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Geometrically and Electrically Optimized Electromagnetic Micro Power Generator

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Abstract- In this paper, an electromagnetic micro generator is proposed to scavenge low frequency environmental vibrations and convert it into electrical power. The proposed micro generator is composed of cantilever beam, magnet and coil which is connected to a resistance load. Mechanical vibrations bend the beam and force the magnet to oscillate inside coil cross section. This phenomenon induces current in the coil and generates output electrical power. Dimensions and structure of the micro generator is optimized and output power and power density is modified. Consequently, mechanical vibrations could be converted into electrical power. Impact of different parameters such as coil turns, mechanical vibration amplitude, air gap, coil diameter and shape of magnet and coil on output power is studied. Geometrical and electrical optimizations for the proposed power harvester is performed. An innovative configuration for coil and magnet structure is proposed. At a constant special volume, number of coil and magnet composition is varied to find the optimum number of composition. So, the structure of the micro generator for 100 turn coil is optimized. Finally, the optimum design is proposed. The obtained results demonstrate that output power could be increased to 419.98 μW. For validation of the simulation results, a prototype with two types of coils are fabricated; to estimate the practical parameters. The type of utilized magnet is NdFeB grade of N42. The resonant frequency of the beam practically is measured to be 5.61 Hz. Open circuit voltage amplitude for 100 turn and 200 turn coil is measured to be approximately 39.2 mV and 76 mV, respectively. The measured output power is 8.42 μW and 20.91 μW which is delivered to optimal resistance load of 10 Ω and 18 Ω, respectively. The obtained simulation results are approximately confirming the achieved practical results.

Keywords Electromagnetic Micro Generator, Mechanical vibration, Electrical power, Resonant frequency, Low frequency environmental vibrations.

1. Introduction

In recent years, energy harvesting methods have gotten lots of attention to produce energy for micro systems such as implanted biosensors. This energy scavenging methods converts ambient energy such as light, heat, mechanical vibrations, etc. into electrical energy. These methods are a worthy replacement for traditional batteries which have limitations of life time. These limitations may cause to replacement and cost problems [1-4].

Recently generated integrated circuits have lower power consumption. The consumed power is about ten to hundred μW [1]. Consequently, design and utilization of energy harvesters for this range of electrical power is attractive. This energy scavenging methods could supply new devices such as wireless sensor devices for implanted biomedical sensors, intelligent buildings and structures, wearable devices, wireless sensor networks, etc.. Energy harvesting techniques could be utilized to supply these applications due to their infinite life time [5-6].

Photovoltaic method of energy generation, specially from solar energy, is the most recognizable energy scavenging technique which is currently in use. However, it's not appropriate for the conditions with insufficient light source. Micro fuel cells operate by reacting of fuel and oxidizing agent. However, hydrocarbon fuels which produce more energy, is not biocompatible. The most attractive method is electromechanical method, whereas it is regenerative and have higher output power density. Techniques for scavenging energy from mechanical vibrations includes, electromagnetic, piezoelectric and electrostatic [7]. Electrostatic method [8-10] requires initial energy to produce electrical energy. Piezoelectric method [11-15] produces relatively lower electrical current than electromagnetic method and have more output impedance. Due to the advantages, electromagnetic method [16,17] is utilized to convert low frequency environmental vibrations to electrical power. Different energy resources could be selected as mechanical vibrations to generate electrical power such as human walking energy [18], water vortex energy [19], etc..

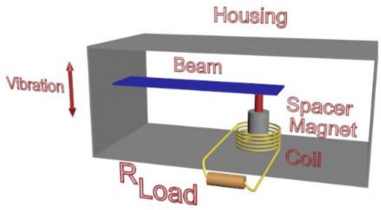
In this work, an innovative electromagnetic micro generator is proposed to scavenge ambient mechanical vibrations and convert it into electrical energy. The proposed method is capable of converting low frequency environmental vibrations to electrical power. The micro generator is composed of cantilever beam, magnet and coil. Mechanical vibrations force the magnet to oscillation. Subsequently, the magnetic flux of the magnet, passing through the cross section of the coil is changed and electrical power is generated at output terminals of the coil.

Different types of configurations are installed and structure optimizations are performed to achieve higher output power and power density. An efficient novel structure is proposed to improve output power. For this purpose, number of magnet and coil composition is optimized. At special constant volume, number of magnet and coil composition is varied. For specific number, output power is maximized. Subsequently, the output power density is optimized. Also, effects of coil turn, mechanical vibration amplitude, air gap, coil diameter and shape of magnet and coil on output power are studied. The generator operation is simulated and the results are collected. For validation, the micro generator device is experimented and the practical results are achieved and compared with simulation results.

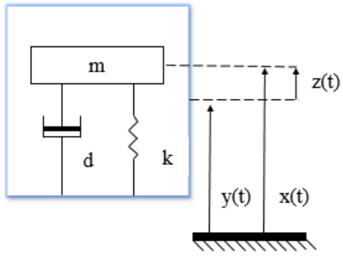
The remainder of the paper is organized as in follow: In section 2, mechanical modelling and equivalent circuit of the micro generator is described. Section 3, discusses the design and simulation of the micro generator. Impact of different parameters on the output power is mentioned and optimization of number of magnet and coil composition is performed. The practical results are shown in section 4 and results validation is performed. Comparison of results, and discussions are demonstrated and tabulated in section 5. Conclusions are given finally in section 6.

2. Mechanical Modelling and Equivalent Circuit

The overall structure of micro generator is composed of housing, beam, spacer, magnet and coil which is connected to resistance load (RLoad). Cantilever beam suspends magnet inside the frame. Spacer connects magnet to beam. Also, coil is fixed to housing. Mechanical vibration is applied to the frame. Subsequently, magnet is oscillated. Variation of magnetic flux of the magnet, passing through coil cross section, induces voltage at output terminals of the coil. The micro generator could be modeled as vibrating system. Any mechanical vibration system consists of mass m, spring with stiffness coefficient of k and damper with coefficient of d, moving within a frame. When the housing is exposed to external vibration, the suspended mass is experienced a vibration which can be modeled with equations. Figure 1 shows the construction of micro generator and the equivalent vibration system model [20].



(a)



(b)

Fig. 1. Vibration system model, (a) Construction of micro generator, (b) Model of micro generator with mass, spring and damper.

