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Nonlinear piezomagnetoelastic harvester array for broadband energy harvesting

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This article proposes an array of nonlinear piezomagnetoelastic energy harvesters (NPEHs) for scavenging electrical energy from broadband vibrations with low amplitudes ($<2\text{ m/s}^2$). The array consists of monostable NPEHs combined to generate useful power output ($\sim 100\text{ }\mu\text{W}$) over wide bandwidth. The nonlinearity in each of the NPEHs is induced by the magnetic interaction between an embedded magnet in the tip mass of cantilever and a fixed magnet clamped to the rigid platform. The dynamic responses of two NPEHs, one with attractive configuration and the other with repulsive configuration, are combined to achieve a bandwidth of 3.3 Hz at a power level of $100\text{ }\mu\text{W}$. A parametric study is carried out to obtain the gap distances between the magnets to achieve wide bandwidth. Experiments are performed to validate the proposed idea, the theoretical predictions, and to demonstrate the advantage of array of NPEHs over the array of linear piezoelectric energy harvesters (LPEHs). The experiments have clearly shown the advantage of NPEH array over its linear counterpart under both harmonic and random excitations. Approximately, 100% increase in the operation bandwidth is achieved by the NPEH array at harmonic excitation level of 2 m/s^2 . The NPEH array exhibits up to 80% improvement in the accumulated energy under random excitation when compared with the LPEH array. Furthermore, the performance of NPEH array with series and parallel connections between the individual harvesters using standard AC/DC interface circuits is also investigated and compared with its linear counterpart. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4960442>]

I. INTRODUCTION

In the last decade, the piezoelectric energy harvesting from ambient vibrations has received significant academic focus due to its potential to replace/recharge the chemical batteries in wireless sensor nodes. However, the conventional linear piezoelectric energy harvesters (LPEHs) generate useful power only in narrow frequency bandwidth while the ambient vibrations are normally scattered over wideband. Many techniques such as multi-modal, active or passive resonant tuning, nonlinear techniques, and oscillator arrays have been proposed for widening the operation bandwidth of harvesters. Some researchers^{1–3} have proposed two degree-of-freedom (DOF) harvesters with two close resonant peaks. However, the electrical response from these harvesters exhibits deep valleys between the adjacent peaks with marginal improvement in the bandwidth and hence not suitable for efficient energy harvesting. Arafa *et al.*⁴ presented a 2-DOF harvester with a dynamic magnifier for achieving higher power output. Roundy *et al.*⁵ proposed a multi-DOF harvester design comprising multiple masses on a bimorph beam. Yang *et al.*⁶ and Tadesse *et al.*⁷ studied multi-modal electromagnetic and hybrid energy harvesters, respectively. However, most of the proposed multi-DOF systems have higher modes far away from the fundamental mode and generated significantly less power at higher modes when compared with the fundamental mode. Tang and Yang⁸ carried

out a parametric study on a multi-DOF harvester system to achieve closer peaks in the frequency response with significant magnitudes of power output to enable efficient broadband energy harvesting. Active resonance tuning technique has also been employed to match the excitation frequency with the resonance frequency. However, the energy needed for the frequency detection and resonance tuning consumes most of the harvested power.^{9–11}

Mechanical preload and magnetic force have been frequently employed to tune the resonant frequency of the harvester to cope with frequency-variant vibration environments. Axial force has been applied on the harvester beam to alter the stiffness and consequently the resonant frequency.^{12–14} However, the energy required for practical implementation of this technique and the structural integrity of harvester beam upon the application of load have not been investigated thoroughly. Magnetic interaction has been extensively utilized to induce nonlinear oscillations for widening the operation bandwidth. Challa *et al.*¹⁵ achieved bi-directional tuning of the resonant frequency by modifying the stiffness of harvester beam with attractive and repulsive magnetic forces. Stanton *et al.*¹⁶ also achieved bi-directional tuning of a monostable energy harvester by altering the magnetic interaction around the tip mass. Erturk *et al.*¹⁷ proposed a bistable piezomagnetoelastic structure consisting of a bimorph with two magnets placed symmetrically at the tip and reported a 200% increase in the open-circuit voltage when excited at 0.5 g. Subsequently, Zhou *et al.*¹⁸ altered the angular orientation of magnets placed at the tip of piezoelectric beam to further enhance the bandwidth of

