Energy Harvesting with Piezoelectric Generators in the Athens, Greece Metro Network

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ABSTRACT: We report here a new approach in human harvesting with piezoelectric generators, for mass energy production. Nanogenerators capable of converting energy from mechanical sources to electricity with high effective efficiency are attractive for many applications, including energy harvesters. For the purpose of massive energy production, the concept of piezo-generators detached from the human body and the idea of viewing population dynamics as mechanical stress sources were tested. Instead of modeling dynamics of traffic states on individuals, we used spatial configurations of traffic states and temporal dynamics in the metro network of Athens. PMS (Piezoelectric Metro Seats) which contain PZT stacks piezoelectric generators considered to be placed in all the EMUs (electric multiple units) of the Athens metro network. The results, either by taking into account the correlation between the amount of passengers and the amount of train departures or considering the frequency of the departures constant, are promising and the energy production can reach the amount of 40 MWh annually.

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There are two types of devices for energy harvesting. The first kind, are devices that use part of the energy of the user of the electronic appliance which are called Human Harvesting devices [1]. The second type, are the Environment Energy devices that harvest the energy from the environment. Considering the energy levels that can be harvested from individuals, only thermal and kinetic energy can provide significant results and the effect may prove noticeable when several devices depend on the activity of a single user [2].

About kinetic energy harvesting, we can distinguish between actions made for the purpose of generating energy and casual movements made during normal behavior. These two cases are called Active and Passive Human Energy respectively [3]. Thermal energy is considered passive. In this project we use Passive Kinetic Human Harvesting devices.

Energy harvesters based on piezoelectric effect have attracted great research interest as the energy conversion efficiencies of piezoelectric materials are higher than those of electrostatic or electromagnetic materials [4]. The Piezoelectric Effect involves the production of an electrical potential in a substance as the pressure on it changes and has been widely used for fabricating electromechanical sensors, actuators, and energy converters. The principle of the nanogenerator is a transient flow of electrons in an external load as driven by the piezopotential.

Taking the forms of irregular air flow/vibration, ultrasonic waves, body movement, and hydraulic pressure, mechanical energy is ubiquitously available in our living environment. It covers a wide range of magnitude and frequency from cell contraction to ocean waves [5]. Mass energy harvesting using piezo-electric materials have not been thoroughly examined, mostly due to the low energy production from these generators. Also, the mechanical-electric energy conversion that has been usually demonstrated is by using piezoelectric cantilevers at their resonating mode. Other limitations in the applicability and adaptability of traditional energy harvesters are the relatively large unit size, large triggering force and specific high resonance frequency.

This article explores the design problem of a human harvesting network system using piezoelectric generators for the purpose of mass energy production. As mentioned above, several devices that depend on the activity of a single user can provide significant amount of energy. Here we test the concept of many devices depending on the activities of multiple users. For this purpose, the devices need to be stationed and detached from the users. As a result, the potential of population dynamics and cycles as energy sources is necessary to be examined. Urban areas provide more spatial and temporal peaks that make them ideal for human harvesting purposes. In this article we modeled those peaks in the metro network of Athens which serves about 1.5 million passengers daily. This analysis culminates in the design of a piezo-seat, ideal for mass energy production by using PZT stack generators for Human Harvesting purposes and a model that estimates the amount of produced energy from a metro network.

The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials that have no center of symmetry [6]. The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the converse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field).The result of the direct piezoelectric effect, defined as piezoelectricity, is the produced charge which accumulates in certain solid materials (notably crystals, certain ceramics, and biological matter such as bone, DNA and various proteins) [7].

The proposed model in order to convert mechanical energy to electrical energy uses PMS generators, where charge is generated when the material is strained by an external stress. The most common device for low frequency stimulations is the piezoelectric stack generator which contains many thin layers of piezoelectric material mechanically connected in series and electrically connected in parallel. A compressive force applied to the stack results in an open circuit voltage (V_{Poc}):

E.1 $$V_{Poc} = \frac{g_{33} t F}{A}$$

Where, g_{33} = the piezoelectric constant of the material for the case in which the force is applied in the same direction the material is poled, A = cross-sectional area of the piezoelectric material, t = the thickness of the individual layers of the stack and F = the compressive force applied to the stack [8,9].

