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Acceleration Sensor Utilizing Electromagnetic Micro Power Harvester and Artificial Neural Network

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Abstract

Micro generators are suitable replacement for limited life power supplies, which could supply electronic devices. This method of energy harvesting converts mechanical vibrations into electrical output power. Electromagnetic transduction method has more advantages in comparison with other methods and it is considered to be applied in this work. The output voltage of micro generator is depended on input mechanical acceleration. Analysis of output voltage could estimate the input acceleration. In this work, transient response of micro generator is studied to achieve input mechanical acceleration. For this purpose, RBF (Radial Basis Function) Artificial Neural Network (ANN) is trained with transient output voltage of power harvester to estimate the input mechanical acceleration. The results illustrate that combination of electromagnetic micro generator model with ANN could be an applied and innovative sensor to estimate mechanical acceleration.

***Key Word**:Electromagnetic micro generator; Energy harvesting; Mechanical vibrations; Electrical power; Mechanical acceleration; RBF (Radial Basis Function); ANN (Artificial Neural Network); Sensor.*

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I. Introduction

Recently designed electronic devices such as Integrated Circuits (IC) have a lower electrical power consumption about few micro watts[1,2,3]. So, energy harvesting methods could be utilized to supply these devices. Subsequently, desire to traditional power supplies such as batteries is obviated. Traditional power supplies have disadvantages such as life time limitation, where, using energy harvesting methods, electronic devices could be supplied for long time duration[4,5,6]. 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[7,8].

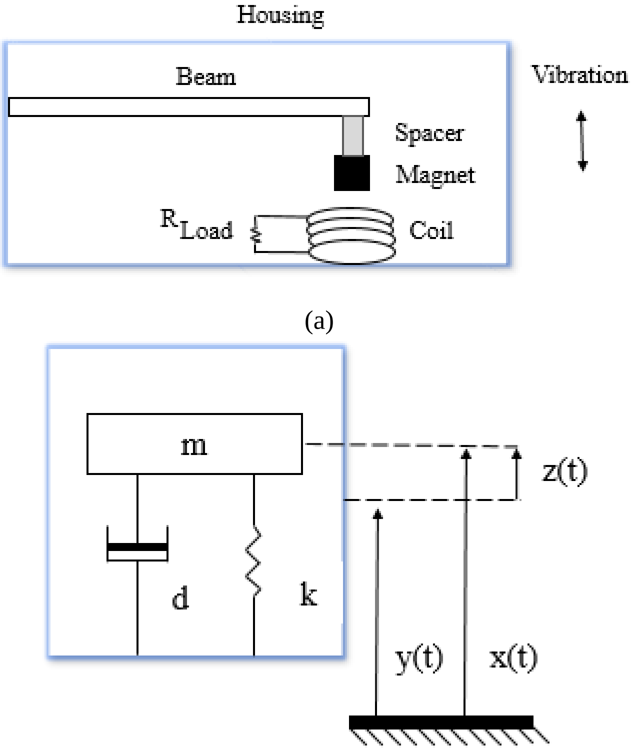
The most attractive method of energy harvesting is electromechanical method, whereas it is regenerative and have higher output power density. Techniques for scavenging energy from mechanical vibrations includes, electromagnetic[9,10,11], piezoelectric[12,13] and electrostatic[14,15]. Due to the advantages, electromagnetic method is utilized to convert low frequency environmental vibrations to output electrical voltage[16].

In this work, electromagnetic power harvester is designed to estimate input mechanical acceleration using RBF (Radial Basis Function) Artificial Neural Network (ANN)[17,18,19]. The model of micro generator is simulated to present the transient response of micro generator for different mechanical accelerations. Transient output voltage is trained with ANN for different accelerations. In this manner, combination of electromagnetic micro generator model with ANN could evaluate input mechanical acceleration. The achieved results, demonstrates that ANN could estimate mechanical acceleration for different unseen inputs. The presented model could act as a forceful acceleration sensor that generates electrical power and senses the mechanical acceleration.

The remainder of the paper is organized as in follow: In section II, mechanical and magnetic modelling and equivalent circuit of the micro generator is described. Section III, discusses the design and simulation of the micro generator using Simulink. The ANN model and the results of the sensor are discussed in section IV. Conclusions are given finally in section V.

II. Mechanical and Magnetic Modeling and Equivalent Circuit of Micro Generator

The overall structure of micro generator is composed of housing, beam, spacer, magnet and coil, which connected to resistance load (R_{Load}). 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)

Figure 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 the displacement of mass is x(t)=y(t)+z(t). 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 electrical 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. The resonant frequency of system is $\omega_n = \sqrt{k/m}$.