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harvester. Tang and Yang¹⁹ proposed a nonlinear piezoelectric energy harvester with magnetic oscillator to widen the operation bandwidth and increase the power output. They reported 100% increase in the operation bandwidth and 41% increase in the power output when the harvester was excited at 2.8 m/s^2 . Later, Upadrashta *et al.*²⁰ carried out a parametric study on the aforementioned harvester design to obtain the optimal configuration by imposing constraint on the maximum strain induced in piezoelectric material. Wu *et al.*²¹ incorporated magnetic interaction in a 2-DOF harvester to further enhance the bandwidth. Apart from the above mentioned works, many other studies^{22–26} have also demonstrated improvement in the operation bandwidth by inclusion of magnetic interaction.

Array of harvester beams with multiple resonant frequencies has been employed for broadband energy harvesting. With proper selection of the geometry of beams and tip masses, close resonant peaks can be achieved for broadened operation bandwidth. Sharuz²⁷ proposed the idea of using band-pass filter which is an ensemble of beams and masses for energy scavenging. Later, Xue *et al.*²⁸ investigated numerically the integration of multiple bimorphs for broadband energy harvesting. Ferrari *et al.*²⁹ used a piezoelectric multi-frequency converter array for powering a battery less sensor module. Lien and Shu³⁰ studied the electrical behaviour of an array of LPEHs working with several interfacing circuits, including the standard AC/DC circuit and parallel/series SSHI (synchronized switch harvesting on inductor) circuits. Litak *et al.*³¹ and Kucab *et al.*³² also carried out analytical examination of energy harvesting systems comprising two bistable magneto-piezoelectric beams for broadband energy harvesting. However, bistable configurations normally require much higher base accelerations to induce high-amplitude oscillations.

So far in the literature, only the array of LPEHs connected to an interfacing circuit has been considered for wide-band operation. In this paper, an array of monostable nonlinear piezomagnetoelastic energy harvesters (NPEHs) is proposed for broadband energy harvesting particularly for low amplitude vibrations ($<2 \text{ m/s}^2$). The monostable NPEHs are realised with the magnetic interaction at the tip of harvester beams, and their dynamic response depends on the beam geometric parameters, distance between the interacting magnets, and their polarity. Two monostable NPEHs, one with attractive configuration and the other with repulsive configuration, are connected to a standard AC/DC interface circuit. The gap distances between the magnets are chosen to achieve favourable dynamics of the harvesters for broadband energy harvesting. The superiority of NPEH array over the LPEH array is demonstrated experimentally under both harmonic and random excitations. Both series and parallel connections between the two NPEHs are investigated and compared. Though the theoretical study and experiments are carried out with only two NPEHs, the idea can be extended for multiple NPEHs in an array.

II. NONLINEAR PIEZOMAGNETOELASTIC ENERGY HARVESTER ARRAY

The conventional LPEH generates the maximum voltage output at resonance frequency only and suffers from narrow

operation bandwidth. Although array of LPEHs provides wider operation bandwidth, the deep valleys between successive peaks in the electrical response are not favourable for efficient energy harvesting. If the parameters of individual LPEHs in the array are designed to achieve close resonant peaks to avoid the deep valleys, the overall bandwidth reduces. NPEHs with magnetic interaction have been thoroughly employed for broadband energy harvesting and experimentally validated. This study proposes an array of NPEHs to achieve more uniform electrical response over a wide bandwidth. First, a monostable NPEH will be introduced in this section followed by the description of NPEH array.

