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The technology of increasing the energy density of batteries by controlling the degree of polarization of ferroelectrics

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The technology of increasing the energy density of batteries by controlling the degree of polarization of ferroelectrics

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Abstract. The paper deals with a power plant developed with the use of ferro-piezoelectric ceramics to increase the energy density of electric vehicle batteries. Electrochemical generator in the plant makes it possible to significantly increase electrical energy by means of controlling the degree of polarization of ferro-piezoelectric ceramics. Application of the plant in an electric vehicle increases the range on a single charge by 3.5…5 times. Efficiency factor of the power plant is about 50...55% and depends on ceramics modification and electric circuit.

1. Introduction

The greenhouse effect, followed by an irreversible climate change, was to a great extent caused by the exhaust gases of internal combustion engines. In this regard one of the solutions to existing serious environmental problems is the production of electric vehicles (or hybrid cars). An electric car can go around 400 km on a single charge (a little less in winter). But its power source (batteries) weighs about half of a car and its cost is also about a half. The reason is that the power of modern batteries is too low. Despite the fact that the energy density of batteries has recently increased by 2 times, they still have large weight and size. Known simple ways to increase the energy density of batteries by improving their internal structure are almost exhausted. In order for batteries to replace traditionally used internal combustion engines, their energy density must be increased by 10–20 times. The invention of energy-intensive batteries is unlikely in the near future. The use of solar and wind energy is also ineffective. In addition, the national interests of countries producing hydrocarbon raw materials are a limiting factor in the development of electric vehicles. Thus, the issue of battery energy requires a solution.

2. Brief description of the design and operation of the power plant. Mathematical model of an electromechanical transducer in conjunction with an electrochemical generator and dependence of the growth of its mass on the electric power

In connection with the foregoing, a power plant of an alternative innovative technology using an electrochemical generator (ECG) based on ferro-piezoelectric ceramics has been developed. Such a power plant simultaneously increases the specific power and the specific energy (energy density) of batteries. Theoretical and experimental research shows that devices based on ferroelectrics, for which artificially obtained ferro-piezoelectric ceramics are used, can be a more effective alternative to devices and technologies currently used for electric drives by leading companies [1-4].

Currently there are opportunities to obtain significant electrical currents (bias currents) in dielectrics due to the improved electrical characteristics of ferro-piezoelectric ceramics and physical-and-technical solutions (technologies) [3, 5].

In experimental dependences of output electric voltage on mechanical load of ferro-piezoceramic elements of various modifications and connection circuits are given [1].

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). The designed system based on ferroelectrics can convert up to 90% of the received energy into net energy [1, 4]. 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 [3-5, 6]. The power plant (interacting electromechanical transducer, device for mechanical energy generation and ECG), figure 2, 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 Pн at the output of the power plant, 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 [2, 3].

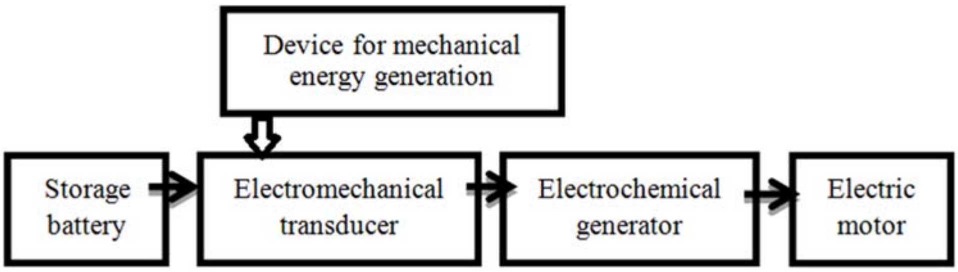

Figure 1. Functional diagram of the power plant.

An increase in the degree of polarization of ferro-piezoelectric ceramic elements is achieved by controlling their compressibility and energy elasticity [1, 5].

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 [1, 6], 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.

For ECG efficient use, it is important to determine the range of its operating oscillation frequencies. Let us consider a simplified mathematical model of an electromechanical transducer in interaction with ECG. Suppose that a ferroelectric ceramic plate serves as an electromechanical transducer and produces compression oscillations along its length, figure 2. To create a mathematical model it is necessary to work out the equation of motion of the transducer, select the ferro-piezoelectric effect equations, and also make basic assumptions. The main assumptions are as follows:

- all mechanical stresses, except for stresses in the direction of the transducer, are zero;

- the amplitude of alternating mechanical stresses and strains is not more than the maximum limiting values;
- the change of the reactive component of the transducer impedance at the operating frequencies has capacitive effect.

