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CLARIFICATION OF UTILIZED MEASUREMENT CIRCUITS FOR PIEZOELECTRIC VIBRATIONAL HARVESTERS

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Abstract

Energy harvesters are promising technology from which clean and renewable electrical energy can be extracted to power low-consumption devices, wireless sensors, and a wide range of medical accessories for remote patient monitoring. They are small, portable, independent and can have a major impact on improving the environmental situation. This is leading to increasing research interest in them, as well as improvements to existing models.

Keywords: piezoelectric; harvester; energy; power.

INTRODUCTION

The aim of this paper is to investigate the possibility of piezoelectric harvesters to generate electrical power. Wireless technologies and microelectronics have led to the proliferation of low-power devices that are powered by batteries or energy harvesting devices. This allows sensors to be installed in remote locations where the electrical grid is difficult to access or unavailable, increasing the need to develop new technologies to make such systems self-powered. This type of energy reduces the risk of further pollution.

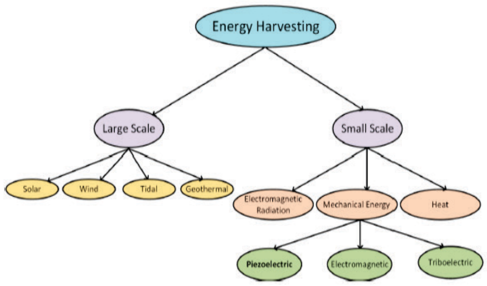


Fig.1 *Classification of energy harvesting sources*

The possible sources for energy extracting for the EH system are as follows (fig. 1):

- Electromagnetic background- using radio waves;
- Photovoltaic - with specially designed amorphous Si-layer and the new technology Dye Sensitisezed Solar Cell;
- Fluid currents- using different turbine or non-turbine technology.
- Thermoelectric – utilizing the Seebeck and Peltier effects.
- Electrostatic devices (capacitive) – based on charging a variable capacitor with movable plates that are exposed to mechanical vibrations.
- Magnetic inductance.
- Pyroelectricity effects.
- Piezoelectric effects.

EXPOSITION

A. Basic form of Energy Harvesting

Typically, an energy harvesting system has three parts:

- The energy source which represents the energy from which the electrical power will be scavenged – this energy can be in distributed form (available from the ambient environment, e.g., sunlight, ambient heat, or wind) or external (energy sources that are purposedly deployed, e.g., lightning, human heat or vibrations);
- The harvesting mechanism consists of the structure which converts the ambient energy into electrical energy;
- The load: the device which consumes or stores the electrical output energy.

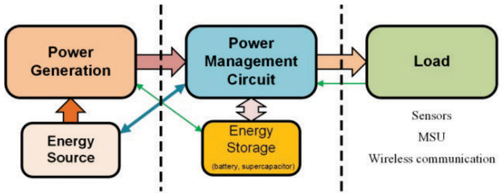
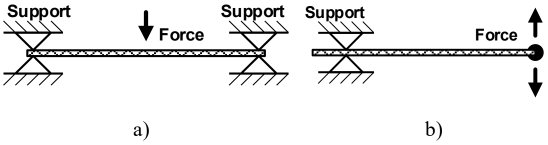


***Fig.2**. Basic Harvesture Structure*

One of more commonly used methods for energy harvesting [1] is the usage of piezoelectric transducers for obtaining the energy that are contained in the mechanical forces that are not of vital necessity for given industrial or more ordinary process. They have curtain advantages- such as relatively high output voltage/mechanical stress ratio: relatively easy methods for manufacturing the active elements. Because of the advantages piezoelectric transducers, they are object for extensive research for mobile micro-electrical autonomous sources [1].

B. Vibrational Piezoelectric EH

The vibrational EH system have relatively the biggest gain [3d] without too much dependence on the external factors. The vibrational harvesters usually convert mechanical energy in electrical one using the piezoelectric materials because of the high ratio of conversion distinctive for the piezoelectric effect [2]. Some harvesters are designed for collecting the waste energy of human motion as they are mounted in the part of human clothing or accessories – for example vibrational harvesters are mounted in the shoe soles [3]. Other types are stationary mounted in appropriate locations so the passing vehicles [4] or the pedestrians are to exert mechanical force over them.



a) b)