Where, the relative displacement of mass to the frame is z(t), the displacement of frame is denoted as y(t) and respectively, the displacement of mass is x(t)=y(t)+z(t). The input vibration is assumed to be y(t)=Y0 cos(ωt). The differential equation which models the system is given by:

$$m\ddot{z}(t) + d\dot{z}(t) + kz(t) = -m\ddot{y}(t) \qquad (1)$$

The damping factor (d) in Equation 1 is caused by electromagnetic parameters such as coil turn, coil area and flux deviation and electrical parameters such as load resistance, coil internal resistance, coil inductance and operating frequency. Further discussions of damping factor are performed in continue. Assume, resonant frequency of system is $\omega_n = \sqrt{k/m}$, where $\omega_c = \omega/\omega_n$ and damping factor is $\xi = d/2m\omega_n$. The Laplace transfer function of relative displacement of mass to displacement of frame is:

$$\frac{Z(s)}{Y(s)} = \frac{-s^2}{s^2 + 2\xi\omega_n s + {\omega_n}^2} \qquad (2)$$

Where, "s" is a complex number frequency parameter. The output power is [21]:

$$P = \frac{\xi\omega_c^3 Y_0^2 \omega^3 m}{[1-\omega_c^2]^2 + [2\xi\omega_c]^2} \qquad (3)$$

The power defined in equation 3 is dissipated power in damper, which, is defined by "d" in Figure 1(b). The equivalent circuit for generator is shown in Figure 2. The circuit shown in Figure 2, shows the model of coil, which is connected to a resistance load (RLoad). Also, internal characteristic of coil, which, is composed of EMF voltage source, coil inductance (L) and internal resistance of coil (RCoil) is demonstrated in Figure 2.

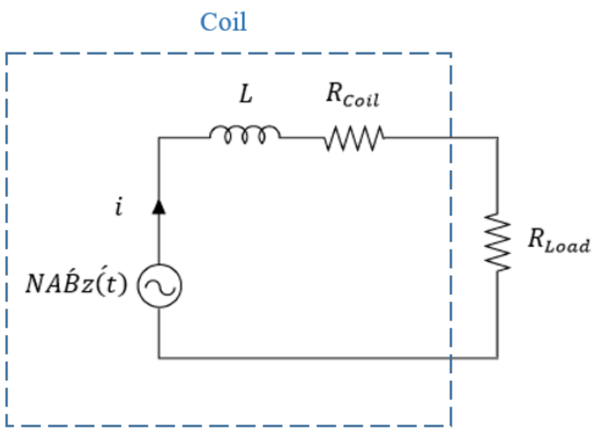


Fig. 2. Equivalent circuit of the proposed electromagnetic micro generator.

where, i is current, L is coil inductance, R_{Coil} is coil internal resistance, R_{Load} is load resistance, N is coil turns, A is coil cross section area, $\acute{B} = dB/dz$, B is magnetic field and $\acute{z}(t)$ is derivative of relative displacement of mass to the frame.

The voltage induced in the coil (Electro Motive Force) is $\varepsilon = NA\acute{B}\acute{z}(t)$. Assume, $R = R_{Coil} + R_{Load}$. So, the damping factor could be calculated as:

$$d = \left(NA\acute{B}\right)^2/(R + Ls) \tag{4}$$

The Laplace transfer function could be rewritten as follow:

$$\frac{Z(s)}{Y(s)} = \frac{-ms^2}{ms^2 + \dfrac{\left(NA\acute{B}\right)^2}{R + Ls}s + k} \tag{5}$$

As mentioned in equation (5), the overall equation of the system is third order. In this work. Operation frequency of micro generator is about few Hz. Hence, imaginary part of coil impedance is neglected. Subsequently, equation (5) is approximately reduced to second order. The dissipated power in the resistor R_{Load} is:

$$P = \left(\frac{R_{Load}}{R_{load} + R_{Coil}}\right)^2 \frac{\left(NA\acute{B}V_0\right)^2}{2R\left(\frac{R_{Load}}{R}\right)} \tag{6}$$

$$= \left(\frac{R_{Load}}{R}\right) \times \frac{m^2\omega^6 Y_0^2 \left(NA\acute{B}\right)^2 R/2\omega_n^4}{R^2(1-\omega_c^2)^2 m^2 + \omega^2[\left(NA\acute{B}/\omega_n\right)^2 + mL(1-\omega_c^2)]^2}$$

where, the maximum velocity of the motion z(t) is V_0.

In the case that, there is mechanical damping in addition to electrical damping, equation 3 could be modified as equation 7. Assume, $\xi_t = \xi_e + \xi_p$ (Total damping factor = Electrical damping factor + Mechanical damping factor). Then the generated power can be rewritten as [20]:

$$P = \frac{\xi_e \omega_c^3 Y_0^2 \omega^3 m}{[1-\omega_c^2]^2 + [2\xi_t \omega_c]^2} \tag{7}$$

Where, $\omega_c = \omega/\omega_n$, Y0 is amplitude of housing vibration, ω is vibration frequency and m is oscillating mass. The generated output electrical power which is calculated using Equation 7, is illustrated in Figure 3. As shown, at resonant frequency, the output power is maximum. Also, reduction of mechanical damping factor increases the output power.

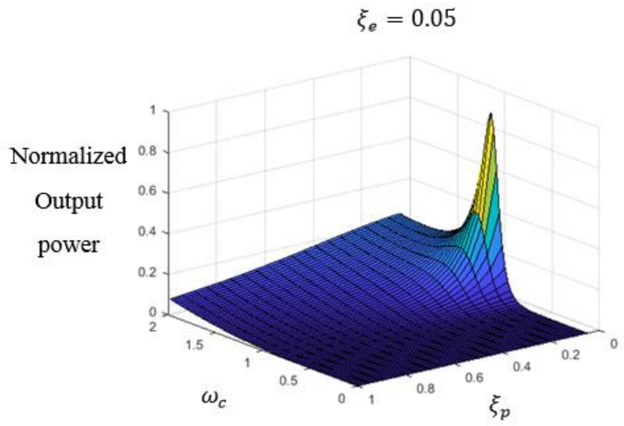


Fig.3. Output power according to damping factors and vibration frequency.