A cantilever beam with a magnet at its tip, interacting with a fixed magnet is a typical configuration of the monostable NPEH (Fig. 1(a)). The magnetization direction is along the beam axis, and both the magnets are assumed to be perfectly aligned when the beam is at rest. When the beam vibrates under base excitation, the lateral force between the two magnets affects the stiffness of beam and also induces nonlinearity in the system. The voltage response of such monostable NPEH is shown in Fig. 1(b) for different magnetic interactions. The resonant frequency of LPEH is shifted as the linear stiffness of beam is affected because of the magnetic interaction. The attractive configuration increases the linear stiffness of beam resulting in higher resonant frequency, while the repulsive configuration reduces the stiffness of beam resulting in lower resonant frequency. It can be observed from Fig. 1(b) that the NPEH configurations have two stable states (higher and lower) in certain frequency range. When coexisting stable states present, the response of nonlinear system depends on the initial conditions.^{16,33} In the figure, solid and dotted lines indicate the higher and lower energy states, respectively. For the NPEH with repulsive configuration under harmonic base excitation, initial conditions in the forward frequency sweep capture the higher energy state while the backward frequency sweep results in the lower energy state and the NPEH with attractive configuration performs conversely.

In this study, two monostable NPEHs, one with attractive configuration and the other with repulsive configuration, are combined to achieve favourable electrical response over wide bandwidth. The schematic of the proposed NPEH array is shown in Fig. 1(c), where one NPEH is attractive magnetic configuration and the other is repulsive configuration. The rationale behind choosing the opposite magnetic configurations for two harvesters can be understood from the voltage response of individual NPEHs shown in Fig. 1(d). With opposite magnetic configurations and suitable system parameters such as beam length, tip mass, and distance between the magnets, two peaks in the electrical response can be achieved over wideband. Furthermore, the electrical response from one harvester is gradually decreasing when the frequency is swept towards the resonant frequency of other harvester. This trend provides an opportunity to achieve better electrical output over wider bandwidth by combining the electrical responses from individual harvesters. As shown in figure, the voltage response from NPEH array is more uniform without a significant valley which is advantageous in the frequency-variant vibration

FIG. 1. (a) Schematic of a monostable NPEH. (b) Voltage response of a monostable NPEH for different magnetic interactions under harmonic excitation. (c) Schematic of NPEH array. (d) Voltage response of NPEH array under harmonic excitation. Solid and dotted lines indicate high and low energy states, respectively.

environment. It will be shown subsequently through the experiments that the NPEH array performs better than the LPEH array. The theoretical modelling of NPEHs and parametric study for obtaining the gap distance between the magnets for achieving wide bandwidth are presented in Sec. III followed by experimental results.

III. THEORETICAL MODELLING OF NONLINEAR PIEZOMAGNETOELASTIC ENERGY HARVESTERS

The considered NPEH in this study comprises an aluminium beam (AL7075⁴¹), and a patch of MFC (M2807-P2⁴²) is bonded near the clamped end of beam. The geometric parameters of two NPEHs are defined in Figs. 2(a) and 2(b). The numerical values of geometric parameters used in this study and the material properties are given in Table I. The governing electromechanical equations of NPEH are given below

$$M \ddot{u}(t) + C \dot{u}(t) + K u(t) + \Theta V(t) + F_{mag} = F(t), \quad (1)$$

