Performance Enhancement of a Piezoelectric Harvester Included into an Autonomous System

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ABSTRACT

Autonomous systems are these systems which power themselves from the available ambient energies in addition to their duties. In the next few years, autonomous systems will pervade society and they will find their ways into different applications related to health, security, comfort and entertainment. Piezoelectric harvesters are possible energy converters which can be used to convert the available ambient vibration energy into electrical energy. In this contribution, an energy harvesting cantilever array with magnetic tuning including three piezoelectric bi-morphs is investigated theoretically and experimentally. Other than harvester designs proposed before, this array is easy to manufacture and insensitive to manufacturing tolerances because its optimum operation frequency can be re-adjusted after fabrication. In this array, each bimorph has its own rectification circuit in order to prevent the interference of its operation with the others. Two electrical connections are investigated: the series connection and the parallel connection. These connections are tested under several cases such as moderate and high excitation level and large and small connected load. The theoretical and experimental works show that each connection has characteristics and can be used to enhance the harvester output power and/or its frequency bandwidth. These characteristics are highly related to the excitation level and the connected load together.

Key words: piezoelectric bimorph, cantilever array, frequency tuning, electrical connections

تحسين اداء حاصدة كهروضغطية تستعمل لتوليد الطاقة الكهربائية اللازمة لتشغيل جهاز ذاتي العمل

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الخلاصة

الاجهزة ذاتية العمل هي تلك الاجهزة التي تستعمل الطاقة الموجودة في البيئة المحيطة لتحويلها الى الطاقة الكهربائية اللازمة لاداء عملها. في السنين القليلة القادمة, تلك الاجهزة ستتوفر بكثرة في المجتمع و سيوجد لها تطبيقات كثيرة متعلقة بالصحة و الرفاهية. الحاصد ات لكهروضغطية هي احدى الوسائل المستخدمة لتشغيل هذه الاجهزة حيث يمكن لهذه الحاصدات تحويل طاقة الاهتزاز الى طاقة كهربائية. في هذا البحث, تم تصميم حاصدة تحتوي ثلاث عتبات المصنوعة من مواد كهروضغطية. كل عتبة تم تثبيتها من طرف واحد و الطرف الاخر ترك حرا. كل عتبة يمكن توليف ترددها الطبيعي باستخدام مغانط ثابتة. تمتاز هذه الحاصدة الجديدة بانه يمكن تجاوز التاثيرت السلبية لسماحات التصنيع بعد تصنيعها وذلك لانه يمكن اعادة توليف ترددها الامثل الذي عنده تحصد اكبر طاقة ممكنة. تم ربط لكل عتبة في هذه الحاصدة دائرة كهربائية تستخدم لتحويل الفولطية المتناوبة المتولدة الى فولطية مستمرة وذلك لمنع التاثير السلبي لكل عتبة كهروضغطية على الاخرى. لقد تم تصنيع هذه الحاصدة و دراستها نظريا و عمليا.تم بحث نوعين من الربط الكهربائي لهذه العتبات الكهروضغطية: ربط على التوالي و ربط على التوازي. هذان الربطان تمت دراستهما بعدة حالات مثلا تمت دراستهما عند تسليط اهتزاز ذو سعة متوسطة و عالية و كذلك عند ربط حمل كهربائي صغير او كبير. نتائج النظري و العملي بينت تحسن كبير في اداء الحاصدة المقترحه مقارنة مع

التصميم المعروف للحاصدات الكهروضغطية. حيث لوحظ ازدياد كبير في الفولطية المتولدة و كذلك توسع مدى الترددات التي ممكن ان تعمل به الحاصدة.

1. INTRODUCTION

Energy harvesting commonly refers to the process of converting the available energy from the environment into electrical energy. The concept of this process can be found in many real-life applications and on different scales. For example, wind turbines and solar panels are used for high amount of energy conversion and solar cells or piezoelectric materials are used for low amount of electrical energy conversion.

The new challenge since about a decade ago is how to exploit this process to design systems which have the abilities to achieve their requirements (duties) and in addition power themselves from the available ambient energies. Such systems are called autonomous systems. In the next few years, autonomous systems will pervade society and they will find their ways into different applications related to health, security, comfort and entertainment.

In the last few years, piezoelectric harvester has received the most attention concerning its potential to power electronic devices; numerous related scientific journals and conferences have investigated this subject intensively.

The basic configuration of an autonomous system typically contains three elements in addition to the piezoelectric harvester: a full-wave rectifier, a reservoir capacitor and an electronic device performing the primary task. **Fig.1** schematically shows the typical arrangement of such systems. It is clear that the autonomous system has two parts: the electrical part and the electromechanical part. These two parts effect on each other and they can prevent the autonomous system from functioning if they are not properly matched.

One major limitation of piezoelectric energy harvester, discussed before by **Al-Ashtari et al., 2012a**, is that it operates effectively at a single excitation frequency. This excitation frequency must match the optimal frequency of the piezoelectric harvester. The optimal frequency is defined as the frequency at which the harvester generates the maximum voltage. It is determined by the harvester properties, geometry and the connected load (electronic device). For example, for a low damped harvester, experiments show that a 5% difference between the excitation frequency and the optimal frequency causes a drop of the harvested energy by about 90%.

Tang et al., 2010 presented a comprehensive review contains most of the techniques developed over the past years to overcoming the bandwidth limitation of piezoelectric harvesters mentioned above. This review classified the known solutions into two main categories: optimal frequency tuning and multimodal energy harvesting. Optimal frequency tuning was sub-classified into mechanical methods, magnetic methods and piezoelectric methods; multimodal energy harvesting is divided into hybrid energy harvesting schemes and cantilever arrays.

Optimal frequency tuning techniques can be classified more conveniently into manual and self-tuning methods. The self-tuning methods also should be subdivided into active tuning and passive tuning techniques. Active tuning techniques continuously consume power while passive tuning techniques require power only initially for tuning the harvester frequency. Up to now, there is no robust self-tuning harvester that can power its tuning process independently.

This contribution focuses on the cantilever array approach either for increasing the magnitude of the generated voltage or extending the bandwidth of an energy harvester. A cantilever array consists of multiple piezoelectric cantilevers integrated in one harvester in order to increase its frequency bandwidth and/or output power. Increasing voltage is achieved when all the piezoelectric cantilevers have equal optimal frequency. While, extending the frequency bandwidth is accomplished if each piezoelectric cantilever has a certain optimal frequency so that at a certain range of excitation frequency all (or a group) of the piezoelectric cantilevers operate together to generate the required voltage.

