M. Tech (Power System)

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RENEWABLE ENERGY HARVESTING SYSTEMS USING RAILWAY TRACKS

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
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SUBMITTED BY:

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UNDER THE SUPERVISION OF

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DELHI TECHNOLOGICAL UNIVERSITY

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2020

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CANDIDATE'S DECLARATION

I, MANVI MISHRA, Roll No. 2K18/PSY/19 student of M.Tech (Power System), hereby declare that the project Dissertation titled "**Renewable Energy Harvesting Systems Using Railway Tracks**" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. The work has not been previously formed the basis for the award of any Degree, Associateship, Fellowship or other similar title or recognition.

Place: Delhi

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CERTIFICATE

I hereby certify that the Project Dissertation titled "**Renewable Energy Harvesting Systems Using Railway Tracks**" which is submitted by Manvi Mishra, Roll No. 2K18/PSY/19 student of M. Tech. (Power System), Electrical Engineering department, Delhi Technological University, Delhi in the partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi
Date: 04-09-2020

(Prof. PRIYA MAHAJAN)
SUPERVISOR

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ABSTRACT

The electrical energy is the basic requirement for any nation to achieve the goal of development**.** The demand of electricity is increasing day by day, also due to the rapid increase in population all over the world. Conventionally, the electricity generation is depends on the non renewable sources of energy like coal, which develops huge amount of CO_2. This CO_2 when comes in the atmosphere it makes effect on the ozone layer. Thus, there is a need to move forward with the renewable sources of energy which will not generate the CO_2**.** Therefore, many sectors moving towards installing more and more renewable energy resources in their premises for electricity production. Railway sectors are also using the rooftops for installing solar panels. This study is focused on using the railway tracks for installation of renewable energy units, so that good amount of electrical energy can be generated. Moreover, there are some types of renewable energy sources like electric energy generation from piezoelectric effect and other electromechanical energy conversion which can generate good amount of electrical energy. The piezoelectric effect converts the mechanical energy into the electrical energy. There are mainly two types of piezoelectric structures i.e. compression type piezoelectric system and cantilever beam type piezoelectric system, which help in generating electricity. The compression type piezoelectric system uses the force or weight applied on the piezoelectric unit, whereas, the cantilever beam type piezoelectric system uses the vibrations of the moving object to generate electrical energy. The location suggested for the compression type units is on the cross junctions of the railway track and sleepers, whereas, the location for cantilever type units must be on very side of railway tracks. The comparison of two piezoelectric systems has been done which suggests that compression type piezoelectric unit can generate more electrical energy than cantilever beam type piezoelectric system. Also, the technical analysis of both the piezoelectric structures, using the sensitivity analysis has been done. And finally the cost analysis of both the piezoelectric structures has also been done.

The Solar PV panels are used for converting the solar energy into the electrical energy. The solar PV panel has been emerging as one of the most prominent way of generating electrical energy from the sunlight or solar radiations. One of the drawbacks of the solar PV panel is that it requires large area for the system installation. The thesis suggests to use the distance

between two metro stations which includes the bridge construction over the railway track. The rooftop of the bridge can be used to install the solar PV panel. The electrical energy generated by the system over a day is going to store in a battery.

Based on these analyses, the prototype model has been suggested which have the compression type piezoelectric system on the cross section of railway track and sleeper, and also on the floor of the railway platform so that the number of foot-falls on platform can be used for generating electrical energy. Also the distance between two metro stations can be used to have bridge, whose rooftop can be used for installing the solar PV panels. This combination can produce good amount of electrical energy.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLE

LIST OF ABBREVIATIONS

S.No.		Full-Form
1.	PZT	Lead Zirconate Titanate
2.	PES	Piezoelectric Energy System
3.	PV	Photo Voltaic
4.	IGBT	Insulated Gate Bipolar Transistor
5.	MOSFET	Metal Oxide Silicon Field Effect Transistor
6.	MPPT	Maximum Power Point Tracking
7.	P&O	Perturb And Observe
8.	AC	Alternating Current
9.	DC	Direct Current

CHAPTER-1

INTRODUCTION

1.1 General

The electrical energy is becoming one of the basic utility for the human beings. There are number of operations whose basic requirement is electricity. The electrical energy is become one of the key parameter for the development of every country along with all other parameters. The easy availability of electricity and efficient production of electrical energy with low fault occurrence, is gaining the interest of research area in electrical engineering.

The conventional methods of electrical energy production use the main element as coal. But this method of production of electricity is non-renewable. Also the given method produce higher amount of CO_2, which is one of the main component to deal with when we consider the air pollution. Due to the limited availability of non-renewable sources and also due to the higher amount of production of CO_2, the research has been started to develop the method of electricity production with the help of renewable sources of energy. The Fig.1.1 is showing the contribution of different sources of electricity generation. However, the main renewable sources of energy could be as:

1. Solar Energy
2. Wind Energy
3. Hydro energy plant
4. Biogas

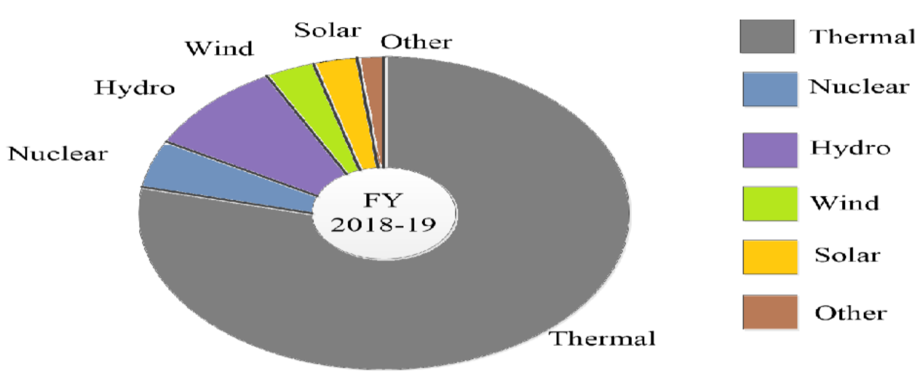

Fig.1.1 Electricity Generation by Different resources

The railway in any country uses an amount of electricity which should be continuously supplied by the grid for smooth working of railways. With the development of electrical energy production with the renewable energies, the railway department is also trying to harvest more electricity from the renewable sources of energy. The different types of renewable energies that can be used by the railways are-

1. Solar Energy
2. Wind Energy
3. Supercapacitors
4. Electromechanical Energy

The railway department mainly trying to study on the areas where they can install the solar panels to harvest electrical energy. Also the train rooftop has been started using for the installation of solar panel. The wind energy along with the solar energy power plant is trying to tie up with the grid so that the large amount of electricity can be produced. The super capacitors are used to store and produce energy when the train accelerates and decelerates at the platform. Some small amount of energy can be produced by using electromechanical methods like using the vibrations to produce electricity. One of the methods under this category could be piezoelectric energy harvesting system, which can generate electricity when the train passes over the piezoelectric pads and also by using the ground vibrations when the train crosses the particular point. All the above method discussed is environment friendly.

1.2 Piezoelectric Energy Harvesting System

The term piezoelectric has “piezo” which is a Greek word which means to press. The energy produced by the piezoelectric is by mechanically pressing the piezoelectric pads. The Curie brothers were the one who discovered the piezoelectric effect during World War II. They discovered the relationship between the crystal structure and method of piezoelectric generation. They started to study about some materials. The materials which generate the piezoelectricity is divided into natural and man- made. The man made piezoelectric is new discovery in case of piezoelectric material which generate more electricity than natural material. There are two type of physical structure of piezoelectric energy generation i.e. compression type piezoelectric system and cantilever beam type piezoelectric system.

1.2.1 Compression Type Piezoelectric System

The compression type piezoelectric energy harvesting system uses the mechanical force for generating electricity. The mechanical force on the piezoelectric pad, energize the electrons present in the structure and hence the polarization of the piezoelectric pad has been occurred. This polarization helps in generating electricity. For the energy generation through the railway tracks, the cross junction of rail track and sleeper has been suggested to embed the piezoelectric array. Therefore, whenever the train passes through that point of installation due to the weight of bogie the electrical energy can be generated. The length, width and thickness could be the main parameters which can be varied in order to get desirable electrical output.

1.2.2 Cantilever Beam Type Piezoelectric System

The cantilever beam type piezoelectric system is also one of the known physical structures known in the world of piezoelectric energy harvesting system. The beam vibrates whenever the structure gains the vibrations and these vibrations are the source of excitation for electrical energy generation. For the energy generation through the railway tracks, the cantilever beam type structure should be present on the very side of railway track. Therefore, whenever the train passes the particular location of installations, the ground vibrations will help in generating the electrical energy from the piezoelectric material.

The above systems are compared with respect to their structure, source of excitation, electrical energy output and cost. The conclusion from that comparison is drawn that the compression type piezoelectric system is better than the cantilever beam type piezoelectric energy system.

1.3 Solar Energy

The Solar energy is considered as one of the most preferable and advanced source of renewable energy power generation. This source of electrical energy is used by many countries to meet their need of electricity. India is also expanding in this field with installing more solar power plants to meet the need of future India. Photovoltaic cell is the basic unit of solar panel. This cell is converting the solar energy directly into electricity. The temperature and irradiance present in the area plays an important role on the estimation of electrical power generated by the solar power plant. There is tremendous research is going on in this field to generated electricity with higher efficiency and lower cost.

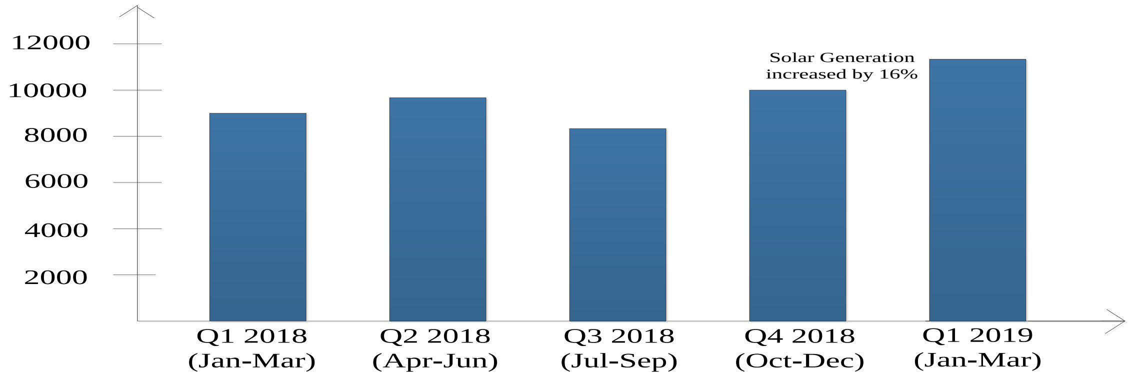

Fig.1.2 Quarterly Solar Electricity Generation

Fig.1.2 is the timely analysis of the increase in solar generation in India, the solar generation is getting more and more attention with the time. The reason behind such expansion in solar generation is that this type of system generates in good quality and quantity of electricity. As compared to piezoelectric energy harvesting system, solar power plant is more cost effective, higher efficient and low maintenance cost power plants.

1.4 Motivation

The world is moving towards the maximum usage of natural resources for the generation of electricity or even for utilizing these resources for day-to-day activities. The solar energy is emerging as one of the promising energy to harvest the electrical energy. The Solar power plants are presently boosting the electrical power generation in many countries including India. The research has also been moving toward the conversion of one form of energy into another useful form of energy and one of the example of such concept is “Piezoelectric Effect”. This effect converts the mechanical energy that is going to be wasted, into the electrical energy. The advantageous points which involved in this project are:

1. No need of extra piece of land or area for installing the solar power plant as the bridge constructed can be used for the installation.
2. Both the solar and piezoelectric energy harvesters can produce enough amount of electricity on daily basis.

3. The piezoelectric units can help in generating electricity from the kind of energy of energy which has been going wasted anyway.

The combination of solar and piezoelectric energy harvesting units around the railway station can help in generating good amount of electrical energy which in turn can help in railway lightings and other stable loads.

1.5 Problem Formulation

The sequence followed for making this thesis work involves:

1. The study of piezoelectric effect and its application in day-to-day life. This study suggested that the piezoelectric structure can be either compression type piezoelectric units or cantilever beam type piezoelectric units. In view of application of piezoelectric units on the railway tracks for the production of electrical energy, the study has been done for location of installation of these piezoelectric units.
2. The further study involves the comparison study of both types of piezoelectric units. The technical analysis i.e. sensitivity analysis and cost analysis of both the units has been done.
3. The study of solar power plant has been done with the point of view of using the space around the railway stations.
4. The combination of both the energy harvesting system i.e. piezoelectric and solar power plant has been suggested to be installed around the railway station. The total number of batteries used for the whole system has been calculated. This work has been done in the form of case study.

1.6 Dissection of Thesis

The thesis contains the following chapters:

Chapter 1- This chapter involves the introduction of piezoelectric effect and the type of structures and models used for generating electrical energy from the piezoelectric effect. The solar energy and the generation of electrical energy from the solar PV array has been discussed.

Chapter 2- This chapter gives the list of research papers, giving motivation to develop this project. A lot of deep research has been done to develop this idea into simulation. At first the piezoelectric effect is analyzed. The different type of structures, their specification and mode of generation of electricity has been analyzed through number of research papers. The solar power plant study and converter study has also been studied in order to combine the solar power plant with the piezoelectric energy harvesting system.

Chapter 3- this chapter is study of two types of piezoelectric energy harvesting system. The compression type PES and cantilever beam type PES has been analyzed by developing the MATLAB simulation model. The mechanical to electrical conversion of parameters has been studied. The output voltage and the energy generated by the single unit of each system has been analyzed.

Chapter 4- This chapter involves the technical and economic analysis of the two PES. The sensitivity analysis of both the PES has been done by developing the energy and power functions. The cost of the single unit of both the PES has been analyzed. Based on the comparison done on the basis of technical and economic aspects, the array of compression type PES has been suggested with the amount of electrical energy produced in a day.

Chapter 5- this chapter involves the study of solar power generation. The solar photovoltaic has been studied. The MPPT controller techniques used has been analyzed and the converter used for the steeping up and stepping down the voltage level has been studied. The idea of solar rooftop bridge has also been discussed in this chapter.

Chapter 6- This chapter involves the case study in which the distance between two consecutive stations has been used to installing the piezoelectric pads and constructing the solar rooftop bridge. The amount of electrical energy produced and battery used to store that energy has been studied in this chapter.

Conclusion- The final conclusion of this thesis has been stated in this chapter. The amount of electrical energy produced and how efficiently this energy can be stored is discussed in this chapter. The advantages of the prototype energy harvesting system have also been discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The project thesis has been designed into two parts. The first part consists of the study and analysis of the piezoelectric effect, and how the array of piezoelectric material can be used for the generation of electrical energy. The second part consists of studying and storing the electrical energy generated from the solar PV power system. The following studied has been conducted:

2.2 Study of Piezoelectric Effect

The study of piezoelectric effect is not only electrical engineering related but it also involves the mechanical and civil engineering departments. The mechanical engineering department works for the optimization and modifications in the structure of piezoelectric energy harvesting system so that the maximum electrical energy can be harvested. The civil engineering department going ahead in research of implementing the piezoelectric pads on the highway road so that the electrical energy can be harvested from the sources which is usually being wasted. The concept of using number of renewable resources to harvest good amount of electrical energy has been under the research from last several years. The combination of solar energy with the hydro or wind energy can harvest enough amount of electricity. But there can be the combination of other small renewable resources like supercapacitors, biogas plants, piezoelectric pads, etc. can be used to harvest some more electrical energy as this type of energy is being wasted(1)-(5). The physical modelling and studying the analogy between the mechanical structures to the electrical equivalent circuit is the first step to study about the harvesting electrical energy from the piezoelectric effect. In case of compression type piezoelectric energy harvesting system, the amount of charge produced due to the applied force is studied. In case of cantilever type piezoelectric energy harvesting system, the generation of oscillations and frequency in the cantilever beam has been studied (6)-(10). In general, the piezoelectric effect is used in implementing the tiles having piezoelectric material, so that the electrical energy can be generated with the footsteps of human at the crowded place. Some countries have involved in studying the amount of electrical energy, if the piezoelectric material is embedded on the road. The Innowattech Company of Israel had filed the patent suggesting all the possible places around the railway track which can be used as the location of installation of piezoelectric materials (11)-(15). The cantilever beam type piezoelectric energy harvesting structure is more complicated as compare to the compression type energy harvesting structure. The compression type PES only involves the force which will proportional to the charge generated in the piezoelectric unit. But in case of cantilever beam type, the matching of the frequency generated by the cantilever structure and the frequency generated by the ground vibrations due to the movement of train, should be equal to generated maximum amount of electrical power. For matching these frequencies, the tip mass proof is applied at the tip of the cantilever beam so that the unnecessary oscillations which occur in the system can be damped (16)-(17). The electromechanical energy conversion concept is studied for understanding the concept of conversion of one form of energy into the other form of energy. The energy generated from the vibrations of train movement has been the area of research for generating the electrical energy. Although the energy generated from this concept is small and can be used for sensing purpose only. The specifications of the railway tracks for installing the piezoelectric pads has also been studied(18).

2.3 Sensitivity Analysis of Parameters of Piezoelectric Units

The technical analysis of the different parameters of both the piezoelectric units has been done by using the sensitivity analysis. The technical analysis helps in studying the effect of different parameters of the system on the working of the structure (19)-(21). The compression type piezoelectric unit has the energy expression which contains different parameters like length, breadth, thickness of the piezoelectric units and also the force applied on the piezoelectric unit. The study helps in suggesting which parameter is most sensitive and will produce variation in the production of electrical energy. Similarly, the cantilever beam type piezoelectric unit has the frequency expression and the expression of output power developed. The parameters like tip mass, beam mass, moment of inertia of beam, etc. can be varied to produce the variation of electrical output energy produced (22)-(24).

2.4 Study of Solar PV Energy Harvesting System

The Solar PV energy harvesting system has been studied (25)-(27), the study of solar photovoltaic concepts and connections of the solar PV array in these papers. The dc-dc boost converter has been used to step up the voltage level to generate maximum amount of electricity. The MPPT controller has been used to sense the voltage and current coming out of the solar PV array. The perturb and observe algorithm has been used to detect the voltage and current, to made the change in duty cycle of converter for providing the gating signal to the switching device i.e. MOSFET. The buck converter has also been used in between to step down the voltage level to feed the electrical energy to the battery bank (28)-(33).

At the end, the prototype model containing the solar PV power plant and piezoelectric energy harvesting. The solar PV power plant is suggested to be installed on the bridge which is to be constructed on the railway track between two metro stations(34)-(39). The piezoelectric pads can also be embed at the cross junction of railway track and sleepers and also on the floor of the metro railway platform.

CHAPTER 3

PIEZOELECTRIC ENERGY HARVESTING SYSTEM

3.1 Introduction

The piezoelectric effect came into consideration during 1880s by Curie brothers. They discovered that some materials have the property that when the mechanical stress or force is applied to the material it produce some electricity. Piezoelectric materials belongs to the category of dielectric material, which when polarized by using the mechanical stress become polarized. Due to the polarization the electric field is produced inside the material which helps in producing electrical energy. Piezoelectric material is divided into two categories polar and non- polar. The polar piezoelectric material possess a net dipole moment and the non-polar piezoelectric material have dipole moment in different directions to give a total null net moment. Fig.3.1 shows the flow chart of electrical energy generation.

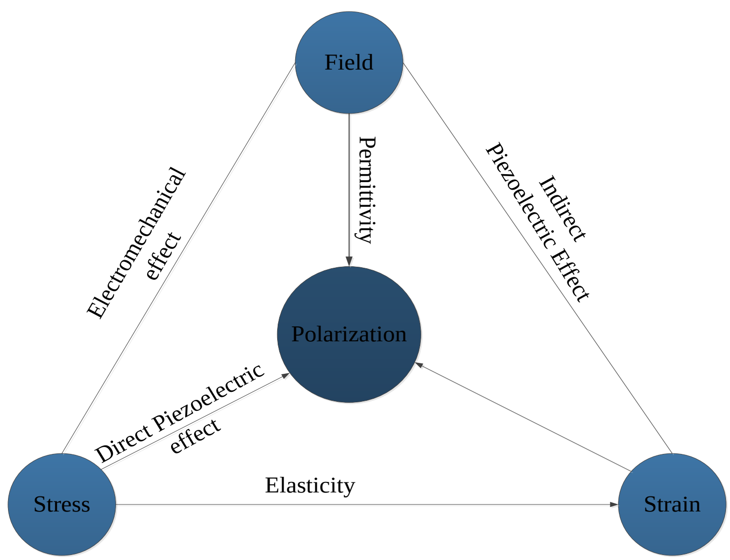

Fig.3.1 Flow Chart of Electricity production in Piezo Material

Before subjecting the mechanical stress the centres of negative and positive charge of each molecule coincide, as a result it will be an electrically neutral molecule. However, when a mechanical stress is applied on the structure the internal structure get deformed which causes the separation of positive and negative centres of the molecule and generating the little dipole. As a result the opposite facing poles inside the material cancels each other and fixed charges appear on the surface. The material gets polarized and the effect is called as direct piezoelectric effect. This polarization generates an electric field which is used to change the mechanical energy, used in material deformation, into the electrical energy.