$$\frac{V(t)}{R_L} + C^s \dot{V}(t) - \Theta \dot{u}(t) = 0, \quad (2)$$

where $V(t)$ is the voltage across the resistor R_L ; $u(t)$ is the modal displacement in single mode approximation with displacement $w(x,t) = u(t)\phi(x)$; M , K , C , and Θ are the modal mass, stiffness, damping, and electromechanical coupling terms, respectively, corresponding to the fundamental mode $\phi(x)$; C^s is the clamped capacitance of MFC patch; and $F(t)$ is the mechanical forcing due to the base excitation. These modal terms can be evaluated from the expressions given in Refs. 34–36 using the material properties^{41,42} and tabulated parameters. The mode shape of the beam is evaluated using ANSYS 14.0 finite element package and used in the calculation of modal terms in the governing equations. The lateral force (F_{mag}) between the cylindrical magnets is evaluated using the very accurate closed form expression given by Vokoun *et al.*³⁷ Cylindrical NdFeB magnets (N35H grade) of 10 mm diameter and 5 mm thickness are used in this study. The governing equations (1) and (2) are written in the state-space form and solved in MATLAB for the voltage $V(t)$ across the resistor and the tip displacement $u(t)$ for the respective NPEHs.

The theoretical open-circuit voltage response of each NPEH for different gap distances (D) between the magnets under harmonic base excitation of 2 m/s^2 is shown in Fig. 3. It is worth mentioning that the theoretical study is carried out with different resistors for each harvester to find the gap distance D for the respective configurations. The voltage responses are combined using circuitry only in the experiments. The resonant frequencies of harvesters without magnets are 15.6 Hz and 28.1 Hz, respectively, because of the different length of substrates (107 mm and 73.5 mm). All the other geometric parameters are identical for both harvesters. When the magnetic interaction is induced, the response of NPEH with attractive configuration moves towards higher frequencies while that of NPEH with repulsive configuration moves towards lower frequencies as shown in Fig. 3. A parametric study is carried out by changing the gap distance D for each harvester until the voltage responses from both harvesters are sufficiently close. From the results of parametric study shown in Fig. 3, the voltage responses from attractive and repulsive configurations are sufficiently close for $D = 17 \text{ mm}$ and 9.5 mm , respectively. At these distances, peak voltages of $35 \text{ V}_{\text{rms}}$ and $28.5 \text{ V}_{\text{rms}}$ are obtained at 17 Hz and 20.2 Hz, respectively. It can also be observed that the

FIG. 2. (a) Parametric representation of NPEH. (b) Harvester cross-section details.

responses from both configurations intersect at 18 Hz with a voltage output of 10 V from each harvester. When the responses are combined, the expected output voltage would be more than 10 V between 17 Hz and 20.2 Hz even after accounting for losses during the rectification process in circuitry. Experiments are carried out on the prototype and findings are presented in Sec. IV.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

An array of NPEHs consisting of two harvesters is fabricated and experimentally tested. The overall experimental setup is shown in Fig. 4(a), and the prototype mounted on the shaker is shown in Fig. 4(b). The prototype is tested under both harmonic and random excitations using the APS113 ELECTRO-SEIS shaker, a long-stroke electrodynamic shaker designed for emulating low frequency vibrations. The shaker is capable of generating base accelerations up to 10 m/s^2 for frequencies below 100 Hz. The prototype is tested between 14 Hz and 24 Hz with base accelerations of 1 and 2 m/s^2 . The drive power for the shaker is provided through a power amplifier (APS125). The platform of the prototype is firmly attached to the shaker arm, and the base

excitation to the shaker is regulated by a vibration controller (VR9500). The MFC is bonded to the aluminium substrate using DP-460 epoxy adhesive at 10 mm away from the clamped end. The MFC consists of rectangular PZT fibers embedded in the epoxy matrix and Kapton protective layers. The MFC is used as an energy conversion material in this study because of its excellent flexibility (low elastic modulus), confirmability, and durability as compared with other piezoceramic materials. Tip masses are made of acrylic material and the magnets are embedded in them. Provisions are made on the platform to slide the holders containing the fixed magnets to vary the gap distance D between the fixed and vibrating magnets. The voltage response is acquired through an NI data acquisition module NI-9229.