Let us determine the frequency constants of the transducer by solving the differential equations of the piezoelectric oscillations for the assumptions defined above.

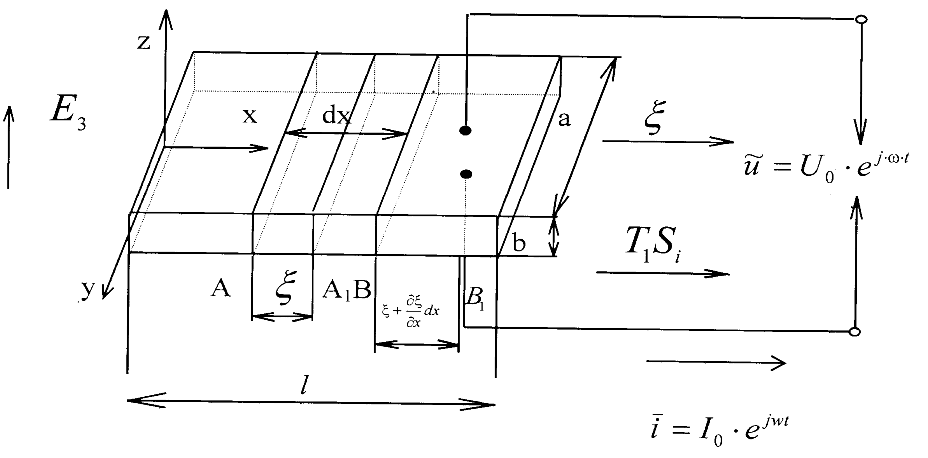

Figure 2. Diagram of the electromechanical transducer in interaction with ECG.

The equation of motion of the transducer is:

$$\frac{\partial^2 \xi}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 \xi}{\partial t^2}, \quad (1)$$

where ξ is amplitude of oscillation (displacement), $v = \sqrt{\gamma/\rho}$ - speed of elastic wave propagation in the plate, γ - modulus of elasticity of ferro-piezoelectric ceramics, ρ - ferro-piezoelectric ceramics density, l, a and b - length, width and thickness of the plate, respectively, t - time. This is a well-studied partial differential equation of second order. The equation of motion of the transducer is solved by variable separation method:

$$\xi(x,t) = X(x) \cdot T(t), \qquad \frac{1}{X(x)} \cdot \frac{\partial^2 X}{\partial x^2} = \frac{1}{v^2} \frac{1}{T(t)} \frac{\partial^2 T}{\partial x^2} = -n^2. \quad (2)$$

The solutions are the following, respectively:

$$X = A \cdot cos(nx) + B \cdot sin(nx),$$
$$T = C \cdot \cos(nvt) + D \cdot \sin(nvt) = M \cdot \cos(nvt + \varphi), \quad (3)$$

where $n = \frac{m\pi}{l}$, $(m = 1,2,3 \ldots)$. The resonance and antiresonance oscillation frequencies of the ferro-piezoelectric plate are determined for a fixed transducer. The boundary conditions are written as follows:

$$\xi(x,t) = X(0) \cdot T(t) = 0, \qquad \xi(x,t) = X(l)T(t) = 0, \quad (4)$$

where l is length of the plate. Omitting the intermediate calculations shown in [1, 4], we present the unknown expressions for f_r and f_a, given in kHz.

$$f_r = \frac{1}{4l}\sqrt{\frac{\gamma_{11}}{\rho}}, \qquad f_a = f_r\left(\frac{K_C^2}{2.46}+1\right) = \frac{1}{4l}\left(\frac{K_C^2}{2.46}+1\right)\sqrt{\frac{\gamma_{11}}{\rho}}\ . \tag{5}$$

Thus, it is possible to determine approximately the resonance and antiresonance frequencies, which is important for calculating the technical specifications for the power plant.