The equivalent circuit of a piezoelectric generator is a voltage source (V_P) in series with a capacitance (C_P). In order to complete a simple load circuit a diode bridge, a load capacitor (C_L) and a load resistor (R_L) are included.

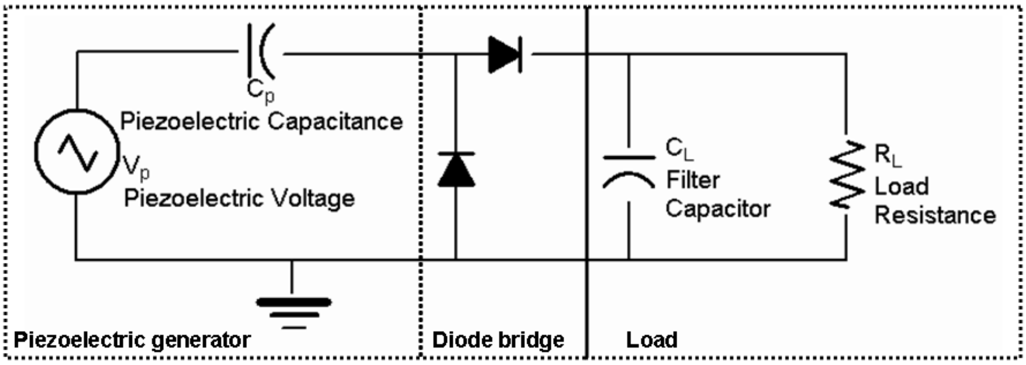

Figure 1. Circuit representation of the generator system.

V_P depends upon the type of piezoelectric generator used and the applied force (E.1). C_P is described by E.2:

E.2 $$C_P = \frac{n E_r E_o A}{t}$$

Where, n = number of layers of piezoelectric material, E_r = dielectric constant of the piezoelectric material, E_o = the dielectric constant of free space = 8.9 pF m^{-1} and A, t as defined above [10]. The diode bridge rectifies the piezoelectric voltage and the charge generated by the piezoelectric generator is stored in the load capacitor. The charging time of the load capacitor increases and the leakage current decreases as the size of the capacitor increases. For maximum power conversion, the load resistor should be matched to the impedance of the piezoelectric generator:

E.3 $$R_L = \frac{1}{f C_P}$$

Where, f = the frequency of force application [11]. The output power of the generator is calculated by the steady state voltage (V_{Lss}) across the load resistor using E.4:

E.4 $$P_{out} = \frac{V_{Lss}^2}{R_L}$$

The steady state output voltage will equal one half of the peak piezoelectric voltage when the impedances are matched, neglecting the voltage drop in the diodes:

E.5 $$V_{Lss} = \frac{V_{Pm}}{2} = \frac{g_{33} t}{2A} F_m$$

F_m is the peak amplitude of the input force pulse and V_{Pm} is the peak piezoelectric voltage [12]. The average optimal output power ($P_{out-opt}$) in terms of the system parameters by substituting E.2 into E.3 and E.3and E.5 into E.4 results in Eq. I-6 is:

E.8 $$P_{out-opt} = \frac{V_{Pm}^2 f C_P}{4} = \frac{g_{33}{}^2 F_m{}^2 tnE_r E_o f}{4A}$$

From the above equations it is evident that the output power of the generator depends on the material properties of the piezoelectric generator. The output power of the generator depends on the square of the voltage generated by the piezoelectric material, its capacitance and the frequency at which the generator is driven. The piezoelectric voltage depends on the piezoelectric constant of the material and the input force and the capacitance depends on the dielectric constant of the material.