A. Harmonic excitation

The experimentally obtained open-circuit voltage response from both NPEHs for different gap distances (D) is shown in Fig. 5(a) and compared with theoretical predictions in Fig. 5(b). It is evident from both figures that the experimental results are in good agreement with the theoretical predictions. The NPEH with attractive configuration and with $D = 17 \text{ mm}$ achieves peak voltage of $34.8 V_{\text{rms}}$ at 16.8 Hz experimentally compared to the theoretical prediction of $35 V_{\text{rms}}$ at 17 Hz. The parametric study predicts $D = 9.5 \text{ mm}$ as the gap distance between the magnets for the NPEH with repulsive configuration, but the experiments show favourable voltage response at a distance of 10 mm. The repulsive configuration achieves a peak voltage of $27 V_{\text{rms}}$ at 20.1 Hz compared to the theoretical prediction of $28.5 V_{\text{rms}}$ at 20.2 Hz. The damping ratio values used in the theoretical study are measured using the amplitude decay method,³⁸ and the values are 0.77% and 0.85% for the attractive and repulsive configurations, respectively. For the linear cases, i.e., when the magnets are absent, the damping ratio values are 0.74% and 0.62% at 15.6 Hz and 28 Hz, respectively. Overall, the discrepancy between theoretical and experimental voltage responses is below 6%, indicating a good accuracy of theoretical model. While some experimental errors are unavoidable, the simplified theoretical study also contributes to the discrepancy, where the single mode approximation is adopted. Since both

TABLE I. Geometric parameters and material properties of nonlinear piezomagnetoelastic harvesters.

Geometric parameters		
Parameter	NPEH-1	NPEH-2
Magnetic configuration	Attractive	Repulsive
$L_s \times B_s \times T_s$ (all in mm)	$107 \times 18 \times 0.65$	$73.5 \times 18 \times 0.65$
$L_p \times B_p \times T_p$ (all in mm)	$28 \times 7 \times 0.3$	$28 \times 7 \times 0.3$
L (mm)	10	10
Tip mass, M_t (g)	8.2	8.2
Gap distance, D (mm)	17	9.5
Material properties		
Property	Aluminum	MFC
Density (kg/m^3)	2700	5440
Elastic modulus (GPa)	69.5	30.336
Poisson's ratio	0.33	0.31
Piezoelectric constant (C/m^2)	...	-5.157
Capacitance (nF)	...	14.3

FIG. 3. Theoretical prediction of voltage output from two NPEHs with different gap distances D between the magnets. Atr = Attractive; Rep = Repulsive.

FIG. 4. (a) Overall experimental setup. (b) Prototype of NPEH array.

the harvesters operate away from their respective fundamental frequencies because of magnetic interaction, some error in the theoretical predictions is admissible. Finally, slight discrepancy in the material properties and measured damping ratios also contributes to the overall error.

The voltage responses from both NPEHs are combined after rectification to avoid the charge cancellation. Both series and parallel connections (Fig. 6) between the harvesters are investigated and compared. A filtering capacitor (C_f)

is added to smooth the DC voltage output, and a resistor (R) is used as terminal load. The combined voltage response from two NPEHs using both series and parallel connections is shown in Fig. 7(a). Clearly, a more uniform voltage output is achieved over wideband using the NPEH array which is desirable for broadband energy harvesting. Experiments have also been carried out on the LPEH array for comparison purpose. Two LPEHs with substrate lengths (L_s) of 99.5 mm and 95 mm have been used to obtain the response in the

FIG. 5. (a) Voltage output of two NPEHs from experiments with various gap distances (D) between the magnets. (b) Comparison between voltage outputs from experiments and theoretical predictions. Atr = Attractive; Rep = Repulsive; Exp = Experiment; The = Theoretical.