3. Design and Simulation

The proposed micro generator is composed of mechanical and electromagnetic parts. The mechanical part is a suspended cantilever beam which will be oscillated due to environmental vibrations. The electromagnetic part is a magnet which is connected to the beam and suspended inside a coil. The coil is fixed to micro generator frame and output terminals of the coil is available. The output terminals of the coil are plugged to a resistive load. By means of mechanical vibrations, the voltage is induced at the coil. The coil is installed in a specific height; so that, at steady situation, the magnet is exactly in center of the coil. Also, a plastic cylinder is interface between the beam and the magnet. The proposed architecture for the micro generator is shown in Figure 4.

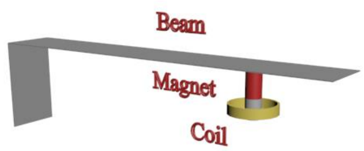


Fig. 4. The proposed architecture of the micro generator.

In Figure 4, utilized material for the beam is galvanized iron which could be bend by mechanical forces and vibrations. Type of magnet is NdFeB (alloy of neodymium, iron and boron) with grade of N42. These materials and characteristics of them are considered in both simulations and practical experiments. In follow, mechanical and electromagnetic simulations are presented.

3.1. Mechanical Simulations

The mechanical system shown in Figure 4, has a specific resonant frequency which the beam vibrates at this frequency for input impulse force. The output electrical voltage frequency is twice of mechanical resonant frequency. At the resonant frequency, the electrical output power will be maximized. Consequently, the resonant frequency should be estimated. For simulation and experiment of the system a mechanical beam is proposed. Using COMSOL software [22], the resonant frequency for experimental setup is achieved as illustrated in Figure 5. Beam length is 20 cm, width is 3 cm, and thickness is 0.5 mm. Anchor height is 5 cm, width is 3 cm, and thickness is 0.5 mm. The estimated Eigen frequency is 6.4598 Hz. Also, stiffness coefficient of the beam for the practical device is analyzed. The stiffness is calculated to be 27.793 N/m.

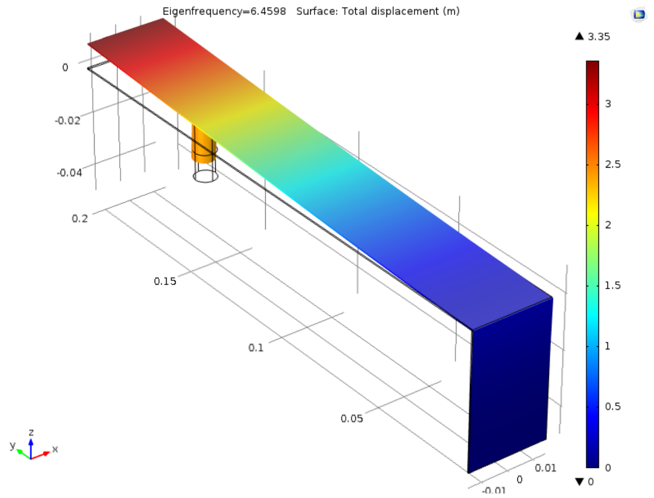


Fig. 5. Resonant frequency of the mechanical beam.

Also, effect of different dimensions on resonant frequency is attained. The obtained results are tabulated in Table 1. As shown, higher dimensions lead to reduction of resonant frequency, while, increase of dimension will increase mass in comparison with stiffness, hence, the result is decrease of Eigen frequency.

Table 1. Effect of cantilever beam dimension on resonant frequency.

Beam length (cm)	Beam width (cm)	Beam thickness (cm)	Eigen frequency (Hz)
20	2	0.05	6.63
20	3	0.05	6.45
20	4	0.05	6.16
20	5	0.05	5.86

Beam length (cm)	Beam width (cm)	Beam thickness (cm)	Eigen frequency (Hz)
5	3	0.05	43.53
10	3	0.05	18.43
20	3	0.05	6.45
30	3	0.05	3.30

Beam length (cm)	Beam width (cm)	Beam thickness (cm)	Eigen frequency (Hz)
20	3	0.05	6.45
20	3	0.1	6.42
20	3	0.15	5.57
20	3	0.2	4.93

The parameters which is assumed in this section to evaluate the resonant frequency and stiffness of the beam, could be varied. These parameters are beam length, height and width, utilized materials, dimension of magnet, position of magnet and other properties. The parameters should be adjusted to achieve a specific or optimum resonant frequency and stiffness.

3.2. Electromagnetic Simulations

In this section, analysis of the magnet flux is performed. Together with, generator operation of the device is described. Also, effect of physical, electrical and electromagnetic parameters on output power is discussed. In this design, number of coil turn, displacement of magnet, air gap and different configuration of magnet and coil, is studied to attain optimum design. An innovative configuration for magnet and coil composition is proposed to achieve higher output power and power density. Finally, the optimized micro generator is designed.

3.2.1. Magnet

Micro generator requires a magnetic source that generates electrical current when the magnetic flux passing through the coil cross section varies. So, NdFeB permanent magnet with grade of N42 is utilized. The remanence (Br) of the magnet, practically is measured to be 1.28T. The utilized magnet is cylinder shape with length of 10 mm and diameter of 8 mm. The magnetic flux density of the magnet inside infinite box is analyzed with Flux software [23]. In Figure 6, the magnetic flux inside the magnet and the air around it, is depicted. Flux arrows for cross section view of the utilized magnet are demonstrated.

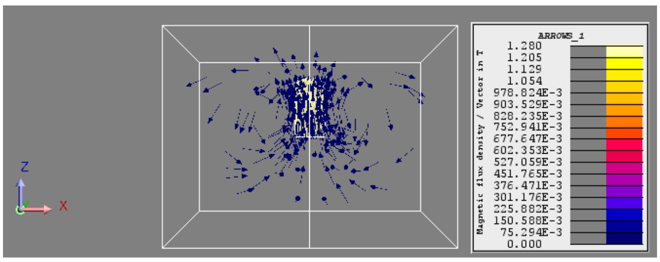


Fig. 6. Cross section view of magnetic flux density around the magnet inside infinite box.

3.2.2. Generator operation

The device is analyzed for generator setup. At generator operation, transient analysis is performed. For realization of this purpose, an initial position is assigned to the magnet. Hence, magnet is pushed downward to a specific displacement. Subsequently, the magnet is released to vibrate freely. So, magnetic flux of the magnet passing through the coil cross section is changed. According to faraday's law of induction, Electro Motive Force (EMF) is induced at the coil terminals. For example, (Displacement of 12 mm, coil turns of 100, coil diameter of 14 mm, coil height of 5 mm and copper wire diameter of 0.15 mm) The open circuit output voltage of the coil terminals is illustrated in Figure 7. Frequency of the output voltage is twice as resonant frequency of the beam (6.45 Hz). Consequently, the output voltage frequency is nearby 12.9 Hz. In section 3.2.3, effect of different parameters on output voltage and power is completely investigated in details.