Throughout the literature, it can be found that many attempts to design and model cantilever arrays. For example**, Shahruz, 2006a, b, and c** introduced so-called mechanical band-pass filters which consist of multiple cantilevers. Dimensions and proof masses are calculated from the predefined optimal frequency. These works generally do not consider the electrical characteristics and thus cannot investigate the electrical effect of each cantilever on the others. **Xue et al., 2008** presented another design of an array with cantilevers of different optimal frequencies. Each cantilever includes two piezoelectric layers and its resonance frequency is adjusted by varying their thickness. The authors concluded that connecting multiple bimorphs in series increased not only the harvested power but also the harvester bandwidth. They used 10 piezoelectric bimorphs of different thicknesses to harvest power across a bandwidth of 25 Hz. The mathematical model given in this work ignores the electrical effect of the bimorphs on each other. Also, the effect of connecting multiple bimorphs in parallel or in series on the optimal load of the complete harvester is not investigated. **Ferrari et al., 2007** designed a multi-frequency piezoelectric harvester which consists of three cantilever bimorphs of the same dimension. The authors determined the resonance frequency of each bimorph by adjusting the tip mass. They modeled the piezoelectric harvester as a voltage source in series with a branch consisting of a resistor and a capacitor connected in parallel. This allows describing the effect of the bimorphs on each other. In this setup, a half-wave AC-DC rectifier was used for each bimorph for two main reasons: The electronic application needs DC power and power transfer between the bimorphs shall be prevented.

It is hard to realize any of the harvesters presented in the aforementioned works in industrial applications. The setups in those works require very accurate manufacturing processes and careful handling, and operate at an unchangeable frequency band. If the frequency spectrum of the host changes, for example due to wear or changed operating conditions, those arrays will be useless. Another fact worth mentioning is that the characteristic frequencies of piezoelectric elements might also change due to aging temperature, vibration level etc. **Al-Ashtari et al, 2013** introduced a cantilevers array have no such limitations. This cantilever array is developed basing on their magnetic tuning technique addressed in **Al-Ashtari et al., 2012b**. The optimal frequency is tuned by changing the attraction force between two permanent magnets by adjusting the distance between the magnets. The optimal frequency and bandwidth can be re-adjusted at any time. This makes the proposed cantilever array insensitive to the effects of manufacturing tolerances of both the piezoelectric elements and the harvester structure on the optimal frequency of the system.

In this contribution, a new cantilever array is designed based on that proposed by **Al-Ashtari et al., 2013**. This array was used as the energy harvester in an autonomous system similar to that shown in **Fig. 1**. In such systems, the electrical connections between the piezoelectric elements of the energy harvester, as well as the electromechanical characteristics of each one, are the important parameters which can be adjusted in order to increase the generated power, enhance the frequency bandwidth or make the system more reliable. There are two primary possible electrical connections to connect the piezoelectric elements together: the series connection and the parallel connection. Each one of these connections has its own characteristics and is suitable for different requirements. The model describing the operation of such system is derived and its operation is analyzed. This theoretical work is supported by the corresponding experimental results. The results of these two sections show good agreement between them.

2. AUTONOMOUS SYSTEM

It has been mentioned above that the autonomous system has two parts: the electrical part and the electromechanical part. In this section, these parts will be discussed in details.

2.1 Electrical Part

In this paper the, behavior of an energy harvester connected to a rectifier circuit is introduced. As shown in **Fig. 2**, the rectifier circuit consists of four diodes: D_1, D_2, D_3 and D_4. These diodes are connected in the standard arrangement to convert the generated AC voltage from the harvester $u(t)$ into an output DC voltage U_{dc}.

Fig. 3a shows the generated AC voltage $u(t)$ during the first two periods of operation, where t_p is the period. The corresponding output DC voltage is shown in **Fig. 3b**. These two figures show that the first period of operation is very important and it includes four intervals; these intervals are dependent on the design of the autonomous system components and their properties. Thus, the autonomous system should be designed with this in mind to operate successfully. These intervals are: the dead zone interval t_0, the diode transient conduction interval t_{tr}, the open circuit interval t_{op} and finally the diode steady-state conduction interval t_{ss}.

The rectification process starts when the dead zone interval ends. This interval is defined as that time interval during which the AC voltage is applied and there is no corresponding output DC voltage. That’s because the input AC voltage amplitude is less than that required to overcome the diode barrier voltage U_d. The dead zone interval exists only in the first quarter of the first period of operation (between 0 and t_0) as shown in **Fig. 3b**.

At the end of the dead zone interval t_0, the transient conduction interval t_{tr} will start when the amplitude of the generated AC voltage rises to be greater than the diodes’ barrier voltage. Within this interval, either the first pair of diodes (D_2 and D_4) is on and the other pair (D_1 and D_3) is off or vice-versa. This causes the current to flow from the harvester into the parallel loads C_R and R_l. The size of the reservoir capacitor C_R should be calculated carefully so that it will be is fully charged at the end of this interval; otherwise the transient conduction time will continue over into the next periods until the capacitor is fully charged. When the capacitor voltage rises higher than the amplitude of generated AC voltage, the diodes will be off because the capacitor will try to discharge its stored energy through them in their reverse direction.

This means the harvester is now disconnected from the load side i.e. it is in open-circuit condition. This will continue until the amplitude of the input AC voltage becomes greater than the capacitor voltage. This happens in a time interval called the open circuit interval t_{op}. The load R_l in this interval is electrically powered only by the energy stored in the capacitor and the harvester in open-circuit condition.

When the capacitor voltage becomes smaller than the amplitude of the applied AC voltage $u(t)$, then this interval will be ended and the steady-state conduction interval t_{ss} starts. Within this interval, the other pair of diodes that were not conducting earlier will do so and the first conducting pair will not. Within this time, the capacitor should be recharged.

The second and also all the next periods of operation have only the open circuit interval and the diodes steady-state conductions intervals i.e. the system will be in its steady state operation as shown in **Fig. 3b**.

In most real-life applications, the required charging time of the reservoir capacitor is much smaller than required time for its discharging. This enables us to assume that almost all the generated current flows into the connected load during the diodes steady-state conductions intervals i.e. during the steady state operation the harvester will serve two different loading conditions: the open-circuit condition and resistive load condition. In this article, the connected load is chosen to be large enough in order the generated voltages have almost the characteristics during these alternative intervals.

2.2 Electromechanical Part

The electromechanical part (the piezoelectric harvester) has related mechanical and electrical characteristics. These characteristics are determined by the mechanical and electrical boundary conditions of the harvester. The open circuited condition refers to the case when the electrodes of the included piezoelectric elements are not connected. The resistive load condition means that the electrodes of the piezoelectric harvester are connected to each other via a resistive load.

