

**Energy Harvesting from Ambient Vibrations by  
Electromagnetic Transduction mechanism**

**A THESIS IN PARTIAL FULFILMENTS OF REQUIREMENTS  
FOR THE AWARD OF THE DEGREE OF  
Bachelor of Technology**

**in**

**Electrical Engineering**

**By**

**Regan Kumar Sethi  
(108EE053)**



Department of Electrical Engineering  
National Institute of Technology, Rourkela  
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**Under the supervision of**

**PROF. G . Krishna**



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# NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

## CERTIFICATE

This is to certify that the Project entitled “**Energy Harvesting from Ambient Vibrations by Electromagnetic Transduction mechanism**” submitted by Regan Kumar Sethi(108EE053) in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Electrical Engineering at National Institute of Technology, Rourkela (Deemed University) and is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date: 08/05/12

(Prof. G . Krishna)

Place: Rourkela

Department of Electrical Engineering

NIT, Rourkela

# Abstract

This report presents the detailed study of utilization of ambient vibration energy present in a system by converting it into usable electrical energy. With the huge decrease in electrical energy consumption in portable electronic devices the concept of harvesting electrical energy from the renewable sources in the surroundings of the system arouses its great importance. These low power micro electromechanical systems that can scavenge electrical energy from their operating environment are very long lasting, less economical, need no maintenance, and most importantly can be operated in inaccessible sites.

There are mainly three transduction mechanisms employed to extract electrical energy from the vibration energy present in the surrounding of the system namely:-

- Electromagnetic
- Piezoelectric
- Electrostatic

This paper is a study of electromagnetic transduction mechanism to harvest useful electrical energy from the ambient vibrations.

# Acknowledgement

I am extremely grateful to **The Department of Electrical Engineering**, for giving me the opportunity to carry out this project, which is an integral fragment of the curriculum in B. Tech program at the National Institute of Technology, Rourkela.

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Last but not the least , I would love to acknowledge the contributions of my parents and family members, for their constant and never ending motivation.

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# CHAPTER I

## Introduction

The omnipresence of wireless systems in day today technologies because of its advantages over the existing wired system such as flexibility, very easy to implement. The most significant advantage is placement of wireless micro sensors in applications of condition based monitoring at inaccessible locations to provide continuous monitoring without much expense and inconvenience of wiring.

But these low power wireless sensor nodes need an alternative power source to the existing batteries, so that the inconvenience of replacing them and the chemical disposal problem can be sorted out.

Renewable power can be obtained by generating electricity from sources like solar energy, thermal energy and kinetic energy available within the system's environment. Though the other sources can be alternatives but have some disadvantages like in the case of solar cells as it is of no use in locations where there is no sunlight or dim light is present

Kinetic energy is typically present in the form of vibrations, random displacements or forces. The review of this report is scavenging electrical energy from the vibrations, which can be converted mainly by means of three transduction mechanisms namely

- Electromagnetic
- Piezoelectric
- Electrostatic

The amount of electrical energy converted mainly depends upon

- The quantity of vibrational energy available.
- The efficiency of micro generator used
- Power conversion electronics

The following pages are on the discussion of the three transduction mechanisms and the micro generators that are used.

# CHAPTER II

## Background and Literature Review

Kinetic Energy which is present in the ambient vibrations requires a transduction mechanism to convert it into Electrical Energy. This would require a mechanical system that couples maximum ambient displacements to the transduction mechanism.

Conversion of ambient vibration energy best suits to an inertial generator that consists of a mechanical component attached to an inertial frame which acts as a fixed reference. The vibrations are transmitted through the inertial frame to a suspended inertial mass producing a relative displacement between them.

Such a system will possess a resonant frequency. So the system needs to be designed in such a way that the characteristic frequency of the application environment matches the resonant frequency. This approach magnifies the environmental vibration amplitude by the quality factor of the resonant system.

The transduction mechanisms generate electricity by exploiting either the relative displacement or the mechanical strain (in case of piezoelectric materials) occurring within the system. The strain effect utilizes the deformation within the mechanical system and typically employs active/ piezoelectric materials. In the case of relative displacement, either the velocity can be coupled to a transduction mechanism which is typically associated with electromagnetic transduction or the relative position can be coupled to a transduction mechanism that is associated with electrostatic transduction.

In the academic literature, the first reported inertial micro-generator was an electromagnetic type driven by reciprocating vibration, presented by Williams and Yates in 1995 from the University of Sheffield, UK. Amirtharajah and Chandrakasan from the Massachusetts Institute of Technology describe an integrated circuit for self powered low-power DSP applications. They also worked on Electrostatic transduction. And they were 1<sup>st</sup> to report the electrostatic micro-generator work in the literature.