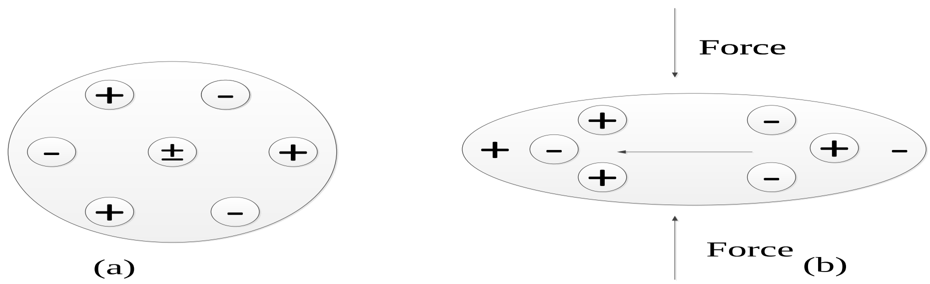

Fig.3.2 (a)Neutral Piezo Material and, (b) Excited Piezo Material

For electrical conduction, the piezoelectric material is placed in between the two metal electrode. If the electrodes are externally short circuited, with a galvanometer connected with the short circuiting wire, and a force is applied on the surface of the piezoelectric material, a fixed charge density appears on the surfaces of the material in contact with the electrodes. The polarization occurs within the material cause the electric field to develop which helps in the movement of free electrons. Depending upon their signs, the free electrons move towards the end where the fixed charges generated by the polarization are of opposite sign. This flow of free electron will continue until the free electron neutralizes the polarization effect.

When the applied force has been removed, the free electrons will move in reverse direction as the polarization disappears, the material will again come back into its original standstill position. This process has been indicated by the galvanometer, by flowing the current in opposite direction. If the short circuiting wire is replaced by the resistance/load, the current will flow through this system. This process will indicate that the mechanical energy is being converted into the electrical energy.

3.2 Classification of piezoelectric Materials

The piezoelectric materials are mainly classified into two categories depending on their occurrences:

a) Natural Piezoelectric materials-

The natural piezoelectric material includes quartz, Rochelle salt, topaz, tourmaline group minerals. Some organic substances like silk, wood, enamel, dentin, bone, hair and rubber are also the good examples of the natural piezoelectric materials.

b) Man- made Piezoelectric materials-

The molecular structure of man-made piezoelectric material is same as that of natural piezoelectric material. Thirty two such crystal classes are present which are classified into seven groups depending upon their material properties: monoclinic, orthorhombic, trigonal, cubic, triclinic, tetragonal and hexagonal. Out of these thirty two classified categories, ten do not have the piezoelectric properties because their unit cells are associated with the materialized electric dipole moment which causes undesirable polarization even in the absence of any physical stress.

Based on the structural electrical and polarization properties, the piezoelectric material is again classified into two categories:

c) Ferroelectric Materials

The ferroelectric type piezoelectric materials possess the electric polarization properties even in the absence of any physical stress. The atomic structure is the basic agent of possessing piezoelectric effect. Depending on type of crystal, variation in the stress may variant the polarization capacity. For instance, the crystal structures of a traditional piezoelectric ceramic at temperature above or below the curie temperature are cubic with no spontaneous polarization.

d) Non- ferroelectric piezoelectric material

The non-ferroelectric material gets micro-structural modification when a mechanical force is applied on this type of material. Due to this stress, the ions get separated, which lead to the formation of electric dipole moment in the structure. In order to develop a net polarization, the generated dipole is required to be not neutral in a unit cell. Thus, the atomic structure of this type of material has to be non- centrosymmetric. When the electrical voltage is applied to such material, electric dipole are generated which lead to physical deformation in the structure.

When the electrical voltage or mechanical force is applied from the material, the electric dipole disappear.

The lead zirconate titaanate ($Pb[Zr_{(x)}Ti(_{1-x)]}O_3$) is one of the widely used piezoelectric ceramic. The basic PZT has the perovskite crystal structure, each unit of which consists of small tetravalent metal ion in a lattice of large divalent metal ions. This tetravalent metal ion is usually titanium or zirconium and the large divalent metal ion is lead. PZT is a metallic oxide based piezoelectric material which is developed by scientists at the Tokyo Institute of Technology in 1952. In comparison of other metallic oxide piezoelectric material, the PZT has the greater sensitivity and higher operating temperature. In this project, the structural and electrical properties of PZT has been used.

3.3 Compression Type piezoelectric system

With the advancement in technology and research in the piezoelectric field, Japan has already started to use this piezoelectric effect for energy harvesting at the busiest station by installing the special piezoelectric tiles. These tiles are installed in front of ticket turnstiles. Due to which every time when a passenger steps on a tile, they trigger the small vibration that can be stored as energy. This energy generated by over 400,000 people who use Tokyo station on an average day, can generate a reasonable amount of energy, which is sufficient energy to light up the electronic signboards. An average person is weighing 60kg will generate only 0.1 watt in a second required to take two steps across the tile, but they are covering a large area of floor space and thousands of people are stepping on them, then significant amount of electrical energy can be generated (11). This generated energy is sufficient to run automatic ticket gates and electronic displays. By taking this analysis as base, the project is analyzing the technical aspects of installing the piezoelectric pads on railway tracks to harvest maximum amount of energy.

Piezoelectricity describes the conversion of mechanical energy into the electrical energy or vice-versa. The total mechanical stress is the sum of the mechanical stress due to mechanical strain and the mechanical stress due to the electric field. Analogously, the total electric charge is the sum of the electric displacement due to mechanical strain and electric field.

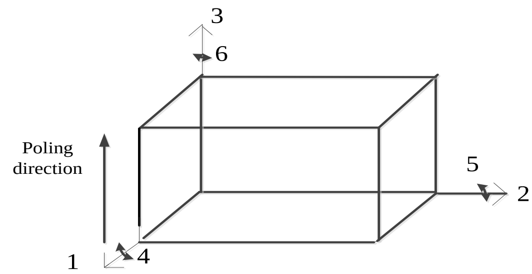

Fig.3.3 Three Dimensional Directions of Piezo Material

In the given figure, the polling direction which is parallel to any of the three direction, in this case it is axis number 3. This direction of polling is decided at the manufacturing level by using the high DC voltage, that is applied between a pair of electrode faces to the activate material. With the polling in axis 3 direction, the electric field is always applied in the same direction. The other two directions, namely direction 1 and 2 are physically equivalent so they can be defined arbitrarily, perpendicular to direction 3 and also with each other. The directions 4,5 and 6 define the tilting (shear) motion around the three axes 1, 2 and 3.

In shear elements, the poling element get removed at the later stage and replaced by the electrodes deposited on the second pair of faces. In this event, the axis 3 is not changed, but is parallel to the electrode faces found on the finished element. If the operating field is in direction 1, the wanted mechanical strain is shear around axis 5.

In context of this direction alignment, there are different type of constants relating to mechanical strain produced by electric field. One piezoelectric deformation constant is “d”, expressed in coulomb per newton [C/N]. this is piezoelectric charge constant which is relating the charge collected on the electrodes to the applied mechanical stress. In addition, several piezoelectric constants are defined with double subscripts to define the electrical field and mechanical stress applied directions. Fig.3.4 is showing the proper definition of each constant with the directional parameter.

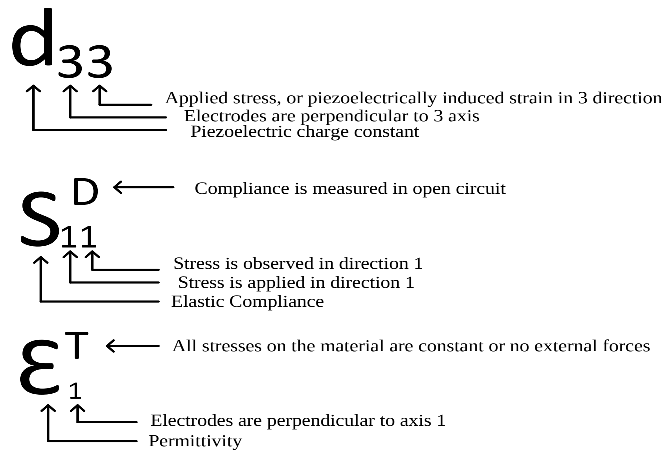

Fig.3.4 Constant defining electrical and mechanical nature of Piezo

There are some basic quantities which define the process of mechanical deformation and electric field production like T (constant stress), E (electric field), D (constant electrical displacement), S (constant strain). The axial direction of mechanical force applied and electric field produced is defined with the help of subscripts as shown in Fig.3.4. The number of basic equations are used to define the piezoelectricity process, the total strain produced in the transducer is assumed to have a sum of mechanical strain produced by mechanical stress and the controllable actuation strain caused by the electric field. As shown in fig.1, the initial polarization direction has been assigned to axis 3, the other two axes 1 and 2 are mutually perpendicular to the axis 3. The describing electromehanical equations defining piezoelectric behaviour has been given as:

$$\varepsilon_i = S_{ij}^{E}\sigma_i + d_{mi}E_m \quad (3.1)$$

$$D_m = d_{mi}\sigma_i + \xi_{ik}^{\sigma}E_k \quad (3.2)$$

Where i, j=1,2…6 and m, k=1,2,3 refers to the different directions within the piezoelectric material coordinate system. The above equations can be written in the following form:

$$\varepsilon_i = S_{ij}^{D}\sigma_j + g_{mi}D_m \quad (3.3)$$

$$E_i = g_{mi}\sigma_i + \beta_{ik}^{\sigma}D_k \quad (3.4)$$

where σ is the stress vector (N/m^2), ε is the strain vector (m/m), E is the vector of applied electrical field (V/m), ξ is permittivity (F/m), d is the matrix of piezoelectric strain constants (m/V), S is the matrix of compliance coefficient (m^2/N), D is the vector of electric displacement (C/m^2), g is the matrix of piezoelectric constant (m^2/C) and β is the impermittivity component (m/F).The equation 1 and3 defines the converse piezoelectric effect and equation 2 and 4 defines the direct piezoelectric effect, which cause the transformation of mechanical energy into the electrical energy. In matrix form the equation 1to4 can be defined as:

$$\begin{bmatrix}\varepsilon_1\\\varepsilon_2\\\varepsilon_3\\\varepsilon_4\\\varepsilon_5\\\varepsilon_6\end{bmatrix}=\begin{bmatrix}S_{11}&S_{12}&S_{13}&S_{14}&S_{15}&S_{16}\\S_{21}&S_{22}&S_{23}&S_{24}&S_{25}&S_{26}\\S_{31}&S_{32}&S_{33}&S_{34}&S_{35}&S_{36}\\S_{41}&S_{42}&S_{43}&S_{44}&S_{45}&S_{46}\\S_{51}&S_{52}&S_{53}&S_{54}&S_{55}&S_{56}\\S_{61}&S_{62}&S_{63}&S_{64}&S_{65}&S_{66}\end{bmatrix}\begin{bmatrix}\sigma_1\\\sigma_2\\\sigma_3\\\tau_{23}\\\tau_{31}\\\tau_{12}\end{bmatrix}+\begin{bmatrix}d_{11}&d_{21}&d_{31}\\d_{12}&d_{22}&d_{32}\\d_{13}&d_{23}&d_{33}\\d_{14}&d_{24}&d_{34}\\d_{15}&d_{25}&d_{35}\\d_{16}&d_{26}&d_{36}\end{bmatrix}\begin{bmatrix}E_1\\E_2\\E_3\end{bmatrix}$$

(3.5)

$$\begin{bmatrix}D_1\\D_2\\D_3\end{bmatrix}=\begin{bmatrix}d_{11}&d_{12}&d_{13}&d_{14}&d_{15}&d_{16}\\d_{21}&d_{22}&d_{23}&d_{24}&d_{25}&d_{26}\\d_{31}&d_{32}&d_{33}&d_{34}&d_{35}&d_{36}\end{bmatrix}\begin{bmatrix}\sigma_1\\\sigma_2\\\sigma_3\\\sigma_4\\\sigma_5\\\sigma_6\end{bmatrix}+\begin{bmatrix}e_{11}^{\sigma}&e_{12}^{\sigma}&e_{13}^{\sigma}\\e_{21}^{\sigma}&e_{22}^{\sigma}&e_{23}^{\sigma}\\e_{31}^{\sigma}&e_{32}^{\sigma}&e_{33}^{\sigma}\end{bmatrix}\begin{bmatrix}E_1\\E_2\\E_3\end{bmatrix} \quad (3.6)$$

Assuming that device is poled along the axis 3, and viewing the piezoelectric material as a transversely isotropic material, which is true for piezoelectric ceramics, many of the parameters in the above matrices will be either zero, or can be can be expressed in terms of other parameters. In particular, the non-zero compliance coefficients are:

$S_{11}=S_{22}$; $S_{13}=S_{31}=S_{23}=S_{32}$; $S_{12}=S_{21}$; $S_{44}=S_{55}$; $S_{66}=2(S_{11}-S_{12})$. The non-zero piezoelectric strain constants are $d_{31}=d_{32}$ and $d_{15}=d_{24}$. Finally the non-zero dielectric coefficients are $e_{11}^{\sigma}=e_{22}^{\sigma}$ and e_{33}^{σ}. Subsequently, the equations given above can be simplified as given below:

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0\\ S_{12} & S_{11} & S_{13} & 0 & 0 & 0\\ S_{13} & S_{13} & S_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & S_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & S_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & 2(S_{11}-S_{12})\end{bmatrix}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_{23}\\ \tau_{31}\\ \tau_{12}\end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31}\\ 0 & 0 & d_{31}\\ 0 & 0 & d_{33}\\ 0 & d_{15} & 0\\ d_{15} & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}E_1\\ E_2\\ E_3\end{bmatrix} \tag{3.7}$$

$$\begin{bmatrix}D_1\\ D_2\\ D_3\end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0\\ 0 & 0 & 0 & d_{15} & 0 & 0\\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{bmatrix} + \begin{bmatrix} e_{11}^{\sigma} & 0 & 0\\ 0 & e_{11}^{\sigma} & 0\\ 0 & 0 & e_{33}^{\sigma}\end{bmatrix}\begin{bmatrix}E_1\\ E_2\\ E_3\end{bmatrix} \tag{3.8}$$

The "piezoelectric strain constant" d, is defined as the ratio of developed free strain to the applied electric field. The subscript d_{ij} implies that when the electric field is applied, the charge is collected in the i direction for the force or displacement in the j direction.

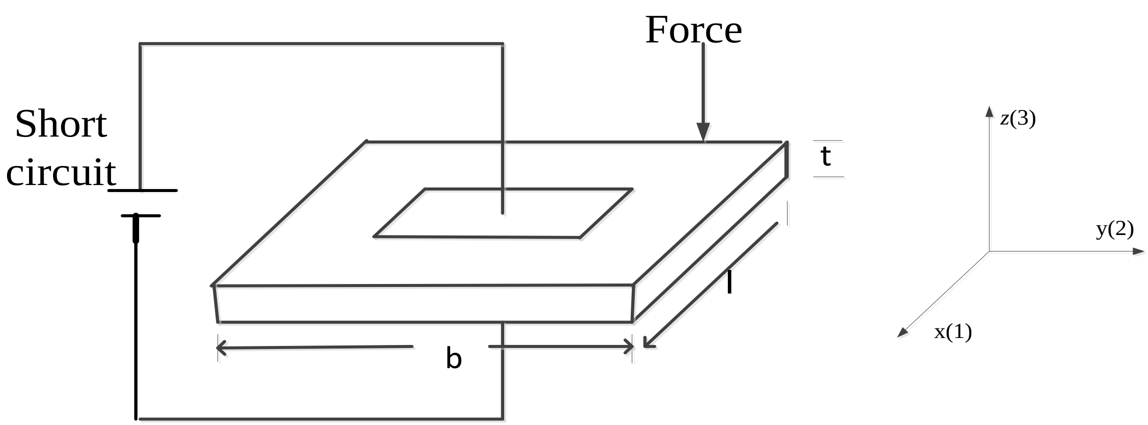

Fig.3.5 Diagrammatic View of Electrical Output Voltage Generation

The piezoelectric constant d_{ij} defined as the strain in i direction to the electric field develops in j direction, when all other external stresses are held constant. When the voltage is conversely given to the piezoelectric material, the electric field is generated is given as:

$$E = \frac{V}{t} \tag{3.9}$$

This equation suggests that the electric field strains the transducer. The strain is given as:

$$\varepsilon_1 = \frac{\Delta l}{l} \tag{3.10}$$

With the help of given equation, the change in length of the piezoelectric material is

$$\Delta l = \frac{d_{33} V l}{t} \tag{3.11}$$

The piezoelectric constant d_{31} is usually a negative number due to the direction convention used to define piezoelectric properties. Another interpretation of d_{ij} is the ratio of short circuit charge per unit area flowing between the electrodes perpendicular to the j direction to the stress applied in i direction.

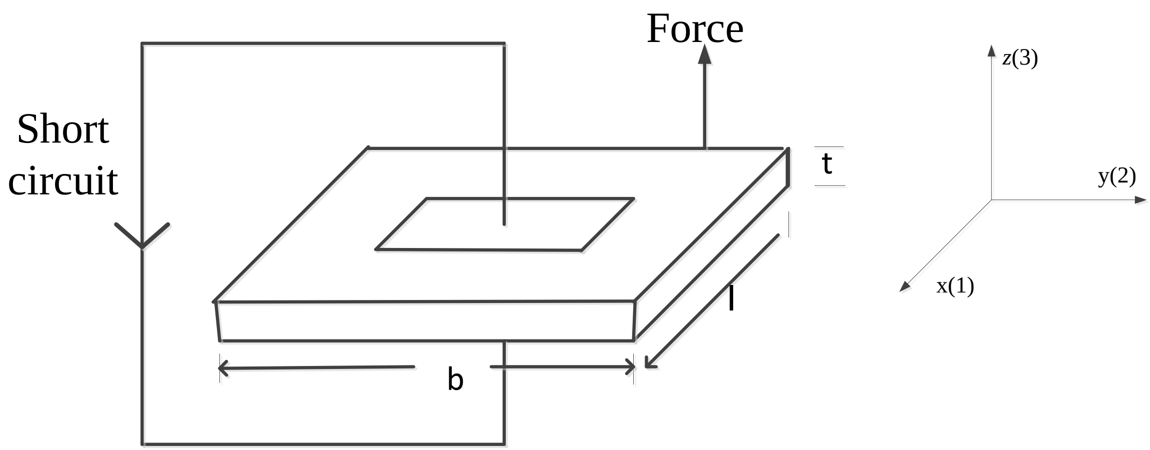

Fig.3.6 Piezoelectric alignment in direction 3

As shown in Fig.3.5 and Fig.3.6, the piezoelectric unit gets the mechanical force as actuator. This actuator produces the stress $\sigma_{33} = {}^{F}/_{lw}$, which results in the production of electric charge $q = d_{33} \times F$.

This charge is flowing through the short circuit as shown in figure. There is one more constant g_{ij} which defines the electric field produced in I axis when the stress is applied in the j axis. Thus the voltage produced in piezoelectric material is:

$$V = \frac{g_{ij} F t}{A} \tag{3.12}$$

3.3.1 Circuit Implementation and Calculation

The compression type PES solely uses the force applied by the body on the piezoelectric pads. There is an analogy between the mechanical and electrical equivalent circuit of the piezoelectric unit. The Fig.3.7 given below, shows the mechanical to electrical conversion of quantities which helps in generating electricity.

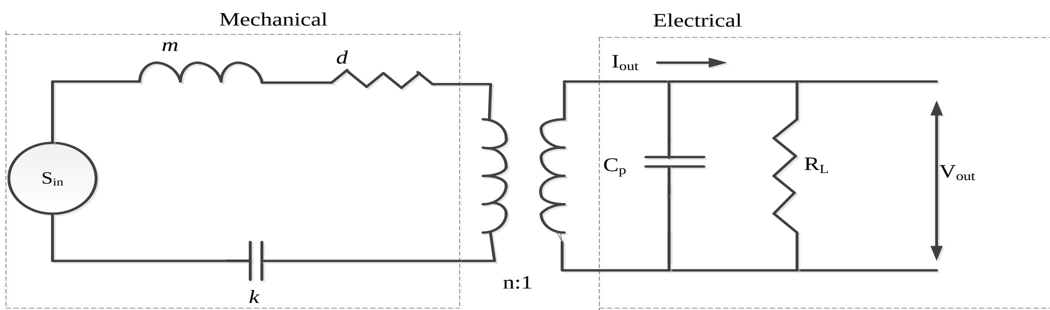

Fig.3.7 Mechanical to Electrical Conversion Analogy

The analogy describing parameter is given below:

1. The current source is equivalent to the force applied on the piezoelectric unit.

$$I = \frac{\Delta Q}{\Delta t} \tag{3.13}$$

The charge present in the circuit is

$$Q = d_{33}F \tag{3.14}$$

2. The capacitance is equivalent to the compliance which is inversely proportional to the stiffness. The piezoelectric material is covered with metal on top and bottom, which makes the structure as capacitor

$$C = \frac{\varepsilon_{\circ}\varepsilon A}{t} \tag{3.15}$$

where $\varepsilon_{\circ}$ is the permittivity of free space, ε is the relative permittivity of PZT material and t is the thickness of electrode.

3. The resistance is equivalent to mechanical damping. Known that piezoelectric material produce charge on the application of force, but the charge does not stays on the surface

forever. This charge gets the leakage path from the parallel capacitor hence it will get diminished. The resistance showing the damping in electrical equivalent circuit will have very high value.

The electrical equivalent circuit has been given below in Fig.3.8:

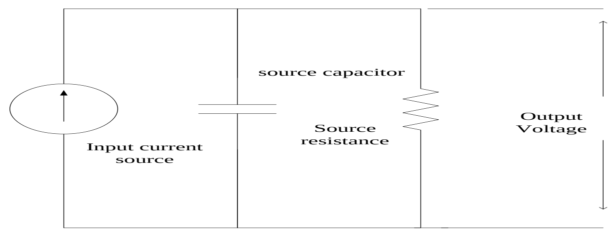

Fig.3.8 Electrical Equivalent Circuit of Piezoelectric Harvester

The electric field produced in the electrical equivalent circuit will polarize the electric ions inside the piezoelectric material. Hence, the current starts flowing and this current will be represented as current source for piezoelectric electrical equivalent circuit. The capacitor preset in the parallel to the current source will represent the compliance i.e. the electric charge polarization when the top and bottom of the piezoelectric material is connected with the metal plate. This structure will than behave as a capacitor.

$$C = \frac{\varepsilon_o \varepsilon_r A}{t} \quad (3.16)$$

Where ε_o is the permittivity of free space with value 8.854×10^{-12}F/m, ε_r is the relative permittivity with the value of 3400, A is the area of the parallel plates as the product of length 58mm and width 15mm of the single piezoelectric unit and t is the thickness 1.82mm of the piezoelectric unit. The calculated value of the capacitor is 14.39×10^{-9}F.