2.2.1 **Open circuit condition**

The system representing the piezoelectric harvester of the autonomous system in an open circuited condition is shown in **Fig. 4** (the electrical subsystem has been removed for purposes of clarity). Based on the model introduced by **Al-Ashtari et al., 2012a,** the equivalent systems (mechanical and electrical) of the harvester in this condition are shown in **Figs. 5a** and **5b**, respectively. All the parameters in the figures are the same as defined previously. $u_o(t)$ and $x_o(t)$ are the generated open voltage and the corresponding harvester deflection resulting from force application $F(t)$, respectively. If the excitation force $F(t)$ shown in **Figs. 5a** and **5b** is described by

$$F(t) = F\sin\omega t, \tag{1}$$

then the generated AC voltage can be expressed as

$$u_o(t) = U_o\sin(\omega t + \varphi_{uo}) \tag{2}$$

where ω is the excitation frequency in rad/s, F and $U_o$the amplitudes of the excitation force and the generated AC voltage, and φ_{uo} is the phase difference between them. The governing equation of such system is

$$M\ddot{x}_o(t) + B\dot{x}_o(t) + Kx_o(t) = F(t) - \alpha u_o(t) \tag{3}$$

For the electrical side, the following equation can be derived:

$$\alpha\dot{x}_o(t) = C_p\dot{u}_o(t) \tag{4}$$

Therefore, the transfer function between the excitation force and the generated voltage is

$$\frac{U_o(s)}{F(s)} = \frac{\alpha}{MC_ps^2 + BC_ps + KC_p + \alpha^2} \tag{5}$$

where $F(s)$ and $U_o(s)$ are the Laplace transforms of the excitation force and generated AC voltage, respectively. In terms of the series resonance frequency ω_s, the parallel resonance frequency ω_p and the system damping ratio ζ, it becomes

$$\frac{U_o(s)}{F(s)} = \frac{\left(\alpha/MC_p\right)}{s^2 + 2\zeta\omega_s s + \omega_p^2} \tag{6}$$

Where,**Al-Ashtari, 2012a**

$$\omega_s = \sqrt{\frac{K}{M}}, \tag{7a}$$

$$B = 2\zeta M\omega_s , \tag{7b}$$

$$\alpha^2 = M\left(\omega_p^2 - \omega_s^2\right)C_p \tag{7c}$$

The generated AC voltage amplitude can be expressed as

$$U_o = \frac{\left(\alpha/MC_p\right)F}{\sqrt{\left(\omega_p^2 - \omega^2\right)^2 + (2\zeta\omega_s\omega)^2}} \tag{8}$$

and the phase difference is

$$\varphi_{uo} = -\tan^{-1}\left(\frac{2\zeta\omega_s\omega}{\omega_p^2 - \omega^2}\right) \tag{9}$$

2.2.2 Resistive load condition

Resistive load condition refers to the condition in which the electrodes of the piezoelectric element in a harvester are connected by a resistive load R_l as shown in **Fig. 6**. All the parameters of the systems are as defined previously. $x_R(t)$ is the beam deflection from the external force $F(t)$ applied to the system. $u_R(t)$ and $q_R(t)$ are the corresponding generated voltage and charge across the connected resistive load. **Figs. 7a** and **7b** respectively show the equivalent mechanical and electrical systems of a piezoelectric harvester at resistive load condition.

Now, the first goal is to calculate the generated voltage as a function of the connected load R_l and the excitation frequency ω, and then to derive the relationship between these two variables in order to determine the condition at which the maximum power can be generated. The governing equation is the same as that for the open circuited condition, thus

$$M\ddot{x}_R(t) + B\dot{x}_R(t) + Kx_R(t) = F(t) - \alpha u_R(t) \tag{10}$$

for the mechanical side; for the electrical side, we have

$$\alpha\dot{x}_R(t) = C_p\dot{u}_R(t) + \dot{q}_R(t) \tag{11}$$

and

$$\dot{q}_R(t) = \frac{u_R(t)}{R_l} \tag{12}$$

As before, the transfer function between the excitation force and the generated voltage is

$$\frac{U_R(s)}{F(s)} = \frac{\alpha R_l s}{MR_lC_p s^3 + \left(M + BR_lC_p\right)s^2 + \left(B + KR_lC_p + \alpha^2 R_l\right)s + K} \tag{13}$$

In terms of series resonance frequency ω_s, parallel resonance frequency ω_p and damping ratio ζ, which are defined by Eqs. (7a) ,(7b) and (7c), then Eq. (13) can be rewritten as

$$\frac{U_R(s)}{F(s)} = \frac{(\alpha R_l/M)\ s}{R_lC_p s^3 + \left(1 + 2\zeta\omega_s R_lC_p\right)s^2 + \left(2\zeta\omega_s + \omega_p^2 R_lC_p\right)s + \omega_s^2} \tag{14}$$

This gives the amplitude of the generated AC voltage as

$$U_R = \frac{(\alpha R_l\omega/M)\ F}{\sqrt{\left[\omega_s^2 - \left(1 + 2\zeta\omega_s R_lC_p\right)\omega^2\right]^2 + \omega^2\left[2\zeta\omega_s + R_lC_p\left(\omega_p^2 - \omega^2\right)\right]^2}} \tag{15}$$

and the phase difference is

$$\varphi_{uR} = -\tan^{-1}\left(\frac{\omega\left[2\zeta\omega_s + R_lC_p\left(\omega_p^2 - \omega^2\right)\right]}{\omega_s^2 - \left(1 + 2\zeta\omega_s R_lC_p\right)\omega^2}\right) \tag{16}$$

Usually, a piezoelectric harvester is an electromechanical device that is located in or on a vibrating host structure to generate AC voltage, which can be used to power an electronic application. Therefore, the base of the piezoelectric harvester is excited, thus exciting the entire structure. The derived model can be valid if the force F is replaced by the force MA_b. Where A_b is the amplitude of the base acceleration. The generated DC voltage of a harvester U_{dc} in an autonomous system can be expressed as

$$U_{dc} = U_R - 2U_d \tag{17}$$

where U_R is the generated voltage under R_l conditions.

3. CANTILEVER ARRAY

There are two main connections can be used to connect electrically multiple piezoelectric elements: the series connection and the parallel connection. Also, each of these connections can be performed by two different ways as will be shown later: direct connection and indirect connection.

3.1 Series Connection

The series connection of the piezoelectric elements can be classified into two types: the direct and the indirect series connections.

3.1.1 **Direct series connection**

The direct series connection is when the electrodes of all the piezoelectric elements are connected together in series before the rectification process – for example, the system that is shown in **Fig. 8**. For this connection, all the piezoelectric elements should have exactly the same optimal frequency in order to gain an output voltage equal to the generated voltage of one element, times the total number of elements (i.e., the ideal output).

