Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2017, 4(11): 858-865

Research Article ISSN: 2394 - 658X

Energy Harvesting for Electric Train: Application of Multi-Renewable Energy Sources with Sophisticated Technology

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ABSTRACT

Utilization of multi-renewable energy sources for railway vehicle or train is highly beneficial as an alternative source of energy for its operation. Harvesting energy from various sources such as solar, wind and piezoelectric material is focused in this paper. It is performed employing efficient methodologies found in previous research and concurrent technology with a view to increasing power generation and reducing electricity demand from the third rail (a semi-continuous rigid conductor along the rail track available for electric power supply). Choice of high performing solar panel, proper selection and positioning of wind turbine, introduction of aerodynamic shape to train body pave the way for harvesting greater amount of energy. This paper also describes the suitable methodology required for generating electricity from piezoelectric materials. Eventually, an integrated HESSs is implanted for storing energy in a reliant way.

Keywords: Solar, wind, piezoelectricity, ultra-capacitors and renewable energy

INTRODUCTION

At present, the world is faced with a problem of rapid declination of fossil fuel reserves which is a source of electricity and nuclear power plants fulfil energy demand significantly in many cases. But nuclear power plants are much expensive for third world countries. Therefore, to cope up with the increasing demand of energy in the modern era of technology, it is the prime concern of the researchers to develop the alternative sources of energy such as renewable energy and proper utilization of it. Implementation of various types of renewable energy harvesting methods is emphasized in this paper for the electric train. The train is one of the most common media of transportation for passengers and carriage [1]. Burning of fossil fuel for generating electricity causes greenhouse effect which is responsible for global warming. As a result, recent trend in railway transportation is to employ solar system for reducing greenhouse effect, decreasing dependency on fossil fuel based electricity generation. Structure of energy harvester in this regard is also free of complexity and pollution [2]. Adopting the effective technology, significant amount power from solar radiation can be extracted for a train. In the recent years, wind energy has reached to a maturity level of development and if wind turbine is associated with trains, wind energy to electrical energy conversion is performed which will reduce the dependency on electricity from third rail [3]. It is the quickest developing power source with numerous benefits such as green power, sustainable, moderate and monetary improvement. Introducing sophisticated design for harvesting wind energy with higher efficiency is one of the major challenges in this paper. A speedy train produces a huge blast that causes complication in wind energy conversion. Moreover, the usage of turbine may reduce the speed of the train. Quantitative analysis of the previous models was performed properly to overcome such type of drawbacks. Implementing wind energy harvesting method alongside with solar energy will reduce the weather dependency for energy harvesting. It is also one of our distinct goals to apply property of piezoelectric materials for generating power utilizing the heavy load of thetrain. Piezoelectric materials capable of generating electricity when compressed or vibrated is used for this purpose [4]. The fruitful implementation of stress will produce voltage and current (power) within the material, yet the stress must be reset in the state of relaxation with a view to generating power again.

The main contribution of this paper is to develop the operating system of the traditional train with multiple energy harvesting systems such as solar and wind. In addition to this, a special electrical property like piezoelectricity was employed in a benefitting manner to increase the production of electricity for the smooth operation of train. Emphasis was not only given for the implementation of the alternative energy sources but also adequate mathematical and technological analysis was done for the selection of the specific energy harvesting elements like the solar panel, wind turbine and it's positioning for increasing efficiency. Implementation of piezoelectric materials was also shown with high technical method analysing the previously established models. In a nutshell, aiming at an efficient and reliable performance of multi-level energy harvesting, numerical analysis was illustrated for different methodologies of solar, wind and piezoelectric material based energy harvesting and a smart train was introduced for meeting up the worldwide demand.

SOLAR ENERGY HARVESTING

The solar photovoltaic effect is the process where the light (photons) is converted to electricity. Semiconductor thin layers are used to be charged up differently between the top and bottom layers. Glass sheet casing or polymer case can be used to protect the semiconducting material. When they come in touch with daylight, the electrons of the semiconductor material absorb the protons and they become highly energized. The electrons move between the two layers. As a result, a dc current is produced. After passing through an inverter, the power is converted to alternating current. Fig1 shows the cumulative solar installed capacity for 16 years and in the 21th century the increasing rate is high which is very much convincing of solar energy conversion.

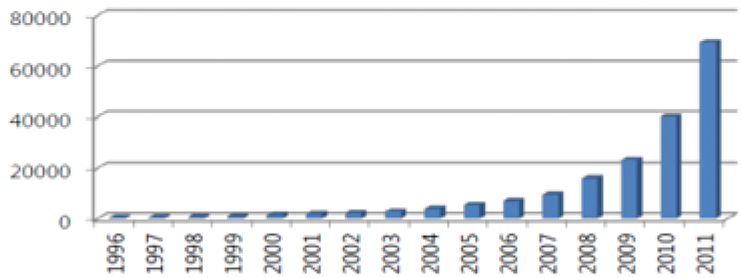

Fig. 1 Cumulative solar installed capacity [6]

Selection of High Performing Solar Cell

A larger amount of harvesting solar energy is significantly dependent on the performance of solar cell. The high performing solar cell shows several characteristics such as- 1. Abundance 2. Non-toxicity 3. Proper maintenance of high minority carrier lifetime. Silicon solar cell is proficiently used in solar panels as its upper limit efficiency is 29% [5]. We desire to recommend improved and efficiently designed silicon solar cell analysing different types of solar cell which has low reflection, low parasitic absorption, better light tapping capacity and these parameters reflects high conversion efficiency of solar cell. Silicon hetero-junction solar cell is used attractively now a day for its thinner substrate, low processing temperature and conversion efficiency of 23-24% in industrial environment [6, 7]. Analysing previous works, it is decided that designed methodology in [5] is more effective than other solar cells. It is realistically advantageous with back contact design which decreases resistive loss. Fill factor expresses the quality of a solar cell which is defined as the maximum power from the solar cell is to the product of V_{oc} and I_{sc}.