## Basic Principle

A simple micro electromechanical vibration-driven generator is considered which consists of a proof mass, moving a frame. The inertia of the mass causes it to move relative to the frame when the frame experiences acceleration from ambient vibrations. This relative displacement is used to generate energy by doing work against a damping force, realized by an electric or magnetic field, or by straining a piezoelectric material. The proof mass is attached to the frame by a suspension which may be designed solely to constrain the motion of the mass, as in the case of a resonant mass-spring system. The displacement of the mass from its rest position relative to the frame is denoted as  $z(t)$ .



Assuming that the mass of the vibration source is significantly greater than that of the proof mass and the external excitation is harmonic, the 2<sup>nd</sup> order differential equation of the motion can be written as

$$m\ddot{z}(t) + d\dot{z}(t) + kz(t) = -m\ddot{y}(t) \dots\dots\dots[2.1]$$

Where,

m:-Mass of the seismic body

k:-Spring constant

y(t):-External Sinusoidal Vibration

$$y(t)=Y \sin(\omega t)\dots\dots\dots[2.2]$$

$$z(t) = \left[ (\omega^2) \left\{ \left( \frac{k}{\omega} - \omega^2 \right) + \left( \frac{c\omega}{m} \right)^2 \right\}^{-1/2} \right] Y \sin(\omega t - \phi)\dots\dots\dots[2.3]$$

$$\phi = \tan^{-1} \left( \frac{c\omega}{k} - \omega^2 m \right)\dots\dots\dots[2.4]$$

Where ,

$\omega$ : Excitation frequency

$\phi$ : The phase angle

And “c” is the damping coefficient comprising parasitic losses and the electrical energy to be extracted.

z(t) is the net displacement of the mass.

$$\omega = \sqrt{\left( \frac{k}{m} \right)}$$

The whole system can be visualized in Fig. 2.6.