FIG. 6. NPEH array: (a) series connection and (b) parallel connection.

same frequency spectrum as the NPEH array. All the other geometric parameters have been kept the same. The comparison between open-circuit voltage of NPEH and LPEH arrays using both series and parallel connections at harmonic base acceleration of 1 m/s^2 and 2 m/s^2 is shown in Figs. 7(b) and

7(c), respectively. The NPEH array achieves a minimum of 10 V_{dc} throughout the bandwidth. It can be clearly seen that the NPEH array has a much wider operation bandwidth than the LPEH array, especially when the NPEH array operates at the high energy states. The NPEH array shows 70% and

FIG. 7. (a) Combined voltage response from two NPEHs using both series and parallel connections. Comparison between open-circuit voltage responses of NPEH and LPEH arrays under harmonic base acceleration of (b) 1 m/s^2 and (c) 2 m/s^2 . Comparison between power output of NPEH and LPEH arrays under harmonic base acceleration of (d) 1 m/s^2 and (e) 2 m/s^2 . Solid and dotted lines indicate high and low energy states, respectively.

TABLE II. Performance metrics of various nonlinear piezomagnetoelastic harvester designs.

Author	Tested frequency range (Hz)	Base acceleration (m/s^2)	Peak open-circuit voltage	Peak power output (mW)	Bandwidth corresponding to 100 μW (Hz)
Tang and Yang ¹⁹	23–32	1.4	...	0.475	1.5
		2.8	...	1.43	4
Wu <i>et al.</i> ²¹	12–22	1.4	17.5 (V_{AC})	...	...
		2.8	25 (V_{AC})	...	...
Su <i>et al.</i> ²⁶	8–18	3	...	1	4
Fan <i>et al.</i> ³⁹	25–50	10	15 (V_{AC})	...	...
Zhou <i>et al.</i> ⁴⁰	5–20	3.5	19 (V_{AC})	0.16	1
Present study	14–24	1	19.9 (V_{DC})	0.4	1.7
		2	34.9 (V_{DC})	1.1	3.3

100% improvement in the bandwidth over its linear counterpart at 1 m/s^2 and 2 m/s^2 , respectively. Even at the low energy states, the bandwidth of NPEH array is still larger than the LPEH array. It is observed that the rectification losses are between 0 and $2V_{dc}$ for each harvester. The performance of NPEH array can be further enhanced using nonlinear SSHI and SCH circuits, which is beyond the scope of this article.

The power outputs from the NPEH and LPEH arrays are compared in Figs. 6(d) and 6(e) for base excitations of 1 m/s^2 and 2 m/s^2 , respectively. The power outputs are measured at the optimal resistance values obtained for the respective configurations. The optimal load resistances for series and parallel connections of the NPEH array are $750 \text{ k}\Omega$ and $600 \text{ k}\Omega$, respectively, and those of LPEH array are $950 \text{ k}\Omega$ and $700 \text{ k}\Omega$, respectively. The NPEH array achieves a minimum of $100 \mu\text{W}$ and $200 \mu\text{W}$ over wider bandwidth at 1 m/s^2 and 2 m/s^2 , respectively. Clearly, the NPEH array achieves useful power output over wider bandwidth when compared with the LPEH array. It is worth mentioning that depending upon the minimum power required for a specific application, the distance between the magnets in the NPEH array can be adjusted accordingly. The minimum power output from the NPEH array over the operation bandwidth can be increased by adjusting the gap distances between the magnets but at the loss of bandwidth. As shown in Figs. 6(d) and 6(e), the LPEH array achieves higher peak power outputs but the bandwidth is less, and it also suffers from deep valleys in between the peaks. NPEH array generates a peak power output of $1146 \mu\text{W}$, and more than $200 \mu\text{W}$ of power output is harvested over a bandwidth of 2.8 Hz under harmonic excitation of 2 m/s^2 . On the other hand, LPEH array generates a peak power output of $1328 \mu\text{W}$ at 2 m/s^2 which is more than the NPEH array but the bandwidth corresponding to power output of $200 \mu\text{W}$ is only 1.3 Hz . The above results clearly indicate the obvious advantage of the NPEH array over the LPEH array.