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. Also, internal characteristic of coil, which is composed of EMF voltage source, coil inductance and internal resistance of coil is demonstrated in Figure 2.

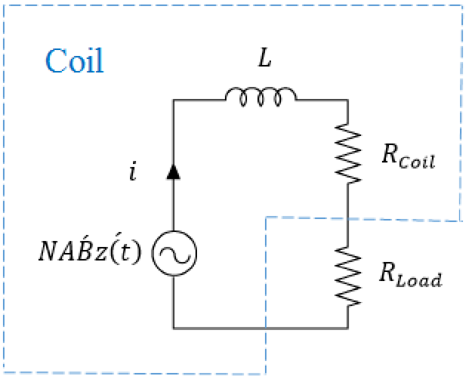


Figure 2. Equivalent circuit of the proposed electromagnetic micro generator.

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 electrical damping factor could be calculated as:

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

So, the output power could be calculated as $P \approx V_{load}^2 / R_{Load}$. V_{load} is voltage of the resistance load terminals, which is approximately $\varepsilon/2$, where, imaginary part of coil impedance is neglected, and coil internal resistance is equal to load resistance to deliver maximum output power to load.

A cylinder magnet is utilized to generate magnetic flux. Hence, calculation of flux deviation ($\acute{B} = dB/dz$) is necessary to model the power harvester. For this purpose, flux deviation is approximately considered on axial direction of magnet as shown in Figure 3.

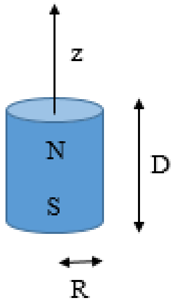


Figure 3. Cylinder magnet model with axial flux.

Magnetic flux derivative on axis of cylinder magnet could be calculated as follow:

$$\frac{dB}{dz} = \frac{B_r R^2}{2}\left(\frac{1}{\left(R^2 + (D+z)^2\right)^{3/2}} - \frac{1}{\left(R^2 + z^2\right)^{3/2}}\right) \tag{3}$$

where, B_r is remanence, R is magnet radius, D is magnet height and z is distance from magnet pole on the axis.

III. Modelling of Electromagnetic Micro Power Harvester Utilizing Simulink

In this section, electromagnetic micro generator is modeled using Simulink. The Simulink model of system is demonstrated in Figure 4. In Figure 4, the implementation of Equations 1 and 2 is presented.