## Figures

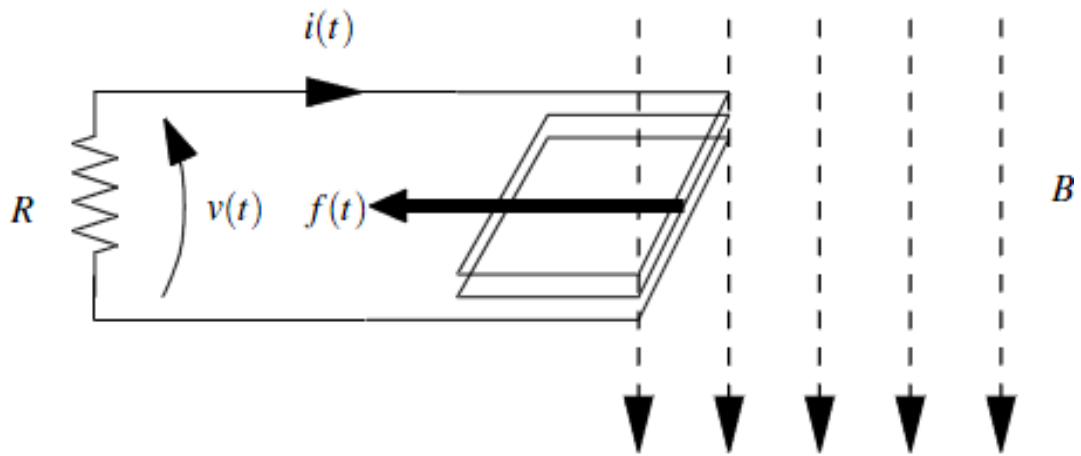


Fig 2.1: Electromagnetic Transduction

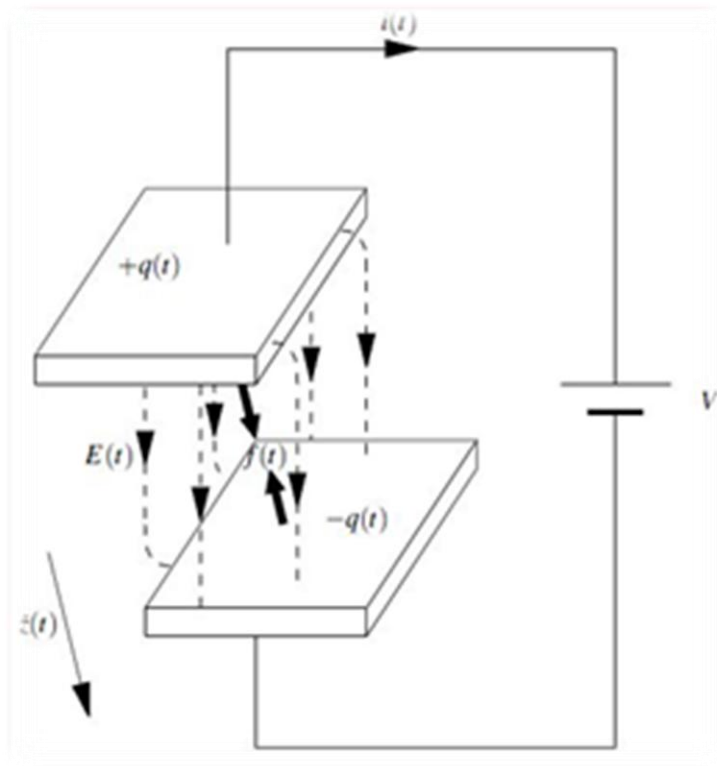


Fig 2.2: Electrostatic Transduction (Constant Charge Separation)

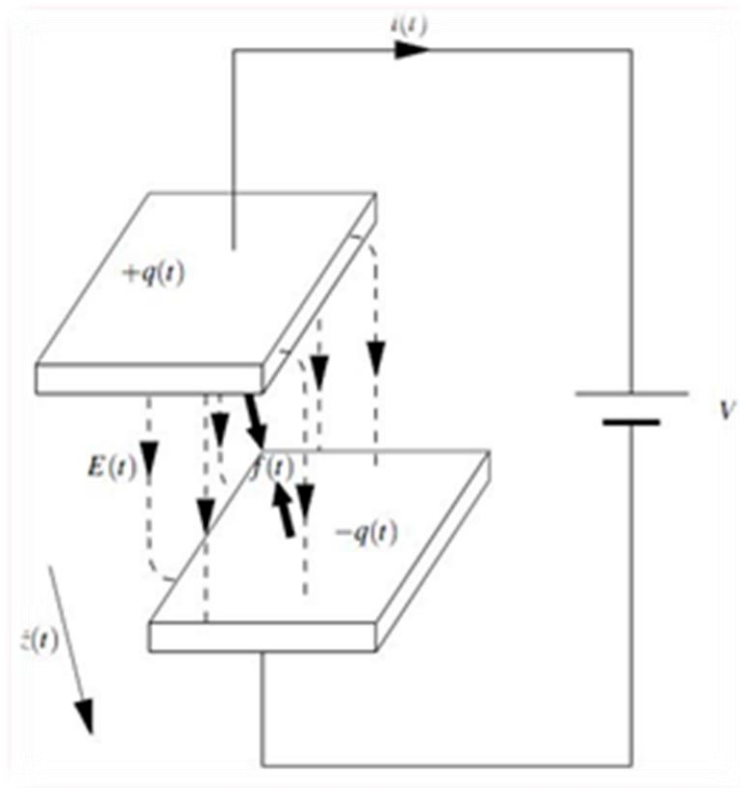


Fig 2.3: Electrostatic Transduction (Constant Voltage Operation)