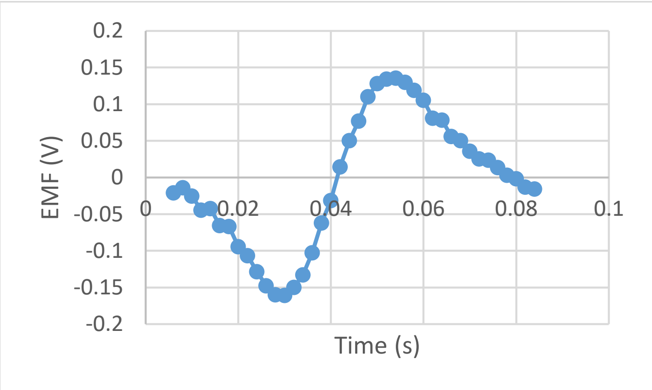


Fig. 7. The sample output voltage waveform of the micro generator.

3.2.3. *Optimization of the Micro Generator*

Different optimizations are performed to achieve higher output power and power density. These optimizations include coil turn, displacement, air gap, magnet and coil composition, cubic shape of magnet and coil, and saddle shape coil. Different dimensional parameters are assumed for simulations. These parameters are shown in Figure 8.

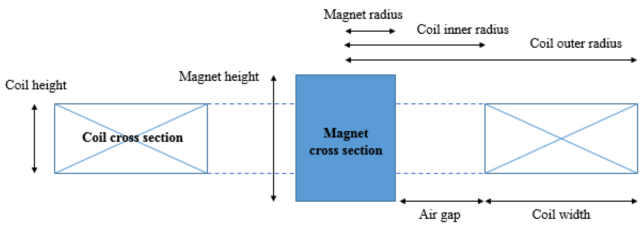


Fig. 8. Dimensional parameters of coil and magnet.

3.2.4. *Coil Turn*

First of all, different number of turns for the utilized coil is analyzed. For this purpose, two simulations with different wire diameter is performed. The primary simulation parameters are as in follow: height of the magnet and the coil is 10 mm; radius of magnet is 4 mm; air gap is assumed to be 5mm; so, inner radius of the coil is maintained on 9 mm; number of turns is varied from 100 to 500; diameter of wire is assumed to be 0.5 mm; subsequently, coil width is altered form 2.5 mm to 12.5 mm; the displacement amplitude of the magnet is assumed to be 10 mm.

The obtained results of simulation using Flux software [23] is illustrated in Figure 9. The results illustrate that the output power is increased with the turn; due to increase of the induced voltage. After an optimum turn, the output power is decreased; because the far loops from the magnet practices lower magnetic flux and higher number of turns will lead to more internal resistance for the coil. Where, due to low inductance of the coil and low frequency, the imaginary part of coil impedance is neglected. The results approve that the optimum number of turns for the coil is 400 turn.

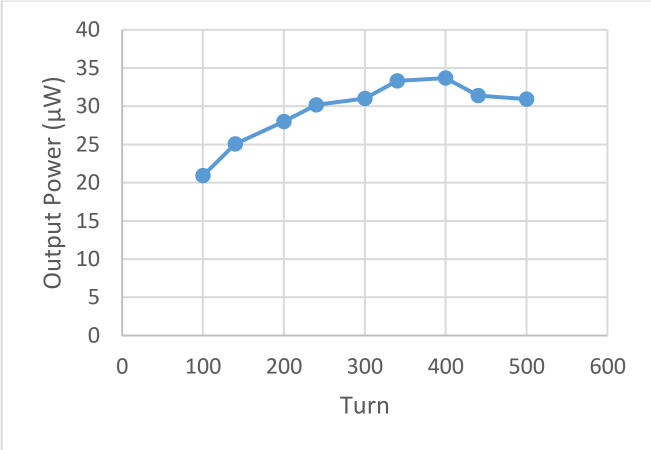


Fig. 9. Impact of different number of turns for the coil (wire diameter = 0.5 mm).

The second simulation has the same parameters; instead of wire diameter which is assumed to be 0.25 mm. So, the number of turns is varied from 400 to 2000. The output power in terms of turn is shown in Figure 10. Where, the optimum number of turns is 1600.

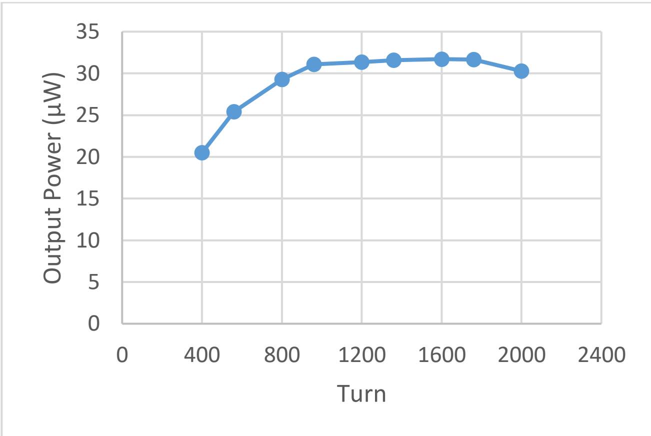


Fig. 10. Impact of different number of turns for the coil (wire diameter = 0.25 mm).

For analyzing the effect of wire diameter, output power according to coil width is demonstrated in Figure 11. Where, the output power is approximately the same for two cases of wire diameter.

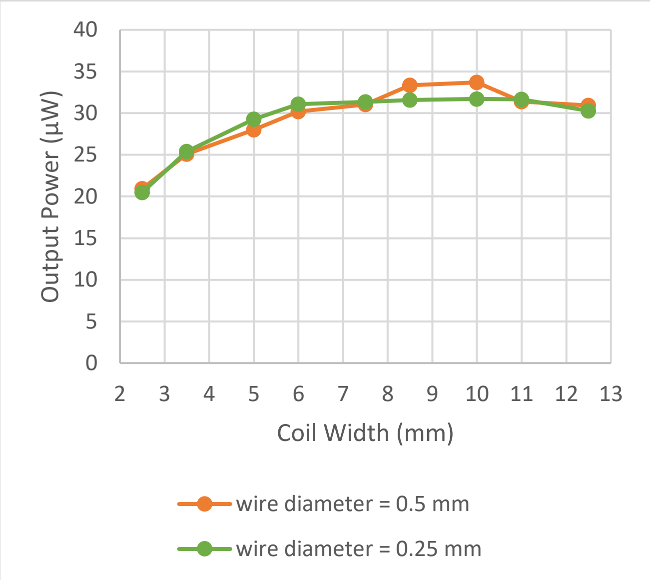


Fig. 11. Output power in terms of coil width.