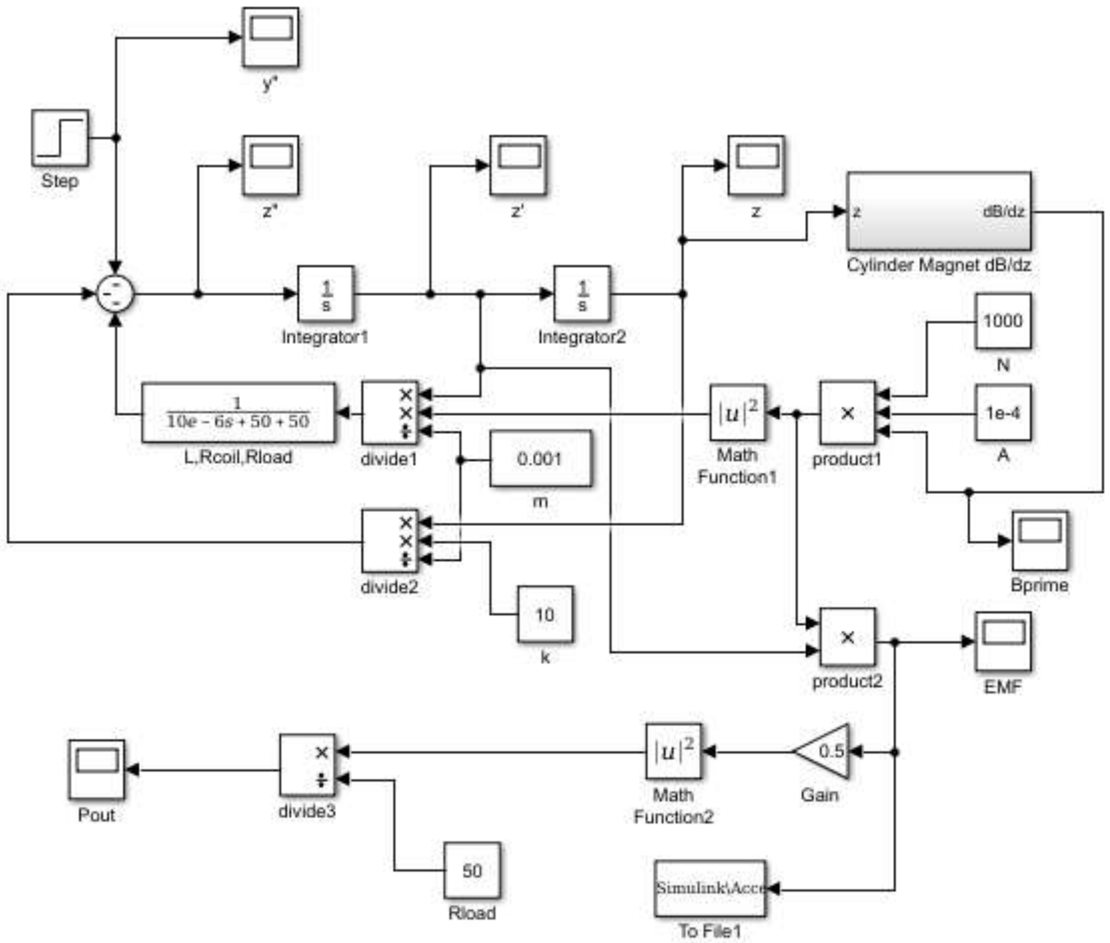


Figure 4. Simulink model of electromagnetic micro generator.

Simulink model of cylinder magnet flux deviation on magnet axis is demonstrated in Figure 5. In Figure 5, implementation of Equation 3 is presented.