Whenever the train passes through the point of installation of piezoelectric unit, the electric field produced in the piezoelectric material and charge will developed. The charge produced will be:

$$Q = d_{33}F \quad (3.17)$$

Where d_{33} is the charge sensitivity coefficient which relates the force applied on the unit with the amount of charge developed, its value is 390×10^{-12}C/N. The force applied by the single wheel of the bogie is around 98kN. The charge Q developed is 38.22×10^{-6}C. The input resistance which is connected in parallel having the analogy of frictional coefficient or damping is 5MΩ. Table 1. contains the parameters which are used for calculation of different quantities.

Table 1. Parameters used for calculation in ComPES system

S. no	Constants	Value
1.	Charge constant(d_{33})	390×10^{-12}
2.	Length(mm)	58
3.	Width(mm)	15
4.	Thickness(mm)	1.82
5.	Permittivity of free space($\varepsilon_\circ$)	8.854×10^{-12}
6.	Relative permittivity(ε)	3400
7.	Voltage constant(g_{33})	48×10^{-3}

The MATLAB simulation model with all the quantities calculated with above described equations has been shown in Appendix A1. The Fig.3.9 shows the output current and voltage of single compression type piezoelectric unit.

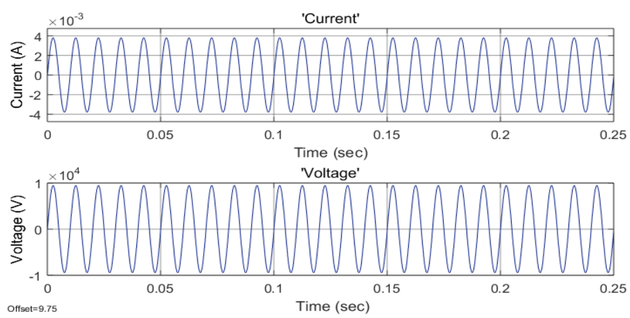

Fig.3.9 Current and Voltage of Single Compression Type PES unit

The location which is suggested for the installation of compression PES unit as an array could be a cross point junction of railway track and sleeper which is shown in Fig.3.10.

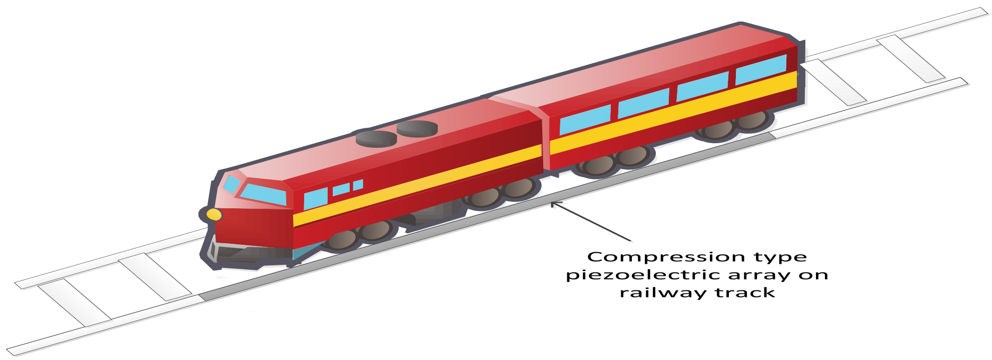

Fig.3.10 Location of array of ComPES units

The area of cross section is 34290mm^2 and the area of one piezoelectric unit is 870mm^2 (24). Therefore, at each cross section there will be a piezoelectric pad containing 40 piezoelectric units. Over a stretch of certain kilometer, 500 sleepers has been used for PES. This array is connected in parallel, thus the total charge accumulate wheel a wheel crosses a system is around 0.76C.

The total energy generated by units on both sides= $Q \times V$=7.544kJ. If the train has 4 wheel-axel system and 20 bogies, the total energy generated is 603.57kJ. The train is travelling with 90km/hr, it takes around 37sec to cross these installed pads, thus total energy generated by one train is 6.2kWh. If 20 trains crosses through that track than total energy over a day is 84kWh.

3.4 Cantilever Beam Type Piezoelectric System

The cantilever beam type piezoelectric structure is also one of the most commonly used physical structure. This structure is used to obtain high output power as it can apply larger strain to the given piezoelectric element under the presence of ground vibrations. A general and commonly used physical model of cantilever beam type PES is explained below with an illustrated figure, formulae and equations. The cantilever beam type harvester consists of piezoelectric ceramic, elastic body and the proof mass. This type of structure helps in allowing large amount of deformation in the structure in the presence of vibrations and hence, this structure is helpful in collecting large amount of electrical power from the piezoelectric material with the help of 31 mode. The operating performance of the harvester is determined by each physical factors like length, width and thickness of the beam, position of piezoelectric material and elastic body structure used for the model. The power output of the structure depends upon the acceleration of the moving body and ground vibrations present for this structure. The cantilever beam type PES produce small amount electrical power by converting the mechanical energy produced by the ground vibrations of moving train on the track into electrical energy. The acceleration of the moving train on the track and the ground vibrations produce due to this movement is the important factors to produce voltage in this PES.

3.4.1 Circuit Implementation and Calculations

The cantilever beam type PES consists of the cantilever beam with unimorph i.e. piezoelectric material at one side only (top of the beam) or bimorph i.e. piezoelectric material on both sides in the cantilever beam (both on top and bottom of the beam), elastic body and a tip mass. A simple single degree-of-freedom is discussed below with the help of fig. As shown the harvesting system will have the mass m, spring of stiffness k, total damping coefficient c_T. This system is excited by the external source of vibration which is defined by the sinusoidal function $y(t) = Asin(\omega t)$(where A is the amplitude of acceleration and ω is the frequency of the vibrations), which cause the movement in the mass m as *x(t)* shown in Fig.3.11.

$$m\ddot{x}(t) + c_T\dot{x}(t) + kx(t) = -m\ddot{y}(t) \tag{3.18}$$

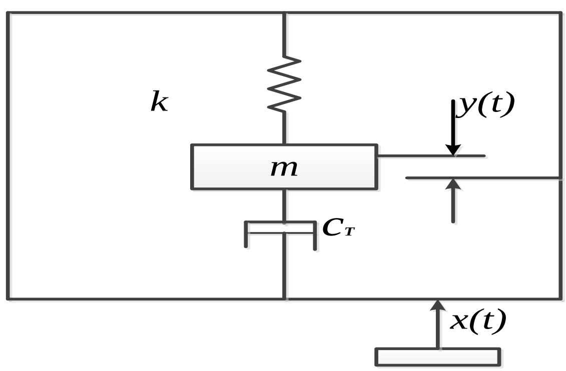

Fig.3.11 Mechanical Equivalent of the cantilever beam system

The cantilever beam type piezoelectric system generate electrical energy whenever this structure get excited from the vibrations. As the Fig.3.11 shows, when the system comes in the contact with the vibration, the mass gets deflected from its original position and this deflection causes the deformation in the piezoelectric material. This deformation is the polarization of the electric particles in the piezoelectric material which is present on the top of the cantilever beam, which helps in generating electrical energy. The acceleration of the moving train and the ground vibrations are two important factors to generate voltage. Since the electrical energy is extracted due to the relative motion between the mass of the beam and base, the maximum power in this case is maximum when the excitation frequency become equal to the natural frequency of this system. The natural frequency of the structure is given as:

$$\omega = \sqrt{\frac{K_{eff}}{m_{eff}}} \tag{3.19}$$

Where $K_{eff} = {3EI}/{L^3}$ and $m_{eff} = {33m_b}/{140 + m_t}$. In this equation K_{eff} is the effective spring constant of the structure, m_{eff} is the effective mass of the structure, E is modulus of beam, I is moment of inertia, L is the length of the beam, $m_b$is the mass of the beam and $m_t$is the tip mass on the cantilever beam. There is also one more quantity whch is helpful in handling power generation i.e. total damping ration of the system. The damping ratio helps in preventing power to go infinity when the harvesting system vibrates at the resonant frequency. The total damping ratio is given as:

$$\zeta_t = \frac{k}{2m\omega_n} \tag{3.20}$$

Where k is the spring constant, m is the mass of the system and $\omega_n$is the natural frequency of the structure. The tip mass which is to be added to the given cantilever beam system plays an important role, as it can be helpful in controlling the oscillations of the cantilever beam and matching the system frequency with the frequency of the excitation.

According to Challa's work[19], the open circuit voltage which can be generated y this system is dependent on the stress σ in the structure and other material properties of the piezoelectric material, as given in the equation:

$$V_o = \frac{-d_{31} t_p \sigma_n}{\varepsilon} \tag{3.21}$$

Where $t_p$is the thickness of the piezoelectric beam, -d_{31} is the piezoelectric strain constant and ε is the dielectric constant of the piezoelectric material used and $\sigma_n$is the stress produced in the system structure at the resonating frequency. The expression of the stress σ_n is:

$$\sigma_n = \frac{3EAh}{4L^2 \zeta_t \omega_n^2} \tag{3.22}$$

Where E is the effective modulus of the beam, h is the distance of the piezoelectric layer from the neutral axis, L is the length of the piezoelectric cantilever beam and A is the acceleration of the moving train.

When this given cantilever beam type structure is converted into electrical equivalent, the power generated by the circuit is given as;

$$P = \frac{V_o^2 R_{Lp}}{(R_s + R_{Lp})^2} \tag{3.23}$$

Where R_s is the internal resistance of the circuit, R_{Lp} is the applied load resistance. With the help of maximum power theorem, which states that the circuit can produce maximum amount of power when the load resistance is equal to the internal circuit resistance. Thus as internal resistance of the circuit is much greater than the load resistance, the load resistance can be neglected. And hence, the power generated from the cantilever beam type PES is small in amount.

The given Table 2, contains all the constants and their values specified, which is used in the calculation of voltage and power output.

Table 2. Parameters used for Calculation in CanPES System

S.No.	**Constants**	**Values**
1.	E= Modulus of beam(GPa)	3.81×10^{9}
2.	I= Moment of inertia(mm4)	0.36
3.	L_{eff}= Effective length of beam(mm)	36
4.	ω_n=frequency of structure	93.54
5.	h= distance of piezoelectric layer from neutral axis(mm)	0.3
6.	A= acceleration(m/s^2)	2.5
7.	ζ_t =damping ratio	0.015
8.	d_{31}= piezoelectric strain constant(C/N)	1.75×10^{-10}
9.	t_p= thickness of piezoelectric layer(mm)	0.16
10.	ε =permittivity of piezoelectric	1.55×10^{-8}
11.	m_b=mass of beam(g)	44.3
12.	m_t= tip mass(g)	5

The calculated value of K_{eff} is 8.82×10^4kg/s2, m_{eff}=10.08kg, therefore the value of ω_n is 93.54Hz. The value of stress σ_n is 1.26×10^7 N/m2 and voltage is 22.7V. Hence with source resistance 5MΩ, the power is 25.76μW.

The location for cantilever type piezoelectric system can be the very side of railway tracks, shown in Fig.3.12. These units must be present very near to the railway platforms as the voltage generated in this case is dependent on the acceleration of the train.

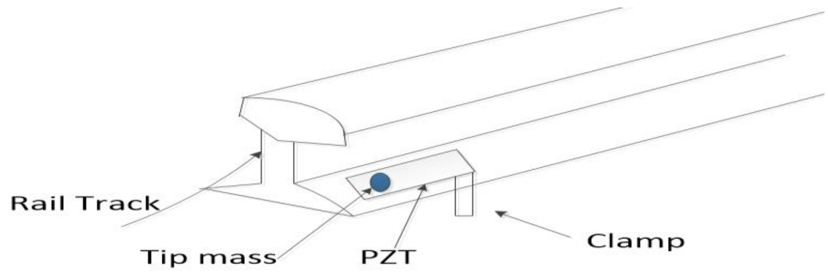

Fig.3.12 Location of CanPES unit

The MATALB Simulation has been used for the analysis of cantilever beam PES for the output voltage and current by applying the sinusoidal frequency to the harvesting system, shown in Appendix A2. The electrical equivalent circuit is same as that of compression type piezoelectric system, with the difference that current source and capacitor value has got changed due to material properties and type of excitation.

The simulation output of the single cantilever beam type PES is given below in Fig.3.13:

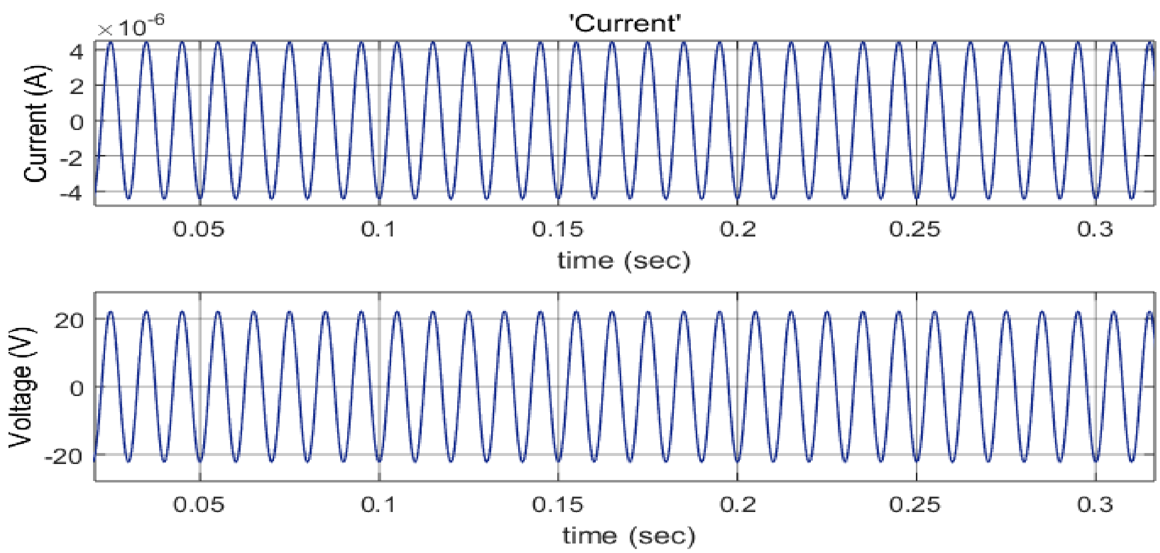

Fig.3.13 Current and Voltage Waveform of single unit of Cantilever Beam Type PES

The voltage generated by a single unit is 22.7V and current is 4.4μA. The expression of power generated by the single unit is given as:

$$P = \frac{9}{64R_s}.\left(\frac{d_{31}t_pEAh}{\varepsilon L^2\zeta_t\omega_n^2}\right)^2 \tag{3.24}$$

The power generated by single unit is. This type of PES is used to give electrical power to the small power loads like signalling panel.

3.5 Conclusion

The study suggests that the production of electrical energy through the piezoelectric effect depends on the type of structure which is going to be used. The compression type structure can produce more electrical energy than the cantilever beam type piezoelectric system. Thus, using compression type piezoelectric energy harvesting system can be more useful in constructing array of piezoelectric units and getting good amount of electrical output.

CHAPTER 4

TECHNO-ECONOMIC ANALYSIS OF SUGGESTED PES

4.1 Introduction

The Techno-Economic analysis of the project involves the analysis of technical aspects of the piezoelectric harvesting system along with the cost analysis of the harvesting system. The cost analysis involves the comparison of cost of per units of both compression type piezoelectric system and the cantilever beam type piezoelectric system, the amount of energy produced by these systems. Hence, based on such analysis the comparison of the two types of piezoelectric harvesting system can be made.

The technical analysis of the piezoelectric systems involves the sensitivity analysis of the expression of the power output, voltage and frequency expressions. The sensitivity analysis defines the variation in the output expression if there is any change in input parameter. The sensitivity analysis helps in determining the variation in the parameters which can be modified in the system to get the maximum output. The economic analysis involves the study of the cost involved in installing the project and the amount of gain or cost, which can be get in return with time. For the system to be advantageous, the cost of return within couple of years should be more than the cost required for the installation of the system.

4.2 Techno-Economic Analysis

There are many uncertainty encountered during the modeling of the system and analysis of the system output. These uncertainties can be in the parameter value chosen for the designing of the system. The parameter values should be strictly between the minimum and maximum value assigned for the system design. There may be the selection of imperfect value in the initial stage of designing any system. In piezoelectric harvesting system, the parameters like length, width and frequency can be affected by the conditions around the system. Thus, their values should be chosen with proper analysis.

One of the basic method to solve these inaccuracy, is sensitivity analysis of the power, generated voltage and frequency function. If the system is insensitive with the external disturbances applied to the system, that system is known as robust system. The sensitivity analysis of the system defined as the variation in the function or expression, whenever the system parameter changes. It is the ratio of the percentage change in the function expression A, to the change in the system parameter K.

$$Sensitivity = \frac{\%\, change\ in\ A}{\%\, change\ in\ K} \tag{4.1}$$

$$\hat{S}_K^A = \frac{\partial A/A}{\partial K/K} \text{ or } \hat{S}_K^A = \frac{K}{A} S_K^A \tag{4.2}$$

The notation $\hat{S}_K^A$ denotes sensitivity of variable A with respect to parameter K.

4.2.1 Sensitivity Analysis Of Compression Type PES

The compression type PES uses the force as the actuator to produce electrical energy. The force of the wheel of the bogie has been applied on the piezoelectric pad. This weight of the wheel polarized the internal electric particles inside the piezoelectric material, due to which the electric field developed and hence, the voltage is generated. In the compression type piezoelectric system, the energy expression is

$$E = \frac{1}{2} QV = \frac{1}{2} d_{33} g_{33} \frac{F^2 t}{lb} \tag{4.3}$$

The expression of energy contains the constants d_{33} and g_{33}, which are material specific, but the other variable like force impact i.e. weight of the wheel of the bogie on the piezoelectric unit, length, breadth and thickness of the piezoelectric unit can be changed according to the requirement. Hence, sensitivity analysis of these variables is analyzed.

The sensitivity function of the energy expression with respect to the force of the wheel of a train bogie is given as:

$$S_F^E = \frac{\partial [E]}{\partial F} = d_{33} g_{33} \frac{Ft}{lb} \tag{4.4}$$

The sensitivity function of energy expression with respect to the thickness of single compression type PES unit is given as:

$$S_t^E = \frac{\partial [E]}{\partial t} = \frac{1}{2} d_{33} g_{33} \frac{F^2}{lb} \tag{4.5}$$

The sensitivity function of the energy expression with respect to length of a single compression type PES unit is given as:

$$S_l^E = \frac{\partial[E]}{\partial l} = -\frac{1}{2} d_{33} g_{33} \frac{F^2 t}{l^2 b} \qquad (4.6)$$

The sensitivity function of the energy expression with respect to breadth of a single compression type PES unit is given as:

$$S_b^E = \frac{\partial[E]}{\partial b} = -\frac{1}{2} d_{33} g_{33} \frac{F^2 t}{l b^2} \qquad (4.7)$$

Table 3. Normalized Sensitivity of Compression type PES System

PES	**Functions**	**Parameter**	**Normalized Sensitivity**
Compression	Energy	Force	$\hat{S}_F^E = 2$
	Energy	Thickness	$\hat{S}_t^E = 1$
	Energy	Length	$\hat{S}_l^E = -1$
	Energy	Breadth	$\hat{S}_b^E = -1$

Table 3. contains the normalized sensitivity of different parameters. The above analysis shows that the energy produced by the single compression type piezoelectric pad can be varied by changing the magnitude of the force applied. Although the force of magnitude 73kN can only produce energy of 0.1055J, but connecting number of piezoelectric pads together to form an array of piezoelectric pads can produce a good amount of energy. The sensitivity of energy function with respect to the force having value 2, shows that the given system is highly sensitive with the force applied.

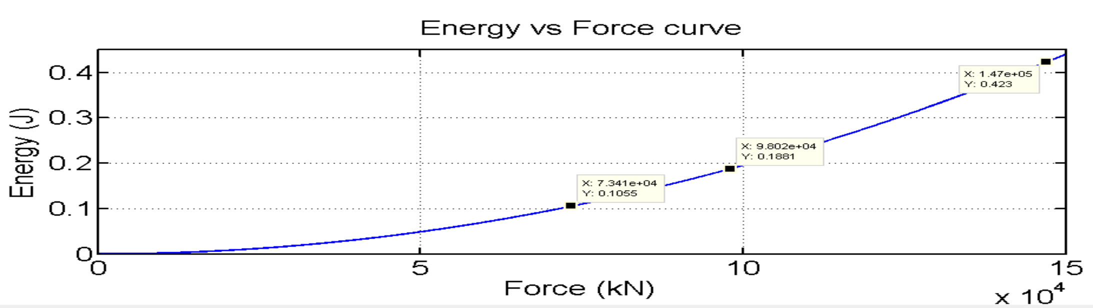

Fig.4.1 Energy Vs Force Curve

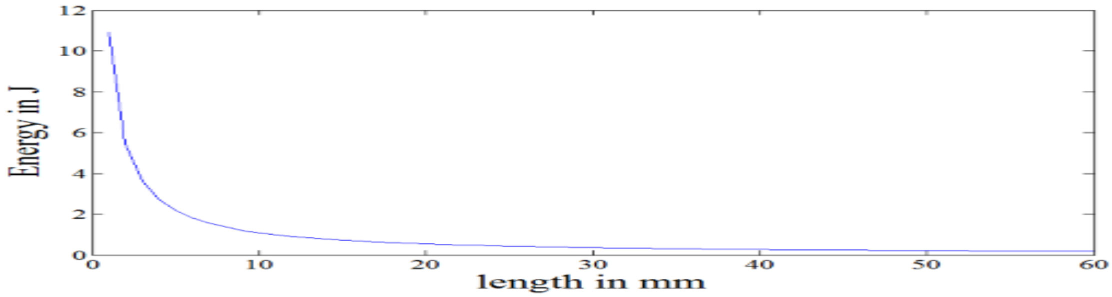

Fig.4.2 Energy Vs Length Curve

The Fig.4.2 given above shows the variation of the energy produced by single unit with respect to the length of single compression type piezoelectric pad. As shown in equation (4.3), the energy expression is inversely proportional to the length, there should be some constraint limits should be followed to optimize the length of the piezoelectric pad to design the accurate system.