The difference between responses from series and parallel connections can be observed only between 18 Hz and 18.6 Hz , where the responses from two harvesters are converging (Fig. 7(a)). The responses from NPEH array have exhibited considerable difference between series and parallel connections when tested at $R \leq 200 \text{ k}\Omega$. However, there is no significant difference when R increases from $400 \text{ k}\Omega$ to

$1000 \text{ k}\Omega$. Moreover, the two optimal resistances $750 \text{ k}\Omega$ (series) and $600 \text{ k}\Omega$ (parallel) are quite close. The open-circuit voltage responses plotted in Figs. 7(a)–7(c) are obtained at $R = 1 \text{ M}\Omega$, and therefore, no significant difference in the voltage output is observed. There is hardly any increase in the two peak power outputs or voltage outputs as the contribution from the other harvester is negligible at each peak point.

The performance metrics of the NPEH array and similar designs in literature are tabulated in Table II. For a fair comparison, only designs employing multiple harvester beams with magnetic interaction are considered. In Table II, the tested frequency range, base acceleration, peak open-circuit voltage, and peak power output of various designs are compared. The operation bandwidths corresponding to $100 \mu\text{W}$ of power output are also listed. It is evident that the NPEH array generates higher open-circuit voltage than other designs, which shows the superiority of the proposed NPEH array. Despite using lower base accelerations (1 and 2 m/s^2), the peak power output and bandwidth corresponding to $100 \mu\text{W}$ from NPEH array are still comparable to other works. The experimental results for the prototype tested with random excitation are presented in Sec. IV B.

B. Random excitation

The majority of the ambient vibration sources are random in nature with their energy usually distributed over a wide frequency range. Hence, the proposed NPEH array is also tested for random excitations within the frequency range 14 Hz – 24 Hz and at amplitudes of 1 m/s^2 and 2 m/s^2 . Again, the LPEH array is tested for comparison purpose. The input signal to both NPEH and LPEH arrays for random excitation level of 2 m/s^2 in the bandwidth 14 Hz – 24 Hz is shown in Fig. 8(a). The voltage response from each harvester is rectified and then combined using parallel connection between the harvesters. The time-history of voltage responses from NPEH and LPEH arrays for 30 s is shown in Fig. 8(b). The fast Fourier transforms (FFTs) of both voltage responses are plotted in Fig. 8(c). It is evident from Fig. 8(c) that the NPEH array has better operation bandwidth over the LPEH array. It is worth noting that the plotted FFT has peaks in the frequency range of 32 Hz – 42 Hz . It is because FFT of a rectified signal gives amplitudes at even multiples of the frequency components in the original signal along with a DC

FIG. 8. (a) Input signal to shaker-controller for random excitation level of 2 m/s^2 . (b) Time-history voltage responses and (c) Fast Fourier transform of time-history voltage responses from NPEH and LPEH arrays with parallel connection under random excitation in the frequency range 14 Hz–24 Hz at an amplitude of 2 m/s^2 . Accumulated energy on $510 \mu\text{F}$ capacitor under random excitation levels of (d) 1 m/s^2 and (e) 2 m/s^2 .

offset value. Since the excitation frequency is between 14 Hz and 24 Hz, the FFT comprises amplitudes in the range of 28 Hz–48 Hz and its higher even multiples. The DC offset voltage values are 9.7 V and 8.4 V for the NPEH and LPEH arrays, respectively.

