increasing the energy density of batteries is mainly determined by the following:

- The modification of ferroelectrics and the electrical connection scheme;
- Mechanical loading (design features of the EU);
- interlayer or dipole polarization of ferroelectrics in the frequency range of the order of 1...1.5 (103 - 105) Hz.

References:

[1] Zubtsov V I , Zubtsova E V and V V Derugin The technology of increasing the energy density of batteries by controlling the degree of polarization of ferroelectrics. Jornal of Physics: Conf. Series 1400, 066061, 2019.

[2] Zubtsov V.I. Control of the physical properties of materials using piezoelectrics. Riga: LAP LAMBERT Academic Publishing, 2020. - 262 p.

[3] Zubtsov V.I., Zubtsova E.V. Segnetoelek ics in improving the efficiency of electric vehicles/ (Europe an Union: LAP LAMBERT Academic Publishing), 2021 - 54 p.

[4] Okazaki K. Manual on Electrical Materials (Moscow: Mechanical Engineering), 1979, - p. 432.

[5] Zubtsov V I , Zubtsova E V, Senterova V. V. Control of ferroelectrics polarization for increasing of alternative energy device's efficiency coefficient. IOP Conf. Series: Journal of Physics: Conf. Series 1038, 012113, 2018.

[6] Zubtsov V.I., Zubtsova E.V. Ferroelectric polarization control in technology for reducing power consumption when charging batteries // International Journal of Power Systems. – 2022. – No. 7. - pp. 10-14.

[7] V. I. Zubtsov, A.V. Zubtsova. Ecologically clean power plant to increase energy consumption by transport batteries // Ecological systems and devices. - 2019 - No. 5. - P.38-43.

[8] Zubtsov V.I. Efficiency of ferroelectrics application in technologies of simultaneous increase of specific capacity and electric drive power of light electric vehicles and alternative energy devices. Jornal of International science project. - 2017 - No7. - pp 15-20.

[9] Zubtsov V.I. Application of ferroelectrics in technologies for simultaneous increase in specific power and specific energy of light transport electric drive//Mat. intl. conf. on physics and astronomy /FTI im. A.F. Ioffe. - St. Petersburg, 2018 - pp. 243-244.

[10] Zubtsov V.I. Application of Segantoelectrics to Increase Drive Efficiency of Electric Vehicles //Mat. intl. conf. on physics and astronomy /FTI im. A.F. Ioffe. - St. Petersburg, 2021 - pp. 273-274.