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Tracking Of Maximum Electrical Power for a Piezoelectric Energy Harvesting System

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Abstract**:** ***Recent global environmental challenges have urged researchers to work on renewable energy resources. One major category of these resources is piezoelectric materials. This paper presents dynamic modeling of a piezoelectric energy harvesting system and then presents two level methodology using artificial neural networks to reach its maximum power output. Simulation results show desirable performance of the system, which leads to output increasing and tracking of maximum power in a limited time.***

Index Terms**:** ***Energy harvesting, maximum power, neural networks, piezoelectric.***

I. INTRODUCTION

Nowadays, renewable energy resources have become a vital necessity regarding energy costs and environmental issues. Piezoelectric materials are energy transducers capable of mechanical energy to electrical and vice versa. Although these materials were discovered a century ago, their capability as an energy source has not yet been utilized properly [1].

Recent advances in design and fabrication of electronic devices have reduced electric power usage that can be reduced to microwatts in some applications. For this sake, researches have paid much attractions to energy resources independent of power transmission network [2].

It is estimated that a person by average walks 150 million steps in his life. Their periodic mechanical loads in streets sidewalks and also high periodic loads of automobiles in streets and highways can be used as a electric power source [3]. To profit piezoelectric materials in highways, they can be used along with a suitable circuit to save energy [1].

Minazara et al [4] used piezoelectric materials to convert mechanical vibrations in a bicycle to electric energy and proposed a suitable position to assemble it. Prasannabalaji et al [5] investigated energy harvesting from stairs while people ascending or descending it. Aditya et al [1] proposed utilizing this method for lighting streets and highways. Kong et al [6] presented a low power system for energy production using piezo and proposed some methods to reduce system losses. They analyzed energy loss sources to increase efficiency and then utilized a flyback converter to implement maximum power tracking. Several research works have presented modeling of piezoelectric energy harvesting systems [8].

In this paper, electrical energy harvesting using piezoelectric materials is modeled. It has two challenges of having low efficiency and fluctuant output. A DC-DC transducer model and the assumed load model are presented. Finally, a two-level algorithm for maximum power tracking of the array using artificial neural networks is presented. The proposed method improves both of the above-mentioned problems. In addition, advantages of this method compared to previous methods is investigated.

II. THE SYSTEM DESCRIPTION

Block-diagram of the overall system for energy harvesting is shown in Fig. 1 whose main components are as follows:

A. Piezoelectric Material

In direct piezoelectric effect, an electric voltage is produced as result of external strain, and in inverse piezoelectric effect, a displacement is generated as a result of applied electric voltage. Piezoelectric materials include piezo-ceramics and piezo-polymers. Mechanical and electrical behavior of piezoelectric material is modeled as (1) for inverse piezoelectric effect and (2) for direct piezoelectric effect [7].

$$\boldsymbol{S} = s^{E}\boldsymbol{T} + d\,\boldsymbol{E} \quad \mathrm{S} = \mathrm{s^{E}T} + \mathrm{dE} \qquad (1)$$

$$\boldsymbol{D} = d\,\boldsymbol{T} + \varepsilon^{T}\boldsymbol{E} \quad \mathrm{S} = \mathrm{s^{E}T} + \mathrm{dE} \qquad (2)$$

In these equations, $\boldsymbol{S}$ is the strain vector, s^{E} is the elasticity matrix at constant electric field, $\boldsymbol{T}$ is the stress vector, d is the piezoelectric coupling coefficients matrix, $\boldsymbol{E}$ is the electric field vector, $\boldsymbol{D}$ is the electric flux density vector, ε^{T} is the dielectric matrix at constant mechanical strain. Direct and inverse piezoelectric effects are illustrated in Fig. 2.