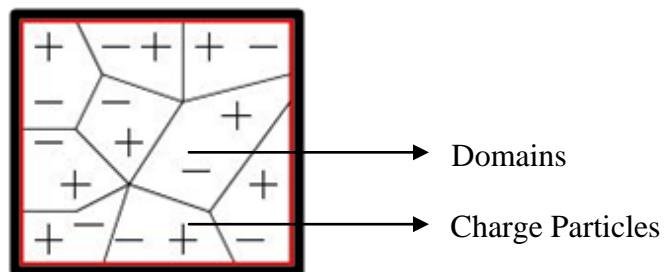


Fig 2.4: Piezoelectric Material before Stress

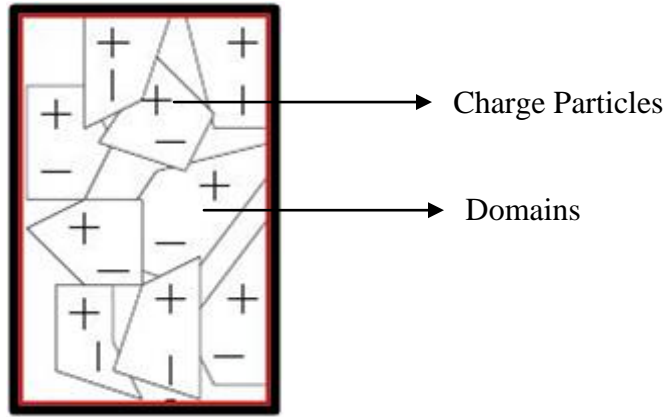


Fig 2.5: Piezoelectric Material after Stress

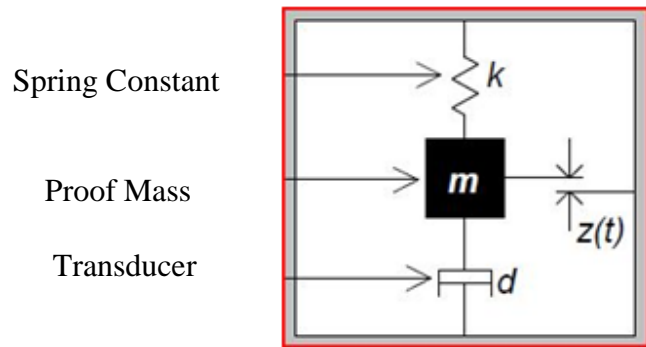


Fig 2.6: General Model of Generator

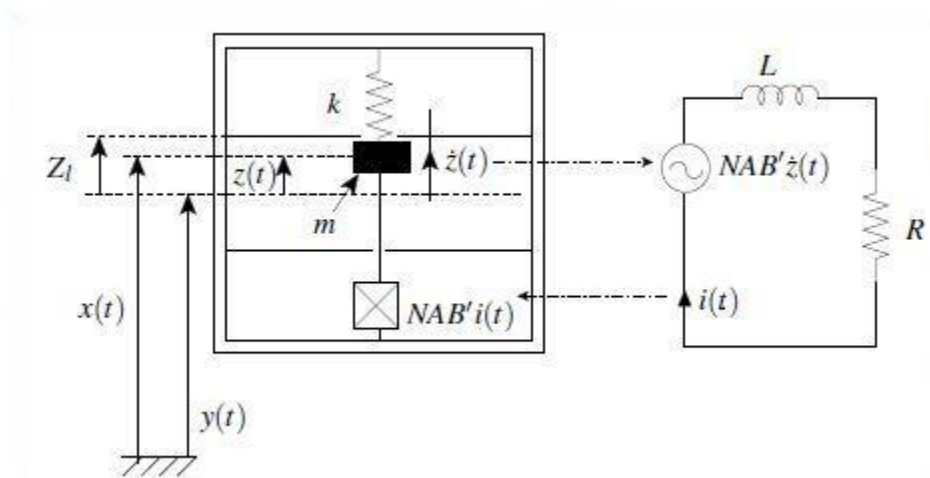


Fig 2.7: General Model of Resonant Electromagnetic Generator

## CHAPTER III

### Principle of Operation of Electromagnetic Transduction

The damper of a micro-generator is implemented using the principle according to Faraday's law of induction. The principle can be explained as:-A change of magnetic flux linkage with a coil induces an EMF in the coil, driving a current in the circuit. According to Lenz's Law the combined force on the moving charges in the magnetic field acts to oppose the relative motion which is causing the change in flux linkage. The mechanical work done against the opposing force is converted to heat in the resistance of the circuit and to stored energy in the magnetic field associated with the circuit inductance. The method can be visualized in Fig 2.1.

Thus electromagnetic induction can be achieved by means of permanent magnets, a coil and a resonating cantilever beam. Either the magnet or coil can be chosen to be mounted on the beam while the other remains fixed. It is preferable to have magnet attached to the beam as these can act as the inertial mass.

Such systems will possess resonant frequencies which have to be designed to match the characteristic frequency of the application environment to magnify the environment vibration amplitude by the quality factor of the resonant system

### Principle of Operation of Electrostatic Transduction

There are two methods of operation of an electrostatic transducer. The first involves moving a fixed amount of electric charge through an electric field and thus increasing the electrical potential of that charge.

This method is CONSTANT CHARGE SEPARATION. This can be visualized in Fig 2.2.

Consider a parallel plate capacitor having a constant overlap with a negligible fringing field and with a variable separation by isolating the plates from each other by air or vacuum. The electrostatic field strength is proportional to the (constant) charge and therefore it is independent of plate separation. As the separation of plates is increased by doing mechanical work against the force of attraction between the plates in a direction normal to the plates, an additional electrical potential energy is stored in the increased volume of electric field.

By moving the plates relative to each other with a sliding motion at a constant separation, mechanical work is done against the existing fringing field which results in increased electric field strength. Therefore there is an increase in stored electrical energy with the reduction in plate overlap as the energy field density which is proportional to the square of field strength increases faster than the volume of the field decreases.