The energy (E) needs of the target application depend on the amount of power (P) it draws and the duty cycle (t_C), or the time that it is operational. The amount of power an application draws depends on the operating voltage (V) and the amount of charge (Q) it uses per second (t_Q). For a dc system, the equations to describe this are:

E.9 $$P = VI = \frac{VQ}{t_Q}$$
$$E = Pt_C$$

Where the unit of P is Watts (W) and the unit of E is Joules (J). The amount of energy needed by an application can be compared to the amount of energy that can be produced by the generator. The energy that can be stored in the generator is given by:

E.10 $$E = C_L V_{Lss}^2$$

Where, C_L is the storage capacitor and V_{Lss} is the steady state voltage of the system. The time it takes to charge C_L to this energy level depends on the size of C_L, increasing as the size increases. The average power needs of an application can be compared to the average power generated. For the application, the average power (P_{AveApp}) is:

E.11 $$P_{AveApp} = \left(\frac{VQ}{t_Q}\right)(k_C)$$

where k_C is the duty cycle fraction. The average power produced by the generator (PAveGen) is:

E.12 $$P_{AveGen} = \frac{V_{Lss}{}^2}{Z_L}$$

Where V_{Lss} is the steady state operating voltage of the generator and Z_L is the impedance of the generator load. The maximum energy transfer occurs when Z_L matches the impedance of the piezoelectric generator. If the load is not matched with the generator impedance and power is dissipated through the load at variable times, then the power dissipation will depend on the load impedance. When the switch is closed, the energy in C_L will dissipate through R_L. If R_L has high impedance, the energy dissipation will be very slow. If RL has low impedance, the energy dissipation will be very fast.

In order to exploit the mechanical stress from the natural movements of the passengers of the Metro network, a device called PMS (Piezoelectric Metro Seat) is proposed here. The PMS is a very stiff structure with a high capacitance that converts the mechanical stress of the sitting passengers into electricity. It contains laminated piezoelectric generator. It is suitable for handling high force and collecting a large quantity of charge efficiently. Results in electrical generation depending on the direction of the passenger's force, the direction of polarization, and the wiring of the individual layers of the piezoelectric units inside the PMS. The PMS is designed to allow only vertical forces as the PZT Ceramic stacks are easily damaged by any force applied to the stacks outside of its center cross-section[13]. The theoretical amount of power extraction for the PMS is the sum of the power of the piezo units in their operating points.

E.13 $$P_{PMS} = NP_{unit}$$

Where, N = the number of piezo-units (generators) in the PMS

Calculating the R_L for the piezo-units we saw that the low frequency of the sitting down actions requires huge load resistance, in case a steady state voltage is deemed necessary and only these force applications are considered. One possible solution for reducing the frequency is connecting the PMS in parallel. However, without a prototype tested in real conditions is difficult to define the actual frequency of the applied force due to the fact that during the time a person is seated, derivative of the force applied on the units occur in high frequency due to the train movement and gravity. The above lead to circuit designs capable of harvesting only the sitting down actions which are driven by a frequency of $f = 0.003$ Hz.

From the equations E.1 – E.8 a P_{unit} of 17 μW extracted power from PZT stack generators (part number T18-H5-104, Piezo Systems, Inc. Cambridge, MA), with a volume of 0.5 cm^3 (5 mm x 5 mm x 18 mm). The piezoelectric material of the stack has a piezoelectric constant of 0.013 VmN^{-1} and a relative dielectric constant of 5400. The thickness of each layer is 0.11 mm and the stack contains approximately 164 layers. These values were specified by the manufacturer. Ten layers of these generators cover the space of 45 cm x 40 cm x 18 cm in the metro seat. This leads to approximately P_{PMS}=1.22 Watt