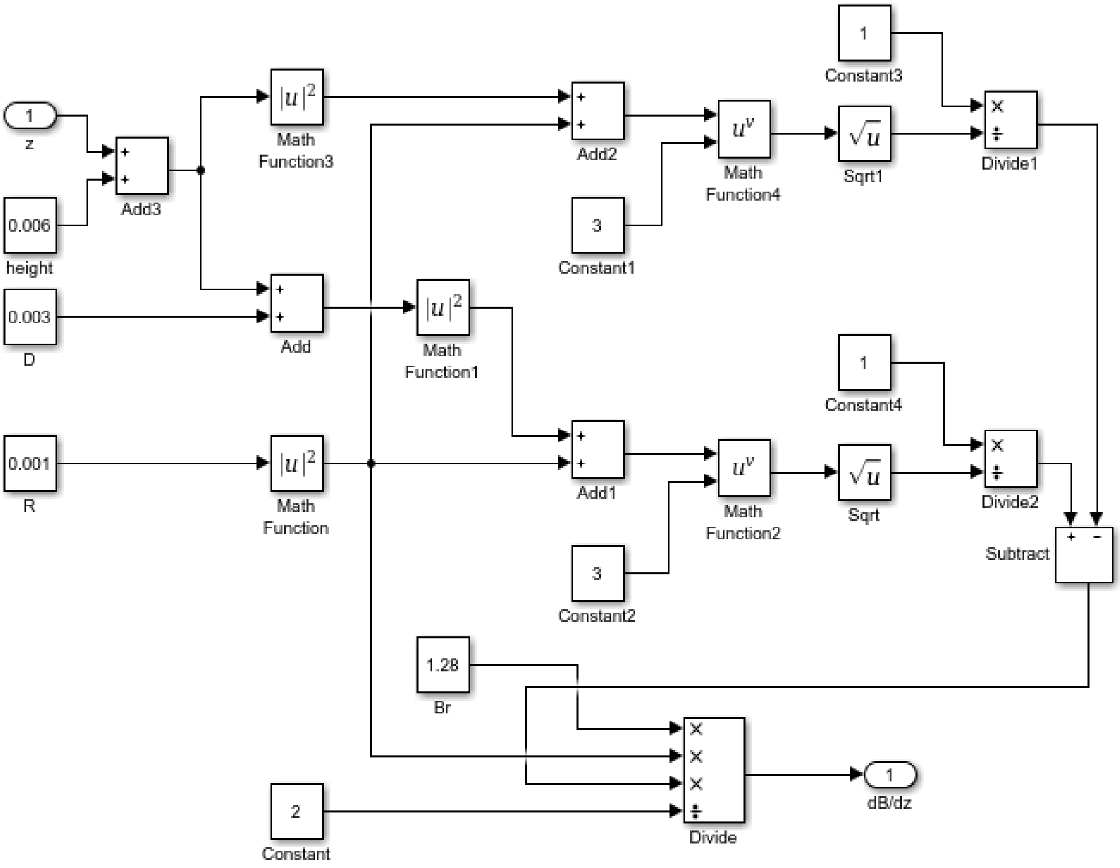
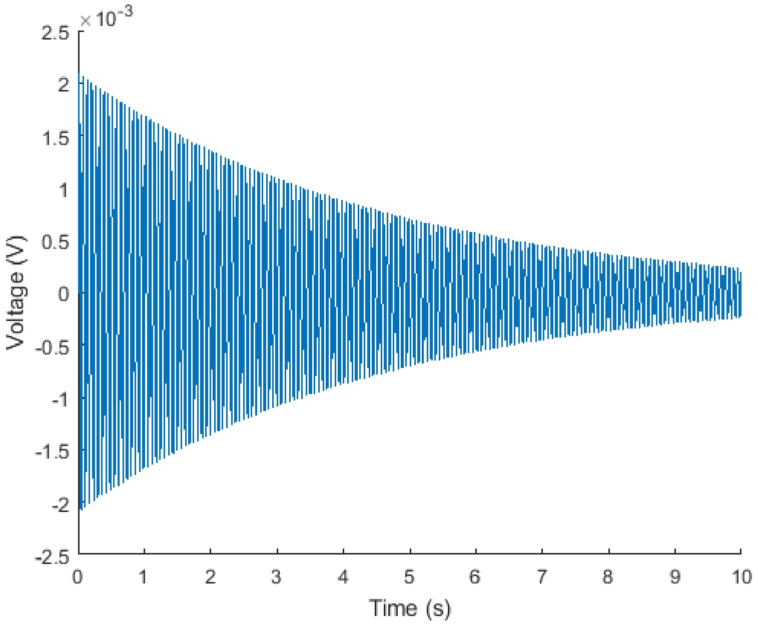
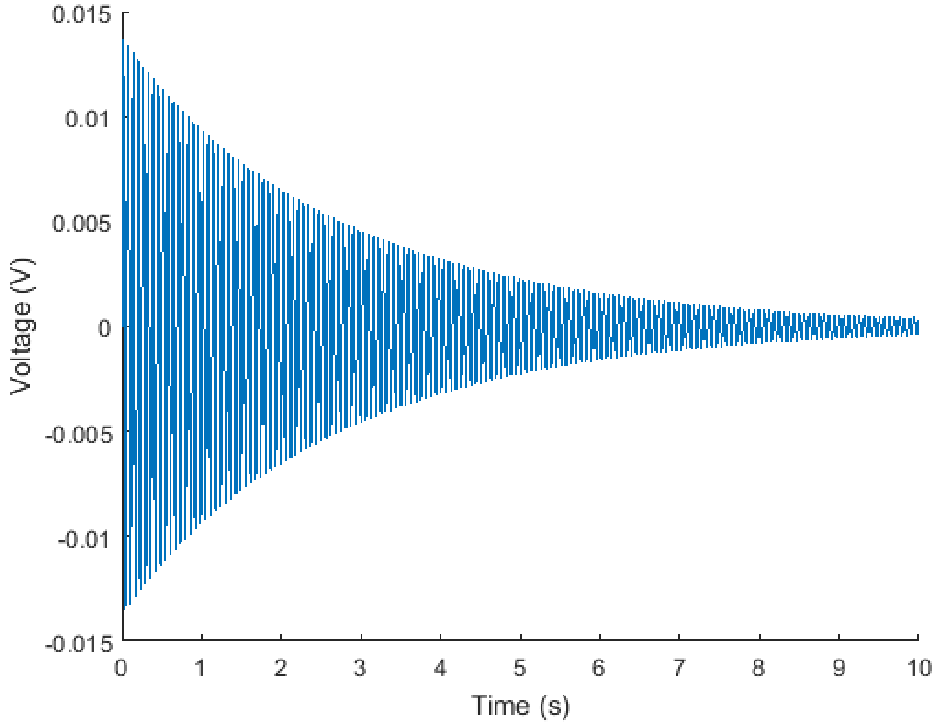


Figure 5. Cylinder magnet model.