The other operation is CONSTANT VOLTAGE OPERATION. This can be visualized in Fig 2.3. Moving the relative positions of the plates by either due to sliding or normal movement

there is a change in the capacitance between the plates under a constant voltage. By increasing the plate separation with a fixed overlap, the electric field strength between the plates falls pushing the charge off the plates into an external circuit causing a current to flow. By moving the plates with constant separation and changing the overlap, the field strength stays constant, but current starts flowing back into the source because the volume of the field decreases. In both the above mentioned cases, the mechanical work done is converted into additional electrical potential energy because of an increased space charge in the voltage source. Electrostatic transducers need an initial amount of electrical potential energy in order to provide an electric field which can be used to generate additional electric energy.

$$C = Q/V \text{ or}$$

$$C = \epsilon A/D$$

- C - Capacitance
- $\epsilon$  - Permittivity of the material between the plates
- D - Separation between the plates
- A - Area of the plates

Energy stored in a capacitor =  $0.5CV^2$

If the charge on the plates is held constant, the perpendicular force on the plates is:

$$F = 0.5Q^2D/A\epsilon.$$

If the voltage between the plates is held constant then the perpendicular force on the plates is:

$$F = \epsilon AV^2/D^2$$

The harvested energy is provided by the mechanical work which is done against the electrostatic force between the plates.

Electrostatic generators can be sub divided into three types

- In-plane overlaps varying.
- In-plane gap closing.
- Out-of-plane gap closing.

The three methodologies can be applied either to charge constrained or voltage constrained operations. In general more energy can be harvested in the voltage constrained than the charge constrained operation. However, by adding a capacitor in parallel with the energy harvesting capacitor, the energy can flow from the charge constrained system to the voltage constrained system as the parallel capacitance approaches infinity. The parallel capacitor makes the system more efficient by effectively constraining the voltage on the energy harvesting capacitor.

**Table 3.1:** Electrostatic force variation for the three configurations.

<b>Structure</b>	<b>Charge Constrained</b>	<b>Voltage Constrained</b>
In-plane overlap varying	$F_e \sim 1/x^2$	$F_e$ constant
In-plane gap closing	$F_e \sim x$	$F_e \sim 1/x^2$
Out-of-plane gap closing	$F_e$ constant	$F_e \sim 1/x$

## **Principle of Operation of Piezoelectric Transduction**

It is a phenomenon in which a strain in a material produces an electric field across that material. The degree of polarisation is proportional to applied strain.

It was first discovered by J and P Curie.

When the material is strained, some of the mechanical work done on the device is stored as elastic strain energy, and some in the electric field brought about by the space charge. The material is unpolarised when unstrained (i.e. contains no average space charge across the material), but becomes polarised when strained, so that a net electric field is generated. The effect can be properly visualized in the below given figures. Fig 2.4 depicts the condition of material before applying strain and Fig 2.5 after applying strain. Piezoelectric materials are widely available in many forms including single crystal (e.g. quartz), piezoceramic (e.g. lead zirconate titanate or PZT), thin film (e.g. sputtered zinc oxide), screen printable thick-films based upon piezoceramic powders and polymeric materials such as polyvinylidene fluoride (PVDF).



## Methods of Modelling a Generator

The generator can be modelled either by inertial mass system or direct force system. These are properly described in the subsequent paragraphs.

The power generation for a given inertial generator is ultimately dependent upon the nature of the damping force by which energy is extracted. There are mainly two different ways of subdividing inertial generators namely;-

- Resonant Generators
- Parametric Generators

In the case of Resonant Generators the proof mass is suspended on a spring and resonant energy exchange occurs between mass and spring. The highest possible power can be achieved by tuning the resonant frequency of the mass-spring system to the frequency of the driving motion. In the case of Parametric Generators suspension doesn't employ any spring or the spring is negligible, therefore no resonant energy transfer occurs.

Considering the Resonant Generators only, there are two types of resonant generators. One is damped by a force which is proportional to velocity called the velocity-damped resonant-generator (VDRG), and the other is damped by a constant force called the Coulomb-damped resonant-generator (CDRG), and also one nonlinear generator, the Coulomb-force parametric-generator (CFPG). All three can be implemented in MEMS, using electromagnetic (for the VDRG) or electrostatics (for the other two).

Now let me consider a Velocity Damped Resonant Generator similar to the general model of generator as shown in the Fig 2.7. The generator is to operate in modes in which the proof mass does not strike the end limits because in the modes of operation in which the proof mass reaches the limits results in collision leading to dissipation of energy reducing the efficiency of the device. The forces acting on the proof mass are inertial, spring, damping force and gravity. The optical power is derived as a function of  $Z_l/Y_0$  and  $W/W_n$  and can be normalised to  $Y_0^2 w^3 m$ . This normalisation is used because it has dimensions of power and has a fraction of maximum kinetic energy of the mass that is dissipated in the damper each cycle.