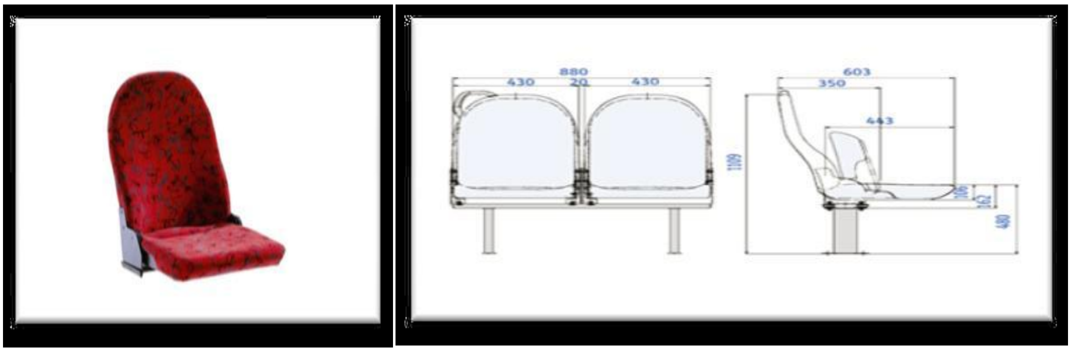

Figure 2: Athens metro seats

In the capital city of Athens the rush hours are usually 7 p.m to 10 p.m. and 4 a.m. to 7 a.m. During these hours, there is congestion of the Athens Mass Transit System, most notably in buses and metro, as well as road traffic. In the 3 lines of Athens Metro, the 6-car trains transport almost 1.5 million passengers during a typical week day. In order to define the human harvesting capabilities in the Metro, data about the train departures schedule and the number of passengers are used. Due to the lack of data about the amount of passengers in line 1, we assume that it is the average of the amount of passengers from the lines 2 and 3. As thus, we have the number of passengers per 15 minutes for the rush hours of the whole network.

The number of train departures, per 15 minutes, is defined and two variations of the variable are being calculated for the three lines and their two directions. The first definition comes from the given data about the amount of departures (40 departures per hour in line 2 and 30 departures per hour in line 3), and we use the average again for line 1. The second, from the hypothesis that the amount of departures is related to the amount of passengers. In this case the frequency of the departures is varied from 1 per 5 minutes, to 1 per minute. The produced energy for every quarter of the rush hours:

E.14 $$E = P \times \mathrm{T} \times K \times S \times D$$

Where, E=The produced energy (Joule), P= Power produced from a piezo-seat (Joule/sec),T= Time the piezo-seat is producing power per person using the chair (sec/person), K= Number of seats per departure, S= Number of persons per seat, D= Number of departures.

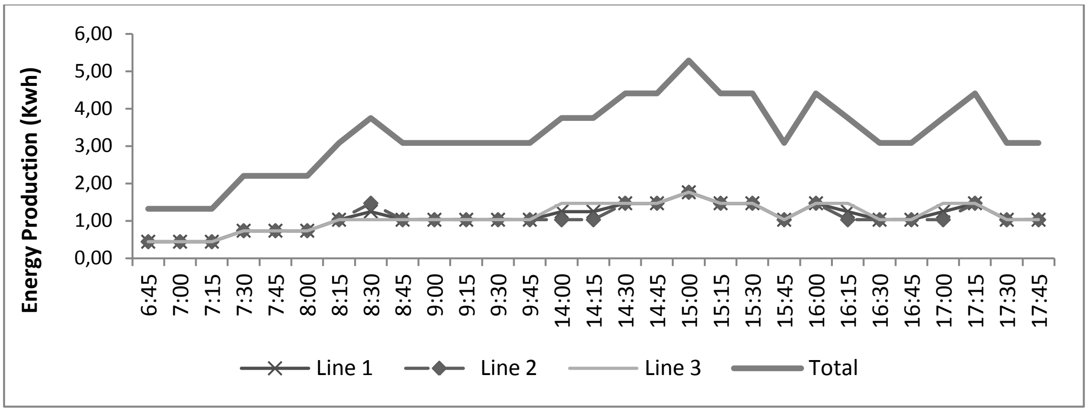

Figure 3. Daily energy production according to population for the metro lines and the whole network

Daily and annual results are presented in Figure.3 and Table.1. For the annual results, 15 days of December are considered to produce double the calculated energy, due to Christmas, and 15 days of August produce half the energy due to holidays.

	Number of Passengers	Number of Departures According to Population	Number of Regular Departures	Energy Production According to Population (kwh)	Energy Production from Regular Departures (kwh)
January	14520816	39525	45570	2903	3347
February	13115576	35700	41160	2622	3023
March	14520816	39525	45570	2903	3347
April	14052403	38250	44100	2809	3239
May	14520816	39525	45570	2903	3347
June	14052403	38250	44100	2809	3239
July	14520816	39525	45570	2903	3347
August	14520816	39525	45570	2200	2537
September	14052403	38250	44100	2809	3239
October	14520816	39525	45570	2903	3347
November	14052403	38250	44100	2809	3239
December	14520816	39525	45570	4307	4966
Total	170970900	465375	536550	34879	40214

Table1. Monthly and Annual results

Two types of results were produced by varying the variable "Number of Departures per 15min". The first approach considers the D variable constant during the rush hours and can be easily defined from the departures timetable of every metro network. The second is a correlation between the amount of passengers and the amount of Departures. In order to verify this correlation, data from various metro networks are deemed necessary. We are not trying to propose the proper number of trains for each network depending on the amount of passengers, but this variable is of great importance and affects the number of departures. The truth is that a network cannot adjust the departures schedule for all the temporal and spatial peaks in the passengers trafficking. Also, in an EMU of 240 seats, all the seats are occupied in both cases of 240 and 1000 passengers.