If an AC electric voltage is applied to ferroelectrics, then the polarization does not have time to follow the electric field, which leads to dielectric losses. When mechanical load is applied, the deformation is set late. That is, a phase shift corresponds to these processes. All materials in varying degrees are subject to relaxation processes. Relaxation processes in ferroelectrics are manifested due to mechanical and dielectric losses. A peculiar feature of ferro-piezoelectric ceramics, operating in dynamic mode, is the presence of both types of losses. At low frequencies, the angles of dielectric and mechanical losses in it make a total loss angle δ, defined through K_C [1,7], see equation (6). Therefore, the polarization is considered as a complex number: $\varepsilon_{rk} = \varepsilon_r - j\,\varepsilon_r'$, where ε_r is relative dielectric constant; ε_r' - imaginary part of the complex number, loss coefficient ($\varepsilon_r' = tg\delta \cdot \varepsilon_r$); tgδ - loss characteristic: δ - phase shift angle.

The frequency characteristics ε_r , ε_r' and δ depending on the normalized frequency ω/ω_0 are as shown in figure 3.

Now it is possible to explain ECG operation principle in more detail. Under mechanical load, as a result of the clamping of ferroelectric, there is a sharp decrease in ε_r , figure 3, which leads to electrical capacity reduction and an increase in K_c, that is, to a sharp increase in the efficiency of conversion of mechanical energy into electrical energy. In a certain frequency range between the resonance and the antiresonance, where the deformation will increase sharply to a greater extent than is due to mechanical load, a sudden absorption of mechanical energy occurs. This leads to a sharp increase in the degree of polarization.

The electrical capacity reduction of ECG ferroelectric leads to an increase in the electric voltage U, see equation (7), and consequently to an increase in the electrical power P_L in the power plant load.

Phase transitions in ferroelectrics occur in certain temperature ranges. In this regard it should be noted that in ferroelectrics, some piezoelectric modules which characterize the change in the degree of polarization under mechanical load, reach very large values in phase transitions, theoretically turning into infinity.

Thus, the effect of mechanical load in a certain frequency range and the effect of thermal energy in a certain temperature range are a sort of a catalyst of chemical reactions in solid solutions of ferroelectrics. Due to the acceleration of chemical reactions, an increase in the number and speed of movement of electric charge carriers occurs.

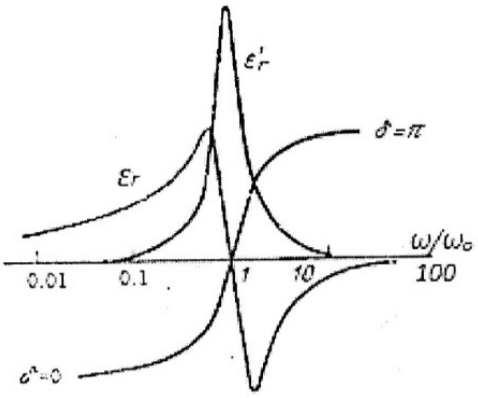

Figure 3. To the analysis of ECG resonance parameters.

The absolute dielectric constants, ε_α^S of the clamped element in this case are, of course, less than ε_α^T of the free one and are linked by equation of electromechanical coupling:

$$\varepsilon_a^S = \varepsilon_a^T\left(1 - \frac{d^2}{s^E\varepsilon_a^T}\right) = \varepsilon_a^T(1 - K_c^2), \tag{6}$$

where K_c is electromechanical coupling coefficient, S^E is elastic compliance while the electric field strength is E=0, ε_α^T is absolute dielectric constants where the mechanical stress is T=0 and d is piezoelectric module [4,5].

The function of ECG transformation is the following:

$$U_0 = K_u\frac{d_{ij}F}{C_{ECG} + C_L}, \tag{7}$$

where U_0 means output electric voltage of ECG, F is acting mechanical force, C_{ECG} is electrical capacity of ECG, C_L is electrical load capacity (load electrical devices), K_u is coefficient of electric voltage increase due to the increased degree of polarization of ferroelectric and d_{ij} is piezoelectric module, induced polarization per unit of mechanical stress.