The differential equation for the motion of mass  $m$ , relative to the frame is;-

$$m\ddot{z}(t) + c\dot{z}(t) + kz(t) = -m\ddot{z}(t)$$

Taking Laplace Transformation of the above equation and dividing it with  $m$  we get;-

$$\frac{Z(s)}{Y(s)} = \frac{-s^2}{(s^2 + w_n^2 + 2\zeta w_n^2 s)}$$

Where,

The damping factor ( $\zeta$ ) =  $\frac{D}{2mw_n}$

The magnitude of the relative motion versus frequency is thus;-

$$\frac{Z_0}{Y_0} = \frac{w_c^2}{\sqrt{(1 - w_c^2)^2 + (2w_c\zeta)^2}}$$

Where,

$$w_c = \frac{w}{w_n}$$

The energy dissipated is the distance integral of the damping force over a full cycle which can be mathematically represented as;-

$$\text{Energy per cycle} = 2D \int_{-Z_0}^{Z_0} \dot{z} dz.$$

Solving the above equation we get;-

$$P = \frac{w_c^3 Y_0^2 w_c^3 \zeta}{(1 - w_c^2)^2 + (2\zeta w_c)^2}$$

For  $w_c=1$ , the power can be increased without any limit by decreasing  $\zeta$ . The source motion has been non constraining as it is capable of supplying infinite power. There is also no parasitic damping present in the system. The maximum power can be obtained is by finding the optimal value of  $\zeta$  that can be found out by;-

$$\frac{dP}{d\zeta} = 0$$

$$\text{Or } \zeta(\text{opt}) = \frac{\sqrt{w_c^4 - 2w_c^2 + 1}}{2w_c}$$

The maximum power can be obtained which is dissipated in the damper and thus converted into electrical energy by substituting the  $\zeta(\text{opt})$  in the equation of Power.

$$P_{max} = \frac{w_c^2 Y_0^2 w_c^3 m}{\sqrt{1 - 2w_c^2 + w_c^4}}$$

But the optimal value of  $\zeta$  may violate some fundamental constraints imposed by the system, one of them is displacement limit. If for the optimal value of  $\zeta$  the displacement limit is exceeded, it is necessary to choose a larger value  $\zeta$  so that the amplitude is just less than displacement limit to achieve an unclipped resonance cycle.

The electromagnetic transduction implementation is best carried out in velocity damped resonance generator which consists of a moving magnet producing a flux that links with a stationary coil of inductance (L) and resistance (R). According to Faraday's law of induction a voltage is induced in the coil due to the varying magnetic flux linkage caused by the movement of the magnet given by:-

$$e(t) = \dot{z}(t)NB^1A$$

Where,

N: Number of turns

$B^1$ : Gradient of flux =  $\frac{dB}{dz}$

A: Coil Area

This causes a resultant current to flow which according to Lenz's law opposes the relative motion of the magnet and the coil. According to the principle of virtual work the rate of mechanical work being done in moving the coil is always equal to the electrical power generated by the EMF. The force on the coil is given by:-

$$f(t).\dot{z}(t) = i(t).e(t)$$

or 
$$f(t) = i(t)NAB^1$$

In the Laplace domain the above equation transforms to:-

$$F(s) = I(s)AB^1$$

$$I(s) = \frac{E(s)}{R+sL}$$

$$E(s) = sZ(s)NAB^1$$

Substituting the values of I(s) and E(s) we get:-

$$F(s) = \frac{(NB^1A)^2sZ(s)}{R+sL}$$

The differential equation for the above system is same as that in the previous mentioned equation 2.1, with the f(t) taking the place of  $d\dot{z}(t)$ . Taking Laplace Transform of the equation and substituting the value of F(s) we get:-

$$\frac{Z(s)}{Y(s)} = \frac{-s^2m}{s^2m + \frac{s(NAB^1)^2}{R+sL} + k}$$

The system would turn out to be a perfect velocity damper at resonance ( $w=w_n$ ) as "wL" term is very small in comparison to R. So neglecting the L terms and finding the modulus of the displacement transfer function by calculating the magnitude of the above function we get:-

$$\frac{Z_0}{Y_0} = m \frac{w_n \sqrt{R^2 + w_n^2 L}}{(NAB^1)^2}$$

From the above equation we can get the values of maximum velocity and power equations similarly as we derived before.

