PAPER • **OPEN ACCESS**

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To cite this article: V I Zubtsov *et al* 2018 *J. Phys.: Conf. Ser.* **1038** 012113

IOP Conf. Series: Journal of Physics: Conf. Series **1038** (2018) 012113 doi:10.1088/1742-6596/1038/1/012113

Control of ferroelectrics polarization for increasing of alternative energy device's efficiency coefficient

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Abstract: A plant, developed with the use of ferro-piezoelectric ceramics for generation of electric power, is studied in the article. The use of electrochemical generator in the plant makes it possible to increase the efficiency of electric power generation by means of polarization of ferro-piezoelectric ceramics control. Polarization control is proved by a mathematical model. Consumption of 1 joule electric power, using mechanical power, generates 3,5…5 joule of electric power output. Efficiency factor of the power plant is about 50…55 percent and depends on ceramics modification and electric circuit.

1. Introduction

The importance of finding balance between scientific and technical achievements and nature are felt badly today. Thus, manufacturing of e-mobiles, as a means of transport, is a possible solution to current serious ecological problems. The most practical of all electric drive means are e-motorcycles, e-scooters, e-bicycles and minivans, which belong to lightweight vehicles. A traditional electric drive comprises a power source (one or several storage batteries), a controller for motor control, an electric motor itself and a mechanism (absent in certain cases) for translation of motion to the movable unit. Storage batteries have a low energy content and provide a low run of an e-vehicle during one charging, and a sufficient weight and size, making the vehicle hard to place.

Problems are seemed to be easily solved by so-called primary electric power sources, generating energy directly from the fuel, e.g. oxygen or hydrogen. Despite a high efficiency factor (about 50 percent), fuel cells have very specific drawbacks: disability for energy recovery during braking, low specific output under great specific energy, etc. Thus the mass of energy cells for lightweight vehicles' capacities (and e-vehicles in general) is great. As a result, power units with driving motors for them are absolutely unacceptable. Today condensing energy storage systems, having a high specific output, are tried to be used together with fuel cells. But it is not efficient, as capacitor-based energy storage systems are characterized with a big size and mass, and they are highly explosive.

2. Construction and Mathematical Model of an Effective Electric Drive. Dependence of Mass Variation on Electric Drive Power

Taking into account the foregoing, an environment friendly unit of alternative technology with the use of electro-chemical generator (ECG), based on ferro-piezoelectric ceramics, is proposed. Such a power plant is characterized with both a high specific output and energy.

Theoretical and experimental research [1-4] prove, that a unit based on ferroelectrics, artificial ferro-piezoelectric ceramics is applied, can be used as the most efficient alternative to devices and technologies, used today for electric drive by foreign companies.

Experimental dependence [3], gained on small-sized full-cycle element (⌀ 2,3×1 mm) made of PZT (lead zirconatetitanate), proves the possibility of current I generation, equal to 4,5 mA, caused by a fluctuating mechanical force F, equal to 15 H, Figure 1. The PZT film composition is solid solutions of $PbZrO_3$ and $PbTiO_3$. The electromechanical parameters (piezoelectric modulus, electromechanical coupling coefficient, dielectric permittivity, etc.) reach their maximum near certain composition of 52% $PbZrO_3$ and 48% $PbTiO_3$. Modification of this composition with oxides of various metals has led to the creation of various PZT mode materials (domestically produced ceramics PZT - 19, PZT - 21, PZT - 23, etc.). Figure 1 shows the dependence for PZT – 23. In order to increase the power density is necessary to consider mainly the modification of the solid solution, electrical circuit, mechanical strength and ferroelectric element configuration when the ratio of the warmth radiation surface to the element volume will be the maximum possible. Furthermore, select of electric-field vector direction and mechanical stress components are taken into account. Dimensions of an element's certain form depend on its mass, the mass depends on electric power. Recalculation for a PZT unit of a bigger mass goes well with calculations made, proving that the specific output and specific energy are enough for the run of a lightweight vehicle.