If the harvester includes n number of piezoelectric elements and all are excited by the applied force $F(t)$, then the amplitude of the generated voltage by the i^{th} element during steady-state operation can be expressed as (based on Eq. (15))

$$U_i = \frac{(\alpha_i R_l \omega / M)\, F}{\sqrt{\left[\omega_{si}^2 - \left(1 + 2\zeta_i \omega_{si} R_l C_{pi}\right)\omega^2\right]^2 + \omega^2\left[2\zeta_i \omega_{si} + R_l C_{pi}\left(\omega_{pi}^2 - \omega^2\right)\right]^2}} \tag{18}$$

If all the elements have the same optimal frequency, then the amplitude of the total generated voltage is

$$U_g = n \cdot U_i \tag{19}$$

and the total output DC voltage can be calculated as

$$U_s^d = U_g - 2U_d \tag{20}$$

For this connection, if the piezoelectric elements have different optimal frequencies, then the generated voltages of each one will have different amplitudes and be in different phases. This will cause them to overlap and may lead to not achieving any enhancement.

3.1.2 **Indirect series connection**

The indirect series connection means that the piezoelectric elements in the harvester are connected together in series, but after the rectification process is carried out, as for example in the system shown in **Fig. 9**.

If this harvester also includes n number of piezoelectric elements, and these elements all have small differences in their optimal frequencies, and if the excitation frequency matches the optimal frequency of one piezoelectric element, then the other piezoelectric elements should be able to generate voltage amplitudes equal to or more than that dropped through the diodes, so the total DC voltage will be

$$U_s^i = \sum_{i=1}^{i=n} (U_i - 2U_d) \tag{21}$$

This connection can be used to expand the frequency bandwidth within which the harvester can supply enough power to the connected load.

It is not practical to use the indirect connection if the piezoelectric elements have large differences in their optimal frequencies. That is because the losses of voltage across the diodes will be very large. Thus, if a harvester includes n number of piezoelectric elements, and is excited by a harmonic acceleration of frequency that activates on piezoelectric element, which then generates voltage while the others do not, then the total DC voltage U_s^l at that case can be expressed as

$$U_s^l = \sum_{i=1}^{i=n} [U_i - (2\, n . U_d)] \tag{22}$$

It seems to be that if a large number of piezoelectric elements are used then this may result in there being no generated voltage anymore.

3.1.3 **Tuning strategy for series connection**

To achieve an expanded frequency bandwidth, each piezoelectric element should be tuned to a different optimal frequency. The spread between the different frequencies defines the bandwidth and the minimum voltage generated in this frequency range. In this paper, the tuning strategy is developed so that at a frequency f_h where two neighbouring piezoelectric elements generate the same DC voltage, the voltage generated by each element is half the mean peak voltage of the two elements.

Fig. 10 shows an example with three piezoelectric elements with approximately equal peak voltages (the solid line curves). It is clear that these elements are tuned in such a way as to ensure that at the frequencies f_{h1} and f_{h2}, the neighboring piezoelectric elements share equally in generating the total voltage. The total generated voltage is similar to that shown in **Fig. 10** in the dashed black line. It seems that the peak voltage that can be generated by a single piezoelectric element at a single excitation frequency is extended across a considerable range as shown in **Fig. 10**.

This tuning strategy has been tested theoretically and experimentally, as will be shown later, and the results show that this strategy is very effective for enhancing the frequency bandwidth of a piezoelectric harvester.

3.2 Parallel Connections

If a harvester includes piezoelectric elements with different optimal frequencies which are connected in parallel, then only the element that generates the higher voltage powers the load, while the other elements do not. In a direct parallel connection, the other elements which are not generating voltage at the moment behave as additional parallel loads. Therefore, these elements cause the generated voltage to decrease. This is because these parallel elements reduce the overall load connected to the operating element.

In indirect parallel connections, the voltage generated by the operating element prevents the rectifier circuits of the other elements from conducting. Therefore, it is not advisable to use either parallel connection type if the piezoelectric elements have different optimal frequencies.

If all the piezoelectric elements have the same optimal frequency and are connected in parallel (direct or indirect), then the generated current increases. This case is not examined further because it is interested in replacing batteries with piezoelectric harvesters in currently commercial electronic applications. In such applications, achieving the required voltage is necessary to ensure achieving of the required power for the operation; the current is therefore uninteresting for this purpose.

4. EXPERIMENTAL VERIFICATION

Fig. 11 shows the experimental cantilever array harvester that was constructed to validate the analytical model presented above. This harvester consists of three piezoelectric bimorphs (SITEX-Module 427.0085.11Z from Johnson Matthey; specifications in Table 1). Magnetic stiffening **Al-Ashtari et al., 2012b** can be used to tune each bimorph individually. The bimorphs are electrically isolated from each other and from the aluminum base by plastic parts. Magnets with a face area of 8.5 x 2 mm² and a thickness of 1.5 mm (from HKCM Engineering, manufacturing code Q08.5x02x01.5Ni48H) were used. The distance between the two magnets is adjusted using a knurled screw.

This harvester is connected to a bridge full-wave rectifier consisting of four Schottky diodes and reservoir capacitor of size 200 µF. The used electrical application is a temperature sensor (TFA Dostmann GmbH & Co. KG Kat. Nr. 30.2018). This sensor requires 1.5 V DC voltage and has a total resistance of 360 kΩ. This system was excited with a harmonic acceleration of amplitude equal to $5.5\ \mathrm{m/s^2}$ and frequency of 250 Hz matches to the harvester parallel-resonance frequency.

Fig. 12 schematically shows the setup that used in the experimental work. The piezoelectric harvester is excited from its base by a harmonic acceleration supplied by an electro-dynamic shaker. In order to keep this acceleration on the desired value, it is monitored by using a laser vibrometer (vibrometer #1) and an oscilloscope. The amplitude and frequency of this acceleration are manually adjusted by manipulating the used signal generator and amplifier.

A second vibrometer of two laser probes is used to measure the deflection of the piezoelectric element included in the used harvester. This deflection is monitored and measured by using also an oscilloscope as shown in **Fig. 12**.

Fig. 13 shows a comparison between the obtained output DC voltages for three cases all excited by the same harmonic acceleration as before ($5.5\ \mathrm{m/s^2}$): the first case when the harvester includes a single bimorph, the second case when the harvester includes three identical bimorphs of the same operational frequency (250 Hz) and connected in indirect series and finally the third case when these three bimorphs are connected in direct series.

It is clear that connecting identical bimorphs of same operational frequency in series directly gives the greater DC voltage and it is more than the required voltage for making the temperature sensor operates. Therefore, this connection can be used to achieve one of two requirements: the first that such harvester of three bimorphs can be excited only by acceleration of amplitude $1.9\ \mathrm{m/s^2}$ to generate the DC voltage required for the temperature sensor operation. This makes such type of harvesters are relevant for small excitation level. The second is that such harvester can be designed not to operate at its parallel-resonance frequency and that causes a considerable reduction in the deflection of the bimorph and so increases the life time of the piezoelectric harvester. For example the autonomous system implemented before which was excited by an acceleration of frequency 250 Hz, if the harvester of this autonomous system includes a single bimorph, then this bimorph should have a parallel-resonance frequency matching the excitation frequency and is deflected 95.2 µm to generate 1.5 V DC voltage. But if the harvester includes three bimorphs, then each bimorph should have a parallel-resonance frequency of 242.6 Hz or 257 Hz and deflects with amplitude of 35.7 µm in order to be the total output DC voltage of 1.5 V.