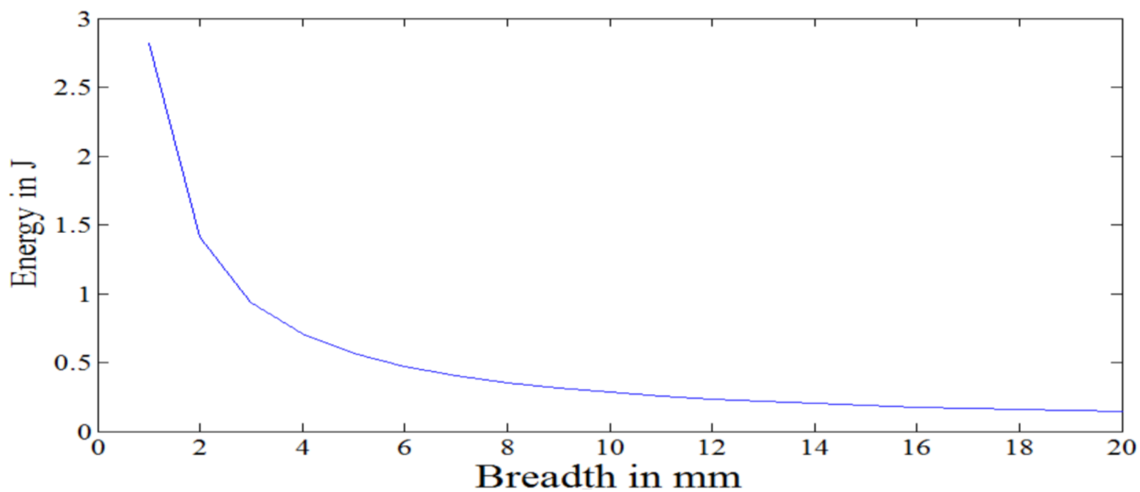

Fig.4.3 Energy Vs Breadth Curve

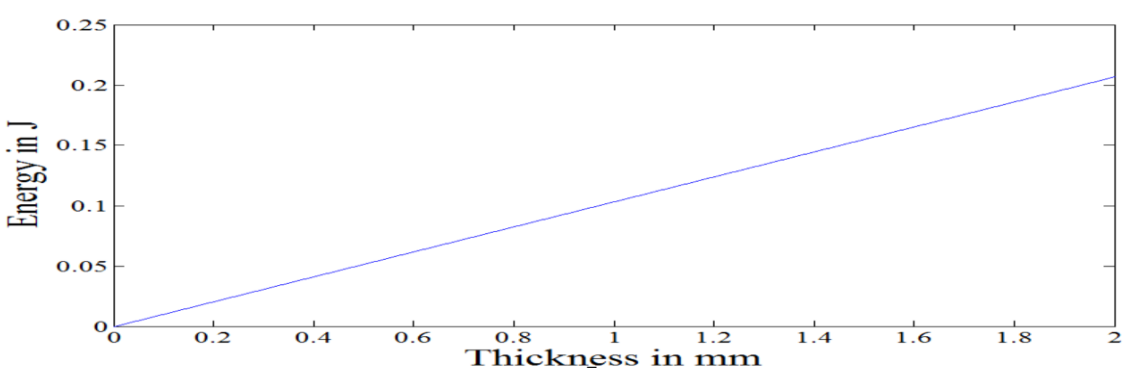

Fig.4.4 Energy Vs Thickness Curve

The given Fig.4.4 shows the variation of energy with respect to change in the thickness of single compression type piezoelectric unit. As shown in equation (4.3), the energy expression is directly proportional to the thickness of the piezoelectric pad used, the straight line shown in figure indicates the increase in energy with the increment in the thickness value. The thickness should follow the constrained boundary to get the maximum optimized piezoelectric system.

4.2.2 Sensitivity Analysis Of The Cantilever Beam Type PES

The cantilever beam type piezoelectric system can have a unimorph or bimorph piezoelectric layer. In general, the bimorph piezoelectric layer has been used as it can have more piezoelectric material used in the structure, so the good amount of electrical energy can be produced. The ground vibrations produced due to the acceleration of the moving train causes the variation of the electrical particles present in the piezoelectric layer, this variation in return help in producing electrical energy.

The sensitivity analysis of the cantilever beam type piezoelectric system has also be done in this section. The cantilever beam type PES is dependent on the frequency of the physical system arrangement. The tip mass is one of the important parameter in this system, which helps in maintaining the resonance frequency of the system. The resonance frequency is that frequency at which maximum electrical power is produced. By varying the tip mass, the structure frequency and power output of the system can be adjusted.

The frequency expression is given below:

$$w = \left[\sqrt{\frac{3EI(140+m_t)}{33m_bL^3}}\right] \tag{4.8}$$

The sensitivity function of frequency with respect to tip mass is given below:

$$S_{m_t}^{w} = \frac{\partial[w]}{\partial m_t} = \frac{1}{2}\sqrt{\frac{33m_tL^3}{33EI(140+m_t)}}\frac{3EI}{33m_bL^3} \tag{4.9}$$

The nominal sensitivity of the frequency function with respect to tip mass is given below:

$$\hat{S}_{m_t}^{w} = \frac{m_t}{w}S_{m_t}^{w} = 0.034 \tag{4.10}$$

The expression of power generated by the single piezoelectric cantilever beam by using eq. (3.24), is:

$$P = 68.06\left(\frac{d_{31}t_p m_b ca}{\varepsilon\zeta_t IR(140+m_t)}\right)^2 \tag{4.11}$$

The sensitivity function of the power expression is given below:

$$S_{m_t}^P = \frac{\partial[P]}{\partial m_t} = -2\left(\frac{d_{31}t_p m_b ca}{\varepsilon\zeta_t IR}\right)^2 \frac{1}{(140+m_t)^3} \tag{4.12}$$

The nominal sensitivity of a power expression with respect to tip mass is given as:

$$\hat{S}_{m_t}^P = \frac{m_t}{P} S_{m_t}^P = -0.068 \tag{4.13}$$

The variation of frequency of the structure with respect to tip mass has been shown in Fig.4.5. The frequency expression is directly proportional to the tip mass as shown in eq. (4.8). The tip mass on the cantilever beam helps in controlling the oscillations produced in the beam and also helps in matching the system natural frequency with ground vibrations frequency so that the maximum amount of energy can be produced.

$$S_{m_b}^P = \frac{\partial[P]}{\partial m_b} = 68.06\left(\frac{d_{31}t_p ca}{\varepsilon\zeta_t IR(140+m_t)}\right)^2 (2\times m_b) \tag{4.14}$$

$$\hat{S}_{m_b}^P = \frac{m_b}{P} S_{m_b}^P = 0.886 \tag{4.15}$$

$$S_I^P = \frac{\partial[P]}{\partial I} = -2\times 68.06\left(\frac{d_{31}t_p m_b ca}{\varepsilon\zeta_t R(140+m_t)}\right)^2 \frac{1}{(I)^3} \tag{4.16}$$

$$\hat{S}_I^P = \frac{I}{P} S_I^P = -2 \tag{4.17}$$

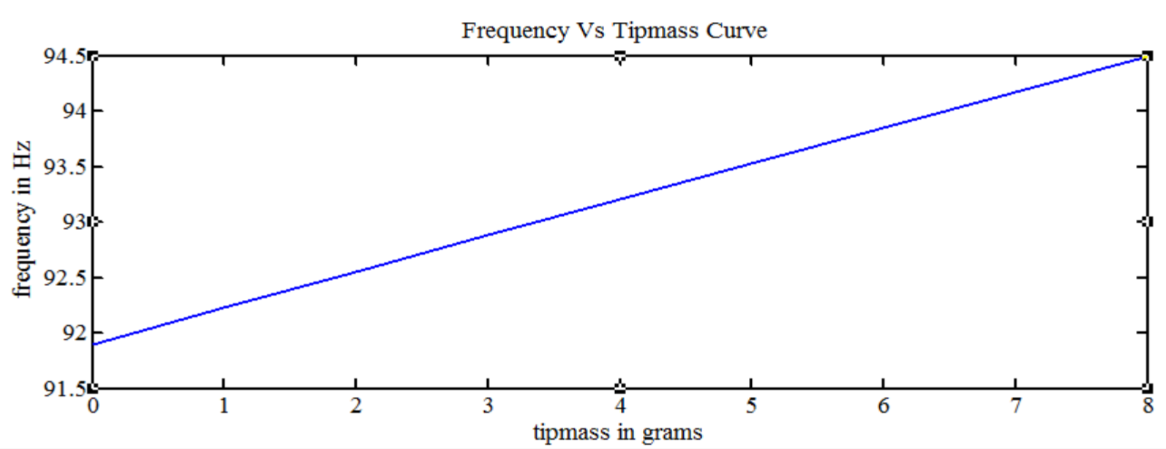

Fig.4.5 Frequency vs Tip mass curve

The variation of the system output power with respect to the tip mass has been shown in Fig.4.6. the expression of power indicates that the power expression is indirectly proportional to the tip mass. The constrained limits of the tip mass should be strictly followed to get the accurate cantilever beam type PES. The nominal sensitivity of power expression with respect to tip mass is -0.068.

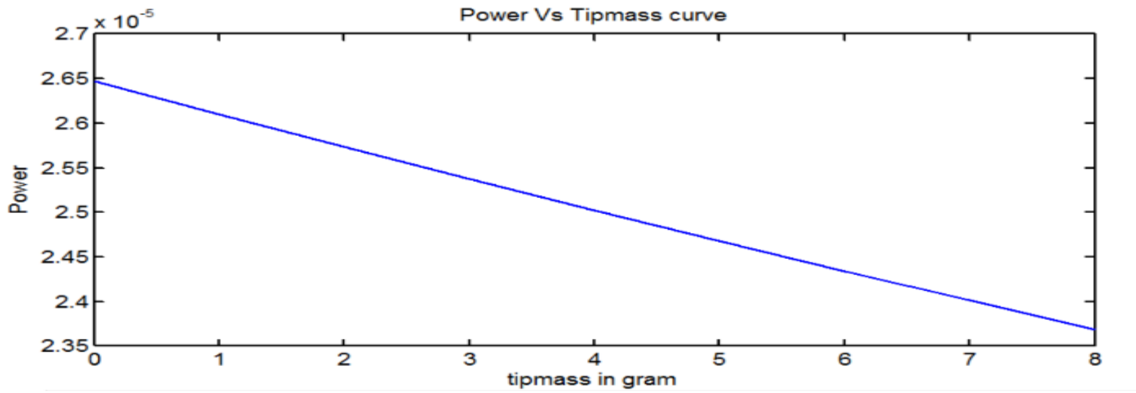

Fig.4.6 Power Vs Tip-mass Curve

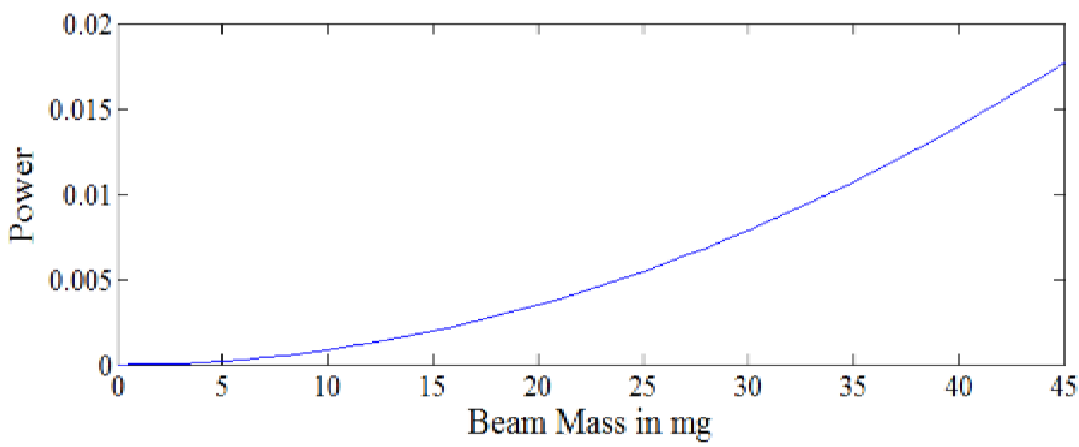

Fig.4.7 Power Vs Beam Mass Curve

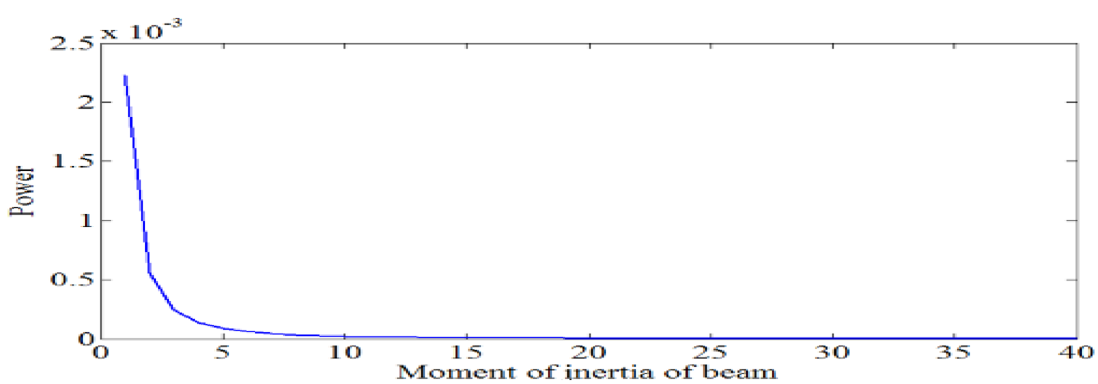

Fig.4.8 Power Vs Moment of inertia of Beam Curve

The variation of power with respect to beam mass and moment of inertia of beam has been shown in the above curves. The value of tip mass is 4g, beam mass 44.3g and moment of inertia is $0.36mm^4$. Table 4, shows the normalized sensitivity of different parameters.

Table 4. Normalized Sensitivity of Cantilever type PES system

PES	Functions	Parameter	Normalized Sensitivity
Cantilever Beam	Frequency	Tip Mass	$\hat{S}_{m_t}^{w} = 0.034$
	Power	Tip Mass	$\hat{S}_{m_t}^{P} = -0.068$
	Power	Beam Mass	$\hat{S}_{m_b}^{P} = 0.886$
	Power	Moment of inertia of beam	$\hat{S}_{I}^{P} = -2$

Compare to the compression type PES, cantilever beam type PES is a complicated system because it is difficult to synchronize the frequency of number of cantilever beam type PES, at a moment when train passes from that junction of installation.

4.2.3 Economic Analysis of Two PES

The economic analysis is one of the aspects which determine the utility of the suggested method or the process. The cost of one compression type piezoelectric unit is only Rs. 3.5, whereas the cost of one unit of cantilever beam type piezoelectric unit is around Rs.150. The above technical analysis and calculations suggest that the compression type unit can produce more electrical energy than the cantilever beam type unit**.** Therefore, it is better to use compression type piezoelectric unit for the installation of array on the railway track.

4.3 Comparison of Two PES

Based on all the electrical, technical and economic analysis of the two types of piezoelectric energy harvesting system, the comparison can be made. There following points of difference between two PES:

i The power produced by the single unit of compression type piezoelectric unit is around 0.2W, whereas the power produced by the single unit of cantilever beam type piezoelectric system is only 25.76µW for same system parameters configuration.

ii In cantilever type piezoelectric system, the voltage produced is dependent on the force applied to the piezoelectric unit, whereas in cantilever beam type piezoelectric system the voltage is dependent on structure frequency and acceleration of the train.

iii The location suggested for the compression type piezoelectric array can be at some distance from the platform. The location suggested for the cantilever beam type piezoelectric system is near the platform to use the acceleration.

iv The technical analysis suggest that the synchronization in the production of frequency in case of two or more cantilever beam type PES is difficult. But, in case of compression type PES, there is no such case of synchronization for output power generation.

v The cost analysis also suggest that the compression type PES is superior as compare to cantilever beam type PES because the initial cost of compression type PES is less that the cantilever beam type PES.

Thus, on comparing the power outputs of the individual unit of compression type piezoelectric and cantilever type piezoelectric system, the output of compression type is more as weight of the train is high.

4.4 Designing of Compression Type PES Array for Railway Tracks

As observed in the above studies, the array of compression type piezoelectric on the railway track could be more helpful. The exact location of compression type piezoelectric array has been shown in Fig. 4.9.

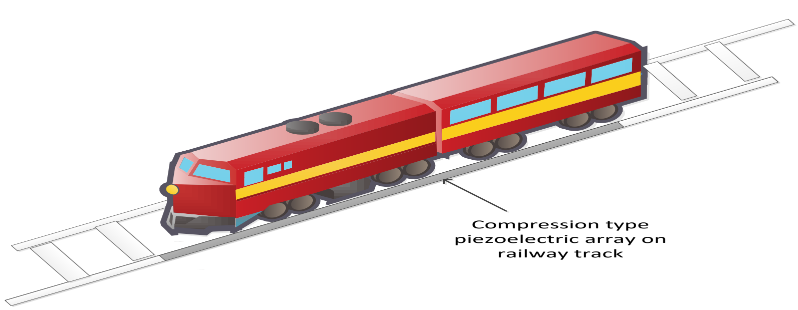

Fig.4.9 Implementation of compression type piezoelectric array

The main aim of piezoelectric array on the railway track is to generate reasonable amount of kWh when a train crosses over it. The piezoelectric pads are installed at each rail sleeper cross section area. The area of cross section is 34290mm^2 and the area of one piezoelectric unit is 870mm^2 (24). Therefore, at each cross section there will be a piezoelectric pad containing 40 piezoelectric units. Over a stretch of certain kilometre, 500 sleepers has been used for PES. This array is connected in parallel, thus the total charge accumulate wheel a wheel crosses a system is around 0.76C.

The total energy generated by units on both sides= $Q \times V$=7.544kJ. If the train has 4 wheel-axel system and 20 bogies, the total energy generated is 603.57kJ. The train is travelling with 90km/hr, it takes around 37sec to cross these installed pads, thus total energy generated by one train is 6.2kWh. If 20 trains cross through that track than total energy over a day is 124kWh.

4.5 Cost Analysis of Compression type PES Array

In this section, the analysis of cost of single unit of compression type PES and cantilever beam type PES has been given. The economic analysis is one of the major parameter to determine the success rate of the project in real world. For the economic analysis, the cost of single piezoelectric unit has been considered and with the help of the amount of energy generated by both the PES, the final cost of installation and cost of return of the project has been analyzed. For the compression type PES array, one module of compression type piezoelectric system which is to be installed at the cross section junction of rail and sleeper, has 40 basic piezoelectric unit (n).

The total number of sleepers used S=500

Total piezoelectric unit used P=$S \times n$ =40×500=20000 (18)

In market, the cost of 1 piezoelectric unit= Rs.3.5

Therefore, total cost of installation= $P \times 3.5$=20000×3.5 = Rs. 7 lakhs

The railway sector in our country pays around Rs 6.5/unit.

The electricity units used by railways in one day= 120 units

The total cost spent by railways in a day= 6.5×120=Rs. 780

In a year, railway spends = Rs. 2.8 Lakhs

The electrical units generated by the project T_p= 124units

The remaining units for which railway will have to pay= T-T_p=150-124=26units

Where T is total electrical units required by railways and T_p is the electrical units generated in the project.

The cost of 26 units= 26×6.5×365= Rs. 61,685

The return cost of installation for this system will comes after 1-2 years.

On the other side, the cost of single unit of cantilever beam type PES is around Rs. 150, which is more than a double of single compression type PES. Therefore, the cantilever beam type PES array will be costlier than the compression type piezoelectric system. Also, the power produced by the cantilever beam type PES is majorly dependent on the frequency of the structure when it gains vibrations. When this vibrating frequency is in range of resonance frequency of the structure, than the maximum power has been produced. Practically, the power output of two cantilever type PES can never be equal. Therefore, the energy extraction from this type of structure is difficult and costlier as compared to the compression type PES.

4.6 Conclusion

The given study has been suggesting which piezoelectric energy harvesting system is better in terms of technical and economic view. The Compression type PES is generating more electrical energy and also less expensive than the Cantilever beam type PES. Therefore, the array of Compression type PES units is better to install at the railway tracks.

CHAPTER 5

BRIDGE ROOFTOP BASED SOLAR PV PANEL SYSTEM

5.1 Introduction

The solar energy has been emerging as one of the reliable sources of energy from the renewable sources. The solar panel has been made up of silicon particles along with some other elements, which get excited as a photon when the sunlight falls on them. There are several renewable energy sources available today like hydro energy, wind energy, solar energy, geothermal energy, tidal energy etc. However solar energy out of all seems to be the future of electricity as many countries across the world are developing capacity for solar energy generation to meet their current and future energy demands. Most of the solar projects developed today are based on Photovoltaic system. Photovoltaic (PV) are semiconductor devices that directly convert solar radiations into electricity. There has been a tremendous research and development in field of PV which has resulted in their reduced cost and increased efficiency. The PV based projects are

cost-effective and have a low operation and maintenance cost therefore making them a more reasonable choice when compared to wind or hydro projects The voltage produced by this system is DC in nature. The solar panel system has been implemented on the bridge whose width is approximately equal to the width of railway tracks lying on the ground.