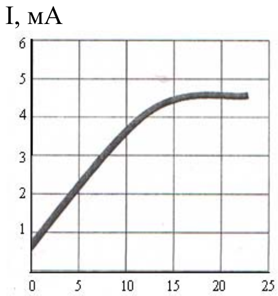

Figure 1. Dependence of the current on mechanical load of a PZT system element

Moreover, today there are multicomponent ferro-piezoelectric ceramics of a considerably higher electromechanical coupling factor K (a kind of efficiency factor of material's role in transformation of mechanical power into electric and vice versa) than a PZT system, expression (9). It also means that there are ways of generating bigger currents (bias currents in dielectrics) [4] describes experimental dependence of output voltage on mechanical load of ferro-piezoelectric ceramic elements of various modifications and closed circuits.

A system, allowing use less storage battery energy and improve the efficiency of transformation of mechanical power into electric, about by an order, due to electric characteristics of ferro-piezoelectric ceramics and physical-and-technical solutions (technologies), is required for efficient use of ferroelectrics. A created system, based on ferroelectrics, can transform up to 90 percent of gained energy into net energy [5-7]. In brief, the idea of ECG operation, the main joint of the plant, includes a release of "frozen" energy of an oxidant chemical reaction and a ferro-piezoelectric ceramic element, a multicomponent system of a solid solution. This energy is generated by mechanical energy, ferroelectric second-kind transition, and interlayer and dipole polarization [5].

Structurally, ECG is a ferro-piezoelectric ceramic element of a certain size and form with metal contacts and attached leads for its engagement into electric circuit. Efficiency rate of the plant, subject to the use of mechanical energy, makes 50…55 percent.

High efficiency of generation electric power in the plant (efficiency of the polarization of ferroelectric increase) is possible due to modification of ferro-piezoelectric ceramics, electric circuit, conditions of mechanic load, and, it was aforesaid, interlayer and dipole polarization. The plant comprises also a power supply (a storage battery for e-vehicle), a device for mechanical energy generation and electromechanical transducer Figure 2. Energy consumption of 1 joule, using mechanical energy, makes it possible to get the output of 3,5…5 joule of electric energy. Used mechanical energy is generated by a device of a simple construction.

Possibility to increase the efficiency of polarization of ferroelectrics' control is explained further on Figure 3 is a simplified mathematical model (electromechanical analog) of the proposed plant [4]. Direction of the electric field vector *E*, exiting a ferro-piezoelectric ceramic element, and that of the mechanical stress component *T* (mechanical power *F*) are the same. Two ferro-piezoelectric ceramic elements are required: the lower is excited by electric means and forces the upper one to fluctuate; the upper one is excited by a running component of the mechanical stress. These processes are described by the equation of piezoelectric effect.

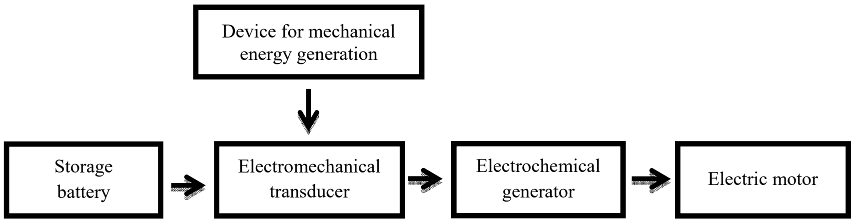

Figure 2. Functional diagram of a power plant.

$$P^E = d \cdot T + \varepsilon^T \cdot E,$$
$$S^T = d_t \cdot E + s^E \cdot T \qquad (1)$$

Equations (1) for this case are:

$$P_i^E = d_{ij} T_j,$$
$$S_j^T = d_{ij} \cdot E_i, \qquad (2)$$

P_i and S_j are tensor components of polarization and deformation, d–ferro-piezoelectric module. Index t goes for transposition. Indexes ij have following values: i = 1÷ 3; j = 1÷ 6