If it is required from using the multiple bimorphs to enhance the frequency bandwidth of the harvester, then operations of the bimorphs should be integrated by tuning each one to a different frequency, as discussed earlier in tuning strategy. **Fig. 14** shows that the single bimorph can generate 1.5 V DC voltage only at a single frequency (250 Hz), but using three bimorphs can extend this frequency into a considerable range of frequencies. It seems for the first moment that using three bimorphs in direct series connection gives a larger range of operational frequencies, but unfortunately the fluctuation in the generated voltage is too large due to the overlap of the generated AC voltages (amplitudes and phases) of three bimorphs. Connecting the bimorphs in indirect series also offers a considerable enhancement in the harvester frequency bandwidth from 243 Hz to 256 Hz with a reasonable fluctuation in output DC voltage.

5- CONCULSION

The feasibility of using harvester with multiple piezoelectric elements has been investigated. For this purpose a cantilever array with three piezoelectric bimorphs was constructed to be used in experimental verification. The results show good agreement between the theoretical and the experimental works. Strategies for connecting multiple bimorphs to increase the maximum generated power and/or enhance the bandwidth compared to a single bimorph harvester were also investigated.

The results show that the harvester with three bimorphs of identical optimal frequency can be used either if the excitation amplitude is small or if it is required to generate higher voltage. The result shows that the generated DC voltage of harvester with three bimorphs can be reached to four times that generated of the harvester of single bimorph.

The results also show that using the proposed strategy of the optimal frequency tuning extends the harvester frequency bandwidth considerably. The harvester of three bimorphs can generate 1.5 V DC for a range 13 Hz instead of generating this voltage at only single frequency.

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NOMENCLATURE

B = equivalent mechanical damping of a piezoelectric device, Ns/m

C_p = equivalent capacitance of the piezoelectric material, F

C_R = reservoir capacitor, F

$F(t)$ = applied excitation force, N

f_a = frequency at which piezoelectric element generates maximum voltage, Hz

f_h = frequency at which piezoelectric element generates half maximum voltage, Hz

K = equivalent mechanical stiffness of a piezoelectric device, N/m

M = total equivalent mass of a piezoelectric device, kg

n = number of used piezoelectric elements included in the harvester

$q_R(t)$ = generated charge of the piezoelectric harvester at resistive load condition, V

R_l = connected Resistive load, Ω

t = time, s

t_p = period

t_0 = dead zone interval, s

t_{tr} = transient conduction interval, s

t_{ss} = steady-state interval, s

t_{op} = open circuit interval, s

U_d = diode drop barrier voltage, V

U_g = amplitude of the total generated voltage of a harvester included multiple piezoelectric elements connected directly in series, V

U_i = amplitude of the generated voltage of the i^{th} piezoelectric element at resistive load condition, V

U_o = amplitude of the generated voltage at open circuit condition, V

$u_o(t)$ = generated AC voltage of the piezoelectric harvester at open circuit condition, V

$u_R(t)$ = generated AC voltage of the piezoelectric harvester at resistive load condition, V

U_s^d = generated DC voltage of a harvester included multiple piezoelectric elements connected directly in series, V

U_s^i = generated DC voltage of a harvester included multiple piezoelectric elements connected indirectly in series, V

U_s^l = generated DC voltage of a harvester included multiple piezoelectric elements when excitation frequency match the optimal frequency of one element, V

$u(t)$ = generated AC voltage of the piezoelectric harvester (general), V

$x_o(t)$ = displacement of the piezoelectric harvester at open circuit condition, m

$x_R(t)$ = displacement of the piezoelectric harvester at resistive load condition, m

α = conversion factor between the mechanical and electrical domains of a piezoelectric device, N/V

ζ = equivalent damping ratio of the piezoelectric device

φ_{uo} = phase difference between the excitation force $\mathrm{F}(t)$ and the generated voltage $u_o(t)$, rad

φ_{uR} = phase difference between the excitation force $\mathrm{F}(t)$ and the relative velocity $u_R(t)$, rad

ω = Angular frequency of the excitation, rad/s

ω_n = natural frequency of piezoelectric harvester, rad/s

ω_s = series frequency of piezoelectric harvester, rad/s

ω_p = parallel frequency of piezoelectric harvester, rad/s

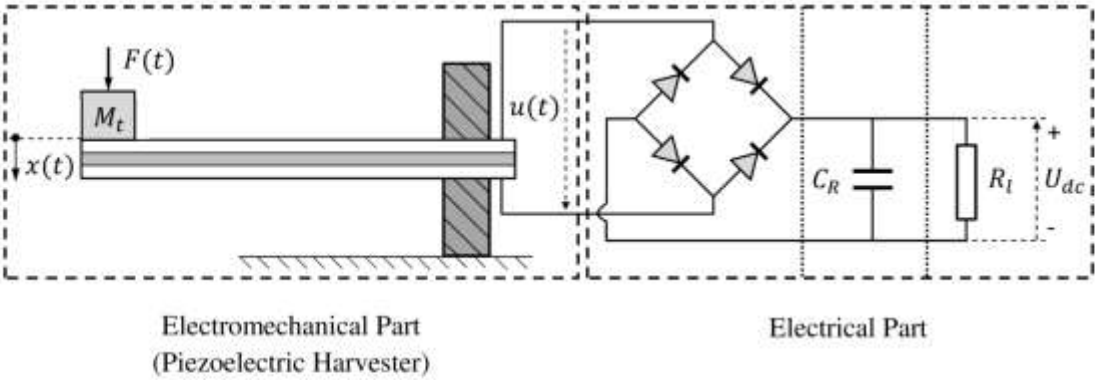


Figure 1. Basic autonomous system.

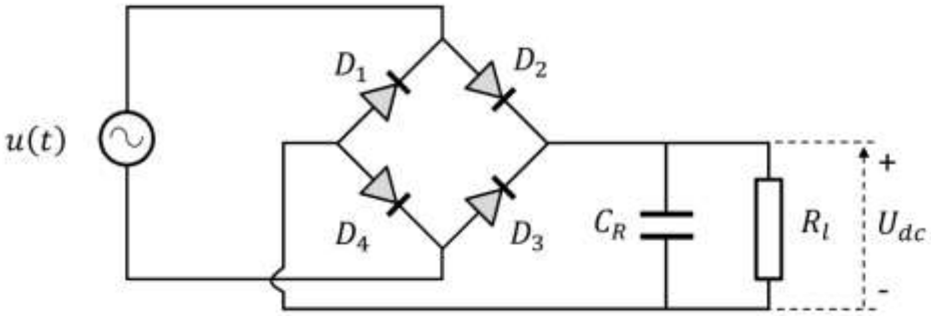


Figure 2. Electrical representation of a basic autonomous system.