***Fig. 3**. Typical mounting of vibrational piezoelectric EH*

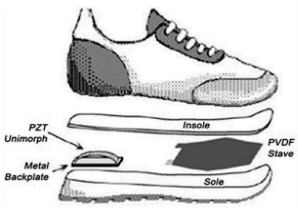


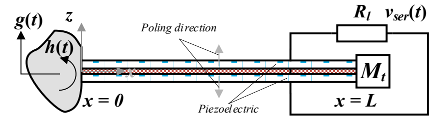
***Fig. 4**. Vibrational EH mounted in shoe.*

***Fig.5**. Compression EH mounted on a pedestrian power generator walkway.*

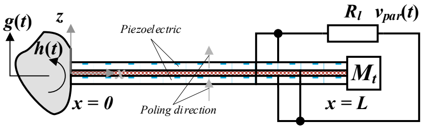
C. Description of piezoelectric vibrational EH

The vibrational piezoelectric harvester can be considered as a generalized case of beam construction with one or two anchored ends (Fig. 3), described in general by Euler-Bernoulli's beam theory [2]. More often used configuration of the vibrational piezoelectric EH is that of the cantilever type (Fig. 6, b) or the cantilever type with semi-anchored point of inflexion that is like that shown on Fig. 6, a.

The parameters described in Fig. 6 are the length of the beam – L, an added tip mass – M_t, the electrical load resistance – R_l, the voltages over the resistive load respectively for the series and parallel connection cases – $v_{ser}(t)$ and $v_{par}(t)$ [2], because the EH that is shown on Fig. 6 has two active (piezoelectric) layers that are connected with the aim to increase the current density output of the piezoelectric EH system.



a) Serial connection



b) Parallel connection

***Fig. 6**. General diagram of EH device with two active layers [2]*

The beam system is typically presumed to be excited due to the motion of its base. Then if the translation and the small rotation of the base are designed by $g(t)$ and $h(t)$, respectively, as shown in Fig. 3, the base motion $w_b(x, t)$ of the beam can be represented as [2, 5]:

$$w_b(x,t) = g(t) + xh(t) \tag{1}$$

The equivalent electromechanical equations governing the mechanical response and the voltage response of a bimorph can be given as [2]:

$$\frac{d^2\eta_r(t)}{dt^2} + 2\zeta_r\omega_r\frac{d\eta_r(t)}{dt} + \omega_r^2\eta_r(t) + \tilde{\theta}_r v(t) = f_r(t), \tag{2}$$

$$C_p^{eq}\frac{dv(t)}{dt} + \frac{v(t)}{R_l} = \sum_{r=1}^{\infty}\tilde{\theta}_r\frac{d\eta_r(t)}{dt}, \tag{3}$$

where:

$\tilde{\theta}_r$ – modal electromechanical coupling term;

C_p^{eq} – the equivalent capacitance (depends on the connection between the layers);

$f_r(t)$ – modal mechanical forcing function.

$v(t)$ – voltage across the resistive load;

ζ_r – mechanical damping ratio;

$\eta_r(t)$ – mechanical modal response;

ω_r – undamped natural frequency of the r-th mode.

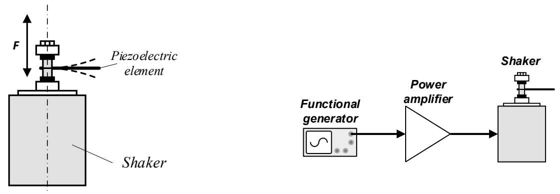
The right part of Eq. 3 is the expression that describes the electrical current that theoretically can be obtained from the harvester. The models usually depict the mechanical stresses that impact the harvester structure through second order partial differential equations (as shown in Eq. 2) [2, 5, 8].

The used second order partial differential equations are suitable to describe the behaviour of the piezoelectric EH system either with continuous external mechanical forces or with brief mechanical pulses. But the problem with a mathematical model based on the equations for vibrational piezoelectric EH systems is that there are some equation constants and variables that are dependent on physical quantities that are indirectly or not at all connected with the main variables that constitute the general mathematical models – for example the temperature in the piezoelectric mediums is not directly included in the describing equations [2, 4].

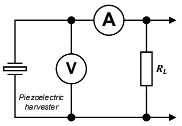
Thus, the experimental research for this type of devices is strongly recommended.