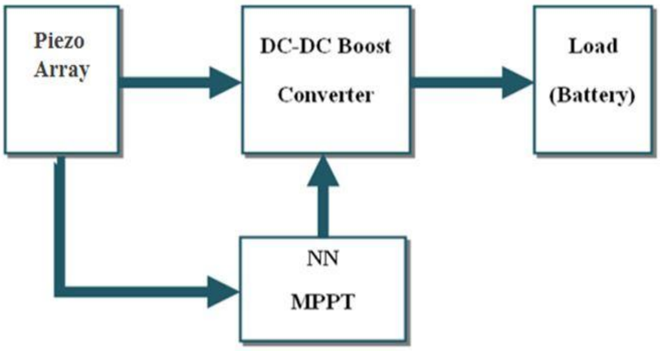

Fig. 1 diagram of electrical energy harvesting system

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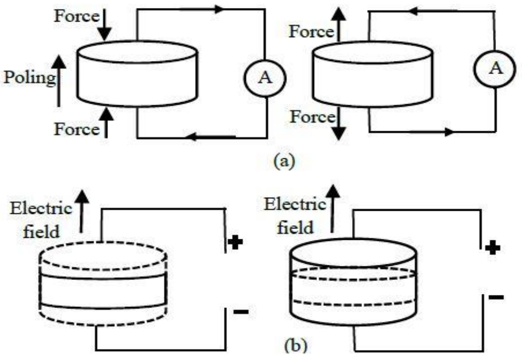

Fig. 2 (a) Direct & (b) inverse piezoelectric effect

The output power of a direct piezoelectric system is multiplication of electric current and voltage that depends on different parameters including dimension and thickness of piezoelectric layers, number of layers, pressure variation or vibrations, temperature variations etc. In addition, *I-V* characteristic of piezoelectric materials is nonlinear. Total energy of piezoelectric materials includes elastic energy and electric energy [9] as:

$$dU_p = \frac{1}{2}ST + \frac{1}{2}DE \qquad (3)$$

in which, dU_p is the energy in unit volume of the piezoelectric material.

To reach the maximum efficiency of the system, maximum point of power characteristic curve has to be obtained and the system state should be maintained around this operation point.

B. DC-DC Converter

To maximize the output power and maintain voltage of piezoelectric arrays in the desired level and to avoid voltage oscillations, we use a power converter with high efficiency. Fig. 3 shows the structure of this converter that has been designed for switching frequency of 10 kHz. To reach this point we should have $L > 68\mu H$ and $C > 147\mu F$.

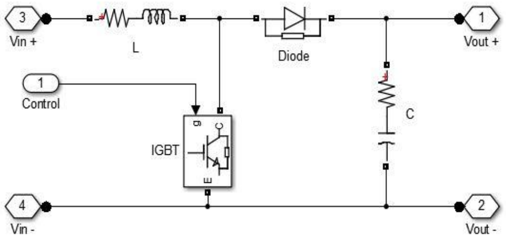

Fig. 3 model of DC-DC converter

The duty cycle of the converter is defined as

$$D = \frac{V_o - V_i}{V_o} \qquad (4)$$

in which, V_i is the output voltage of piezoelectric material and V_o is the output voltage of the converter. By substituting optimal voltage V_{MPP} that is obtained from the tracking algorithm into (4), the optimal duty cycle D_{MPP} is derived that generates the maximum output power.

C. Load Model

Since the goal of the system in this paper is lightening of streets and local uses, it is appropriate to reserve the generated power on a battery and the use the battery for lightening.

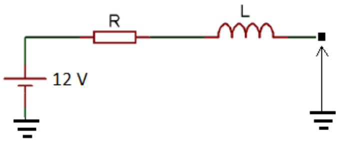

Fig. 4 model of load

For this sake, an RL circuit is used for smoothing the input current to a 12 V battery as shown in Fig. 4. We assume $R = 0.1\Omega$ and $L = 10\mu H$. According to observations applying 0.8 N force to piezoelectric crystal at the frequency of 60 Hz generates an open loop peak to peak voltage of 15 V. By connecting a 8 $k\Omega$ resistance to its ends, the output power will be 3.6 mW [1]. With this scale, a 300 kg weight can generate a peak to peak voltage of 15 V with 1 A current that can be used to charge a 12 V battery.