As demonstrated in Figure 11, reduction of wire diameter in same special volume lead to increase the number of turns. So, output voltage and internal resistance of the coil is increased simultaneously, subsequently, the output power remains in special constant value.

Further simulation is performed to estimate the output power. Where the structure of the device is same, number of turn and wire diameter is changed. So, the volume of the coil is maintained in a predefined special value. The simulation parameters are as in follow: height of the magnet and the coil is 10 mm, radius of magnet is 4 mm, air gap is assumed to be 5mm. So, inner radius and outer radius of the coil is maintained on 9 mm and 19 mm, respectively. Number of coil turn is varied from 1 to 1600. The displacement amplitude of the magnet is assumed to be 10 mm. The obtained results are tabulated in Table 2. The results confirm that, the output power remains approximately constant, where, different number of turns in a special volume is utilized.

Table 2. Output power for different number of coil turn in a special volume.

Coil turn	Output Power (μW)
1	34.32
16	32.47
64	33.99
400	33.69
1600	31.71

The results confirm that for lower coil width (very low than air gap), the output voltage is linearly increased with turn. As coil width increased to be comparable with air gap, output voltage increase nonlinearly with turn and meets a saturation level. Also, higher coil turn numbers will lead to more internal resistance. Therefore, there may be an optimum turn which the output power is maximum.

3.2.5. Displacement of Magnet

An analysis is performed to optimize the efficient size of the micro generator. The efficient volume of the micro generator is cylinder shape, so, two optimizations are applied to find the optimum length and diameter of the micro generator. In this subsection, optimization of length of special volume of generator is studied. Length of micro generator is twice of mechanical displacement amplitude of the magnet, so, effect of displacement is discussed. The simulation parameters are as in follow: magnet height is 10 mm, magnet radius is 4mm, coil height is 5 mm, coil average radius is 12 mm, coil turn is assumed to be 100.
For different displacements, simulations are performed and output power is achieved. The obtained results are tabulated in Table 3. Referring to equation 7, the output power is proportional to square of displacement amplitude, Y_0^2, which is approximately confirmed with results of Table 3.

Table 3. Optimization results of displacement.

Coil diameter (mm)	Displacement (mm)	Output Power (μW)
24	8.5	10.73
24	10	15.39
24	12	26.75

3.2.6. Air Gap

The diameter of the efficient volume of generator is optimized by finding the effect of air gap on the output power, Assuming, diameter of the device is equal to average diameter of the coil. The simulation parameters are as in follow: magnet height is 10 mm, magnet radius is 4mm, coil height is 5 mm, coil turn is assumed to be 100.

Diameter and air gap is varied to find the output power, where the results are demonstrated in Table 4. Plot of output power according to air gap is illustrated in Figure 12, where, the output power is increased with decreasing air gap. Reduction of air gap lead to reduction of reluctance, consequently, flux is increased and reactive power is decreased, where, loss reduction occurrence, results increase of output power and efficiency.

Table 4. Optimization results of diameter of generator efficient volume.

Diameter (mm)	Air gap (mm)	Displacement (mm)	Output Power (μW)
10.2	0.1	12	318.68
12	1	12	213.22
14	2	12	145.8
16	3	12	102.7
18	4	12	71.78
20	5	12	50.05
22	6	12	33.82
24	7	12	26.75

26	8	12	22.07
28	9	12	15.69
30	10	12	10.65
32	11	12	9.36
34	12	12	8.18

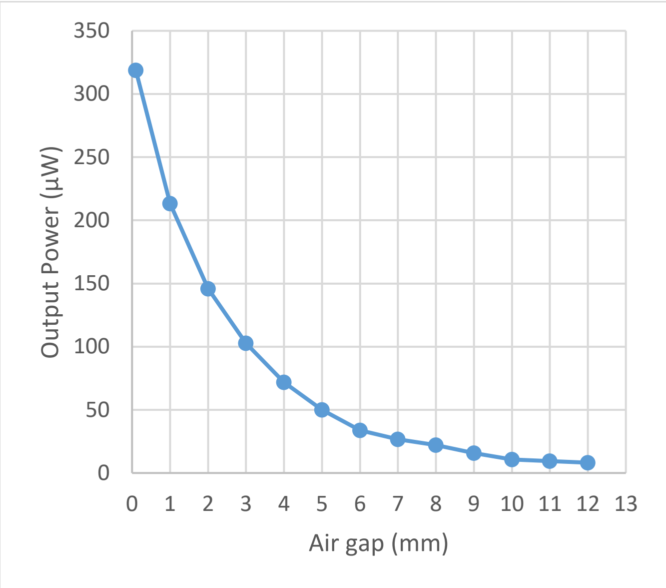


Fig. 12. Output power of different air gaps.

3.2.7. *Magnet and Coil Composition*

A new configuration is proposed to increase output power and power density, number of coil and magnet composition at specific constant volume is varied to achieve higher output power. Coils are connected in series, where, output terminal of the coils is plugged to optimum output resistance load. Subsequently, number of coils and magnets are increased in a specific constant volume. The proposed structure of the micro generator is analyzed to find the optimum number of the coils and magnets. These different configurations which are assumed to have 1–6 coils and magnets, are demonstrated in Figure 13. These configurations are assumed to have the same special volume, where, number of utilized coils and magnets are optimized. The structure is mounted at the end of the beam and coils are connected in series to generate electrical power from mechanical vibrations.

