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Random Vibration Energy Harvesting by Piezoelectric Stack Charging the Battery

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Abstract

This paper highlights the electric energy harvesting system that consists of piezoelectric (PZT) stack transducer which is excited by random mechanical oscillating force and charges the Li-Ion battery. This battery is a power supply for LED lamp lighting. A very big electric capacitance of the multilayered PZT stack affects on the electric energy flow from PZT energy source to the electric sink. The reason for this influence is because the electric capacitance of the device, its mechanical losses and leakage increase along with the increased number of PZT layers. An electronic circuitry of the studied energy harvesting system provides the interfaces between the piezoelectric device and electric load. Such the circuits should match the input impedance of electric load (battery) and output impedance of voltage source (PZT stack). Basing on the experimental data and the finite element (FE) investigation we derive and tune the lumped model of multilayered PZT stack, which transforms the energy of low frequency mechanical excitation with random amplitudes and discretely distributed frequencies to the energy of electric current. In order to optimize an efficiency of harvester we find the number of PZT layers at constrained excitation parameters, stack's dimensions, and generated voltage required by the charging battery. The lumped model of the whole harvesting system has been built in SimElectronics / Simulink MATLAB© environment. It was also simulated to find the best harvesting system parameters.

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Keywords: Structural optimization; mechanical vibration; energy harvesting; piezoelectric transducer; electric circuit.

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1. Introduction

The problem of renewable energy sources' efficient use, such as solar, geothermal, hydro-energy, ambient vibration energy, attracts the growing attention of wide range of engineering specialties. Bridges, buildings, railways, highways surface on which traffic moves, and even human walking are the sources of such mechanical vibrations that can be transformed to the electric energy. Piezoelectric transducers are the most efficient devices to implement such energies transformation and harvesting. Many ways of their use are studied in the fundamental monograph [1] and survey papers, such as [2 - 4] to overcome difficulties, e.g., to the match impedances of piezoelectric transducer and electric loading circuits. In those cases when a host vibrating structure is relatively light, an energy harvesting subsystem acts back to the host structure, e.g. in the form of the structural damping increase [5, 6], and this further complicates design of the harvesting system. Its electronic parts, which usually combine resistive / capacitive / inductive load with rectifier, may be supplemented by the semi-active circuits that open or close a switch when the peak force is achieved across the device, and/or by the active energy harvesting that utilizes a bidirectional switch-mode converter to control the voltage on the PZT device electrodes [7 -10]. Most approaches to the optimization of PZT based vibration energy harvesters implies some conversion of FE model of the piezoelectric transducer to the lumped model, then its merging with equations that describe an electric circuit, and solving this joint system [7 - 9].

To present equivalent circuit equations in the easiest form, most of works study an efficiency of harvesters that are installed on the light weight cantilever in a frequency domain. Such harvesters are developed for the small power AC/DC generation, whereas PZT stack based harvesters can perceive very high vibration forces and they are intended for high power applications. However, reports devoted to the study of high power harvesters based on PZT stacks are very rare [11, 12]. Wang et al. [13] present the analytical model for dynamics of piezoelectric composite stack transducers, on the base of linear piezo-elasticity. This model describes the stack's behavior in a broad frequency range. But it must be admitted that it is cumbersome and difficult for analysis and solving an inverse optimization problem.

It is important to note two things that sufficiently simplify the problem of optimal design the PZT stack based harvesters. The high mechanical stiffness of piezoelectric stacks leads to their very high eigenfrequencies, which are far from the vibrations frequencies; so, we can neglect any resonance phenomena. Another simplification is due to very big mass of the host structures, which transmit mechanical vibrations to the stack. It allows justifying the neglect of the influence of the harvester's dynamics on the host structure, and exclude the energy return phenomenon [1], [5], [9, 10] from our consideration.

At the formulation of the harvester's optimization problem [7], [12] we assume a design space, which includes a number of piezoelectric layers, area of their plane surface, thickness, and the design constraints such as total volume and height. As the operational conditions of power PZT stack we assume random, low frequency range, high force excitation, generated by a moving transport and transmitted to the harvester by a pavement. Due to a high force excitation the minimum value of PZT stack's cross-section area is constrained by the strength of piezoelectric ceramics. Significant decrease of cyclic fatigue properties of poled piezo ceramics, which experience the mechanical loading combined with an electric field [14] are highlighted in many works [14 - 16]. Basing on the above stated, such combined electro-mechanical action can decrease an admissible cyclic stresses twice [16].