The maximum required PV panel which can be installed suitably on the rooftop of bridge is connected with the DC-DC boost converter. The gating pulses for the switch present in boost converter gets the updated value from the MPPT technique applied. The output voltage and PV current is given to the MPPT which update the value of duty cycle every time, to get that value of duty cycle which generate maximum power output. The boost output is given to the buck converter to step down the output voltage to the level which can be feed into the batteries.

5.2 Study of Photovoltaic Cell

The smallest unit in a PV is a photovoltaic cell. Photovoltaic cell is a p-n semiconductor junction which generates dc current when light falls on its surface, the current generated is proportional to the solar irradiation. A PV cell generates a small open circuit voltage (approximately .5 to .6 volt) across its terminals when sunlight falls on it and generate a small amount of power (approximately 0.1 to 3 watt). PV cells are connected in series and laminated together to make a PV module for higher output voltage (about 15 to 20 volt) and power (about 100 to 350 watt).

PV modules are further connected in series and parallel to form PV array and large arrangements of PV arrays can be designed for larger power output (in Megawatt). Figure 5.1 shows structure of PV array composed of PV modules which in turn are composed of PV cells.

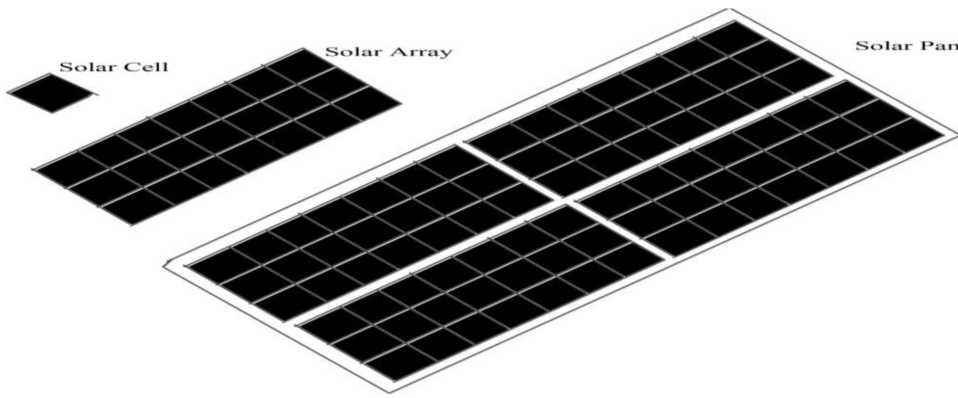

Fig.5.1 Solar Cells Arrangement

In order to understand the solar panel energy harvesting system, it is important to understand the electrical equivalent circuit of the solar PV panel.

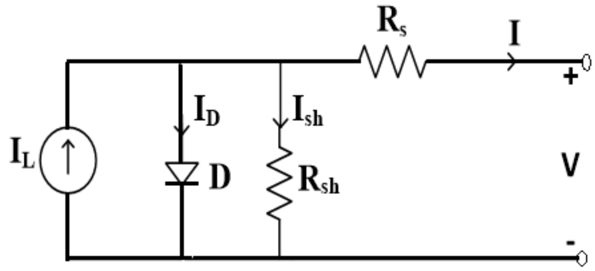

Fig.5.2 Electrical Equivalent Circuit of Photovoltaic cell

The above given Fig.5.2, shows the electrical equivalent circuit of a photovoltaic cell. The photovoltaic output current can be obtained by using KCL method of circuit solving. The photovoltaic output current obtained in eq. (5.1) include the diode current I_d, photo current I_l and shunt current I_{sh}.

$$I = I_l - I_d - I_{sh} \tag{5.1}$$

The diode current I_d is expressed as:

$$I_d = I_o\left(e^{\frac{q(V+IR_S)T}{K}} - 1\right) \tag{5.2}$$

Here I_o is the reverse saturation current which depends on material and the doping level, q is the charge of electron=1.6×10^{-19}C, K is the Boltzmann constant (J/K), T is the photovoltaic cell temperature (K), R_s is the effective series resistance. I_{sh} is the current through shunt resistance R_{sh}. This current can be can be expressed as:

$$I_{sh} = \frac{(V+IR_S)}{R_{sh}} \tag{5.3}$$

Where V is the terminal voltage of PV cell. Therefore, the whole expression of output photovoltaic cell is expressed as:

$$I = I_l - I_o\left(e^{\frac{q(V+IR_S)T}{K}} - 1\right) - \frac{(V+IR_S)}{R_{sh}} \tag{5.4}$$

The above equation is used to define the characteristics of photovoltaic cell. There are two important characteristics of the photovoltaic cell, I-V characteristics between output current and voltage, and P-V characteristics between output power and voltage. This characteristics decides the power that can be delivered by the PV panel and the peak of P-V characteristics helps in to obtain maximum power and hence the value can be found around which the maximum power point tracking technique can be applied.

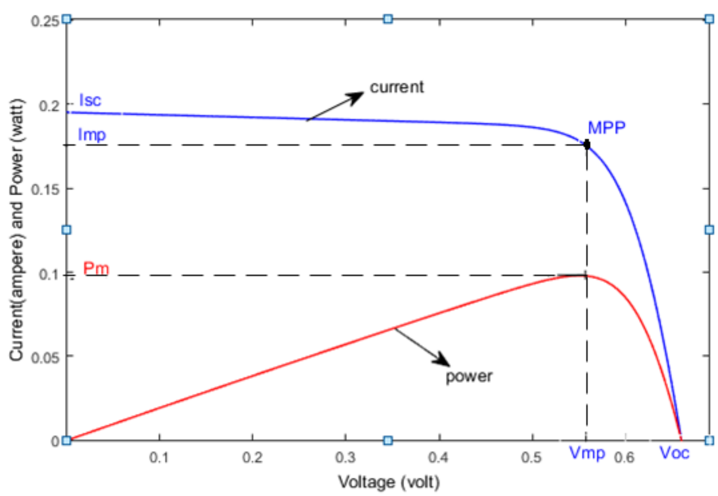

Fig.5.3 I-V and P-V characteristics

In the given Fig.5.3, I_{sc} is the short circuit current i.e, the current which can flow in the PV cell when output terminals are short circuited. I_{mp} is the maximum current that can be flow in the PV cell at a particular temperature and irradiance value, V_{oc} is the open circuit voltage which is present at the output terminal when the PV cell is in open circuit condition and V_{mp} is the maximum voltage that can be present at the output terminal at a particular value of temperature and irradiance. Therefore, it can be state that temperature (^oC) and irradiance (W/m^2) value are the two important factors that define the working of PV solar panel. The Fig. 5.4, shows that as the value of irradiance increases the value of I_{sc} increases and the value of V_{oc} also slightly increase and thus the power output from the PV panel increases.

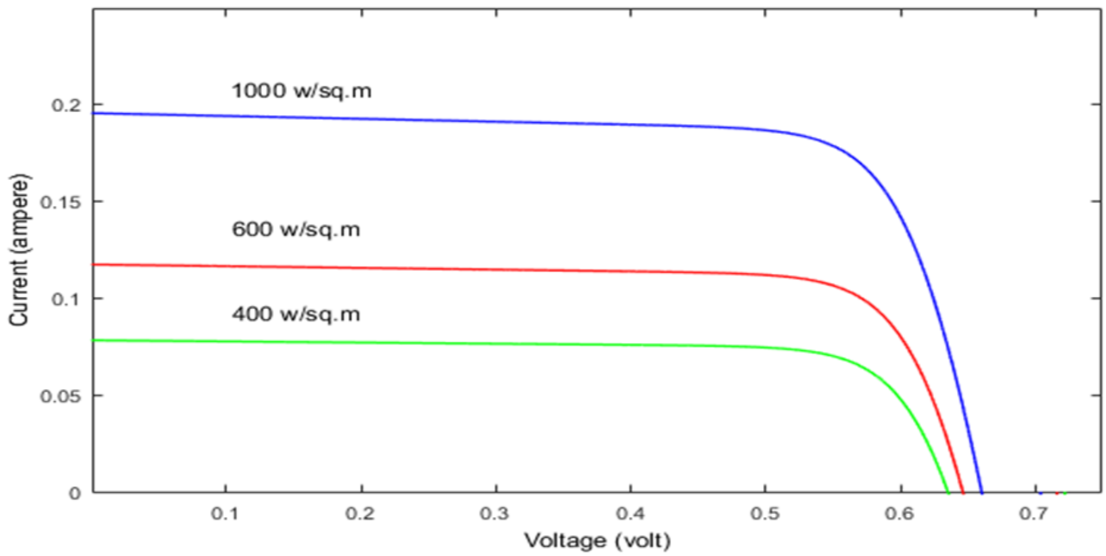

Fig.5.4 I-V characteristics at different values of irradiance

The increase in temperature decreases the value of V_{oc} and slight increase in I_{sc}, thus the power output decreases slightly. The given Fig.5.5 explains this condition:

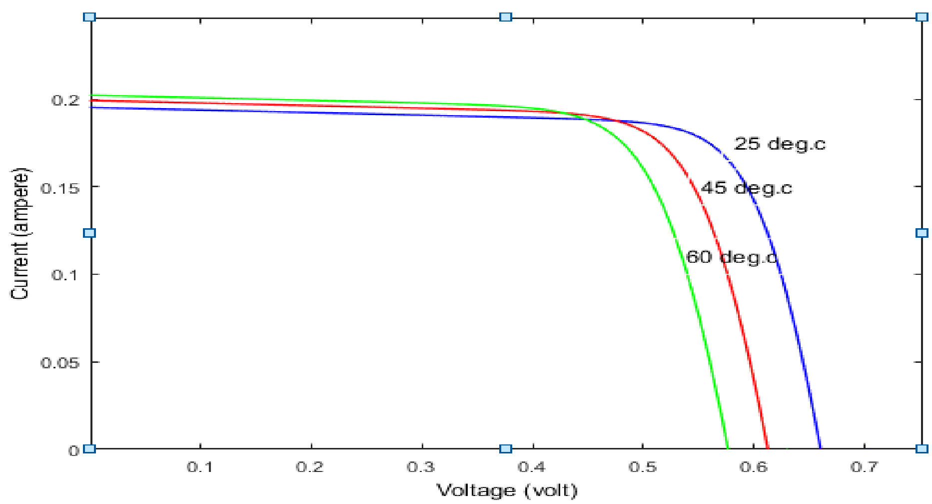

Fig.5.5 I-V characteristics at different temperature

The Solar PV panel has been designed in the MATLAB simulation with all the equations defined above. The basic block diagram shown in fig 5.6 describes the process of production of electrical energy from the solar radiations.

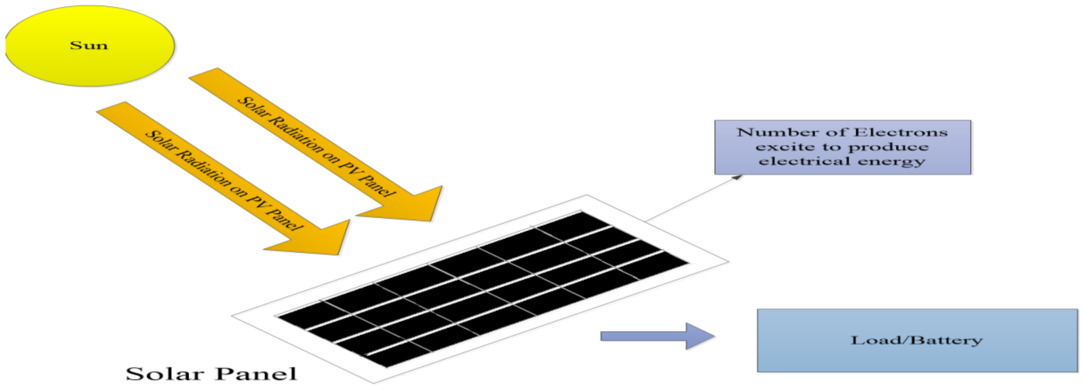

Fig.5.6 Block Diagram of Solar Power Generation

The table 5, shows the rating and standard value used for designing solar PV panel on the MATLAB software.

Table.5. Different Parameters used for Constructing Solar-Bridge Based Solar Power Plant

S. No.	**Parameters**	**Value**
1	Power rating of PV panel	400W
2	Voltage at maximum power (V_{mpp})	27.6V
3	Current at maximum power (I_{mpp})	7.1A
4	Open circuit PV Voltage (V_{oc})	32.8V
5	Short circuit PV current (I_{sc})	8.2A
6	Temperature coefficient of V_{oc} (% per ^{o}C)	-0.36099
7	Temperature coefficient of I_{sc} (% per ^{o}C)	0.102

5.3 Maximum Power Point Tracking Technique

As given in fig 5.3, the maximum point of voltage V_{mp} and maximum point of current I_{mp} has been shown. The output power obtained from the maximum voltage and maximum current values, is the maximum power point (MPP). The maximum power (P_m) of a PV panel is given as:

$$P_m = V_{mp} \times I_{mp} \tag{5.5}$$

As shown in V-I and P-V characteristics of PV vary with the change in the temperature value and irradiance value, thus the value of PV maximum power output also varies. Practically, when a load is connected across PV panel, the power output of the panel depends on the load parameter and the atmospheric conditions present around the panel. Due to this, the point of maximum power also changes and there may be a condition arise when PV panel is in underutilizing capacity. Thus there is a need to keep the operating condition of the PV panel to be around maximum power point so that the panel will operate at its maximum utilization condition. This can be achieved by using the Maximum Power Point tracking (MPPT). The given Fig.5.7 shows the interface between the solar pv panel and DC-DC boost converter using MPPT technique.

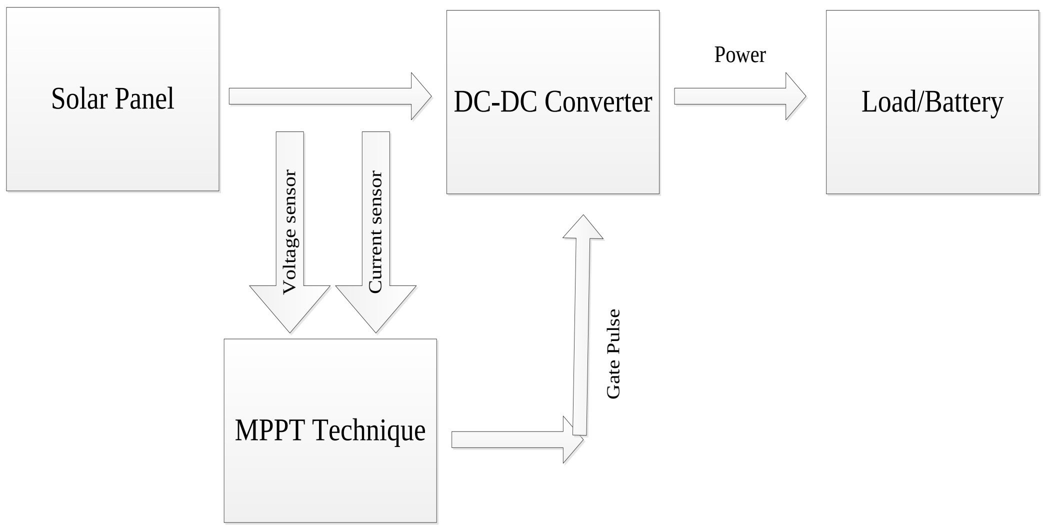

Fig.5.7 General Solar Power to Electrical Power Conversion Block Diagram

There are many MPPT techniques present which can be applied to the dc-dc converter, some examples are listed below:

i Perturb and Observe (P&O)

ii Increment Conductance (INC)

iii Fuzzy Logic Control

iv Neutral Network

There many more new MPPT algorithm present which are based on the many other concepts. However Perturb and Observe is the technique which is used in this project. Using MPPT technique is necessary as it enhance the efficiency of the solar PV system. In this project P&O MPPT Algorithm has been used.

The Maximum power point tracking technique is the promising controller technique to harvest maximum amount of power from the solar PV panel. The perturb and observe (P&O), also called hill climbing method is one of the popular MPPT technique. In P&O technique, the duty cycle of the converter gets update each time by sensing the PV voltage and current. This technique works on the principle to climb the peak of the P-V characteristic curve of the PV panel. There is a small amount of increment in the value of voltage in order to climb the peak of the curve, hence the value of power also increases and duty cycle of the converter also adjusted to maintain the value of output voltage. The further increment of the value of voltage by small perturbation continues until the increment in the power stops. The increment in the value of voltage and current is operated by considering the $dP/_{dV}$ value. As in fig, 5.3, that on the left of MPP, the value of $dP/_{dV}$ is positive, on the right of the MPP, the $dP/_{dV}$ is negative and at the MPP $dP/_{dV} = 0$. Fig.5.8 shows the algorithm of P&O MPPT technique.

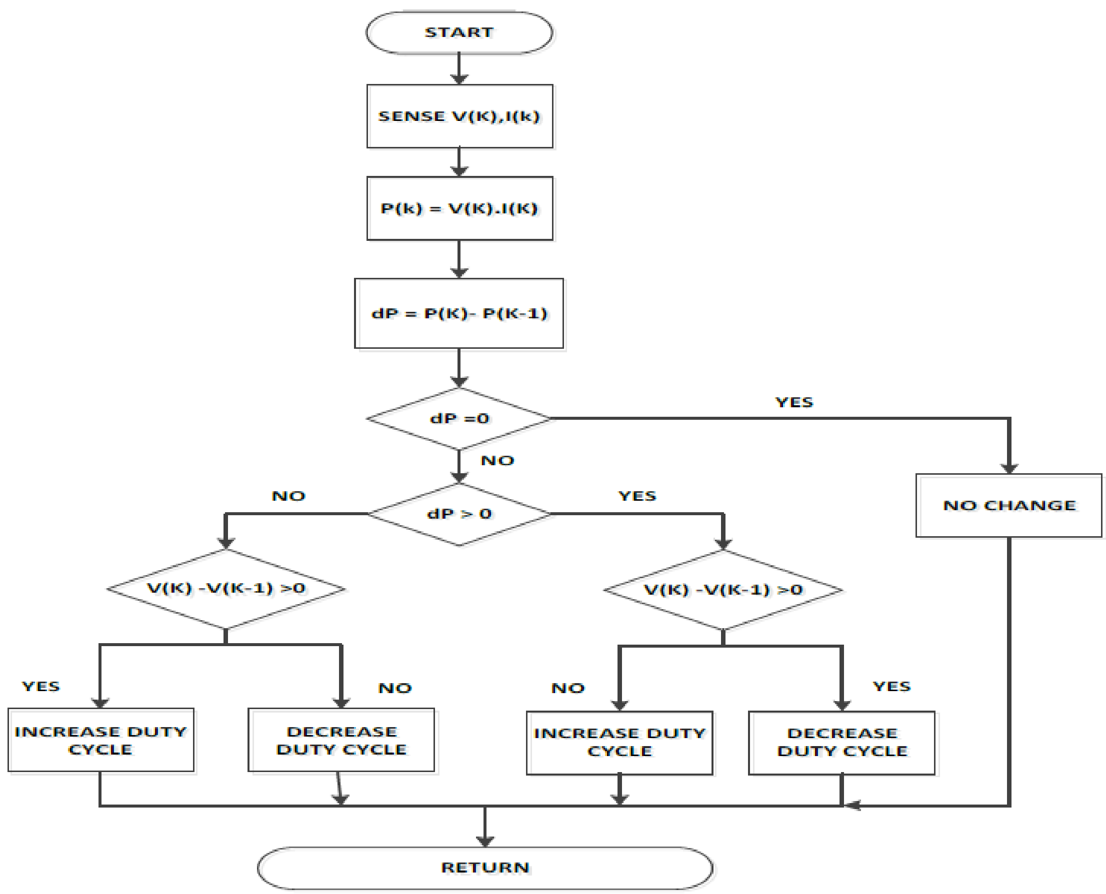

Fig.5.8 Algorithm of P&O MPPT Technique

The Appendix A5 shows the MATLAB simulation block of MPPT boost converter using P&O algorithm. The delay applied in this block is 0.001. The input voltage V_{in} and PV current I_{pv} which are measured from the PV solar panel and given to the MPPT controller block. The

MPPT controller produces the gating pulse which is provided to MOSFET of the boost converter.

5.4 DC-DC Converter

In the given project the voltage level has been converted twice for feeding the output of solar PV panel into the battery. This change in voltage level has been done in two stages. The first converter used is DC-DC boost converter, which is having the gating pulses from the MPPT controller. The other converter used is buck converter which is reducing the voltage level to feed it into the battery. The reason of using two stages DC-DC converters are:

1. To extract the maximum power from the panel MPPT controller is used. The boost converter can extract maximum voltage and hence the power whereas buck converter cannot be advantageous every time.
2. The buck converter with MPPT technique produces the ripples in the further power circuit, whereas the boost converter has the inductor at the starting of the power circuit. Due to inductor position, the current ripples in case of boost converter are much less.
3. The SEPIC type of converter can be used in some cases of PV array plant, but it cannot transfer high power output.
4. This two stage converter has more favourable inductor positions in the electrical connection. The boost converter inductor is used to reduce the current ripples at the starting of solar PV plant and the buck converter inductor is used as the output inductor which helps in reducing the current ripples while the power is feeding to the battery.
5. The efficiency of the two stage converter is higher than the case when only buck converter is taking power from solar panel and feeding the power to the battery (27).

5.4.1 Boost Converter Design

The boost converter is used to step up the output voltage from its initial input voltage value. The duty cycle is one of the parameter which help in increasing the voltage value. The boost converter design depends on the rating of PV panel used, load connected and the range of output voltage ripple and input current ripple. The circuit of boost converter consist of inductor, switch (IGBT/MOSFET), diode and capacitor. The switching device (IGBT/MOSFET) are selected by considering the switching frequency, voltage level and current level. Fig.5.9 shows the block diagram having boost converter circuit.