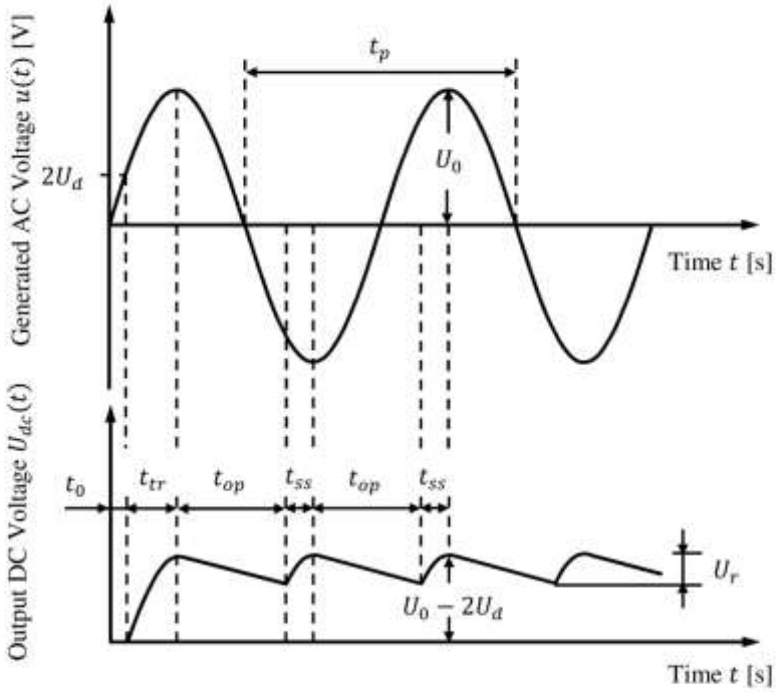


Figure 3. (a) Applied AC voltage $u(t)$ and **(b)** the output DC voltage across the connected load U_{dc}.

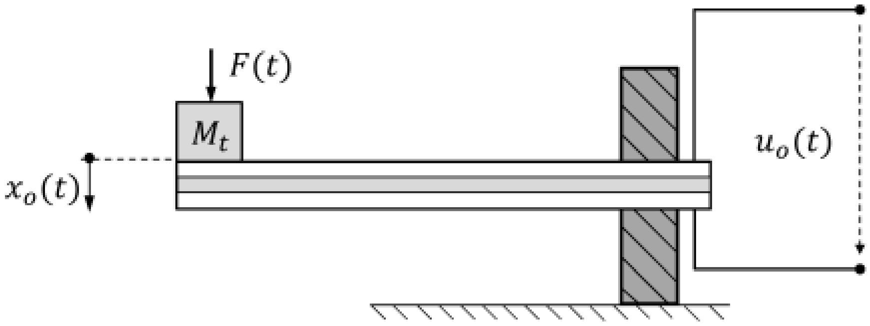
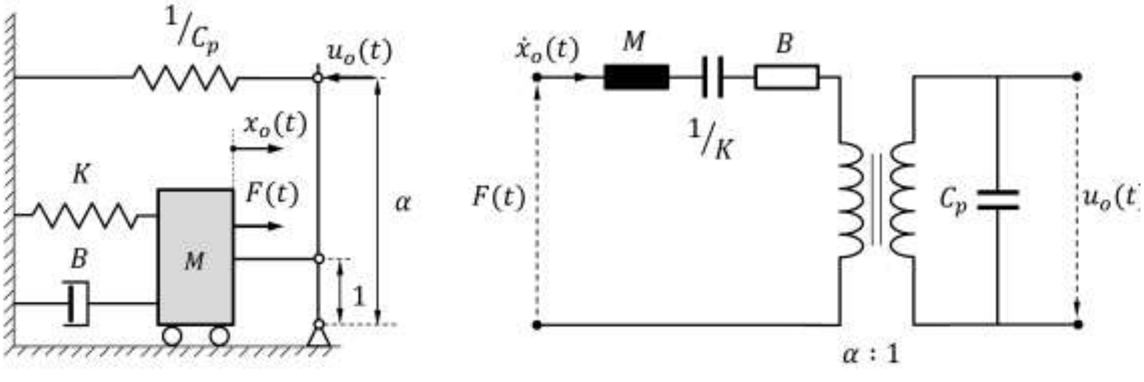


Figure 4. Piezoelectric Harvester in open circuited condition.



(a) (b)

Figure 5. Equivalent systems of the piezoelectric harvester for autonomous system **(a)** mechanical **(b)** electrical

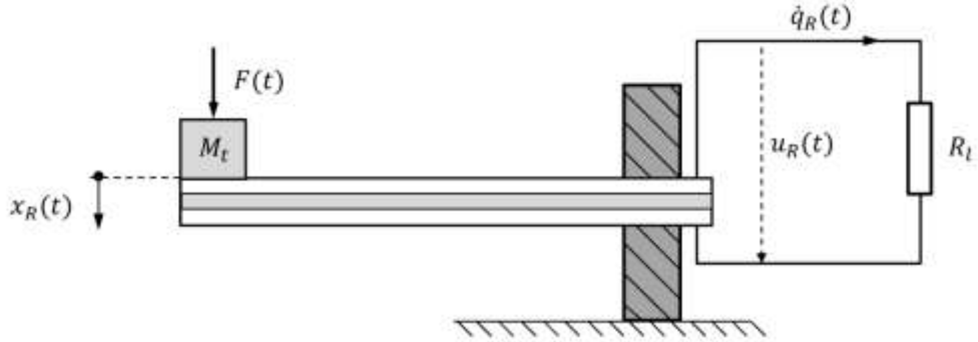


Figure 6. Piezoelectric harvester connected to a resistive load.

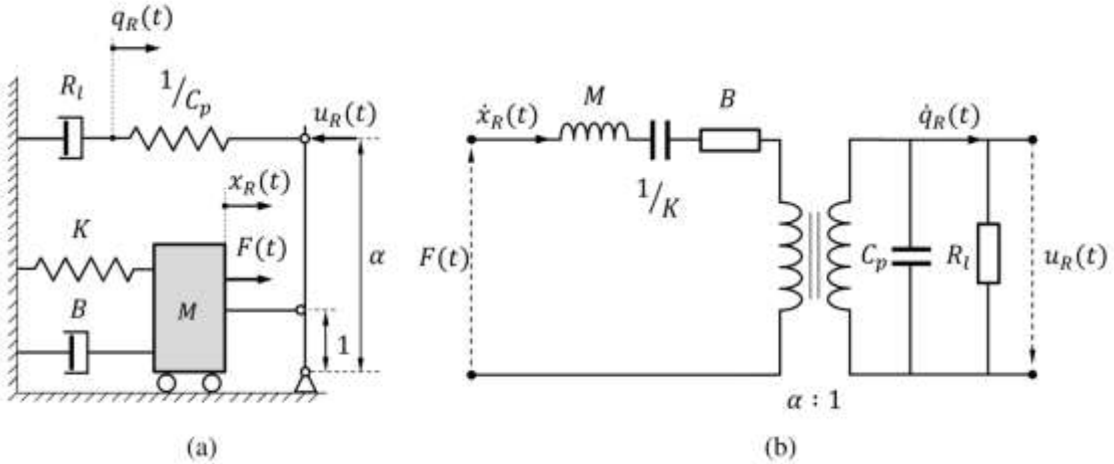


Figure 7. Equivalent systems of piezoelectric harvester connected to resistive load **(a)** mechanical and **(b)** electrical.