All the referred articles inform not only of the investigation in the field of different kinds of harvesters, but only of harvesters with passive load, which consume the entire electric power. Nevertheless, mechanical energy conversion to the electro-magnetic field at the capacitive and/or inductive load) or to the heat, at just resistive load, is unsensed. More by token, power PZT stack harvester cannot be a stable source of electric energy at the random mechanical excitation; as a result an electric power generated by it, cannot be used immediately. The electric battery application as a sink of generated electric energy is a much promising technical solution at these operating conditions. However, the battery impedance varies during charging and discharging, and this makes it difficult impedance matching. Hence, the piezoelectric harvester should operate effectively when the battery status is changing. The hysteretic phenomena that are sufficiently strong for NiSD, Lead-Acid, NiMH batteries, are less significant in the Li-Ion batteries [17, 18], and will be neglected in our study.

This paper is composed as follows. To determine the transverse dimension of the PZT stack's FE models we accept the given vibration excitation spectrum, the maximum mechanical forces, and known fatigue strength properties [15, 16] of used piezoelectric ceramic. In order to tune and validate the studied FE models with different number of layers, we compare their output at the transient analysis with the experimental data obtained for two prototype stacks. Then we investigate and collect the frequency response functions (FRF) of output voltage at the different values of resistance load. After that all the obtained data were used in order to tune the simplified lumped model of PZT stack. As such the lumped model the “Piezoelectric Stack” from the SimElectronics MATLAB© block-library, was chosen. This principal decision allowed to combine together the models of the electric circuit, of stack, and its mechanical excitation. As the electric load for the PZT stack harvester we assume the Li-Ion battery, and we propose new equation for its charge dynamics. Using results of our simulation we found the optimal PZT stack’s design at the varying initial state of charge for the chosen battery.

2. Finite Element-to-Lumped Model of PZT Stack Transducer

In order to investigate how the number of layers affects on the stacks performance, the FE models of stacks with 4, 8, 16, and 32 identical PZT layers were studied at the varied load impedance. These layers were modeled as a circular piezoelectric PZT-5H plate with thickness of 1 mm, whose plane surfaces were coated by the thin Ag electrodes with thickness of 0.1 mm. The governing equations for the linear piezoelectricity were formulated in the strain-charge form

$$\begin{aligned} S &= s^E T + d\mathbf{E} \\ \mathbf{D} &= dT + \varepsilon^T \mathbf{E} \end{aligned}, \tag{1}$$

where S is strain tensor, T is stress tensor, $\mathbf{E}, \mathbf{D}$ is electric field and electric displacement vectors respectively, s^E is elastic compliance matrix, d is piezoelectric constant matrix, ε^T is the dielectric permittivity which is measured at a constant stress.

All piezoelectric layers of 3D FEM model of PZT stack were connected in parallel (refer to Fig. 1), and at the first numerical experiments were loaded on the resistance with varied value. PZT stack’s model was slowly prestressed by compressive axial force to eliminate the tensile strain, which is unacceptable for the brittle ceramic, and then excited by the uniformly distributed force with different frequencies. These simulation results were compared with the experimental data that allowed to validate and tune the built FE model. Electric voltage on the load resistance was determined using Ohm's law

$$V - R\sum_{k}\int_{\Omega} J(t)ds = 0\,, \tag{2}$$

where alternating electric current $J(t)$ through load was calculated by integration of the current density normal to the electrodes surfaces over these surfaces Ω.

In order to the following model simplifications the 3D FE problems were reformulated as axially symmetric, which have a sufficiently lower computational cost. The simulations of these models were carried out at the different number of layers *N*, load resistance *R*, and excitation frequency *f* to reconstruct the stack’s performance parameters. These dependencies (refer to Fig. 2) demonstrate that PZT stack performance is growing as long as the excitation frequency; and for each frequency there is the value of the load resistance, which provides the biggest electric output power. It is a case of full matching of impedances. And such matching load resistance decreases at the bigger quantity of piezoelectric layers.