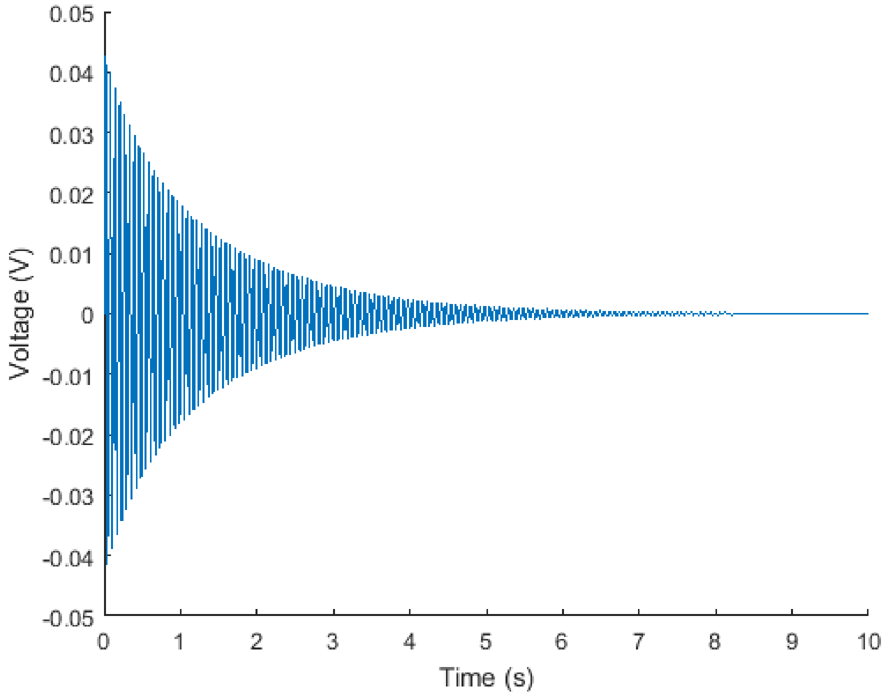
Sample transient responses of EMF voltage for different input mechanical accelerations are achieved and shown in Figure 6. As demonstrated in Figure 6, increasing of the step acceleration, intensifies the initial amplitude of output EMF. Also, higher input acceleration, results in fast damping of EMF. The EMF sample voltages are utilized as input data for artificial neural network to estimate the input step acceleration, which is discussed in the next section.



(a)



(b)



(c)

Figure 6. Micro power harvester transient EMF response for different accelerations(m/s^2): (a) 1, (b) 5, (c) 10.

IV. RBF Neural Network Model

RBF ANN (Radial Basis Function Artificial Neural Network) acts as a potent tool to estimate the mechanical acceleration from output EMF voltage of electromagnetic micro generator. The RBF network is trained with EMF transient response for different input step accelerations. Subsequently, neural network is recalled with seen and unseen data and the results are collected. The trained model illustrates that the ANN could precisely estimate the input acceleration value. RBF neural network model to predict output acceleration using EMF transient response of micro generator is illustrated in Figure 7. The time series (samples) of EMF in a limited range of time is trained with RBF network to estimate the acceleration. For example, network training for EMF transient voltage for 10 s duration and input step acceleration of 2 m/s^2 is shown in Figure 7. The estimated output of the network is predicted to be 2.

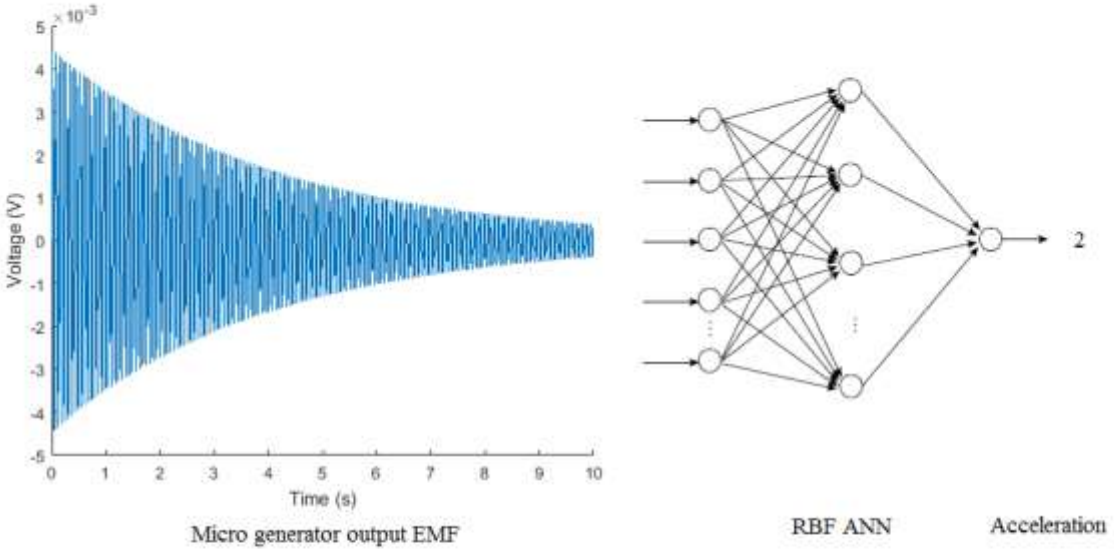


Figure 7. RBF Neural Network training model.