More experiments are carried out to evaluate the energy storing capacity of various configurations. The voltage output from each harvester is rectified and combined using series or parallel connections to charge a $510 \mu\text{F}$ capacitor. The accumulated energy on the capacitor under random excitation in the frequency range 14 Hz–24 Hz using different configurations is compared in Figs. 8(d) and 8(e) at excitation levels of 1 m/s^2 and 2 m/s^2 , respectively. The capacitor is charged for sufficiently long time (200 s), and the voltage across the capacitor is monitored continuously. Each configuration is tested for 3 times, and their average value is used for calculating the accumulated energy. It is evident that the performance of NPEH array is superior to the LPEH array in terms of accumulated energy because of its wider operation bandwidth. At 1 m/s^2 , the NPEH array with series and parallel connections stores 80% and 30% more energy than its linear counterpart, respectively. At higher random excitation level of 2 m/s^2 , the NPEH array stores more energy than the

LPEH array and charges the capacitor much faster. For instance, at 2 m/s^2 , the LPEH array takes approximately 100 s and 140 s to store 3 mJ of energy using parallel and series connections, respectively. However, the NPEH array takes only 80 s and 110 s to achieve the same, respectively, showing the obvious advantage of NPEH array.

From Figs. 8(d) and 8(e), it is evident that the parallel connection stores higher energy than the series connection during the initial period of charging, but the series connection wins back as the charging continues. Note that the capacitor is not charged at its optimal impedance throughout the charging period. The series connection has higher optimal resistance values than the parallel connection as notified in Sec. IV A. When the capacitor is charged, the initial stage is close to the short-circuit condition (low impedance), and the fully charged stage resembles the open-circuit condition (high impedance). Hence, the impedance matching is favourable to the parallel connection during the initial period of charging, thus it stores higher amount of energy. As the charging continues, the impedance values gradually become more favourable to the series connection; therefore, the series connection charges the capacitor more efficiently at the later stage. However, the accumulated energy from both

connections gradually decreases after sometime as the harvesters are not able to harvest sufficient energy to charge the capacitor.

From the above experimental results, it is quite evident that the NPEH array has better performance over the LPEH array under both harmonic and random excitations. For implementation of this idea in real life applications, the geometric parameters of harvesters, the dimensions of magnets, and the gap distance between the magnets need to be carefully selected to match the bandwidth of harvester with the frequency spectrum of vibration source. Although this study is limited to two NPEHs, the idea can be extended to multiple NPEHs to cover a much wider frequency spectrum of the vibration source. It is also worth mentioning that only low amplitude base excitations (1 m/s^2 and 2 m/s^2) are considered in this study contrary to high amplitudes used in many studies as the high amplitude ambient vibration sources are rare. Since the proposed NPEH array outperforms the LPEH array at low amplitude vibrations, an even better performance can be expected at high amplitude vibrations. Similarly, the proposed idea is also applicable to vibration sources with higher frequencies. Contrary to the active resonance tuning techniques where tuning requires a lot of energy, the proposed NPEH array is passive in nature and has good potential for practical implementation.

V. CONCLUSIONS

This article proposes an array of NPEHs for broadband energy harvesting. Its advantage over the LPEH array in terms of broadening the operation bandwidth has been proved experimentally. The theoretical study is carried out with two NPEHs, and a wide operation bandwidth is achieved by proper selection of the gap distance between the magnets. For comparison purpose, the prototypes of both NPEH and LPEH arrays have been fabricated and tested under harmonic and random excitations. The rectified voltage responses from both harvesters are combined using series and parallel connections. Under harmonic base excitation, the NPEH array exhibits 100% improvement in the bandwidth over the LPEH array when operating at high energy states. At the optimal load resistance, the NPEH array generates a peak power output of $1145 \mu\text{W}$ and a bandwidth of 3.3 Hz , corresponding to power output of $100 \mu\text{W}$ is achieved under harmonic excitation of 2 m/s^2 . Under random excitation level of 1 m/s^2 , the NPEH array using series connection stores 80% more energy when compared to its linear counterpart. The proposed idea can be extended to multiple NPEHs to cover the frequency spectrum of wideband vibration sources. The passive nature of NPEH array in achieving the wider bandwidth is advantageous for practical implementation.

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