The lumped model of PZT stack has been constructed using “Piezo Stack” block integrated into Simulink MATLAB block library. This structure and dynamics of this block correspond to the equations (1) when only z-axis is active. Any transversal effects and hysteretic phenomena were neglected. The block adjustment is performed by entering the elements of coupling, compliance, relative permittivity matrices of piezoelectric materials, quantity and thickness of layers into block setting window. The values of mechanical loss factor, and leakage resistance for each stack’s configuration were calculated from the experimental data. Order of these values is present in Fig. 3.

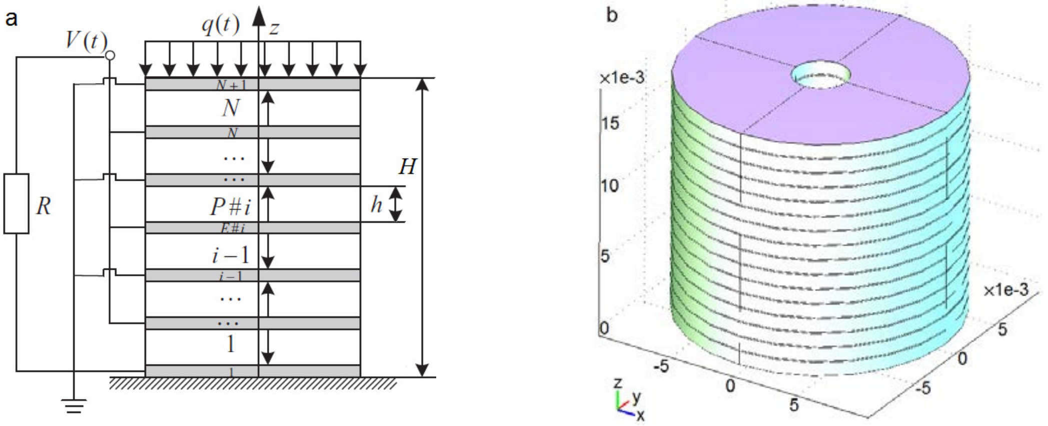

Fig. 1. Piezoelectric stack FE model loaded by uniformly distributed axial stress:
(a) diagrammatic view [13]; (b) an example of the modeled stacks geometry.

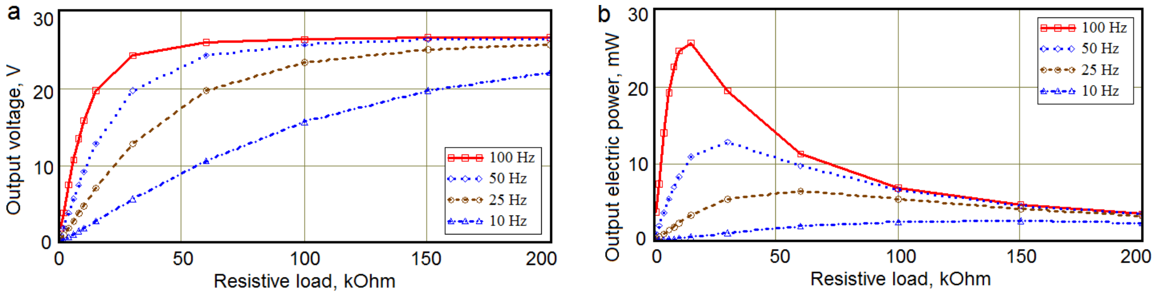

Fig. 2. The dependencies of the output voltage (a) and output electric power (b) generated by PZT stack same as in Fig. 2.

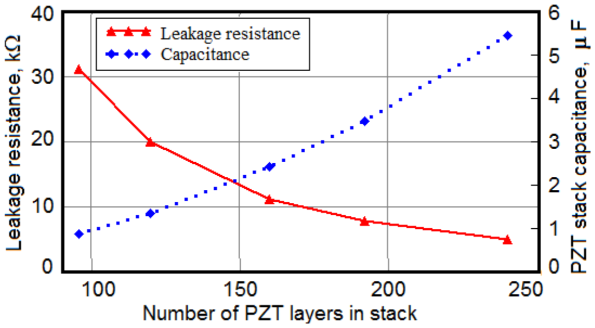

Fig. 3. The values of leakage resistance and electric capacitance for the modeled configurations of stacks with constrained height of 96 mm.