Mean squared error goal for RBF training is 0.001. Input signal sampling time is 1 ms. The time duration of input samples is 10 s. In training phase, five transient response of EMF is trained utilizing RBF ANN. The estimated output accelerations are 1, 3, 5, 7 and 9. In testing phase, ten transient response of EMF is tested utilizing RBF ANN. The estimated output accelerations should be 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10. The results of recall phase is demonstrated in Table 1. As shown in Table 1, odd accelerations (seen data), which are trained to network, illustrate the same value of training phase at recall phase. Even accelerations (unseen data) are not trained with the network. At recall phase, the even accelerations are estimated with an error of lower than 1%. The results demonstrate that the trained model of RBF network could precisely estimate the acceleration in the range of 1 – 10 m/s^2.

Table 1. Results of recall phase.

Actual acceleration (m/s^2)	Predicted acceleration (m/s^2)	Status
1	1	Trained
2	1.9972	Recall
3	3	Trained
4	4.0016	Recall
5	5	Trained
6	5.9978	Recall
7	7	Trained
8	8.0046	Recall
9	9	Trained
10	9.9544	Recall

The predicted and actual results are shown in Figure 8. The achieved results illustrate that the RBF ANN could precisely estimate the input accelerations for seen and unseen data. The trend line which is shown in Figure 8, exhibits the performance of the trained network, where the acceleration could be estimated with error lower than 1%.

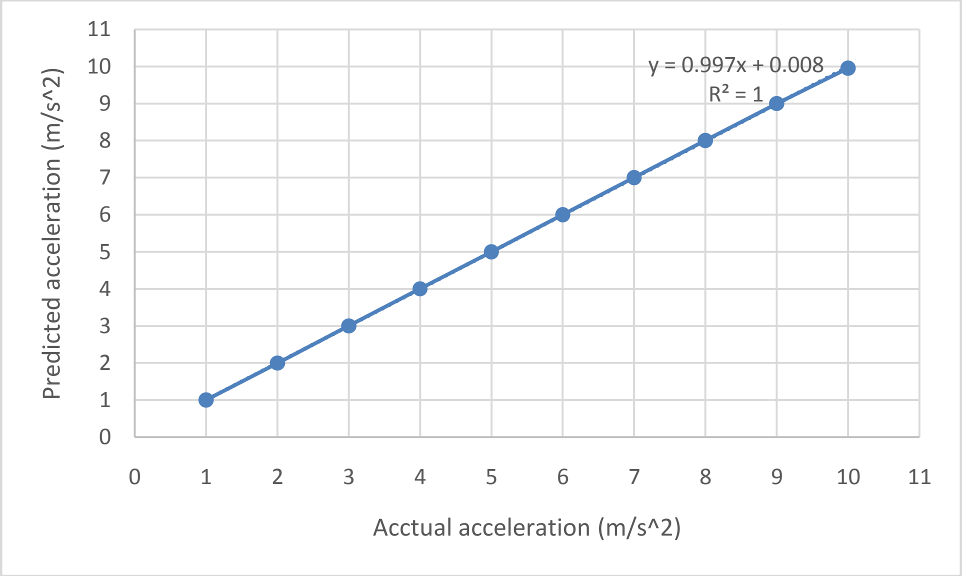


Figure 8. Predicted and actual results.

V. Conclusions and Discussion

In this article, a model for electromagnetic micro power harvester is proposed. In this design, the micro generator could generate output electrical power from input mechanical vibrations. The model could be utilized to design different kinds of electromagnetic micro generator. As a sensor application of micro generator, the output EMF (Electro Motive Force) voltage is utilized to determine the input mechanical acceleration. RBF neural network model is trained utilizing output EMF of energy harvester to estimate acceleration. The recalling results of ANN, exhibits that this model could precisely estimate the mechanical acceleration. The design procedure illustrates that this model could calculate the output voltage and power of micro generator and is a potent tool to estimate the mechanical accelerations as a sensor.

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