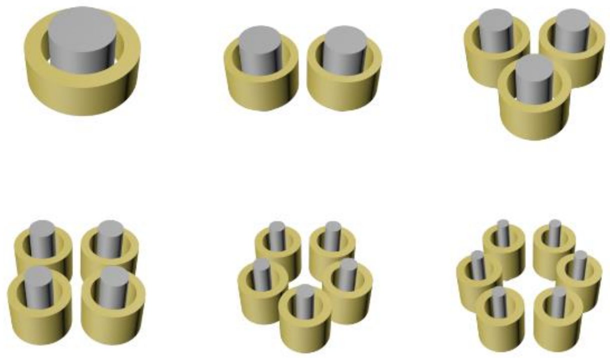


Fig. 13. One to Six coil and magnet configuration; from left to right and top to bottom.

The simulation parameters are as in follow: magnet height is 10 mm, coil height is 5 mm, all of coil turn is assumed to be 100, magnet and coil diameter is varied for different structures to maintain the complete volume of the device in a constant specific value, inner radius of the coil and radius of the magnet is tuned to maintain air gap at 1mm. The output results for different configurations are shown in Table 5 and output power according to different numbers of coils and magnets are illustrated in Figure 14.

Table 5. Output power of different configurations.

Coil No.	Total turn	Coil diameter (mm)	Air gap (mm)	Displacement (mm)	Output Power (µW)
1	100	12	1	12	213.22
2	200	8	1	12	271.12
3	300	7	1	12	293.02
4	400	6	1	12	195.98
5	500	5	1	12	71.57
6	600	4.5	1	12	35.51

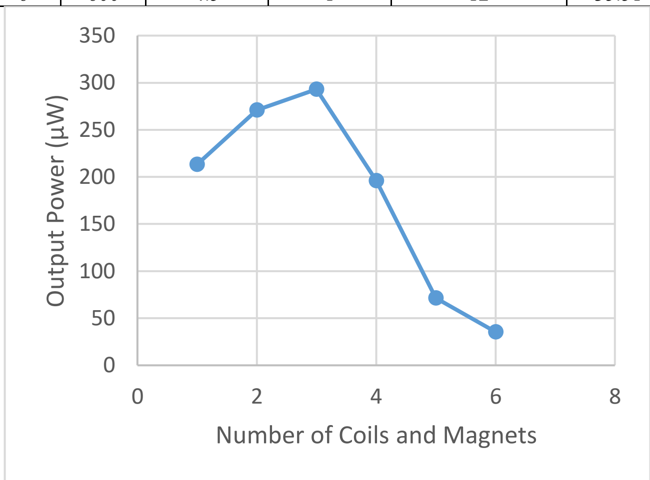


Fig. 14. Output power according to number of coils and magnets.

For series connection of coils, EMF is $\varepsilon = mNA\acute{B}z(\acute{t})$, where, m is Number of Magnet and Coil composition (NMC), N is number of each coil turn, A is cross section area of each coil, $\acute{B}$ is derivative of magnetic flux, $z(\acute{t})$ is motion velocity of the magnet inside coil cross section. Values of mA, N and $z(t)'$ are constant for different structures. The output voltage and power of generator is proportional to $\acute{B}$ and $(\acute{B})^2$, respectively . The obtained results in Figure 14 shows that output power is intensified by NMC. The optimum output power is achieved where NMC meets three, further increasing of NMC, results in significant reduction of output power. It seems that, reduction of output power is due to decline of $\acute{B}$, which is passing through each coil cross section. This phenomenon is emerged due to that, the decreased diameter of the magnet in comparison with air gap results in decreased magnetic field and its deviation, hence, EMF and output power is declined.

3.2.8. *Cubic Shape of Magnet and Coil*

Cubic shape of magnet and coil is proposed to evaluate the output power. The magnet and the coil is designed in cubic shape as seen in Figure 15. All of the parameters are equivalent as shown in Table 5 for NMC equal to one, but the magnet and coil shape is cubic, magnet height is 10 mm, magnet length and width is equal to 7 mm, coil height is 5 mm, coil turn is assumed to be 100, air gap is maintained to be 1 mm. The cubic form exhibits output power of 225.94 µW which is slightly more in comparison with cylinder shape (213.22 µW). The obtained results illustrate that the output power is approximately the same but the loss area is reduced with cubic shape of the magnet and the coil.

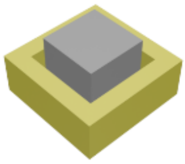


Fig. 15. Cubic shaped magnet and coil.

3.2.9. *Saddle Shape Coil*

A novel structure for multi saddle coil is proposed to improve output power of the micro generator. The configuration of saddle coil is demonstrated in Figure 16. Saddle coils are placed in 6 mm radius around the vibrating magnet. Saddle coils are connected in series, and then connected to the resistance load. The simulation parameters are as in follow: radius of cylinder magnet is 4mm, magnet height is 10 mm, each saddle coil turn is 100 and displacement of magnet is assumed to be 12 mm.

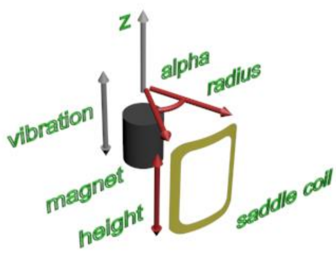


Fig. 16. Characteristics of saddle coil, magnet and vibration direction of magnet.

The output results for the multi saddle structure of coil are tabulated in Table 6. The number of saddle coils are varied from 2 to 4 and subsequently the output power is estimated. The obtained results illustrate that for different number of saddle coil, output power remains in a relatively constant value. As deviation of the flux, passing through the multi saddle coil cross section remains constant, hence, the output power is fairly same for different number of saddle coils. The results approve that saddle shape coils significantly improve the output power in comparison with circular coil, although, a complicated wire winding is required.

Table 6. Results of output power for multi saddle structure.

Saddle coil	α°	radius (mm)	height (mm)	Output power (µW)
2	180	6	10	679.92
3	120	6	10	700.20
4	90	6	10	661.66

3.2.10. *Optimized Micro Generator*

In order to achieve the maximum output power and power density for circular coil structure, all of the design parameters should be optimized. In section 3.2.3, the optimized parameters are presented; air gap is 0.1 mm; displacement is 12 mm; NMC is 3. The simulation parameters are as in follow: magnet height is 10 mm; magnet radius is 2 mm; coil height is 5 mm; coil inner radius is 2.1 mm; coil outer radius is 3.1 mm; coil turn is assumed to be 100, the optimized output power is 419.98 µW. The efficient volume of the micro generator is considered without the beam dimensions. Subsequently, the efficient volume is calculated using magnets and coils dimensions with the effect of displacement. Hence, the optimized output power density is 136.40 µW/cm3. Although, effect of any designed resonator could be considered for estimation of output power density.