3. Lithium-Ion Battery Model

The circuit-based models of the battery, such as RC model, Rint model, Thevenin model or PNGV model [17, 18] are most suitable for the integration into symbolic lumped model that to be created in Simulink MATLAB environment. As the main parameter these models use so-called battery's state of charge (SOC), which is equal to an actual battery charge divided by the maximum battery capacity, and their feature is that they describe the stage of charge and discharge separately. In our investigation we used the discharge model for the Li-Ion batteries that presents in [17]

$$E_{bat} = E_0 - K\frac{Q\cdot Q_{in}}{Q_{in}-0.1Q} + A\exp(-B\cdot it) - R\cdot i\,, \tag{3}$$

In equation (3) E_0 is battery constant voltage (V), Q is the battery capacity (A*h), i_d is discharge current (A), K is the polarization constant (V/(A*h)), A is the exponential zone amplitude (V), B is the inverse time constant of exponential zone (A*h)-1, R is the internal resistance of battery (Ohm), and Q_{in} is the actual battery charge (A*h). During our examination we revealed that known charge models are complicated enough, but they aren't sufficiently stable and accurate. The simple model suggested by us takes into consideration actual state of charge $SOC_{in} = Q_{in}/Q$ of the battery and added charge Q_{add} expressed in terms of SOC

$$SOC(Q_{add}, SOC_{in}) = 1-(1-SOC_{in})\cdot\exp\left[-\frac{2Q_{add}}{Q\cdot(1-SOC_{in})}\right]. \tag{4}$$

where

$$Q_{add} = \int i_c dt\,. \tag{5}$$

Battery voltage after an additional charge Q_{add} is calculated from equation (3) using new value of SOC, which is determined from equation (4). The models (3) and (4) assume that internal resistance and capacity of the battery are constant during discharge and charge cycles and their values did not vary with the amplitude of the current. The self-discharge and memory effect of the battery were not represented.

For chosen 0.25 A×h battery with rated voltage of 12 V and nominal current of 12 mA, the voltage dependencies at discharge, which were calculated from Eq. (3), change of the battery SOC at its charge, which was calculated from Eq. (4), and corresponded battery voltage are present in Fig. 4. These plots are calculated at the assumed battery parameters: K=0.25, A=1 V, B=30 $(\text{A*h})^{-1}$. Figure 4(d) also shows that the battery input impedance sufficiently depends on the SOC, i.e. changes at the battery charge. Workflow diagram for harvester's load with the battery, resistor, inductance, capacitor and element supporting Simscape / Simulink interface are given in Fig. 5. This model can simulate both charge and discharge of the battery, but not simultaneously.