**Table 3.1:** Review of some published inertia electromagnetic micro generator works.

Research Team	References	Generator Volume ( $cm^3$ )	Proof Mass	Input Amplitude	Input Frequency	$Z_1$ ( $\mu m$ )	Average Power(Unprocessed) ( $\mu w$ )
Williams et al	[4] , [7]	0.025	15 mg	30 $\mu m$	70 Hz	50	1
Shearwod et al	[4]	0.015	24 mg	500 nm	4.4 KHz	6.25	0.33
Amritharajah	[4] , [8]	n/a	0.5 g	Spectrum Walking	Spectrum Walking	n/a	400

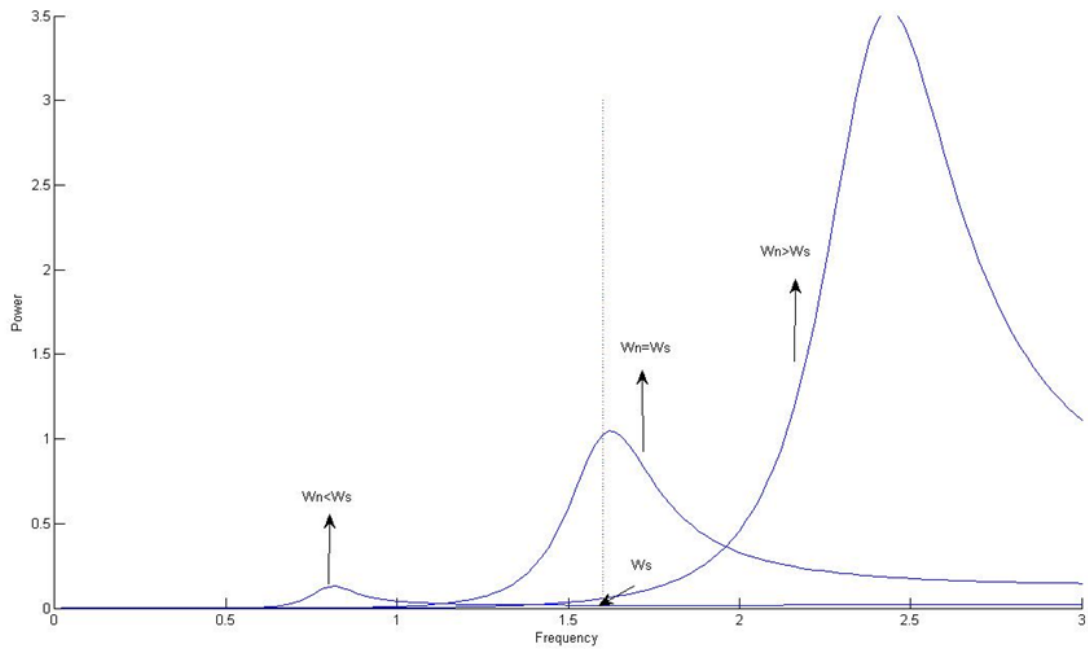


Fig 2.1: Bode Plot of average power output at varying resonant frequency with constant damping ratio ( $\zeta$ ).

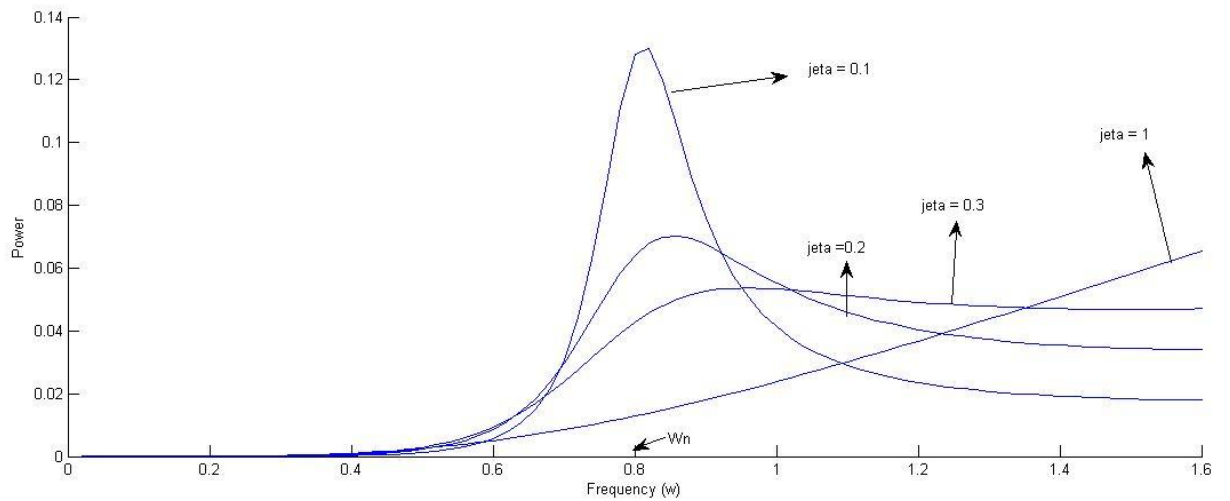


Fig 2.1: Bode Plot of average power output for varying resonant frequency with varying damping ratio ( $\zeta$ )