D. Experimental setup for piezoelectric vibrational EH

Experimental research is carried out over commercially available piezoelectric harvester type [6], which will guarantee that there is ensured degree of a repeatability for the harvester parameters. The harvester is *S233-H5FR-1107XB* – bimorph structure with series layer connection (former designation *PPA-2014*). An electromechanical shaker with acceleration of $a = 5{,}21$ m/s^2 is used to imitate the external mechanical stresses (Fig. 4, a) as a functional generator is being used to supply harmonic signal through amplifier to it (Fig. 7, b). The functional generator is used to change the working frequency as its output voltage is constant and have value of 2 V peak-to-peak. The electrical measurement circuit is from *VA* type (Fig. 7, c) that is been maximally simplified for the research purposes. The measurements are done with digital devices that give the corresponding alternating values in Root Mean Square (RMS) form. This form of data representation should be useful because for alternating electric currents and voltages, RMS is equal to the value of the direct current or voltage that produces the same average power dissipation in a constant resistive load. Thus, the power that is being measured in theory should be the actual active power that can be readily used and is the main aim of a harvesting process.

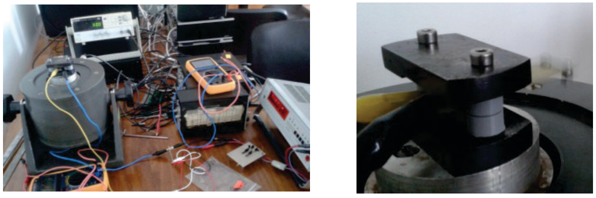


a) Electromechanical shaker b) System control



c) Measurement Circuit

Fig 7. *Initial experimental setup*



a) Research stand b) Working harvester

Fig. 8. *Experimental clamping*

The initial experiment was carried out with the aim of determining the optimal measurement circuit, i.e., between *AV* and *VA* (Fig. 7, c) simple measurement circuits with a follow-up evaluation of the obtainable electrical power. The power output of this type of piezoelectric EH is usually in the range of thousandth of one Watt ([*mW*]) which is a problem of its own. The precise measurement equipment in this value ranges is very rare and usually in these cases the preferred methods for power estimation are indirect ones – usually with the utilization of the measured voltage (as is the case with the electronic load *LD400P* [10]) over beforehand known precise constant load impedance.

The theoretical difference between the *AV* and *VA* types of circuits should be in the values of the obtained voltages and currents as in the *AV* case the currents should be slightly bigger and voltages – slightly less.

E. Initial experiments with inertial mass

First batch of experiments are carried out with inertial load of $m = 1,13$ g with different values for R_L and frequency $f = 113$ Hz, which is near the resonance frequency for the experimental configuration that is set for the piezoelectric EH. The voltage from function generator was 2,65 V peak-to-peak. The piezoelectric sample is double layered, i.e. it has two active (piezoelectric) layers which will nearly double the output current.

The voltage results were in the expected range, but nevertheless the current values were somewhat strange, because they exceeded the expected values.

TABLE 1. VA CIRCUIT (FIG. 7, C) INITIAL RESULTS

R_L, Ω	390	1000	2400	5100	10000	12400	24000	51000	75000	100000
U_{RMS}, V	1,302	1,457	1,872	2,37	3,18	3,47	4,34	5,15	5,47	5,58
I_{RMS}, mA	4	3,92	3,68	3,46	3,10	2,92	2,38	1,62	1,22	1,14

Simple calculations are done to verify the obtained results. The values are in RMS format and theoretically the equations for the simple form of the electrical power should be in force:

$$P = U \cdot I = \frac{U^2}{R_L} = I^2 \cdot R_L \qquad (4)$$

TABLE 2. VA CIRCUIT (FIG. 7, C) INITIAL RESULTS

	U_{RMS}	I_{RMS}	P_U	P_I	P_{UI}
R_L, Ω	[V]	[mA]	[mW]	[mW]	[mW]
390	1,302	4	4,347	6,24	5,208
1000	1,457	3,92	2,123	15,366	5,711
2400	1,872	3,68	1,46	32,502	6,889
5100	2,37	3,46	1,101	61,055	8,2
10000	3,18	3,1	1,011	96,1	9,858
12400	3,47	2,92	0,971	105,727	10,132
24000	4,34	2,38	0,785	135,946	10,329
51000	5,15	1,62	0,52	133,844	8,343
75000	5,47	1,22	0,399	111,63	6,673
100000	5,58	1,14	0,311	129,96	6,361