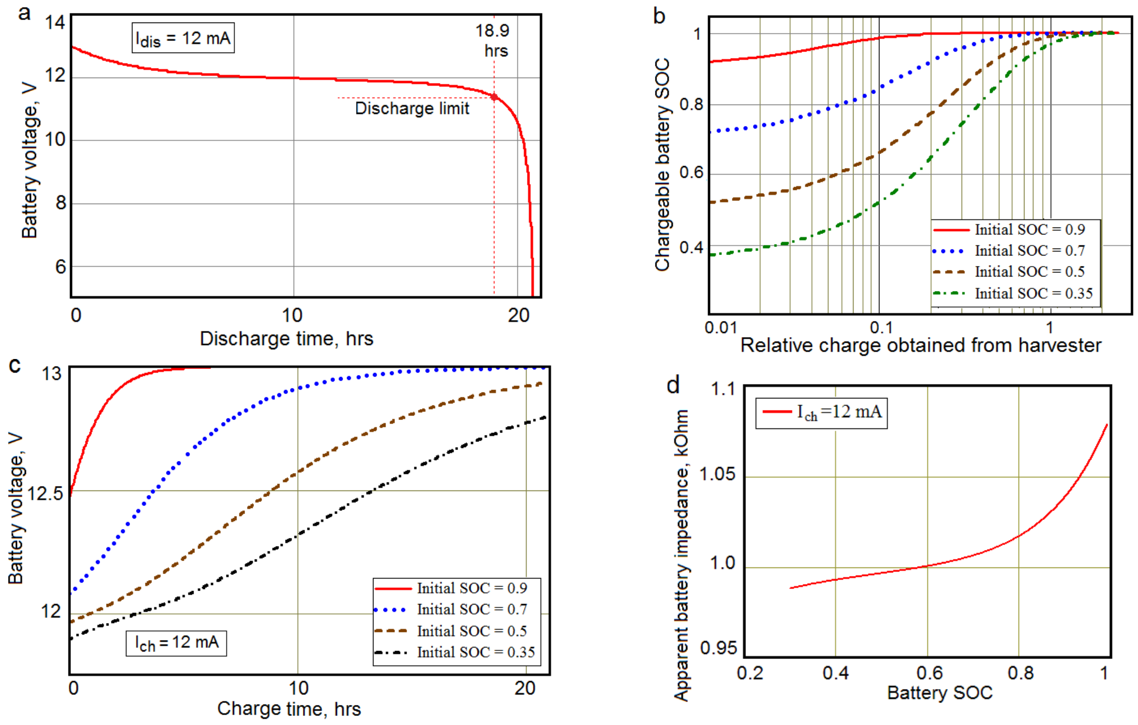

Fig. 4. The dependencies of the battery voltage at discharge (a); SOC (b), voltage (c) and apparent resistance (d) of the battery at its charge.

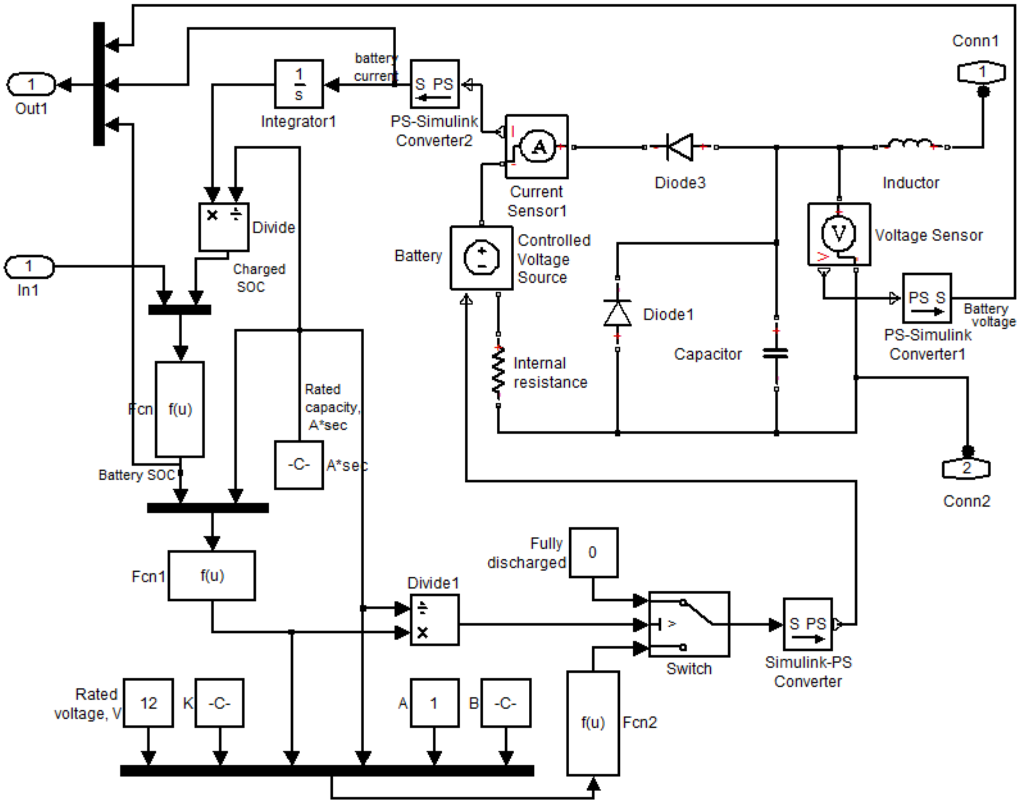

Fig. 5. SimElectronics / Simulink workflow diagram for PZT harvester's load.