From equation (6) it is obvious that the value of K_c has a significant effect on the ratio of dielectric constant of clamped and free ferroelectrics, i.e change in the dielectric constant under the action of mechanical load. For example, in case of K_c = 0.5 (an averaged value), this ratio will be 0.75. Which, in its turn, is highly important (especially since in modern ferro-piezoelectric ceramics K_c = 0.6 - 0.7 for output electric voltage (output power) of the power plant, see equation (7), as dielectric constant and electrical capacity are directly proportional. Tests proved that 2 times increase (decrease) electrical power under load (P_L) leads to 2√2, 3 times - 3√3 times, etc increase (decrease) of ECG mass (M_{ECG}). And an electromechanical transducer and mechanical energy generating device (figure 1.) 2.12 - 2.2 times increase (decreases) this mass. Thus, the mass of the power plant (without battery and electric motor) is 2.12 - 2.2 M_{ECG}.

Figure 4 shows a M_{ECG} - P_L growth-increase diagram. The foresaid and the diagram make it possible to calculate the mass of the plant (without battery and electric motor) taking into account P_L. In the diagram one may find a point where P_L = 1.82 kilowatt and M_{ECG} = 0.83 kg, around which P_L and M_{ECG} are changing almost in direct proportion. M_{ECG} grows slower below this point and faster above it.

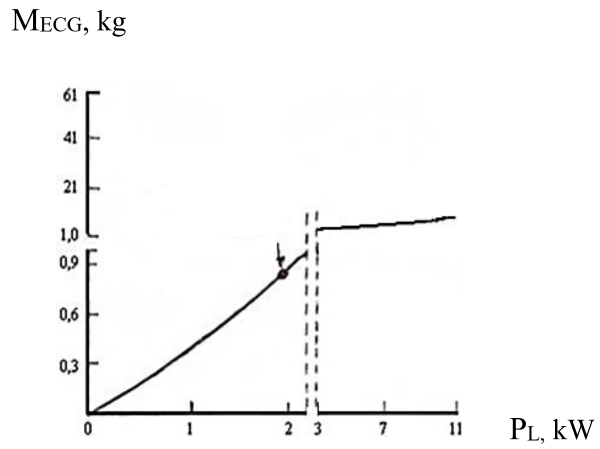

Figure 4. M_{ECG} – P_L growth-increase diagram.

As foresaid, 1 joule energy consumption from battery gives an electrical energy output of 3.5 - 5 joule under mechanical load. It means that power plant allows to reduce battery consumption by 3.5 - 5 times and thereby 3.5-5 times increase the mileage of e-vehicles on a single battery charge. The mass of batteries and the time to charge them are also 3.5 - 5 times reduced. Thus, the use of this power plant with a combination of advantages over the traditional electric drive solves the problem of replacing the traditionally used internal combustion engines with e-vehicles. The use of the power plant with P_L above 50 kilowatt requires ferro-piezoceramic materials with improved characteristics. In addition, an obstacle to generating greater power are the difficulties of ensuring uniform distribution of large mechanical loads on fragile ferro-piezoceramic elements, as well as polarization of large sizes of these elements. But these obstacles are overcome by the use of more advanced techniques of mechanical loads [8, 9] and the quality of manufacture of ferro-piezoceramic materials and elements.

The technology has no analogues. The main components of the power plant are protected by copyright certificates and patents [1], and the performance has been tested in experimental studies.

3. Conclusion

The proposed alternative innovative technology for increasing the energy density of batteries compared to solar and wind energy has an advantage: it does not depend on climatic conditions and time of day and has a high efficiency. The use of the developed power plant due to a combination of advantages over a traditional electric drive solves the problem of replacing traditionally used internal combustion engines with electric vehicles (or hybrid cars).

In addition, for the use of wind generators, it is necessary to study and account for various wind indicators, determined by the results of many years of observations:

- annual and monthly average wind speeds;
- repeatability of wind speed and direction during the year, month, day;
- gustiness, calm and maximum wind speed;
- its changes with height and others.

To use the energy of the sun is also necessary to study and take into account many factors.

The power plant can also be used to power small-sized unmanned aerial vehicles, wheelchairs, office and residential premises.

So, controlling the degree of polarization of ferroelectrics to increase the energy density of batteries is mainly determined by the following:

- modification of ferroelectrics and electrical connection circuit;
- mechanical load (power plant design features);
- interlayer or dipole polarization of ferroelectrics in the frequency range of about 1-1.5 (10^3-10^5) Hz.

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