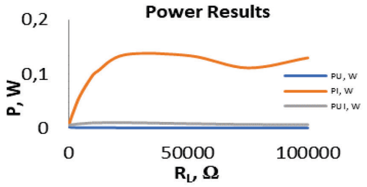


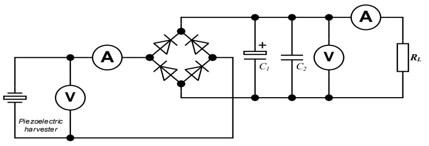
Fig. 9. *Difference between the calculated powers*

The results for the electrical power are so diverging that the assumption for wrong experimental setup is not farfetched. But there is another explanation: the indicated values are for reactance power that is present in the system and is not at all extractable. The process frequency is relatively low (113 Hz) but the piezoelectric element (harvester) that is generating the electrical oscillations has prevailing capacitive features and its internal impedance respectively can be substituted with its reactance in the equivalent circuits as evident in (3) from C_p^{eq}.

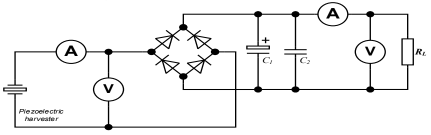
Thus, a rectification of the harvester electrical signal is needed for proper evaluation for the obtainable energy as the rectifier should eliminate the influence of the reactance energy portion. Therefore, the experimental circuit is expanded with the addition of full rectifier bridge.

F. Experimental circuits with rectifier

The rectifier full bridge and capacitive elements are added to the experimental circuit as it is shown on Fig. 6 as the diodes are of 1N4148 type and the capacitive elements have the following values: $C_1 = 1$ µF and $C_2 = 10$ nF.



a) VA circuit with rectifier



b) AV circuit with rectifier

Fig. 10. *Experimental setup with bridge rectifier*

The mechanical frequency is 115 Hz and the magnitude of the generator voltage is 2 V peak-to-peak. The experimental setup is divided on alternating part and direct current part and the experimental circuits are for VA and AV type

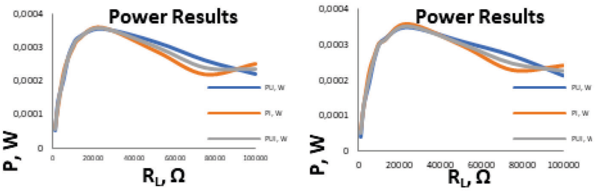
(Fig. 10). Admittedly, part of the energy will be wasted in the rectifier bridge and the capacitance elements, but only the usable part of the electrical energy will be dissipated over the constant electrical load R_L.

TABLE 3. VA CIRCUIT WITH RECTIFIER

	U_{RMS}	I_{RMS}	P_U	P_I	P_{UI}	U_{DC}	I_{DC}	P_{Udc}	P_{Idc}	P_{UIdc}
R_L, Ω	[V]	[mA]	[mW]	[mW]	[mW]	[V]	[mA]	[mW]	[mW]	[mW]
1000	1,31	2,9	1,716	8,41	3,799	0,23	0,246	0,053	0,061	0,057
2400	1,62	2,76	1,094	18,28	4,471	0,58	0,228	0,14	0,125	0,132
5100	2	2,6	0,784	34,48	5,2	1,02	0,209	0,204	0,223	0,213
7500	2,33	2,44	0,724	44,65	5,685	1,43	0,189	0,273	0,268	0,27
10000	2,58	2,3	0,666	53,90	5,934	1,76	0,173	0,31	0,299	0,304
12400	2,78	2,16	0,623	57,85	6,005	2,02	0,161	0,329	0,321	0,325
24000	3,4	1,2	0,482	71,00	5,848	2,92	0,122	0,355	0,357	0,356
51000	4,04	1,14	0,32	66,28	4,606	4,01	0,075	0,315	0,287	0,301
75000	4,25	0,88	0,241	58,08	3,74	4,43	0,054	0,262	0,219	0,239