4. Experiments to Validate Simulation Results

The fabricated micro generator prototype according to designed model is demonstrated in Figure 17, where, the system consists of beam, magnet and coils. Beam length is 20 cm, width is 3 cm, and thickness is 0.5 mm. Anchor height is 5 cm, width is 3 cm, and thickness is 0.5 mm. There are three coils as depicted in Figure 17, with numbers of 100 turn, 200 turn and 20 turn which is utilized for power generation and measuring the resonant frequency. Two coils with 100 and 200 turn are employed for power generation, where, air gap is 7 mm. The coil with 20 turn is applied for measuring the practical resonant frequency of the beam which is measured to be 5.61 Hz.

Fig. 17. The proposed micro generator prototype.

Overall experimental setup of proposed micro generator is shown in Figure 18, resultant of an initially applied impulse to the beam, the magnet together with the beam begin to vibrate, hence power is generated at terminals of the coil. Digital storage oscilloscope (GWINSTEK GDS-1052-U) is utilized for measuring the output electrical voltage of coil and recording the data samples of waveforms. The obtained practical samples of data files are analyzed for evaluating of experimental output power of proposed micro generator. Environmental vibrations could affect the cantilever beam and generate output power. Also, mechanical vibrations are cable of exciting the basis of the device and cause the beam to oscillate and generate electrical power.

Fig. 18. Experimental setup.

The utilized NdFeB magnet with grade of N42 and the coils are illustrated in Figure 19. Height of the cylindrical magnet is approximately 10 mm and diameter is nearby 8 mm, the remanence of the magnet is 1.28T with axial flux direction. Two coils, A and B, are designed and fabricated as shown in Figure 19, different parameters of the coils are measured. Coil A consists of 100 turn copper wire and Coil B consists of 200 turn copper wire, where, diameter of copper wire is 0.15 mm, which is assumed for both simulation and experimental results.

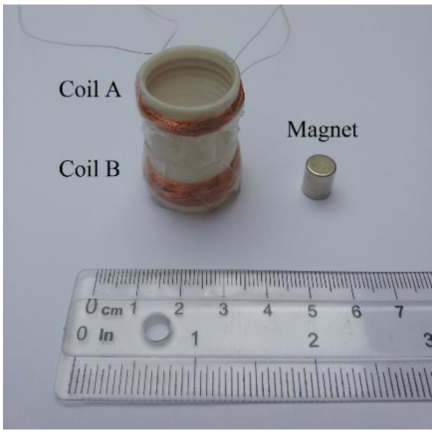


Fig. 19. The magnet and the coils A and B.

The practical measurements are performed and the results are obtained. Experimental performances are carried out for two types of the coils; coil A and coil B, where, coil B has twice turn as coil A. The measured results of internal resistance, inductance, open circuit voltage amplitude, electrical output power, frequency and optimum resistance load are obtained, hence, the obtained results are tabulated in Table 7. Alternatively, the result of output power with frequency which is obtained from simulation performances are also demonstrated in Table 7. In Table 7, the difference of parameters between experimental and simulation performances, is due to lack of accurate measuring processes and imprecise of modelling parameters.

Table 7. The results of practical and simulation performances.

Coil	A	B
Turn	100	200
Internal Resistance (Ω)	9.38	17.39
Inductance (mH)	0.378	1.234
Open Circuit Voltage Amplitude (mV)	39.2	76
Output Power (µW)	8.42	20.91
Frequency (Hz)	11.22	11.22
Optimum Load (Ω)	10	18
Output Power (Simulation) (µW)	10.73	18.99
Frequency (Simulation) (Hz)	12.9	12.9

Internal resistance and inductance for each coil is accurately measured by RLC meter, since, imaginary part of the coils impedance is low, in experimental process, it is neglected, only internal resistance of each coil is considered. For delivering maximum power to load, it's assumed that the optimum load should be equal to internal resistance of each coil. Consequently, the nearest value of the internal resistance is substituted as optimum load and maximum output power is measured. Referring to Table 7, open circuit voltage amplitude has approximately twice as turns of the coils is doubled, which confirm that measurement process is accurately carried out.

A typical practical waveform of output voltage of micro generator with coil A and optimum load of 10 Ω is illustrated in Figure 20. The waveform in Figure 20, indicates that, resultant of initially external applied impulse generates the amplitude of 19.2 mV, where, decreases within time duration due to existence of damping factors.

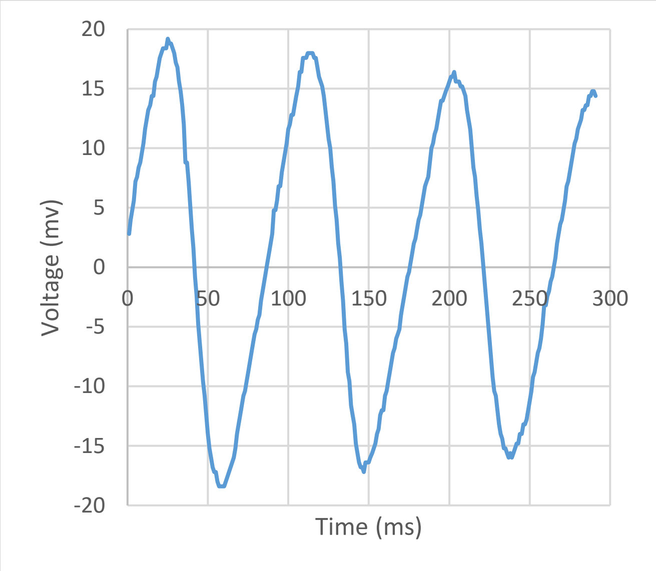


Fig. 20. A typical waveform of practical output voltage of the proposed micro generator with coil A.

5. Comparisons and Discussions of Prior Studies

In this study, several surveys and literature search has been performed within years 1997 - 2023. Content of 26 prior research studies and articles were investigated and results are tabulated in Table 8.

Table 8. Results of prior and proposed studies.