D. The Method of Maximum Power Tracking

In this paper, a two-level tracking method using artificial neural networks is used to track maximum overall power. At the first level, vibration and applied stress to the series arranged piezoelectric components are measured, P-I curve is extracted and the point of maximum power is obtained. If the variation of the stress of vibration becomes more than a specified percentage, a pulse is issued to generate new P-I curve and the search is repeated. This search algorithm finds maximum current and power and then duty cycle of the converter is updated. The second level of the proposed method uses a three-layer neural network to search the real point of maximum power starting from the output of the first level. The input of the neural network is the derivative of the output power relative to voltage and its output is optimal duty cycle of the converter. The number of neurons of the hidden layer is 100 and the learning method is Back Propagation of error. Fig. 5 shows flowchart of the proposed algorithm, in

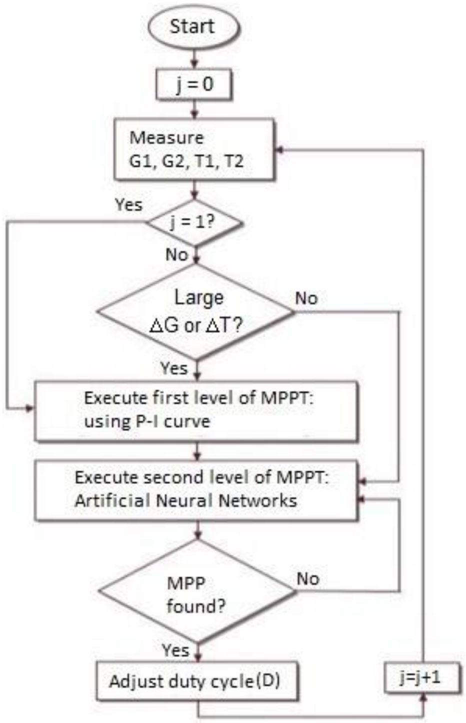

Fig. 5 The flowchart of MPPT algorithm

which, ΔG and ΔT are variation of vibration and stress in each iteration. Whenever they have more than 25% variation, the algorithm goes to level one and produces P-I curve again.

III. SIMULATION RESULTS

In the simulations of this paper, the array includes two piezoelectric circuits in series. The simulations have executed in two cases. In the first case, the variations of vibration and stress are relatively low while in the second case, their variations are high and the first level will be executed several times.

The artificial neural network is offline such that its bias vectors and weight matrices are calculated firstly by learning. Then the trained network is used for tracking. Estimation error has been assumed less than 0.0002. Also, in DC-DC converter in order to reduce the output current and voltage the parameter have been chosen as $L = 22\,mH$ and $C = 220\mu F$.

Percent of tracking error is defined as

$$\%e = \left(1 - \frac{Output\ Power}{MPP\ Power}\right) \times \%100. \qquad (5)$$

Case 1: In this case, the vibration frequency and input stress to piezoelectric arrays are assumed as shown in Fig. 6.

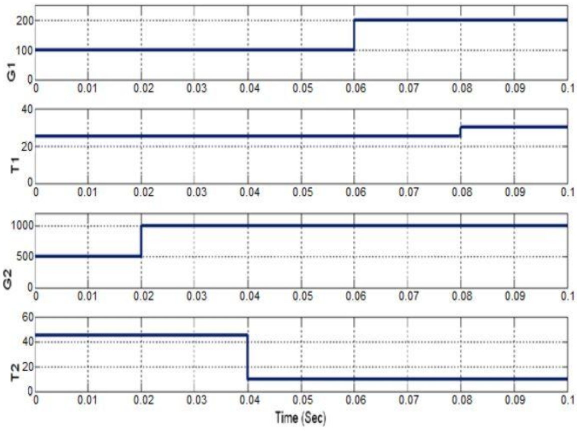

Fig. 6 Inputs of piezoelectric array in case 1

Figs. 7 to 9 show variation of the system output power, voltage, and current in case 1, respectively. According to these figures, the system output approach its maximum value and remain within its vicinity with small fluctuations.