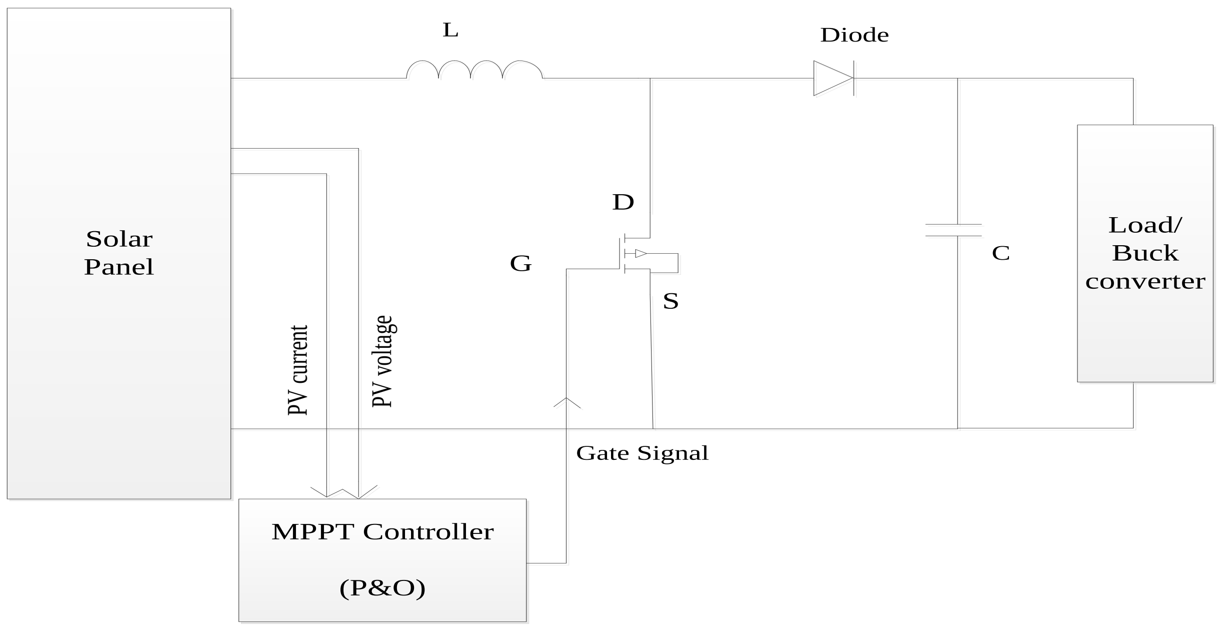

Fig.5.9 Block Diagram of Solar-Bridge Power Plant including Boost Converter

i Inductor value calculation

The inductor present in the boost converter helps in ensuring the minimum harmonic content during the continuous current mode. The value of inductor is expressed as

$$L = \frac{V_{pv} D}{2\Delta I f} \tag{5.6}$$

Where V_{pv} is the pv panel output voltage 328V, D is the duty cycle of the boost converter which is decided by using the input PV voltage and the voltage which is required at the output of the dc-dc boost converter. The value of duty cycle is around 0.23. The input ripple current ΔI should be in the range of 1%-3% of the input current. The input current is calculated as:

$$I = \frac{P_{pv}}{V_{pv}} \tag{5.7}$$

The value of input current comes around 66.87A. Therefore, the input ripple current value is around 6.7A. Also f is the switching frequency of the switch which is MOSFET in this case. The value of switching frequency is 10KHz. Hence, using all of this data the value of inductor calculated is 4.42mH.

ii Capacitor Value

The capacitor is present at the load side of the circuit. The capacitor value can be expressed as:

$$C = \frac{I_O D}{\Delta V f} \tag{5.8}$$

Here ΔV is the output voltage ripple whose value is around 3% of the output voltage. Therefore, the value of ΔV is 12V. I_o is the output current which is observed at the output side of the converter and expressed as:

$$I_o = \frac{P_o}{V_o} \tag{5.9}$$

The value of P_o is equal to the value of P_{pv}. The value of V_o is around 398V. Hence the output current comes around 55.27A. With all the given information, the value of capacitor is 68.78µF.

For proper working of the circuit with the given ratings of PV panel, the value of capacitor used is more than the calculated value because the dc-dc boost converter is handling the maximum power given by the Solar PV panel with the help of MPPT converter. The power rating used for choosing the switching devices should have higher voltage and current ratings, than the actual voltage and current present in the circuit.

5.4.2 Buck Converter Design

The buck converter is used to step down the level of voltage. The voltage present at the input of the buck converter is the output voltage of boost converter used at later stage. The output of the buck converter is going to the battery. The reason of putting the buck converter in before the battery is that, the voltage at the output of the boost converter is high i.e. 398V and a battery of this much voltage will be expensive for the practical use, as battery could be the most expensive part of the battery based solar power energy harvesting system. Thus there is a need of stepping down this higher voltage value to 122V. The duty cycle of the buck converter is given as:

$$D = \frac{V_{out}}{V_{in}} \tag{5.10}$$

The V_{out} is 122V, which is the battery voltage and V_{in} is 398V, which is the boost output voltage. The duty cycle for this converter is 0.31. Fig. 5.10 shows the electrical circuit diagram of buck converter.

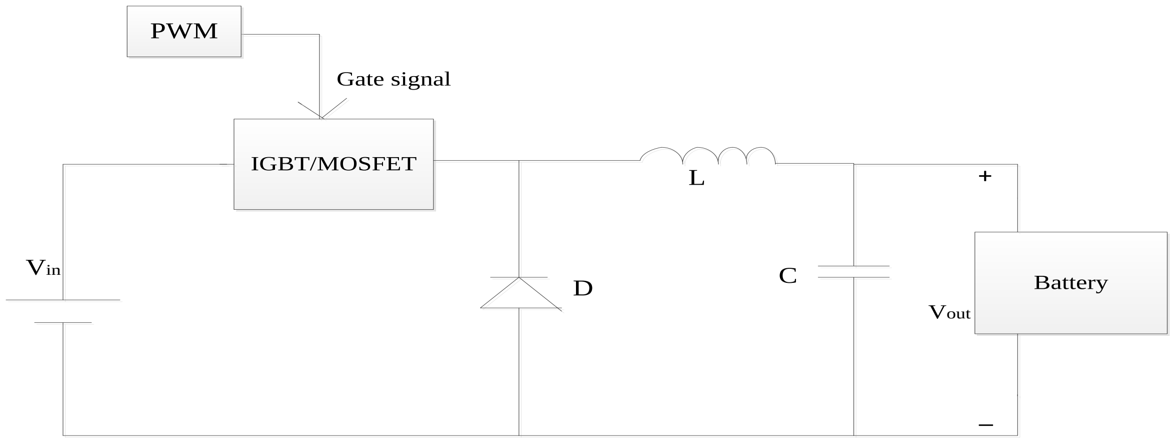

Fig.5.10 Buck Converter

i Inductor value calculation:

The ripple current which is used for the calculation of inductor value. The ripple current indicates the amount of ripples or harmonics present in the circuit. The inductor value can be calculated by:

$$L = \frac{(V_{in} - V_{out})D}{f\Delta I} \tag{5.11}$$

Where f is the switching frequency of the converter which is 10 kHz. The inductor ripple current should be around 2%-4% of the output current value. By putting all the values in eq 5.8, the value of inductor is 2.37mH.

ii Capacitor value calculation

The capacitor is present at the output side of the converter. The value of capacitor can be calculated by using the given equation:

$$C = \frac{\Delta I}{8f\Delta V_{out}} \tag{5.12}$$

The value of ΔI is same as that of inductor case, the value of ΔV_{out} is 2-4% of output voltage to the converter. The calculated value of the capacitor is 12.33μF. But the converter has to handle the maximum power flowing through it, so the value of capacitor used is higher than the calculated value.

The another reason of using the boost- buck combination is that as given in fig 5.3 and fig 5.4, the place of inductor is different due to which if the buck converter is used at initial stage with mppt technique, the ripples and harmonics in the output will be more. And using boost converter can reduce the harmonic content in the output due its inductor position. Also feeding very high voltage value to the battery is very expensive, as this case is generally avoided in this solar energy harvesting system.

5.5 Constructional Details Of The Bridge

The bridge has been suggested to build on the railway track of Metro i.e. the width of the bridge to be constructed should be approximately equal to the width of number of railway track lines present on the ground. Fig. 5.11 showing proposed bridge structure.

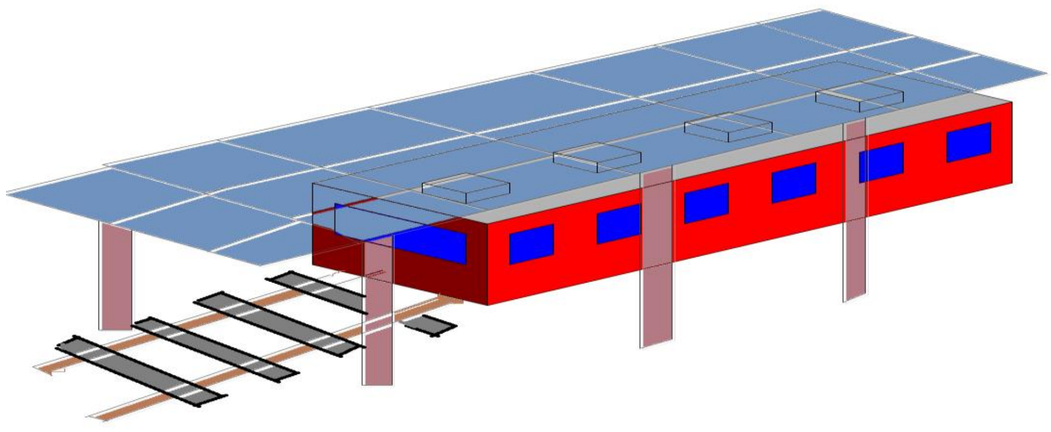

Fig.5.11 Proposed Diagram of Solar-Bridge Electrical energy Harvester

Considering that the distance between two metro stations is 2km. The constructional details for the bridge is given below:

The rating of solar panel=400W

The size specification of the solar panel= 1m×2m=2m^2

Considering the length of the bridge= 1000m. And as the width of the bridge must be around as the width of the railway track. The distance between two railway tracks known as railway gauge is 1.6m. For the to and fro movement of the train, two railway tracks are provided on the ground. Thus, the width of the railway track is around 4m (28). Hence, Width of the bridge= 4m

To install 10 solar panel in series and 3 strings in parallel, the required area =total number of panels used × area of 1 solar panel

=30×2=60m^2

To install 10 solar in series, the length of the bridge used=20m

Total width of the bridge used for 3 strings of 10 solar panels in series= 3.2m

Thus, a set of 10 panel in series and 3 of that string in parallel can harvest 12kW of power. As the distance between two consecutive metro stations is 2Km, there can be 2 sets of this 10×3 solar panel array. Therefore, the total amount of electrical energy produced is 24kW. The main advantage of this type of bridge construction is, there is no need of new spare piece of land as the bridge construction can give the rooftop on which the solar panel can be installed

5.5.1 MATLAB Result And Discussion

The MATLAB simulation has been used to produce result and analyzing the voltage waveforms. The MATLAB simulation has been done on the basis of the given block diagram given in Fig. 5.12.

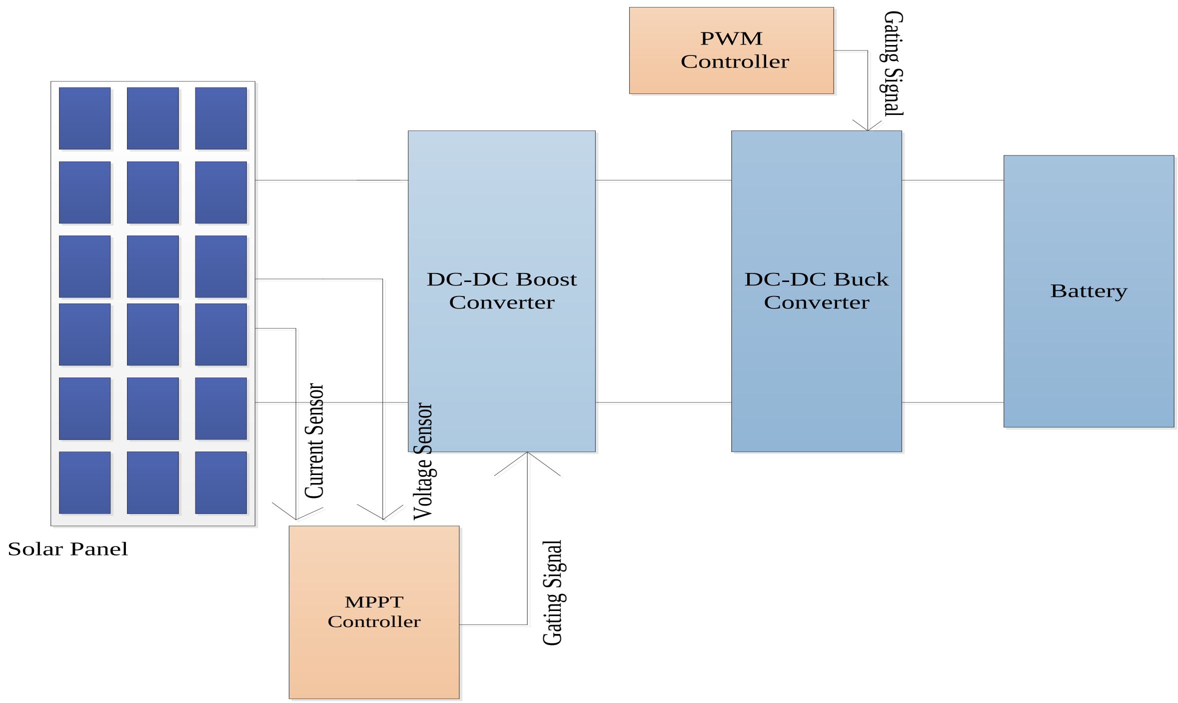

Fig.5.12 Block Diagram Of Solar-Bridge Electrical Energy Harvester

The block diagram shown in fig. 5.12, the solar rays when fall on the PV panel, the electrons get activated and the process of generation of electricity begins. The DC-DC boost converter helps in boosting up the voltage level and then reducing the level to feed the power to the battery. The two controllers i.e. MPPT and PWM controller are used for boost converter and buck converter respectively.

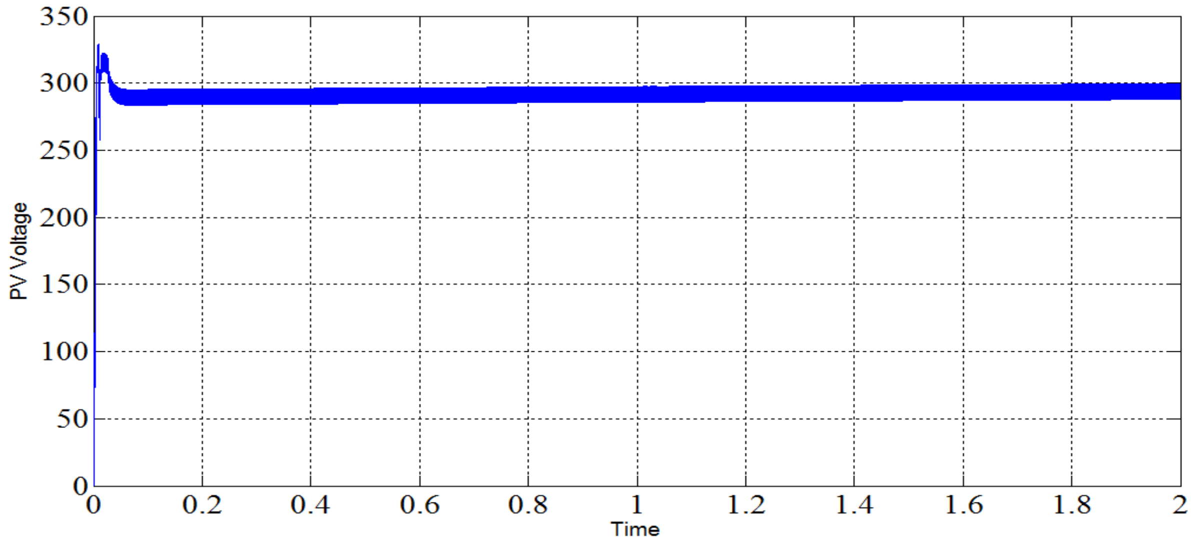

Fig.5.13 PV Panel Output Voltage

The given Fig.5.13 shows the output voltage of the solar panel. There are 10 panels connected in series and 3 strings are connected in parallel, with this type of arrangement, the output voltage of PV panels is around 300V. The voltage and current from the solar panel is sensed by the MPPT controller.

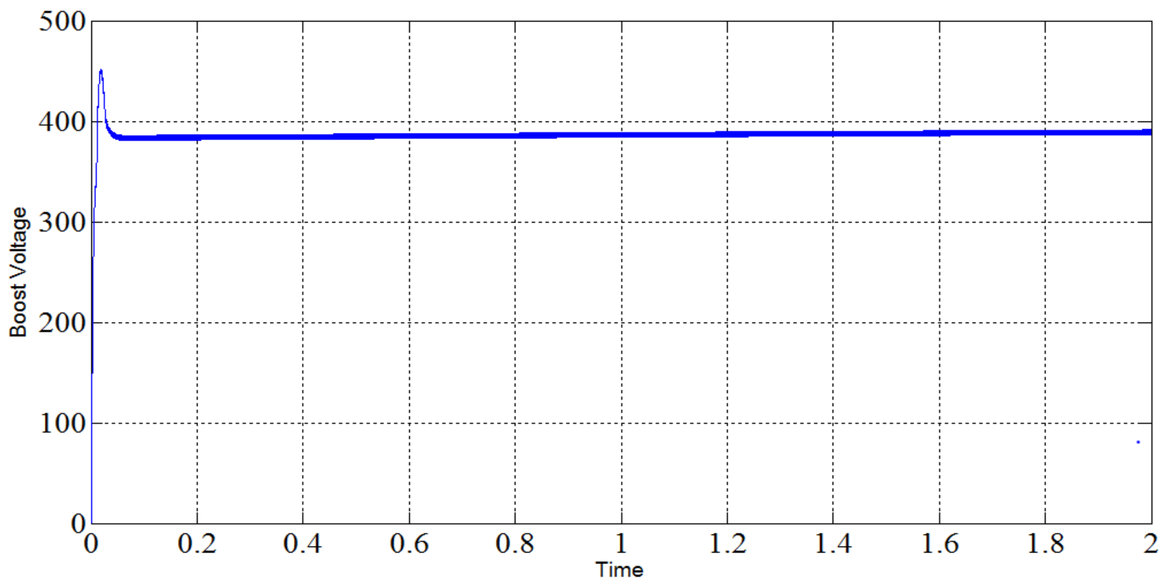

Fig.5.14 Boost Output Voltage

The given Fig.5.14 shows the voltage waveform when the input voltage is boost up to the value of 398V. The MPPT controller helps in generating maximum output power from the solar panel at the particular value of temperature and solar irradiance.

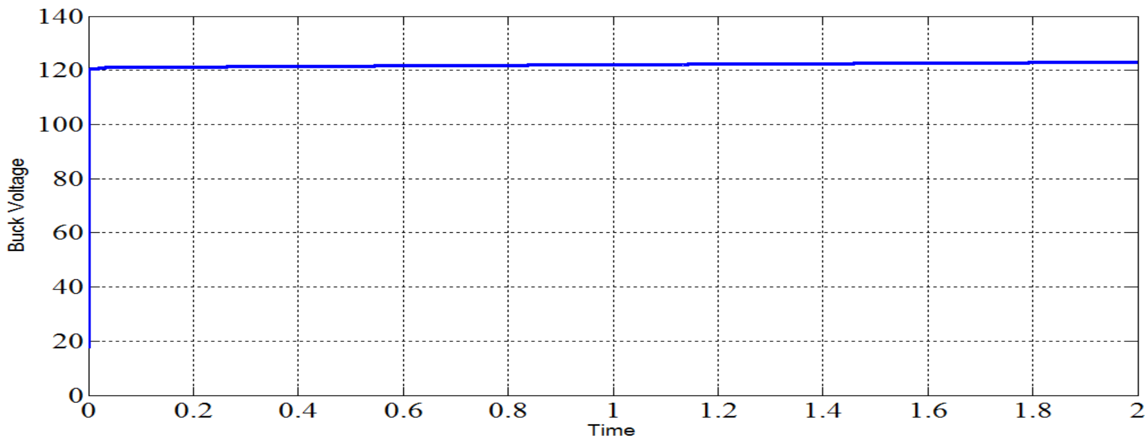

Fig.5.15 Buck Output Voltage

The given Fig.5.15 shows the magnitude of buck converter output voltage i.e. 122V. The PWM controller helps in controlling the gate signal for the switching device present in the buck converter, it also helps in generating constant output voltage of magnitude of 122V, irrespective of change in the output of solar PV panel due to different atmospheric conditions.