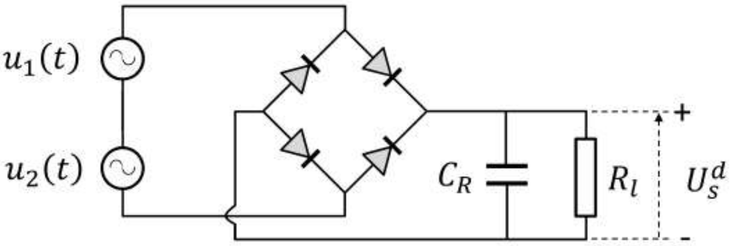


Figure 8. Autonomous system including a harvester with two piezoelectric elements connected in direct series.

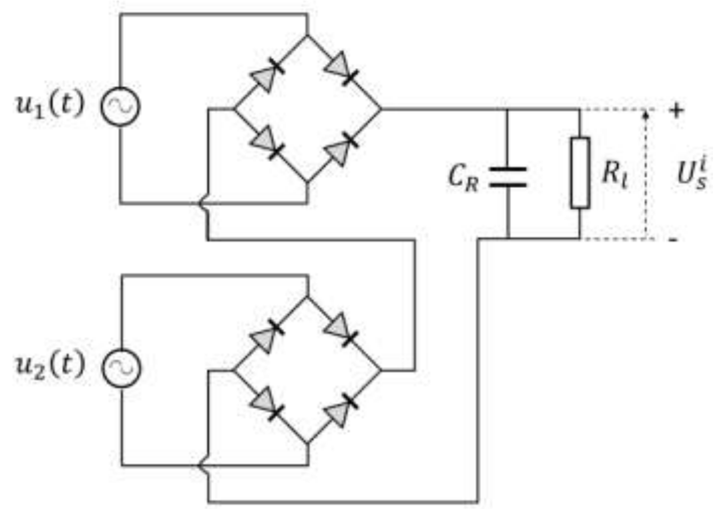


Figure 9. Autonomous system including a harvester with two piezoelectric elements connected in indirect series.

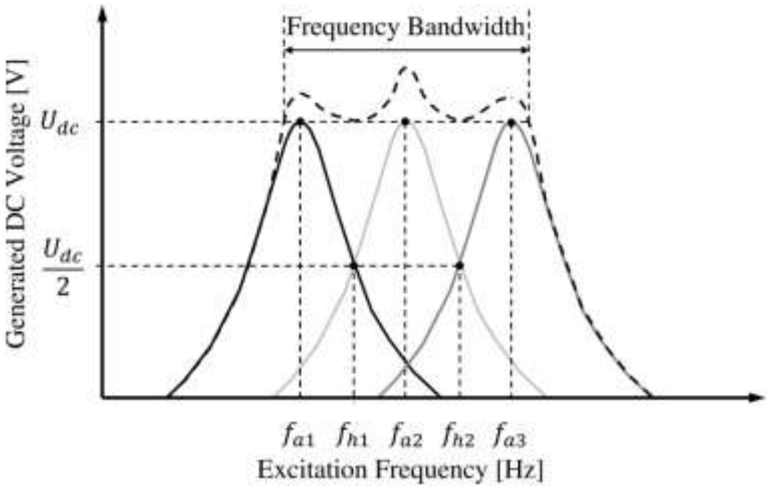


Figure 10. Tuning strategy for bandwidth enhancement.

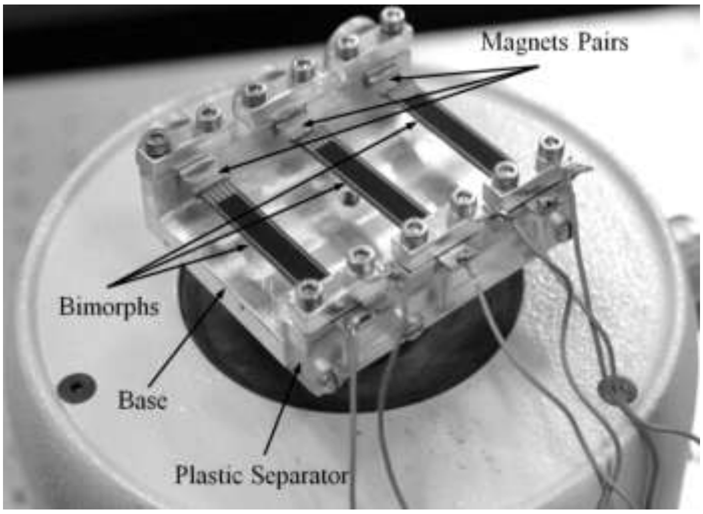


Figure 11. Experimental rig showing a cantilever array of three piezoelectric bimorphs**.**