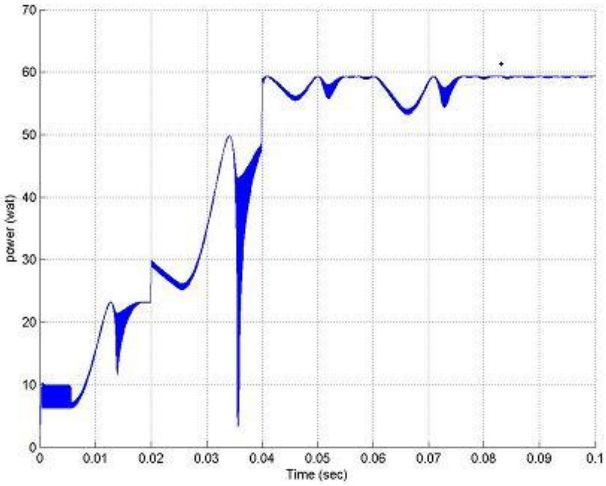

Fig. 7 Output power of piezoelectric in case 1

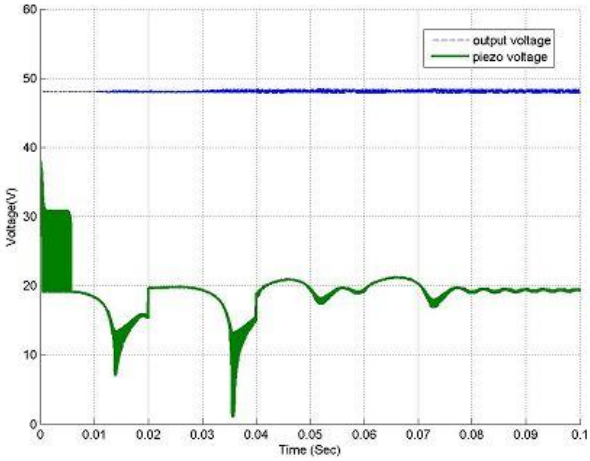

Fig. 8 Piezoelectric voltage and output voltage in case 1

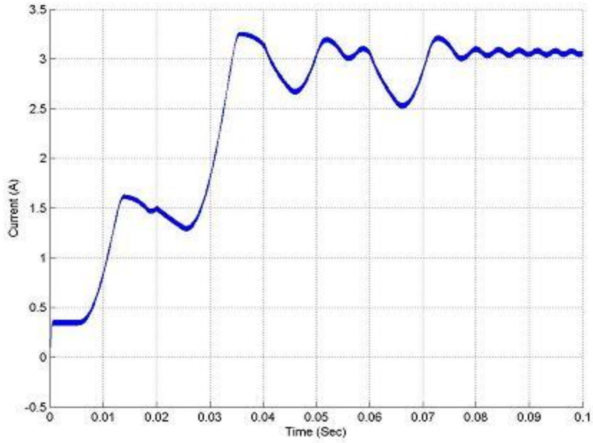

Fig. 9 Current of piezoelectric 1 in case 1

Quantitative results of our maximum power tracking simulation and its comparison to P&O method [10] is summarized in table 1. It shows a good correlation of our results with that reference. Also, the output power of our system converges to the desired value in a very short period of time (0.04 s).

Table 1 The values of MPP and ANN compared to P&O for case 1

Time (s)	MPP Voltage (V)	MPP Current (A)	MPP Power (W)	ANN Power (W)	Error percent	P&O Power (W)
t <0.04	17.69	1.51	26.7	25.6	4	26
0.04 < t < 0.06	19.51	3.01	58.72	58.71	0	59
0.06 < t < 0.08	19.51	2.98	58.15	58.15	0	58
0.08 < t < 1	19.51	3.04	59.30	59.30	0	59

Case 2: Variation of the vibration frequency and input stress to piezoelectric arrays in this case are shown in Fig. 10 and its output power, voltage and current are illustrated in Figs. 11, 12 and 13, respectively.