In order to apply the model in other metro networks, we have the variables that depend on the type of EMUs (e.g. the variable "Number of Seats per Departure") which are easily defined and two variables related with the network itself. These are the "Number of departures (D)" and "Number of persons per seat (S)". As mentioned above for the first type of results, the D variable is easily defined from the schedule and as of the second approach; data for the amount of passengers per time are required. The S variable is crucial. For the purpose of measuring the average amount of passengers that will seat in a single seat in 15min for example, we examined the number and type of the stations a train passes through in that time. In order to be conservative with our results, we made the hypothesis that all the seats are reused only in the beginnings of the lines and the cross section stations. For the Athens metro in 15 min the trains pass through 3 of them. This variable varies between networks and even the lines of a single network.

The most well-known material that has a piezoelectric effect and has been tested for energy harvesting purposes is $Pb(Zr,Ti)O_3$ (PZT). However, PZT is an electric insulator, and it is less useful for building electronic devices. Piezoelectric materials that are used for fabricating electronic and optoelectronic devices are required to be semiconductors, such as ZnO, GaN, InN, and ZnS [14]. Also, the energy production from piezoelectric generators is rapidly improving. For example the scalable sweeping-printing-method, for fabricating flexible high-output nanogenerator (HONG) produces open-circuit voltage of up to 2.03 V and a peak output power density of ~11 mW/cm^3, which is 12-22 times of that from PZT-based cantilever energy harvester [3]. Furthermore, by optimizing the density of the NWs on the substrate and with the use of multilayer integration, a peak output power density of ~0.44 mW/cm^2 and volume density of 1.1 W/cm^3 are predicted.

Comparison of the HONG with the PZT stack is presented in Table 2. HONG cover the area of 45 cm x 40 cm x 25 cm inside the PMS. T of the E.14 is considered 8 sec and P_{PMS}=500 W /50 KW

	Annual Energy Production According to Population (Mwh)	Annual Energy Production from Regular Departures (Mwh)
PZT Stack	35	40
Hong (11 mw/m^3)	372	429
Hong (1.1 w/m^3)	37230	42924

Table 2. Annual energy production results from PZT stacks generators and HONG

The design of a piezo-seat, is mainly a Performance-Safety-Cost threefold issue. There is room for alterations and improvements depending on the goal. For the purpose of maximizing performance, piezoelectric generators can be installed in the back of the seat and the time the circuit produces energy can be modified with layered stacks and other circuit and force distribution modifications. Also if the expectations from the HONG are fulfilled the produced energy is estimated to be 100 times the current one. If there are safety legislation problems, more generators should be in parallel connection. As of reducing the cost, other materials should also be considered both for the piezoelectric generators (PZT, Thunder PZT, PVDF e.tc.) and the cables used, which also depend on the connection type of the installed generators and PMS.

This article has demonstrated a network human harvesting model by using piezo-seats for mass energy production. We designed a piezo-seat, modeled the energy production by using population cycles and applied the model in the metro network of Athens. We conclude that human harvesting is suitable for mass energy production due to the fact that the produced energy is of the scale of a medium-sized solar park or a small wind park. It is worth pointing out that this analysis was not optimistic. Only the rush hours were measured, the piezo-seat was not the best possible for energy production and we made the hypothesis that the seats are reused only in the beginnings of the lines and the cross section stations. The fact is that this technology is rapidly evolving and accordingly the amount of produced energy.

The main issues we are currently examining are the safety and the energy management. About the safety, we are considering modifications in the circuit of the chair to lower the potential. We are also developing the circuit for the train in order to avoid using batteries and capacitors by connecting the chairs to the third rail system with a conductive shoe. The next goals are the economic analysis and possible improvements in the model.

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