Author	Year	Size	Frequency	Acceleration	Voltage	Power	Power density
Shearwood et al. [24]	1997	2 mm dia.				0.3μW	
Yuen et al. [25]	2007	48 mm × 14 mm dia. (AA)	80Hz	4.63 m/s^2	900 μV rms	120 μW	
Buren et al. [26]	2007	0.25 cm^3				25 μW	
Beeby et al. [27]	2007						47 nW/mm^3
Kulkarni et al. (A) [28]	2008	0.1 cm^3	8.08 kHz	3.9 m/s^2		148 nW	
Kulkarni et al. (B) [28]	2008	0.1 cm^3	9.83 kHz	9.8 m/s^2		23 nW	
Kulkarni et al. (C) [28]	2008		60 Hz	8.829 m/s^2		586 nW	
Wang et al. [29]	2009		94.5 Hz	4.94 m/s^2	42.6 mV p-p	0.7 μW	
Sari et al. [30]	2010	8.5×7×2.5 mm^3	70 – 150 Hz		0.57 mV	0.25 nW / Cantilever	
Park et al. [1]	2010		54 Hz	0.57 g	68.2 mV	115.1 μW	590.4 μW/ cm^3g^2
Galchev et al. [31]	2011	2.12 cm^3	10 Hz	9.8 m/s^2		13.6 μW	
Rahimi et al. [32]	2012	16 cm^3	8 Hz		1.46 V DC	54 μW	6.06 $\mu W/cm^3$
Zorlu et al. [33]	2013		10 Hz		9.5 mV rms	363 nW rms	
Munaz et al. [34]	2013		6 Hz			4.84 mW	2.14×10^3 $\mu W/g^2cm^3$
Liu et al. [35]	2013		840 Hz	1 g			0.157 $\mu W/cm^3$
Ooi et al. [36]	2014		21.3 Hz	0.8 m/s^2	259.5 mV rms		
Khan et al. [37]	2014		108.4 Hz	3 g		68 μW	30.22 $\mu W/cm^3$
Sato et al. [38]	2015		30 Hz			0.1 mW	
Kumar et al. [39]	2016		100 Hz >		3.27 mV		
Jagiela et al. [40]	2017		15 - 35 Hz		0.7 V rms	7.5 mW	

El-Rayes et al. [41]	2018		6.5 Hz			154 μW	
Bolat et al. [42]	2019					302 μW	
Dal Bo et al. [43]	2020		10 Hz			70 mW/g	
Li et al. [44]	2021		19.9 Hz	1.0 g		284 mW	
Basaran [45]	2022		6 Hz			290 mW	
Wei et al. [46]	2023	184.5 × 184.5 (mm), array: 5×5					46.4 μW/cm2
The Proposed	**2023**	**3 × 34 mm × 6.2 mm dia.**	**12.9 Hz**		**144.80 mV**	**419.98 μW**	**136.40 μW/cm^3**

Where, in Table 8, Shearwood et al. [24] presents a simple membrane based electromagnetic micro generator with a low output power in comparison with the proposed study. The presented method by Yuen et al. [25] has a lower output voltage and power. In article presented by Buren et al. [26] output power is depended on position of the micro generator on body, which may be reduced to 2 μW. The work presented by Beeby et al. [27] has a lower output voltage, power and power density in comparison with the proposed method. The proposed method has a higher output power in comparison with work of Kulkarni et al. [28]. The proposed work has a higher output voltage and power in comparison with research work of Wang et al. [29]. Sari et al. [30] presents electromagnetic micro generator with frequency up conversion technique, nevertheless, the output power is lower as about 5 nW. The presented method by Park et al. [1] exhibits lower performance in comparison with the proposed method. The proposed micro generator has an average output power higher than work of Galchev et al. [31]. Work of Rahimi et al. [32], shows lower power and power density in comparison with the proposed study. However, presented work of Zorlu et al. [33], utilizes frequency up conversion for energy harvesting, hence, the output generated power is lower than the proposed method. In the work, presented by Munaz et al. [34], usage of multi pole magnets, increases the output power. The proposed method has higher output power density in comparison with work done by Liu et al. [35]. Ooi et al. [36] presents dual resonator which could increase bandwidth of the micro generator. Khan et al. [37] proposed a membrane based electromagnetic energy harvester, where, different vibration frequency and acceleration could increase the bandwidth of the micro generator, but, the proposed study, shows higher output power and power density. The study demonstrated by Sato et al. [38], has higher coil turn which causes higher output power, where, the proposed study has higher output power. Kumar et al. [39] represents a cantilever beam based electromagnetic energy harvester; which has a lower output voltage and power in comparison with the proposed device. However, Jagiela et al. [40] presented a higher output power, but, a relatively high volume and complicated setup is required. The proposed work demonstrates a higher output power in comparison with work of El-Rayes et al. [41].

Bolat et al. presented a hybrid piezoelectric and electromagnetic enrgy harvester. The output electromagnetic power genereted by the lorentz induction is lower than the proposed study [42]. Dal Bo et al. presentred electromagnetic and piezoelectric transducers, where a complicated structure is required [43]. In [44] Li et al. propsed optimized power density electromagnetic generator. The maximum output power is achieved for higher number of magnets and coil array. Basaran [45] presented hybrid energy harvesting. High dimension results in high output power. At the proposed study, power density is optimized for the minmum vloume. Wei et al. [46] presented electromagnetic energy harvesting and wireless power transfer. The proposed energy harveting, generates maximum output power at the specified volume.

Referring to Table 8, advantages of the proposed method is compared with prior works. The optimized output power of the proposed method is about 419.98 μW for circular coil which could supply wireless sensor networks, implantable biomedical devices and etc. [47]. Alternatively, saddle shape coil could be utilized to improve the output power to 700.20 μW, where, a complicated winding is required. In conclusion, the optimization procedure in this study, leads to achieve higher output voltage, power and power density in comparison with most of the articles in literature search.

6. Conclusion

In this research work, a new method for energy harvesting is proposed. The proposed device composed of beam, magnet and coil. This electromagnetic micro generator is capable of scavenging low frequency environmental vibrations and converts it into electrical output power. Different dimensions and configurations are proposed to increase output voltage, output power and output power density. The obtained results, indicates that, at a special constant volume, specific number of coil turn, higher displacement amplitude and lower air gap will increase output power and power density. Also, a new configuration for coil and magnet composition is proposed to increase output power. For coil shape, saddle coil shows higher output power in comparison with circular coil. Finally, the optimized micro generator is designed and simulated. The measured output electrical power is adequate to supply electronic devices such as Integrated Circuits (IC). Hence, the proposed micro power harvester could be an appropriate and applied replacement for limited life time power supplies.

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