4. Dynamic Model to Simulate the Harvesting System

The principal parts of full equivalent circuit model of the harvesting system (refer to Fig. 6) are PZT stack itself, the full bridge rectifier, module generating the random mechanical excitation (refer to Fig. 7), full electric load including battery, R-C-L filter (see Fig. 6), and means for the process monitoring. Battery charging process has been carried out for the initial values of SOC 0.3; 0.5; 0.7; 0.85 and 0.95. We also examined five different numbers of layers in the stacks with constrained height of 96 mm: 96, 120, 160, 192 and 240 layers with their thickness of 1.0; 0.8; 0.6; 0.5 and 0.4 mm, respectively. Mechanical excitation of the harvester was controlled by two modules "Prestress" and "Excitation Force" that provide the slowly growing compression of the stack by the force up to 2500 N, and then application of alternating excitation force with random amplitudes and phases (see Fig. 7). Maximum force amplitude was limited by the value 2000 N to eliminate the tensile strains in piezoelectric ceramics.

At each initial state of the battery charge a simulation time of 60 sec was chosen. During this time the average charge current has been calculated by numerical integration. It allows us to quantitatively estimate the charge rate and efficiency of the harvester at the actual SOC of the battery.

For each PZT stack's design with different number of layers we tried to choose the optimum values for the R-L-C filter components, but the efficiency of the harvester is weakly dependent on these variables that is due to very small impedance of the battery. For more clarity we present some optimization results for five studied PZT stacks in Fig. 8. These results confirm the ability of all studied PZT stacks to fully charge the battery during 10-16 hours. Such charging duration corresponds to intensive transport traffic, when cars motion generates the mechanical excitation of the highway substrate. Furthermore, these plots prove an existence of optimal PZT stack's design that corresponds to case of 160 layers. Naturally, this inference is valid only for the accepted operating conditions and constraints.

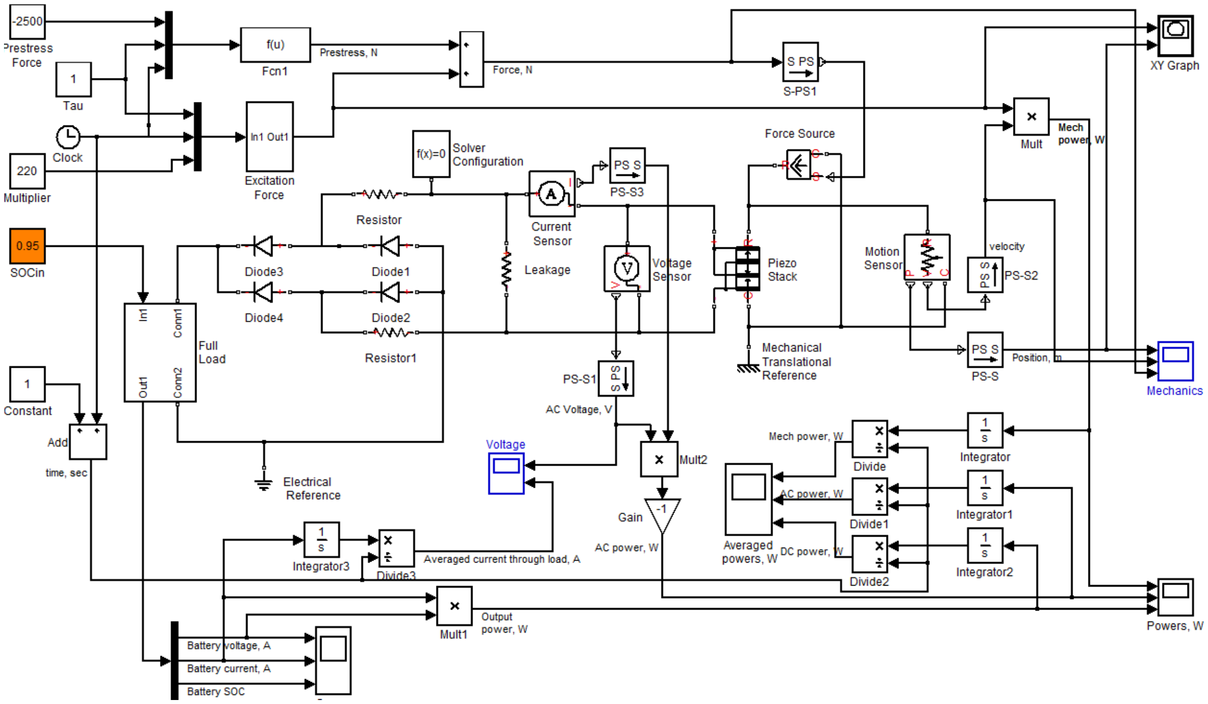

Fig. 6. Assembled workflow diagram for PZT stack - based harvesting system.