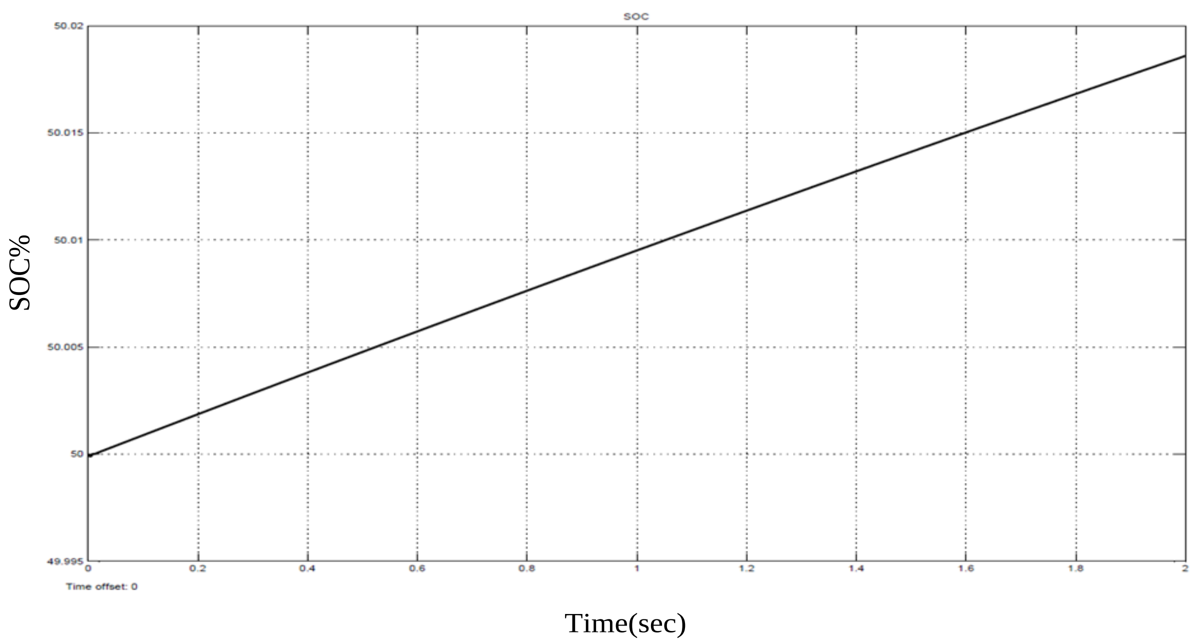

Fig.5.16 SOC of the battery

The given Fig.5.16, shows the state of charging of the battery. In this case SOC% is 50%. The increasing slope of SOC indicates the charging state of battery.

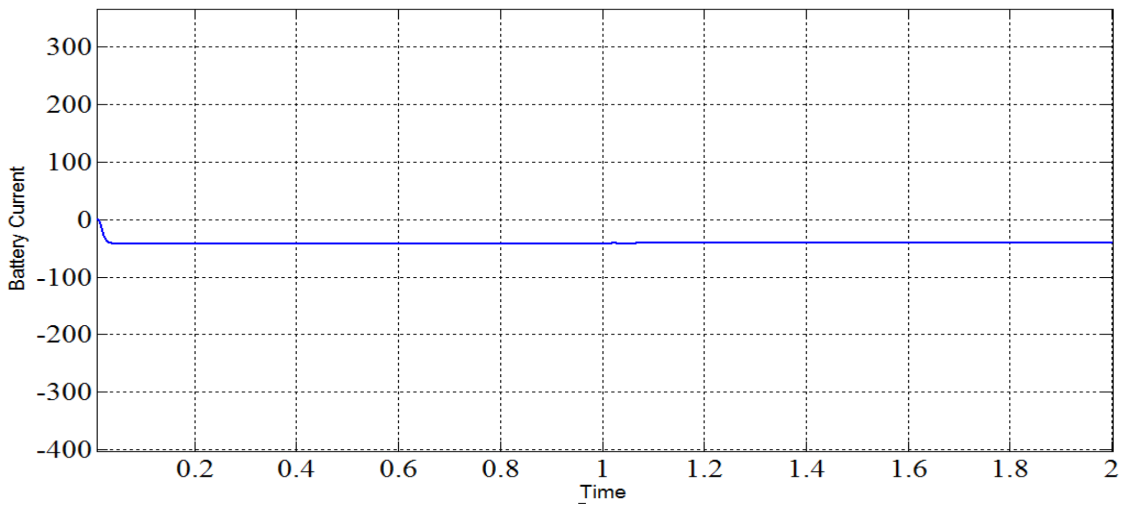

Fig.5.17 Battery Current

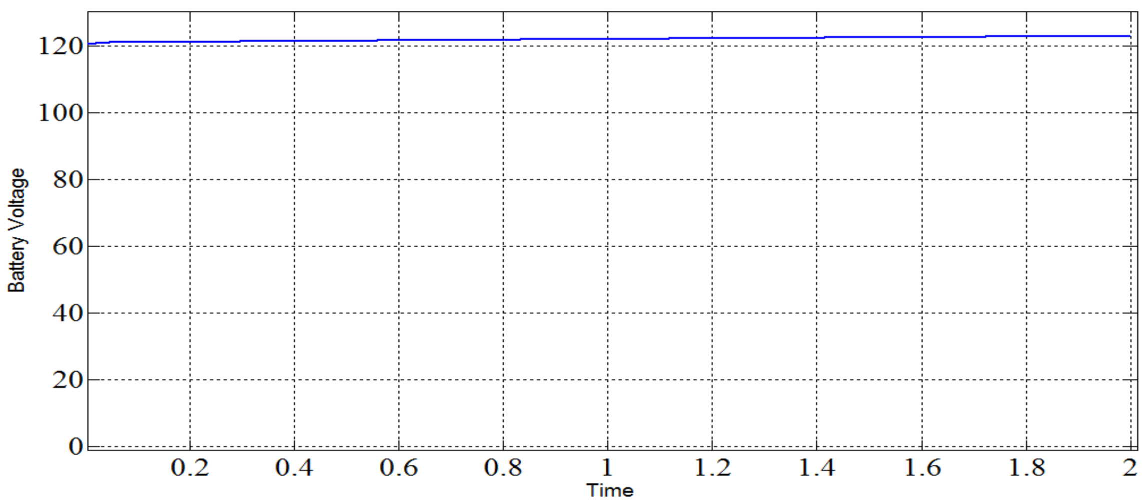

Fig.5.18 Battery Voltage

The given two Fig.5.17 and Fig.5.18 indicates the battery voltage and battery current. The negative battery current indicates that the battery is in charging state. The battery voltage is 123V and battery current is -16A. The lead acid batteries are used for storing the power.

5.6 Conclusion

The Solar PV power plant is one of the efficient system to generate electrical. The project has been suggesting that some vacant space, with the help of some construction can become excellent location for installing solar PV plant. The electrical energy is going to be feed in the battery so that it can be used later.

CHAPTER-6

SOLAR-PIEZOELECTRIC BASED PROTOTYPE MODEL

6.1 Introduction

There are many renewable resources which are in use for generating electrical energy. These renewable resources may complement each other to get good amount of electrical energy output. There are many sectors of the country which are now attempting to move on the renewable sources of energy to generate electricity such as solar pumps are now introducing in the agricultural sectors, industries are trying to get electrical energy from renewable hybrid plants, house rooftops are now started to use as a location for installation of solar panels to generate and use the electrical energy for household purposes, etc. The Railway sector is also attempting to install the solar PV panels at all the possible locations at the railway stations and on the rooftop of the train bogie itself. All these attempts are helping in generating electrical energy from the renewable sources which is also reducing the stress on the grid.

After studying the two types of electrical energy harvester i.e. piezoelectric energy harvester and solar PV panel enabled bridge system, the prototype model has been suggested. This prototype model will have the solar PV panel enabled bridge system between two Metro stations and Piezoelectric pads on the railway tracks i.e. embedded in the cross junction of railway track and sleeper and also some piezoelectric pads on the floor of railway station, so that the number of foot falls can help in generating some amount of electrical energy In this project, the railway tracks are used for installing the renewable sources for generating electrical energy. The project involves the piezoelectric energy and solar energy are used to generate electricity. The compression type PES can generating more electrical energy than the cantilever beam type piezoelectric system. The solar power generating system is one of the promising type of renewable energy sources of energy. The solar PV panel has the photovoltaic cell which generate the electrical particles when the solar rays falls on them. The rooftop of the bridge has been used for installing the solar PV panel. The number of panels to be installed is depend on the amount of electrical energy one want to harvest.

On comparing the amount of power generating by two energy harvesting systems i.e. piezoelectric energy harvesting and solar power plant, the solar power plant generates more electrical energy than piezoelectric energy harvesting system.

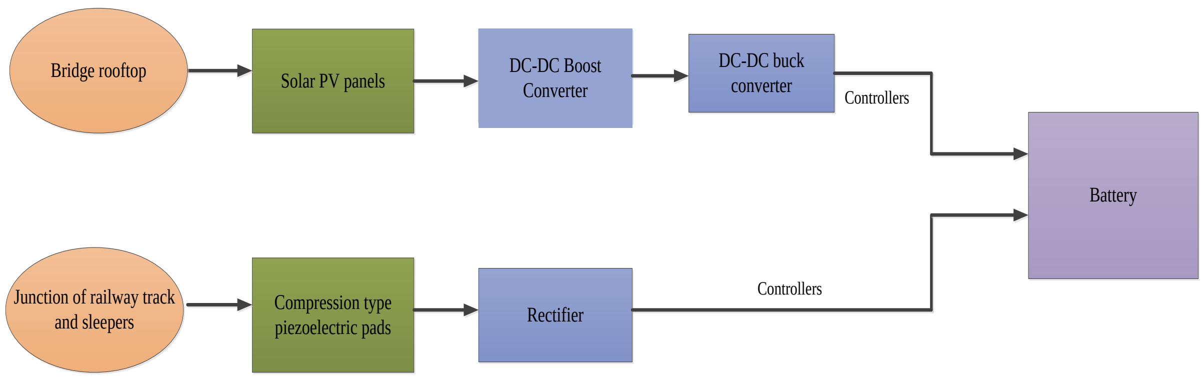

Fig.6.1 Block Diagram of the Prototype Model

The block diagram in Fig.6.1 describes the methodology by which the electrical energy from both the renewable energy sources can be collected in the battery. The controllers are used to control the voltage level so that both the energy sources are feeding the electrical energy at constant voltage to the battery.

The given Fig.6.2, shows the exact positioning or locations of the electrical energy harvesting systems. This figure is only showing one track but in practical here are at least two tracks for to and fro movement of the train. More number of tracks on the ground can increase the width of the bridge and therefore more electrical energy can be harvested from the solar panels. The figure below shows the prototype model.

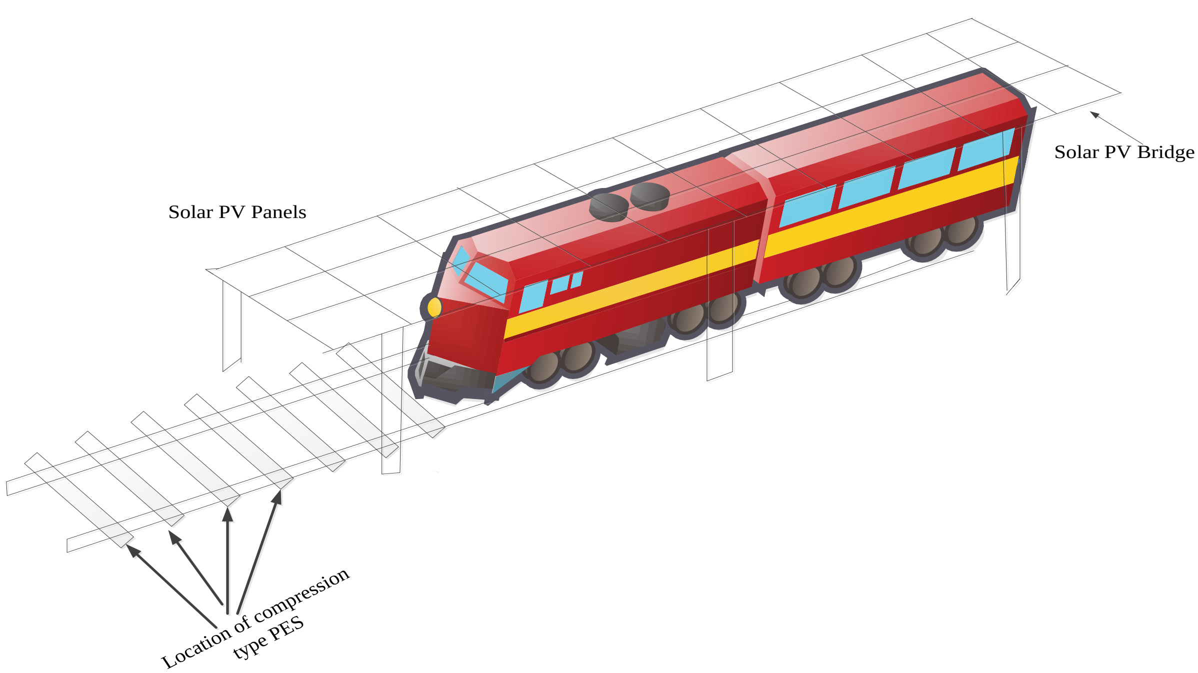

Fig.6.2 Locations for Energy Harvesting Units

6.2 Energy Harvesting System

The two types of energy harvesting system used in this prototype model are solar PV energy harvesting system and piezoelectric energy harvesting system. This type harvesting system can generate good amount of electricity. The solar energy harvesting system to be installed on the bridge constructed on the railway track. While the piezoelectric pads are embed on the floor of the railway platform and also at the cross-junctions of the railway track and the sleeper. The detailed constructional features is given below:

6.2.1 Piezoelectric Energy Harvesting System

The energy harvested by the piezoelectric system is mainly dependent on the physical modal of the generating system. The compression type piezoelectric and cantilever beam type piezoelectric harvesting system are two main types of piezoelectric structures used for generating electrical energy. The piezoelectric harvesting system is converting the mechanical energy into the electrical energy. The electrical energy harvested by the footsteps of human on the piezoelectric tiles and also using the piezoelectric pads in the soldier’s shoes motivates for the idea of generating electricity from large force/ weighted objects. There are many places like Eastern Railway Stations of Japan has been already installed the piezoelectric tiles at the ticket collecting area, hence with each number of footfall some amount of electricity can be generated which is stored in the battery for further use, Also the roads near the California University now trying to build with the piezoelectric pads so that every time when a car or other heavy vehicles moves over it, some amount of electricity can be produced. There is a US patent filed by the Israel company Innowattech suggesting the number of places near the railway tracks and on the railway tracks which can be used for the installation of different types of piezoelectric structures namely the compression type piezoelectric system and the cantilever beam type piezoelectric system. The cantilever beam type piezoelectric structures should be present on the very side of the railway track so that the ground vibrations produced when the train passes through that point can generate electricity. The compression type piezoelectric system should be located at the cross junction of railway track and sleepers so that a good amount of electricity can be produced. As discussed previously that compression type piezoelectric system is more reliable, economical and producing more amount of electricity than the cantilever beam type piezoelectric system. The table 6 shows the amount of electrical energy produced by different types of train:

Table 6. Different types of Trains Generating Energy from Piezoelectric Effect

S. No.	**Type of train**	**Weight(Ton)**	**Energy (J)**
1	Suburban	50	0.105
2	Passenger	60	0.188
3	Freight	80	0.42

A coach of a Metro train can weigh up to 50Tons. For calculating the amount of electrical energy generated by the movement of the metro train on piezoelectric pads enabled tracks, the analysis is given below:

The number of wheel a metro coach has= 8

the weight shared by one wheel= $50/8$ =6.25Tons

the forced applied by the wheel on the track= $6.25 \times 9.8 = 61.25$kN

The charge generated in the piezoelectric unit by this force= $Q = d_{33} \times F$

$=390\times10^{-12}\times61.25\times10^{3}$

$= 23.89\times10^{-6}$C

The number of piezoelectric pad installed on cross junction of railway track and sleeper is 40.

The number of cross junctions used for installing these piezoelectric pads=1000

All the pads are connected in parallel, hence total amount of charge generated by the movement of a wheel= $40\times23.89\times10^{-6}\times1000$= 0.955C

The voltage generated on a single piezoelectric unit by the given force

$V = \frac{g_{ij}Ft}{A} = \frac{48\times10^{-3}\times61.25\times10^{3}\times1.82\times10^{-3}}{58\times10^{-3}\times15\times10^{-3}}$= 6.15kV

The energy generated by a coach= Q×V= 23.507kJ

There are generally 8 coaches in a metro train, the total energy= 188.06kJ

If the metro takes 1.5 min to cross the location of installed piezoelectric pads, the amount of electrical units produced= 4.7 KWh. If the metro train crosses this junction of installed piezoelectric pads 30 times in a day, total amount of energy produced by this array of piezoelectric pads in a day= 141 KWh.

The exact location of piezoelectric pads has been shown in the Fig.6.3:

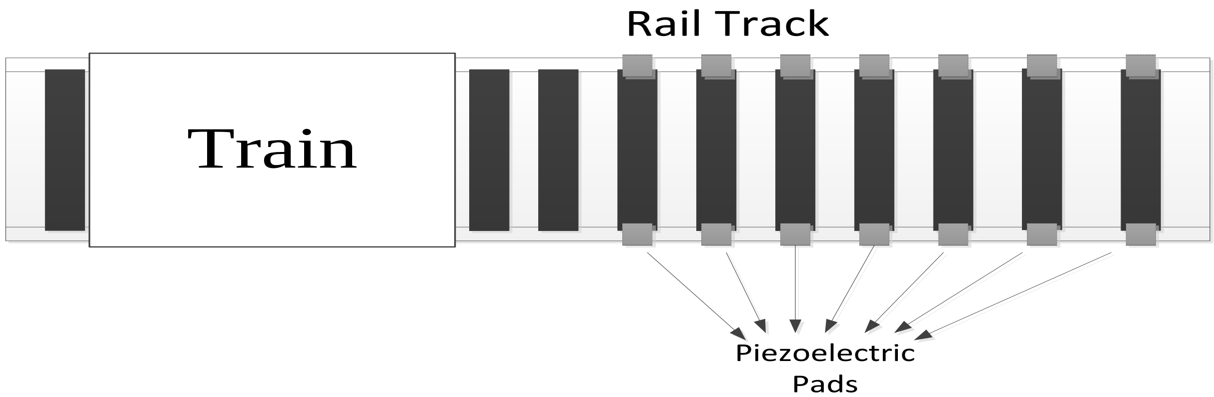

Fig.6.3 Location of Piezoelectric Units

One of the important point in the piezoelectric harvesting system is that the voltage generated by the single unit is high due to high force is exerted on the piezoelectric pad. This voltage is in alternating form which should be converted into the DC form to store it into the battery for further use. The block diagram describing the process is shown in Fig.6.4.

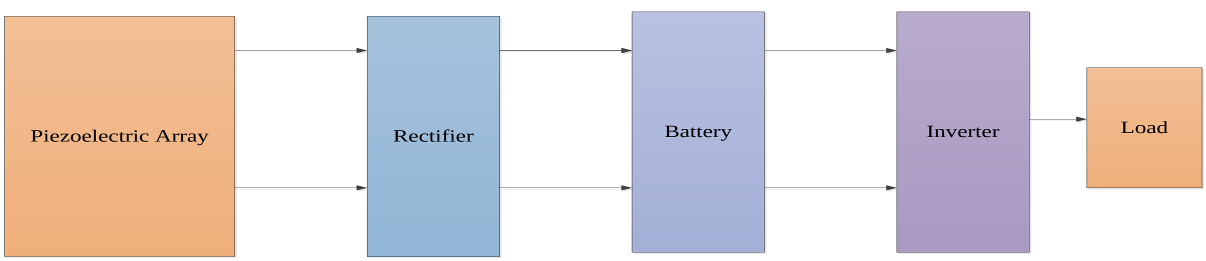

Fig.6.4 Block Diagram for Piezoelectric Energy Conversion

6.2.2 Energy Harvesting System from the Foot-Fall

There are many resources which can be used for the generation of electricity from the number of ways. The electro-mechanical way of producing the electricity involves the use of vibrations and frequencies of the moving object like moving vehicle,etc. The piezoelectric energy harvesting system can be used for the production of electricity from the weight or forces. The number of footfall can be used as the source of generating electricity. The higher the force, the more the electrical energy can be produced. Although, the amount of electricity produced by the foot-fall is not very high but it can be used for the led sensors and lighting system. Fig.6.5 showing the action of force on piezoelectric unit.

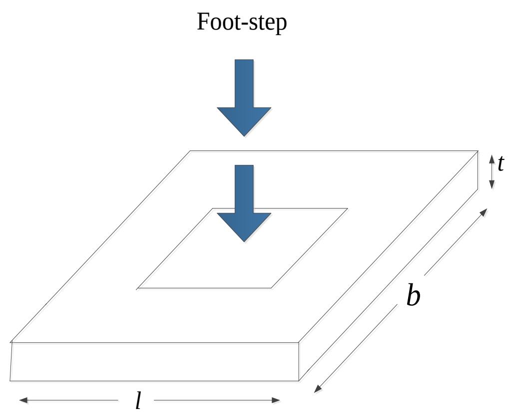

Fig.6.5 Force On One Piezoelectric Unit

The dimensions of the piezoelectric tile used for the production of electricity are 10cm in length, 5cm in breadth and 5mm in thickness. The calculations involved in the production of electricity from the footfall are given below:

The average weight of the person is around 65kg i.e. the person applies around 650N of force on the surface. Therefore, the amount of charge produced by foot step of a person, with the help of eq. (3.14) is 253.5nC.