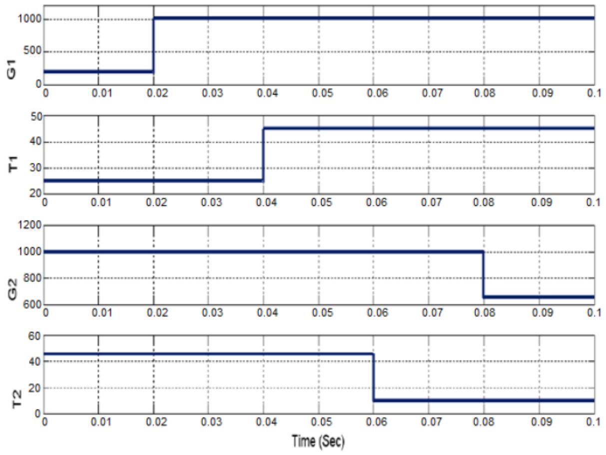

Fig. 10 Inputs of piezoelectric array in case 2

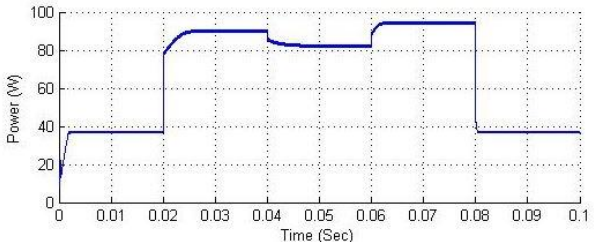

Fig. 11 Output power of piezoelectric in case 2

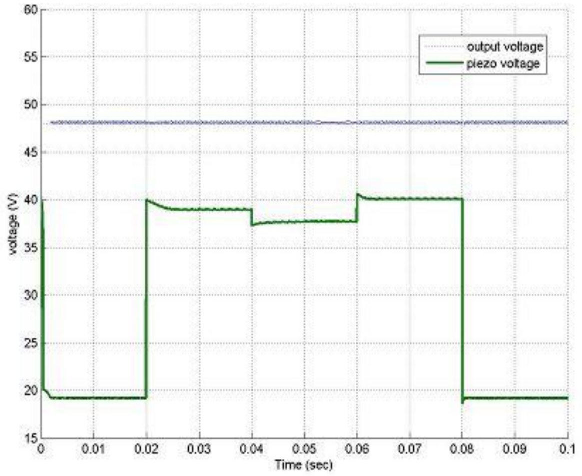

Fig. 12 Piezoelectric voltage and output voltage in case 2

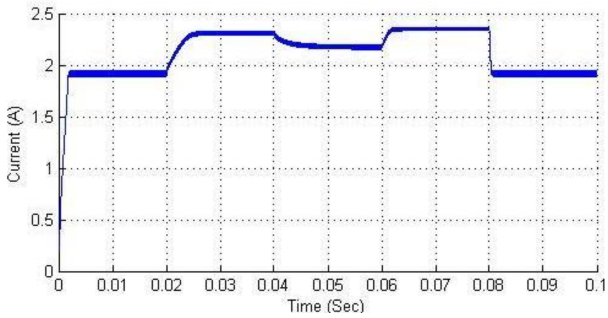

Fig. 13 Current of piezoelectric in case 2

It is observable from simulation results that even in the case of fast variations of input vibration and stress, the proposed method has successfully detected and tracked the point of maximum power.

The simulated numerical values of voltage, current and maximum power for the proposed algorithm compared to P&O method is shown in Table 2. According to these values the proposed method converges to the maximum power point very fast and it has good correlation with reference [10].

Table 2 The values of MPP and ANN compared to P&O for case 2

Time (s)	MPP Voltage (V)	MPP Current (A)	MPP Power (W)	ANN Power (W)	Error percent	P&O Power (W)
$t < 0.02$	18.9	1.91	36.1	36.0	0.3	36
$0.02 < t < 0.04$	38.51	2.39	92.1	92.1	0	92
$0.04 < t < 0.06$	37.79	2.21	83.52	83.52	0	83
$0.06 < t < 0.08$	39.95	2.38	95.1	95.1	0	95
$0.08 < t < 1$	19.25	1.92	36.98	36.9	0.2	37

IV. CONCLUSION

A two-level algorithm was proposed and simulated for maximum power tracking of a piezoelectric array for energy harvesting. The first level included measuring vibration and stress applied to piezoelectric material and obtaining the point of maximum power using P-I curve. The second level included a three-layer artificial neural network to search the real point of maximum power. The ANN uses output of the first level as the start point. The proposed algorithm was applied to an array of piezoelectric devices in two cases with low and high variations of vibration and stress. Simulation results show that the proposed algorithm tracks the point of maximum output power. In addition, they have a very good correlation with previously done P&O method.

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