TABLE 4. AV CIRCUIT WITH RECTIFIER

	U_{RMS}	I_{RMS}	P_U	P_I	P_{UI}	U_{DC}	I_{DC}	P_{Udc}	P_{Idc}	P_{UIdc}
R_L, Ω	[V]	[mA]	[mW]	[mW]	[mW]	[V]	[mA]	[mW]	[mW]	[mW]
1000	1,3	2,9	1,69	8,41	3,77	0,2	0,245	0,04	0,060	0,049
2400	1,6	2,74	1,067	18,02	4,384	0,55	0,227	0,126	0,124	0,125
5100	1,99	2,56	0,776	33,42	5,094	0,99	0,208	0,192	0,221	0,206
7500	2,3	2,42	0,705	43,92	5,566	1,39	0,188	0,258	0,265	0,261
10000	2,58	2,3	0,666	52,90	5,934	1,74	0,174	0,303	0,303	0,303
12400	2,75	2,12	0,61	55,73	5,83	1,98	0,158	0,316	0,31	0,313
24000	3,38	1,72	0,476	71,00	5,814	2,9	0,122	0,35	0,357	0,354
51000	4,03	1,16	0,318	68,63	4,675	3,97	0,076	0,309	0,295	0,302
75000	4,26	0,9	0,242	60,75	3,834	4,5	0,055	0,27	0,227	0,248
100000	4,39	0,82	0,193	67,24	3,6	4,62	0,049	0,213	0,24	0,226



a) VA results b) AV results

Fig. 11. *Experimental results with rectifier 115 Hz*

TABLE 5. AV CIRCUIT WITH RECTIFIER

	U_{RMS}	I_{RMS}	P_U	P_I	P_{UI}	U_{DC}	I_{DC}	P_{Udc}	P_{Idc}	P_{UIdc}
R_L, Ω	[V]	[mA]	[mW]	[mW]	[mW]	[V]	[mA]	[mW]	[mW]	[mW]
1000	1,410	0,023	1,988	0,001	0,033	0,346	0,367	0,127	0,120	0,135
10000	3,510	0,019	1,232	0,004	0,067	2,770	0,279	0,773	0,767	0,778
51000	5,930	0,010	0,690	0,005	0,059	6,220	0,118	0,734	0,759	0,710
100000	6,280	0,007	0,394	0,005	0,045	6,940	0,077	0,534	0,482	0,593

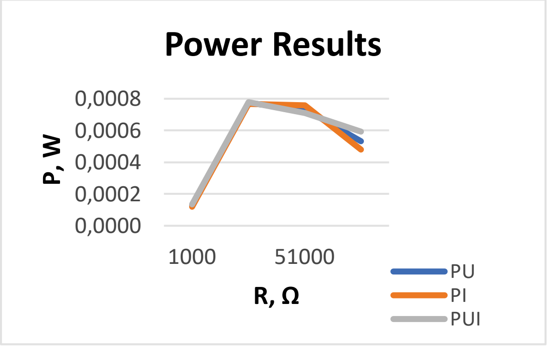


Fig. 12. *Experimental results with rectifier 130Hz*

The mechanical frequency is 130 Hz and the magnitude of the generator voltage is 1V pick-to-pick (fig.12).

The obtained DC energy is much smaller than the indicated one before the rectifier but also there are no signs of heating over the diodes that would indicate more consumption in the rectifier block. But the calculated powers are not noticeably diverging from each other. Thus, it can be assumed that large part of indicated before the rectifier energy is from reactance type and is useless for the harvesting purposes.

It should be mentioned that piezoelectric vibrational harvester is under perfect conditions when being experimented on as the external mechanical force is supplied continuously and the amplitude of the control signal is constant. In real life conditions, the frequency and the magnitude of the mechanical stress will be variables that depend solely on random factors, which will lead to additional decrease in the amount of the obtainable energy

CONCLUSION

The two types of measuring circuits (namely VA and AV type) can be used for determining the possible limit of the obtainable energy as VA will have slightly higher voltage values and AV type – slightly higher current values. They are generally not so different in regards with the measured values.

The bigger problem is the amount of not usable energy in the experimental circuit (the reactance part). Thus, all measurement circuits for evaluating the energy gain ought to be expanded with full bridge rectifier with the appropriate capacitive elements.

The rectifier will prevent the reactance power to be directed to the electrical load and therefore will allow to measure the real power output of the piezoelectric vibrational harvester.

The measurement circuits need further study as in the rectifier is presented as ideal (zero impedance when diodes are forward biased and infinity resistance when they are backward biased). Also, there were no experiments over the connection between the values of the capacitive elements and the volume of the obtainable energy.

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