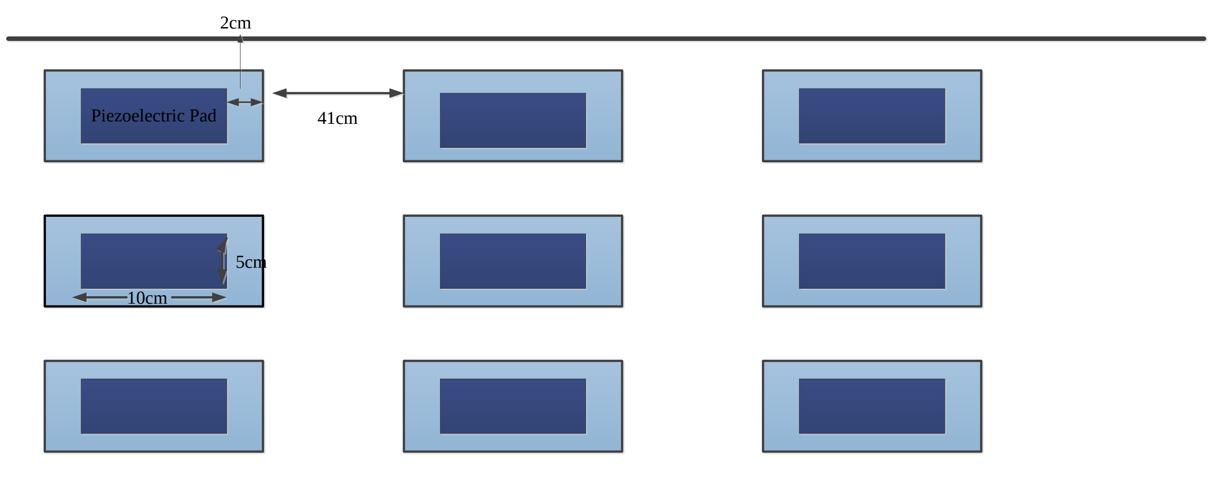

Fig.6.6 Proposed Piezoelectric Mat

As shown in the Fig.6.6, the piezoelectric mate is suggested to embedded on the floor of railway station. The distance of 150m has been used for installing this mat. Considering the fact that there is a distance between two footstep is around 45cm, the total number of piezoelectric pads used for given distance is 333. Three such strings are connected in series. Therefore, the total number of piezoelectric pads used is 999. The total charge generated by the foot steps of the people when the metro arrives at the platform is 0.253mC. Similarly the voltage produced by the foot-steps can be calculated by using eq,(3.12), the voltage produced by unit is 31.2V. The total voltage produced by the foot-steps at a time when metro arrives is 93.6V. If 250 people are passing over the piezoelectric mate at a time, the current produced by the total number of piezoelectric units is 21.08mA. Thus, the voltage and current produced when a batch of people passes over the piezoelectric mate are 93.6V and 21.08mA.

At a metro station, the frequency of Metro Trains arriving at the platform is very high. According to Delhi Metro Authority, the Metro train arrives at every 6-8mins interval of time(29). Thus in a day, there is 150 times the metro train arrives at platform. Therefore, the power produced by the piezoelectric mate at the end of a day will be around 295.5W. This much power can be stored in the battery and can be used for lighting some lights.

6.2.3 Solar Energy Harvesting System

Solar is one of the most important source of energy for earth not for plants and humans for their basic living system but now it start emerging as one of the finest source to harvest electrical energy. Many research projects related to the energy harvesting through solar rays are going on. Now the solar power generation is being used in the space craft to reduce the energy carrying capacity of the space craft and hence weight of space craft is reduced. Combining solar power plant with some other sources of energy can help in generating good amount of electricity like hybrid plant using solar power plant and wind power plant, solar power plant with hydro power plant, and many more combinations to harvest large amount of electricity and tie up this power with grid system.

The solar PV panels are made up of PV modules which contains PV cells. The voltage generated by the single cell is 0.3V-0.5V. The module contain 36 of these cells in series and these modules are connected in series and parallel to form the PV panel. There are many attempts going to combine the solar energy harvesting system with piezoelectric energy harvesting system, so that some disadvantages of piezoelectric system can be compensated with solar power plant. The block diagram describing the generation and storage of electrical energy is given below in Fig.6.7:

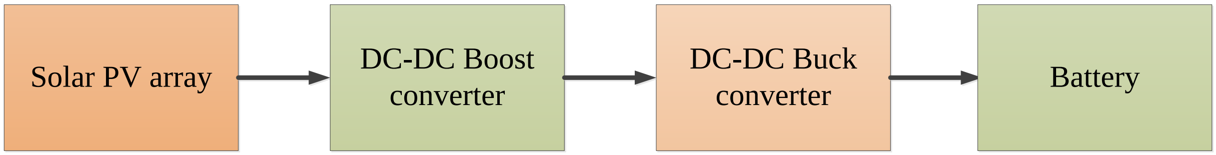

Fig.6.7 Block Diagram for Solar energy Conversion

The solar panel can generate the direct voltage but its value is low, so the DC-DC boost converter has been used in solar power generation to increase this value of voltage. The MPPT controller has been used for generating the gate pulses for the switching device present in boost converter. This controller sense the voltage and current from the PV array and changes the value of power in order to get the maximum power at every perturbation step, hence the duty cycle of the converter also changes to get the maximum power condition. The high value of the voltage is stepped down by using the buck converter to feed the electrical power to the battery. The buck converter uses the PWM controller technique to generate the gate pulse for the switching device.

The specification construction of the bridge containing the solar rooftop is given below:

The length between two consecutive stations is assumed to be 2 km.

The rating of solar panel=400W

The size specification of the solar panel= $1m\times2m=2m^2$

Considering the length of the bridge= 1000m

Width of the bridge= 4m

To install 10 solar panel in series and 3 strings in parallel, the required area =total number of panels used × area of 1 solar panel

$=30\times2=60m^2$

To install 10 solar in series, the length of the bridge used=20m

Total width of the bridge used for 3 strings of 10 solar panels in series= 3.2m

A set of 10 panel in series and 3 of that string in parallel can harvest 12kW of power.

Thus, if the 5 sets of the 10 series and 3 parallel array of PV solar plant is to be installed on the rooftop of the bridge, the total area to be present on the rooftop = $5\times 20\times 3.2=320m^2$. Hence, the total amount of electrical power produced is 60kW.

According to weather study, the good irradiance solar light and temperature is present for about 5 hours in North India. Thus total electrical unit produced by the project is 300kWh. The lead acid battery specification which is used is 120V and 100Ah, which is 12kWh. Thus, the number of batteries used in a battery bank= 300/12=25.

The total energy generated by both the systems=60+141=201kWh. This is a good amount of electrical energy which can be generated by the combination of solar resources and piezoelectric energy harvesting systems.

6.3 Conclusion

The conclusion of given study suggests that the railway station and its nearby area can be used for the generation of electricity from the natural and conventional resources like solar energy and piezoelectric units. The advantage of this type of project is that it does not require the vacant large piece of area for installation of solar and piezoelectric energy harvesting plant. The piezoelectric effect is using the kinetic energy of the person which is not in a proper use and this kinectic energy can be used for the generation of electricity.

CHAPTER-7

CONCLUSION AND SCOPE FOR FUTURE WORK

7.1 Conclusion

The overall project of harvesting energy from the renewable resources is divided into two segments. The first segment involves the study of piezoelectric effect and how an electricity can be generated by this effects. The research study nowadays focusing on the topic of piezoelectric effect. This piezoelectric effect is not only studied by the electrical engineering department but, the mechanical department and civil department also work in this topic. The piezoelectric pads on the periphery of the vehicle tyres is some type of research done by the mechanical department with piezoelectric effect. The construction of roads with the piezoelectric materials embedded on the road is one of the topic which under the research by the civil department. The electrical department is involved in the analysis of amount of electricity produced by the piezoelectric units. The two types of piezoelectric structure used for analysis of the electricity production are- compression type piezoelectric system and cantilever beam type piezoelectric system. The compression type PES is suggested to be installed at the cross junction of sleeper and the railway track, and the cantilever beam type PES is suggested to install at the very side of railway track, so that the ground vibrations can be used for production of electrical energy. The expression of voltage and energy produced by the single compression type piezoelectric unit is analyzed. Also in case of cantilever beam type piezoelectric system, the expression of voltage power and frequency at which the maximum amount of energy is produced has been analyzed. The MATLAB Simulink software has been used for analysis voltage waveform in both the cases, also the curves defining the variation between different parameters.

The technical analysis of the two types of PES has been done by using the sensitivity analysis. In case of compression type PES, the variation of energy function with respect to length, width thickness of the piezoelectric pad and also with the force applied on the piezoelectric pad. In case of cantilever beam type PES, the variation of frequency function with tip mass and variation of power expression with frequency of ground vibrations has been analyzed. With this analysis, the nominal values of sensitivity function has been calculated. The economic analysis of this type of energy harvesting system suggests that the compression type PES is less expensive than the cantilever beam type PES.

Thus, based on this techno-economic analysis, it has been suggested that the compression type piezoelectric system is better than the cantilever beam type piezoelectric system. Hence, an array of compression type PES unit is suggested to be embedded at the cross junction of railway track and the sleeper. The amount of electrical energy produced is good in amount.

The second segment of the project involves the construction of bridge on the railway track lines between the two consecutive urban metro stations so that the bridge rooftop can be used for the installation of the solar PV array. The one of the disadvantage of the solar panel is that it require large amount of area for installation of array if one want to generate good amount of electricity. This project suggests that the construction of bridge on the tracks can provide the area for installation of solar PV array. The good amount of electrical units can be generated by using the concept of construction of bridge because this idea eliminates the necessity to have a vacant area for installation of PV panel. Generally, there are to and fro metro railway tracks lying on the ground, therefore the width of the bridge is enough to install 3 parallel strings of PV solar panel. The distance between two consecutive metro stations is around 2.5-3km, therefore, the length of the bridge is enough to install 5 sets of 10 series connected PV solar panels. This type of installation of PV panels on the bridge rooftop can generate around 60kW. The average time of good irradiance condition in India is around 5 hours, which means it an generate 300kWh units.

The solar PV power generating system will consist of solar panels connected to the boost converter which is connected to buck converter which is feeding the electrical power to the battery. The boost converter has the switching device i.e. MOSFET which gets the gating pulse from the MPPT controller. This controller follows the Perturb & Observe algorithm for generating maximum power. The voltage and current from the panel has been sensed from the PV panel to change the duty cycle of the converter to get maximum power. The buck converter has been used to step down the voltage level to feed this power into the battery. The battery is lead acid type because it is economic for the given type of project.

7.2 Scope for future

There is some scope of future work in the project. The electrical voltage which generates in the compression type piezoelectric system is very high. The safety measures, insulation issues and application of such high value of piezoelectric system is a part which should be focused for future research. There can be some solution to this problem like converting this high AC voltage into the DC form by using rectifier and giving this DC voltage to the DC transmission line present nearby or this high AC voltage should be converted into DC voltage by using the rectifier, then the DC-DC buck converter can be used to step down this voltage level. This voltage level can then be applied to inverter to make it into AC form.

In case of solar power generating system, the multi-tasking converter or controller can be create with an algorithm to change the controller to change the system working as in a charging mode to the discharging mode when load is connected. And also there can be automatic switching of the system to provide the surplus electricity generated from the solar PV array directly to the grid.

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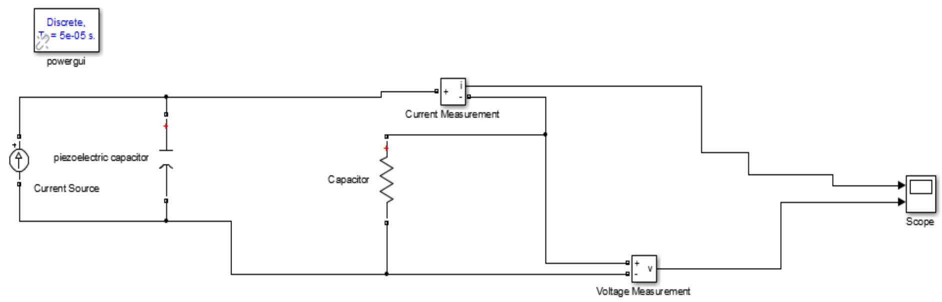
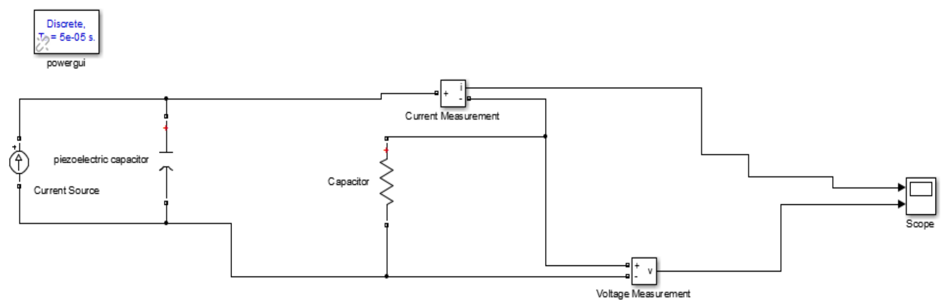
APPENDIX

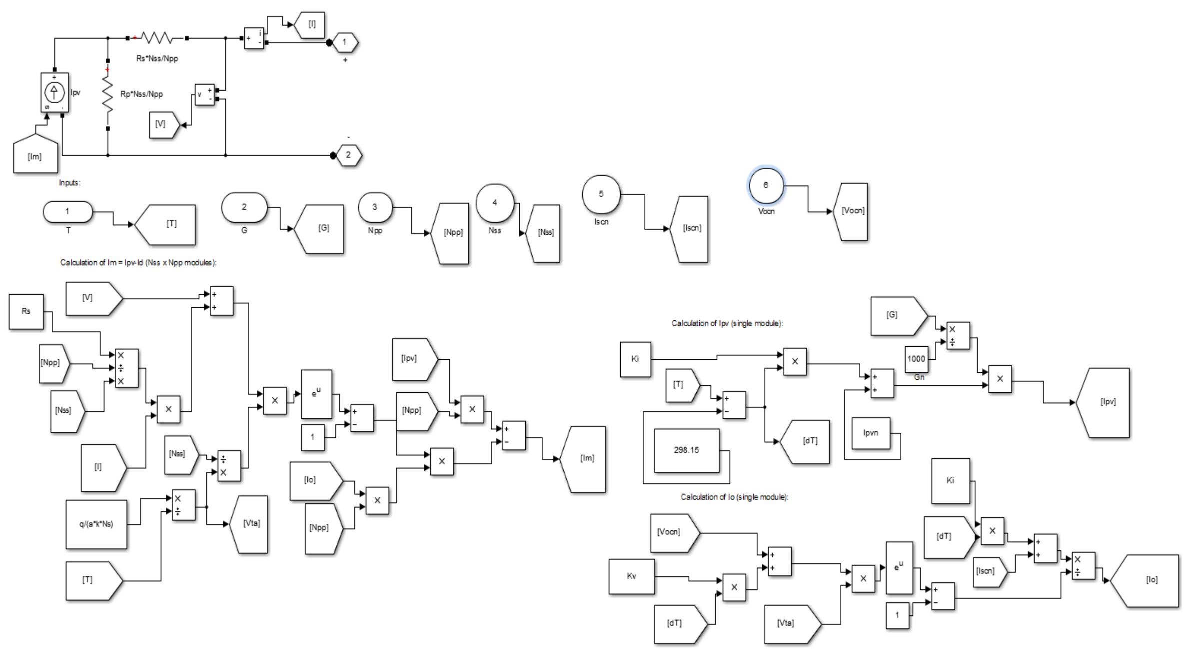
A1. MATLAB Simulink Model of Single Compression Type PES



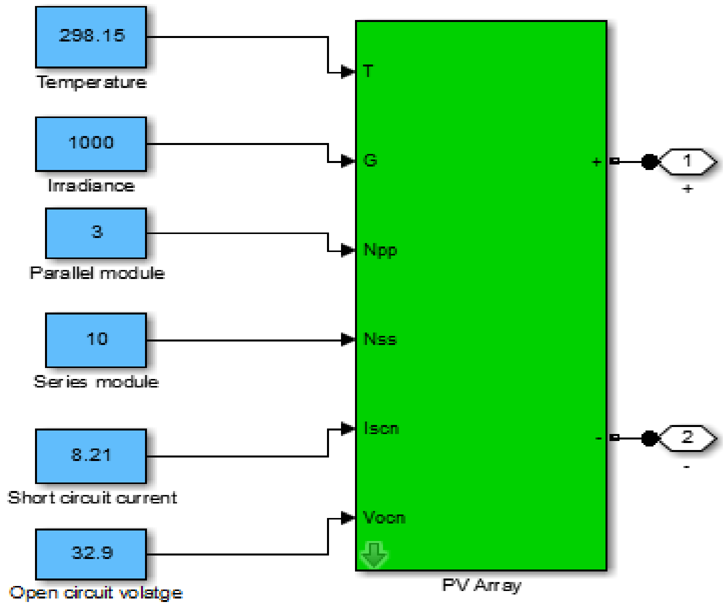
A2. MATLAB Simulink Model of Single Cantilever Beam Type PES



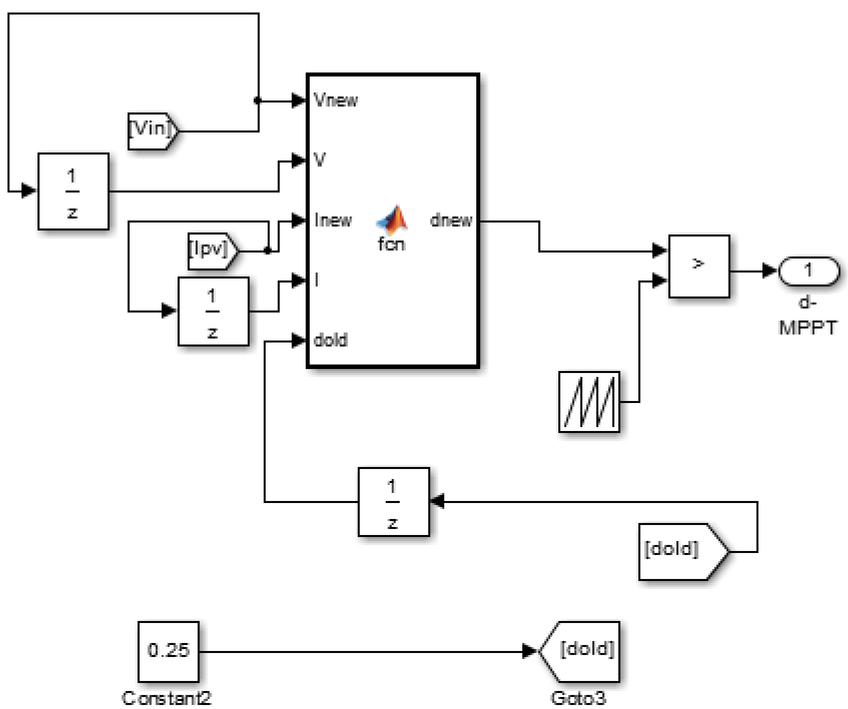
A3. Internal MATLAB Simulation model of PV Panel



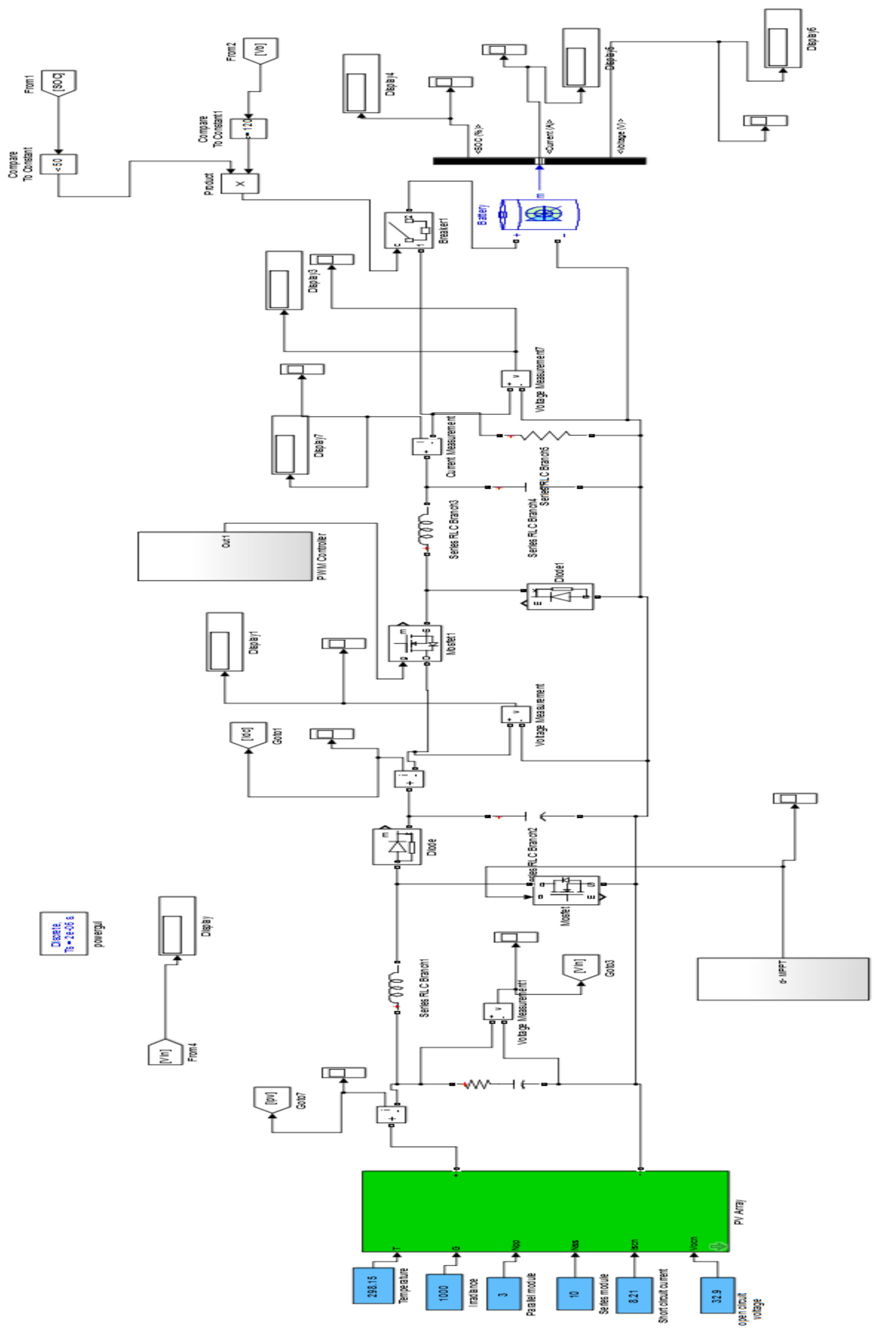
A4. Masked PV Solar Panel built in MATLAB Simulation



A5. MATLAB Simulation of MPPT Controller



A6. MATLAB Simulation of Solar-Bridge Electrical Energy Harvester



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