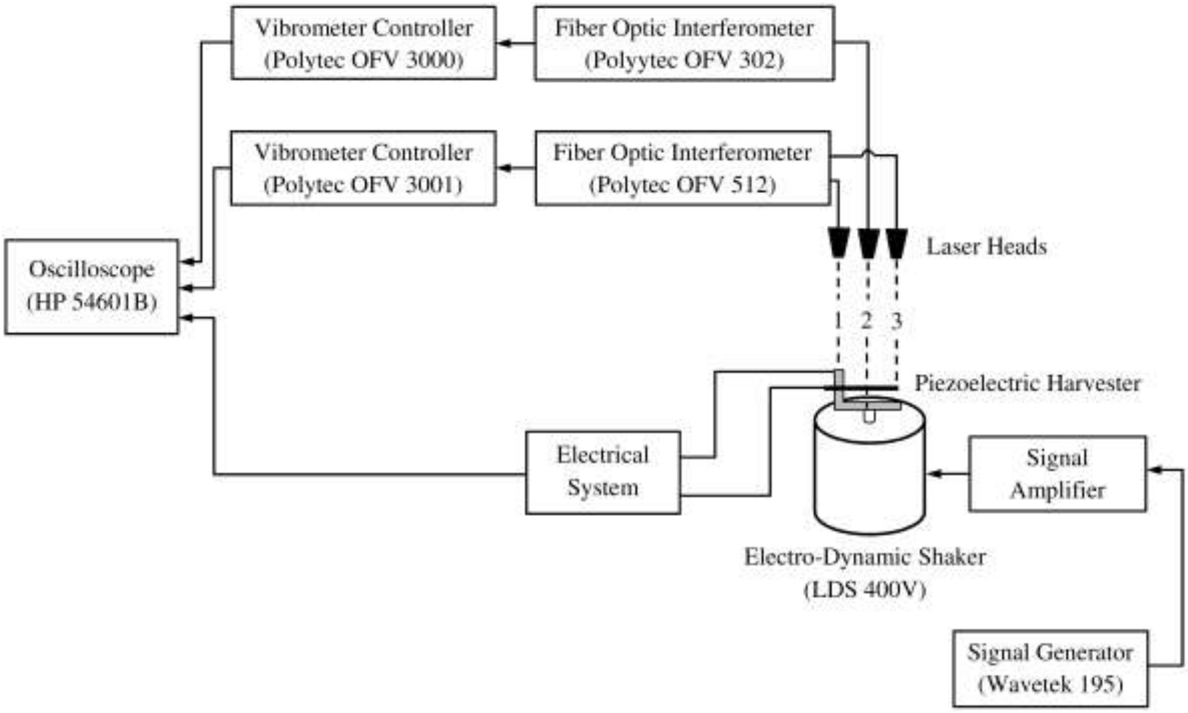


Figure 12. Schematic diagram of the experimental setup.

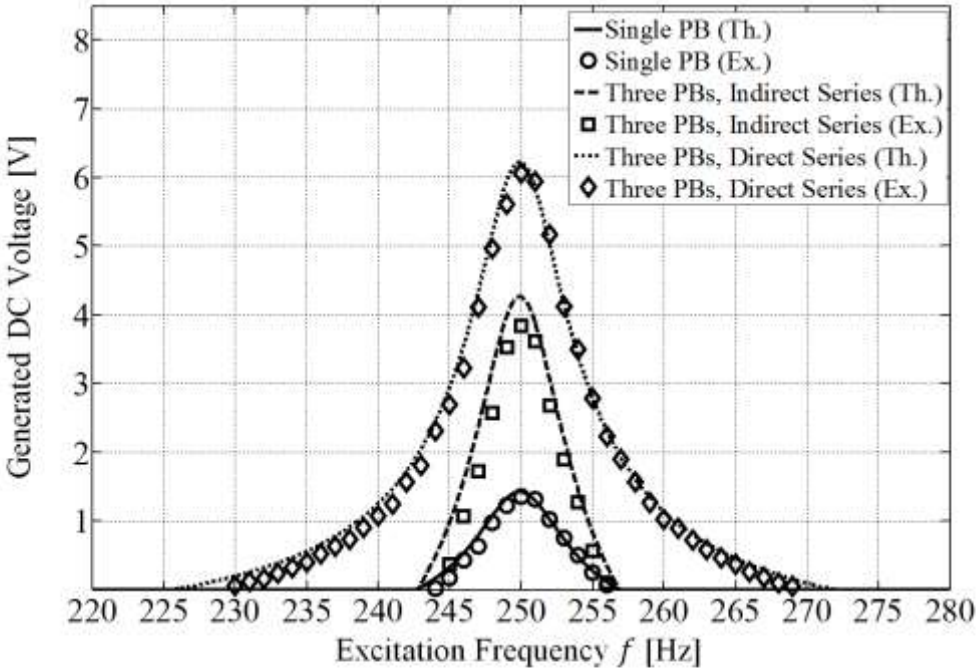


Figure 13. Generated DC voltages of harvesters of differenet number of bimorphs and different electrical connection, all bimorhs are tunned to have same optimal frequency.

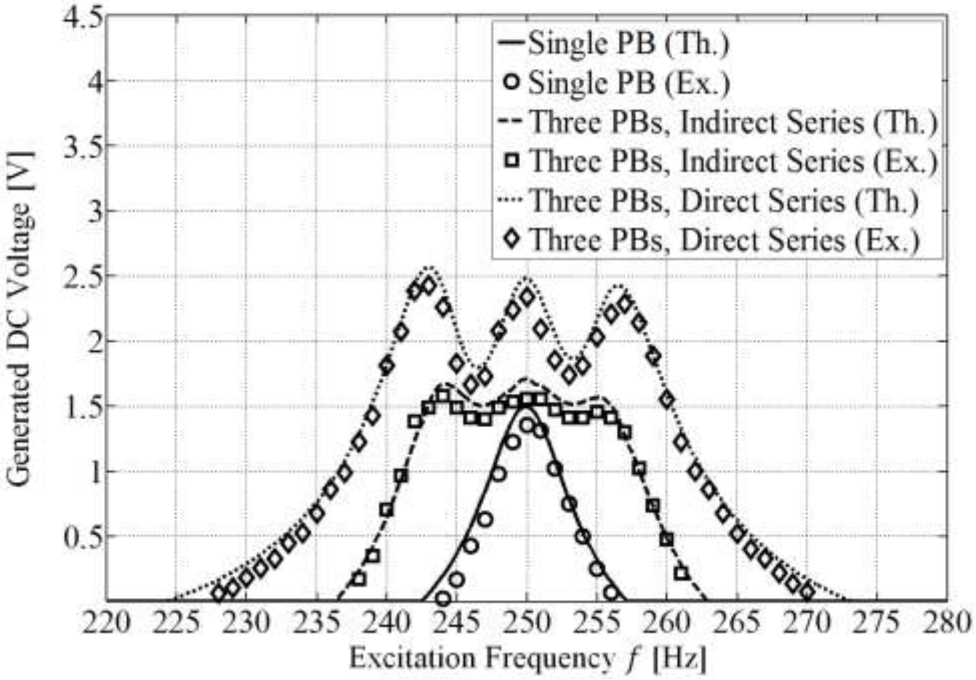


Figure 14. Generated DC voltages of harvesters of differenet number of bimorphs and different electrical connection, bimorphs are tunned using the propsed tuning strategy.

Table 1. Bimorph Specifications.

Parameter	Value
Total length of piezoelectric layers	45.00 ± 0.1 mm
Beam width	7.20 ± 0.1 mm
Total beam thickness	0.78 ± 0.03 mm
Shim layer thickness	0.28 ± 0.05 mm
Piezoelectric layer density	$8000\ \mathrm{kg/m^3}$
Shim layer density	$1800\ \mathrm{kg/m^3}$
Piezoelectric coupling factor	0.38
Piezoelectric compliance	$15.8 \times 10^{-12}\ \mathrm{m^2/N}$
Piezoelectric dielectric constant	$61.95\ \mathrm{nF/m}$
Beam mechanical quality factor	45
Shim layer modulus of elasticity	$120 \times 10^9\ \mathrm{N/m^2}$