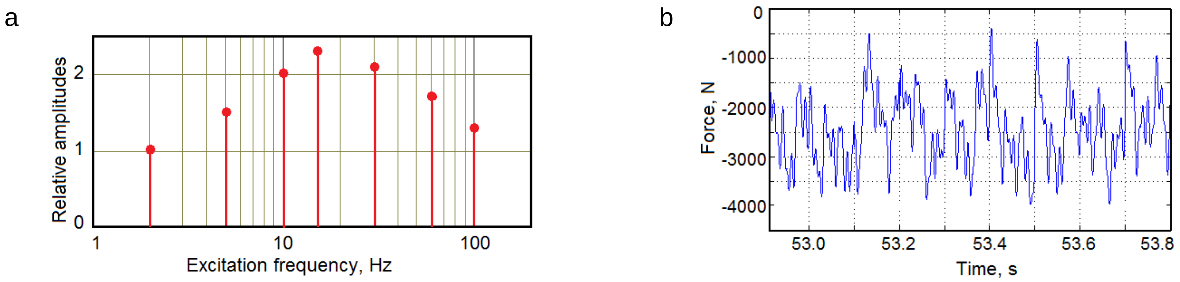

Fig. 7. Discrete spectrum (a); and an example of time history of the random excitation forces (b)

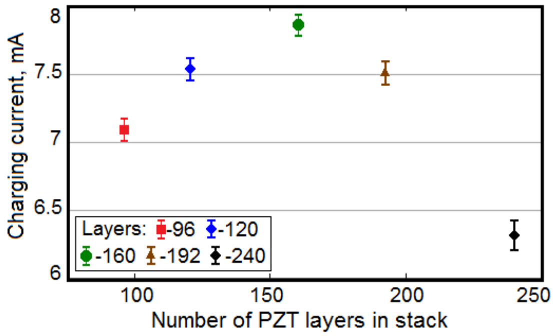

Fig. 8. The dependency of the charging current averaged during full battery charging time on the number of PZT layers for the randomly excited piezoelectric stack harvesters

5. Conclusions

The lumped symbolic model of power PZT stack - based harvester system, which transforms the mechanical vibration energy, generated by moving transport, to the electric energy stored in Li-Ion battery, was developed and studied to optimize the PZT stack's design. The first requirements to their design are dictated by the parameters of mechanical vibrations experienced by PZT stack, and by the nominal voltage and electric power that should be supply the LED lamp, which should illuminate at dark time. In its turn, the parameters of this lamp determine the choice of the battery, which should store the harvested electric energy. The PZT stack's design is constrained also by the fatigue strength of piezoelectric ceramics, its elastic, electromechanical and electric properties.

In order to create a lumped model for the harvesting system we build step-by-step stack's 3D FE model, then compare its simulation results with the experimental data obtained at the study of two prototypes of stacks, further we simplify 3D model to the axially symmetric one, and finally we tune the built-in "Piezoelectric Stack" lumped model from the SimElectronics MATLAB© block-library using the results of the previous researches. On the base of known discharge model of Li-Ion battery we proposed a new battery charge model, which correctly describes the battery state evolution at its charging by a current generated by PZT stack. Both these PZT stack's and battery models together with all electronic components (full bridge diode rectifier, R-L-C filter), the means for the process monitoring, and subsystem, which generates the random mechanical excitation, were integrated into symbolic block-diagram that has been used to investigate the battery charge by the randomly excited PZT stack harvester.

The developed approach and modeling tools allow to accurately estimate the limiting performance of PZT-stack based harvester at the different operating conditions, and to find the parameters of stack's design, optimal for the accepted battery characteristics.

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