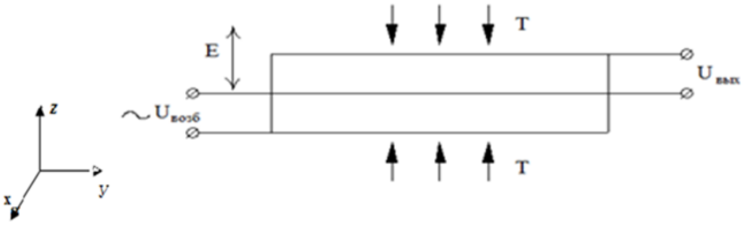

Figure 3. Flow diagram of the plant's electromechanical analog

Upper indexes E and T go for constancy of electric field voltage and mechanical load, respectively.
First equation (2) goes for the run of ferroelectric piezoelectric ceramic element, excited by the strain. The second equation is true to the run of ferroelectric piezoelectric ceramic element, excited by the electric field.
Subject to the known matrix of piezoelectric modules, e.g. for a PZT material [8]

$$d_{ij} = \begin{Vmatrix} 0 & 0 & d_{13} \\ 0 & 0 & d_{13} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{Vmatrix} \qquad (3)$$

the equation for ferro-piezoelectric ceramic element, excited by the electric field, has a tensor form after transformation:

$$\begin{aligned} S_1 &= d_{31} \cdot E_1 \\ S_2 &= d_{32} \cdot E_3 \\ S_3 &= d_{33} \cdot E_3 \\ S_4 &= d_{24} \cdot E_2 \\ S_5 &= d_{15} \cdot E_1 \\ S_6 &= 0 \end{aligned} \tag{4}$$

Equation for ferro-piezoelectric ceramic element, excited by the mechanical stress, after transformation is following:

$$\begin{aligned} P_1 &= d_{15} \cdot T_5 \\ P_2 &= d_{15} \cdot T_4 \\ P_3 &= d_{31} \cdot T_1 + d_{31} \cdot T_2 + d_{33} \cdot T_3 \end{aligned} \tag{5}$$

Analysis of the equations (3), (4) and (5) makes it clear, that excitement of deformation of one ferro-piezoelectric ceramic element along the axes *Z* is required, i.e. S_3, excited only by the electric field vector E_3 (4) for S_3, as far a correspondent mechanical stress component is concerned, e.g. T_3true to the axes *Z*. The other ferro-piezoelectric ceramic element, fluctuating in the same direction under the influence of the strain component T_3 and moving in the same direction as the electric field E_3, is characterized with the existence of a polarization vector P_3, (5) for P_3.
Active mechanical stress components T1 and T2 also cause polarization in ferro-piezoelectric ceramic element and, consequently, charges. However, these charges are not effective because of the static mode of this element's work in T_1andT_2directions. Dynamic mode of ferro-piezoelectric ceramic element's work is achieved in the direction of a mechanical stress component T_3.
Control for polarization of ferroelectrics is achieved due to the proper choice of vector of electric field's mechanical stress *E*, which coincides with the strain component *T* direction.
Moreover, the 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:

$$\begin{aligned} S^E &= s^E T \\ D^E &= P^E = dT \end{aligned} \tag{6}$$

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 (T=0), when the element can be easily deformed. The equation is following:

$$\begin{aligned} S^T &= dE \\ D^T &= \varepsilon_a^T \mathrm{E} \end{aligned} \tag{7}$$

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).
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 [8]:

$$D^T = \left(\varepsilon_a^T - \frac{d^2}{s^E}\right)E = \varepsilon_a^T \qquad (8)$$

Absolute dielectric constants of the pressed element $\varepsilon_a^S$is obviously less than ε_a^T(7) and they are described in equation (9), *K* is an electromechanical coupling factor:

$$\varepsilon_a^S = \varepsilon_a^T\left(1 - \frac{d^2}{\varepsilon_a^T s^E}\right) = \varepsilon_a^T(1 - K^2) \qquad (9)$$

s^E goes for electric field strain compliance *E*=0
$\varepsilon_a^T$is an absolute dielectric constant under mechanical stress *T*=0.
Thus, control of compressibility and electric elasticity of ferro-piezoelectric ceramic elements in the plant allows to increase sensitivity of the output electric voltage of these elements to the acting mechanical load [4,9]. The function of ECG transformation in the plant is following:

$$U_{вых}=K_H \frac{d_{ij}\cdot F}{C_{эхг}+C_H} \qquad (10)$$

Uвых means an output electric voltage of ECG, *F* is acting mechanical force, *Сэхг* goes electro capacity of ECG, *Сн* is electrical load capacity (load electrical devices), *Кн*– an electrical voltage increase rate due to control of polarization of ferroelectrics, *dij*–piezoelectric module, induced polarization per unit of mechanical stress.
Equation (9) proves that electromechanical coupling factor K depends on relations of dielectric constants of pressed and free ferroelectrics, i.e. change of dielectric capacitivity under mechanical load. In case of *K* = 0,5 (an average value) the ratio is equal to 0,75. Which, in its turn, is highly important for output electrical voltage (power density) of the plant (10), moreover, K of modern ferro-piezoelectric ceramics is 0,6…0,7 (ε_a^Tdiffers greatly from ε_a^T, as dielectric constant and electric capacity are in direct proportion). Tests proved that 2 times increase (decrease) of a load electric power (Pн) causes 2 $\sqrt{2}$ times, 3 times - 3$\sqrt{3}$ etc., increase (decrease) of ECG mass (Mecg). All the changes follow the principles of geometric progression. The mass of mechanical transducer together with the mass of the mechanical energy generating device (Fig.2) is 10 – 15 percent more than Mecg and depends on Pн as well.
Figure 4 describes a Mecg - Pн growth-increase diagram. The foresaid and the diagram make it is possible to calculate the plant mass (without a storage battery and actuating device) taking into account Pн. In the diagram one may find a point where Pн = 0,182 kilowatt and Mecg = 0,826 kg, around which Pн and Mec are changing almost in direct proportion. Mecg grows slower below this point and faster above it.

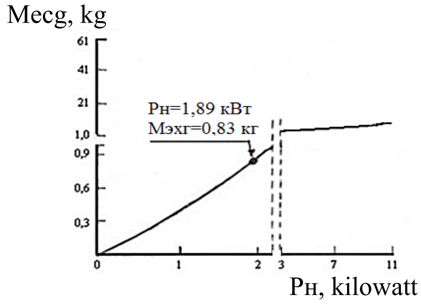

Figure 4 Mecg - Pн growth-increase diagram

As foresaid, 1 joule energy consumption from the storage battery gives an electric power output of 3,5 …. 5 joule under mechanical stress.

As 4 joule of energy is generated per 1 joule of storage battery energy, required for the run of the plant, 4 times energy increase in comparison with the energy, lost by the storage battery, is generated, not taking into account the loss of energy for heat and partial charge of the storage battery. It means that an e-vehicle run charged from one battery is also 4 times longer (an average value) in comparison with the traditional electric drive. The increase of the plant's mass is insignificant.

Thus, an alternative electric drive has certain advantages to a traditional one. But the use of the plant with Pн more than 10 kilowatt is problematic, and more than 50 kilowatt is unreasonable at this stage of experiment, as it cannot compete with a traditional electric drive. The reason is that the mass of the proposed plant increases faster than its power and requires specially developed ferro-piezoelectric ceramic materials of advanced features. Providing a certain level of ferroelectric devices leakage current is required for working in statics and with step electrical voltage change. For example, when objects are precisely moved with the help of actuators having a static leakage current not more than 5 μA. Ferroelectric high electrical resistance reduces the leakage current up to μA units or less. The leakage current can slightly increase, due to improper operation of devices (usually - it's unacceptable temperatures, humidity and electrical voltage), as it causes the activation of electrode material migration into ceramics. In practice, maintaining dynamic conditions (as in the proposed setup) and proper operation it can be neglected. Especially at low electrical voltage and low mechanical stress.

Certain obstacles are also caused by the importance of uniform distribution of great mechanical loads on fragile ferro-piezoelectric ceramic elements [10] and the initial polarization of bigger elements for generating of greater powers. The use of modern methods helps to overcome the obstacles easily.

The plant proposed can also be used as an environment friendly source of electric power, reserved and autonomous (charging from a battery or a power unit). It is important to highlight, that the plant mass is of no importance, as in case of an electric drive, as emergency sources of energy are permanent. Moreover, the plant can be used for charging of small-sized UAVs, wheelchairs, office and country buildings, etc.

3. Conclusion

The advantages of the proposed way of generating electric power to those of solar- or wind energy are: it does not depend on climate and time of the day. Alas, despite all the advantages, the technology has not yet been properly developed.

So, the control of ferroelectrics' polarization is found by means of:

- modification of ferroelectrics and electric closed circuit;
- mechanic load (design features of the plant);
- interlayer and ion polarization of ferroelectrics in the band of about 1 - 1,5 (10^3 - 10^5) Hz.

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