MATLAB Code for Bode Plot of average power output at varying resonant frequency with constant damping ratio ( $\zeta$ ).

```
function [ ] = bodeplot( )
clc;
m = 1;
p = zeros(1,8);
j=0.1;
ws = 1.6;
for wn=0.8:0.8:2.4
for w=1:1:150
    p(w) = ((m*j*0.1) * ((w/(50*wn))^2) * ((w/50)^3)) / (((1-
(w/(50*wn))^2)^2) + (2*j*(w/(50*wn)))^2);
end
w = [0.02:0.02:3.0];
disp(w);
disp(p);
hold on
    plot(w,p);
end
plot(ws,w);
hold off
end
```

MATLAB Code for Bode Plot of average power output for varying resonant frequency with varying damping ratio ( $\zeta$ ).

```
function [ ] = bodeplots( )
clc;
wn = 0.8;
m = 1;
p = zeros(1,8);
ws = [0.02:0.02:1.6];
for j=0.1:0.1:0.3
for w=1:1:80
    p(w) = ((m*j*0.1) * ((w/(50*wn))^2) * ((w/50)^3)) / (((1-
(w/(50*wn))^2)^2) + (2*j*(w/(50*wn)))^2);
end
hold on
    plot(ws,p);
end
j=1;
for w=1:1:80
    p(w) = ((m*j*0.1) * ((w/(50*wn))^2) * ((w/50)^3)) / (((1-
(w/(50*wn))^2)^2) + (2*j*(w/(50*wn)))^2);
end
plot(ws,p);
hold off
end
```

## CHAPTER IV

### Results

All the three transduction mechanisms are studied in details. And suitable generators would be modeled by using any one of the three transduction mechanism which we derived mathematically. All the mechanisms need different ways to model the generator keeping in mind their characteristics to derive maximum electrical energy. The energy harvested from the vibrations are then suitably used using a process that can be visualized in the figure below

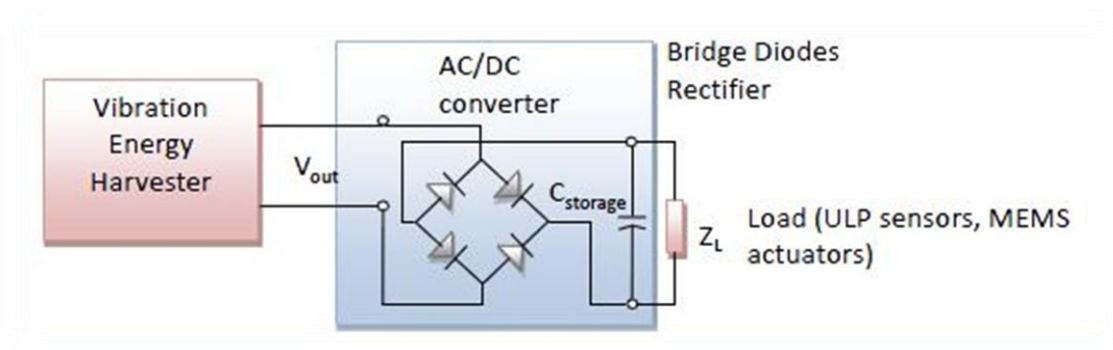


Fig 4

The voltage output is suitable increased by using a transformer of required ratio.



## CHAPTER V

### Conclusion

A vibrating electric generator can thus be modelled using any three of the transduction mechanism which would be capable of generating useful electrical energy from the unwanted vibrations in the surroundings of the system for feeding many low power electronic devices like sensors which can be utilized for long periods in a less economical way without any maintenance. The below mentioned table gives an idea of the importance of micro generators.

**Table 5.1:** Power that can be harvested from different sources

Power source	Power ( $\mu\text{W}/\text{cm}^3$ )	Power ( $\mu\text{W}/\text{cm}^3/\text{yr}$ )
Primary Batteries	N/A	90
Secondary Batteries	N/A	34
Vibrations	375	N/A

### Market size of WSN's

- The overall wireless sensors market is estimated to grow to \$4 billion by 2020 estimated by Frost & Sullivan in 2006.
- The worldwide ULP market reached over 200 million units by 2010.
- Temperature monitoring and vibration spectra of sensitive plant equipment are growing recently around \$22m estimated by ARC Advisory Group in 2007.
- Vibration and velocity sensors and transmitters market is growing from \$17.4m in 2006 to \$112.5m in 2012 at a compound annual growth rate of 34.4%.

**Table 5.2:** Power that can be harvested from ambient vibrations

Energy Source	Harvested Power( $\mu\text{W}/\text{cm}^3$ )
Human	4
Industry	100

Thus there would be a huge requirement of low powered devices in future and the demand can be only be met by harvesting power from renewable sources like ambient vibrations.

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