Fig. 2 shows variation of fill factor with respect to open circuit voltage and fig-3 represents the open circuit voltage vs efficiency. From fig. 2, it can be observed that as the open circuit voltage is high, fill factor is high and efficiency is higher for the first methodology. Fill factor and open circuit voltage depends on thickness which can be illustrated in fig. 4 and fig. 5 [5]. So for achieving better efficiency, the thickness can be set for solar cell using this graphical interpretation. For achieving fill factor 0.850, the thickness was set 100nm.

Solar Power Estimation

A typical power rating for a solar panel is 345 watts. The extent of this board is around 1.54 m by 1.04 m or around 1.6016 square meter. Along these lines, this board, at its most extreme, puts out 345 watts from daylight falling on its 1.6016 m^2 region. Another approach to state this is, a 345-watt sun-powered board puts out a greatest of around 215.409 watts for every square meter (345 divided by 1.6016 equivalents around 215.409) [8].

Let consider,

Single train coach's average length is 20 m and width is 3 m. Also, we assume that there are 15 coaches of a train.

Total area of required solar panel = 20*3*15 = 900 m^2.

Total power generation = 900* 215.409 = 193.87 kw.

The harvested power will vary according to the size of trains. Using silicon solar cell, it will be increased to a significant quantity.

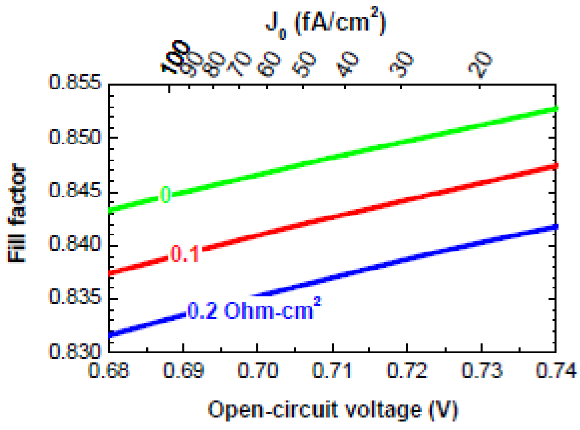

Fig. 2 Fill factor open circuit voltage [5]

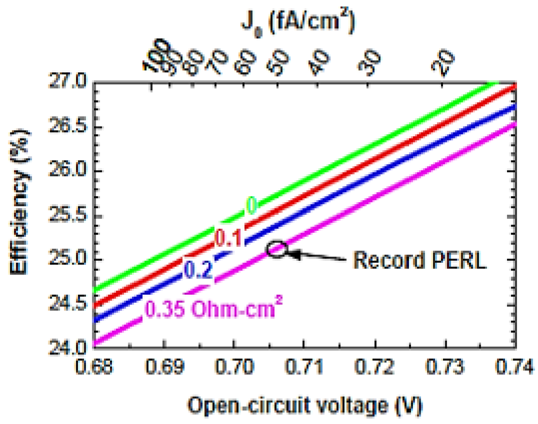

Fig. 3 Efficiency vs open circuit voltage [5]

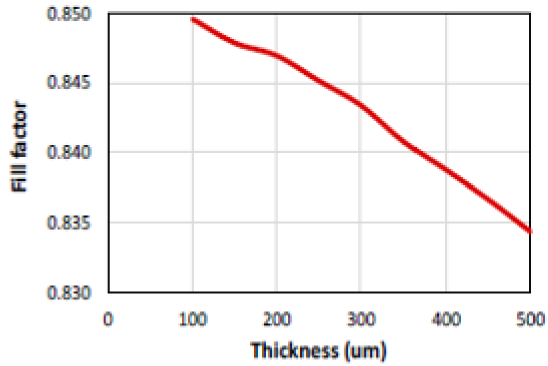

Fig. 4 Fill factor vs thickness

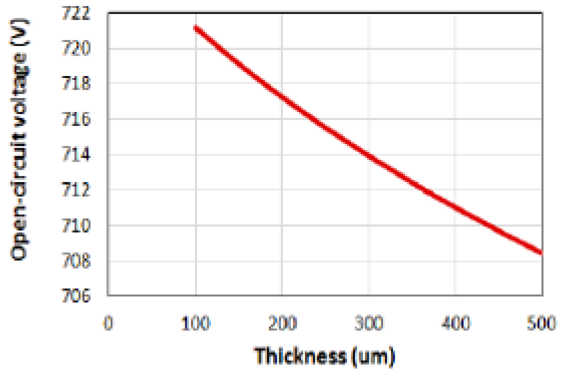

Fig. 5 Open circuit voltage vs thickness

WIND ENERGY CONVERSION

Wind energy conversion can be performed efficiently selecting suitable turbine, fixing proper position of the turbine for harvesting more energy. But setting up turbines on the rooftop of train also causes reduction in speed of train which is eventually impediment for larger amount of energy harvesting. For fruitful solution of this technical draw-back, aerodynamic shape for the train is introduced properly in the paper.

Selection of Suitable Turbine

Wind turbines can be broadly classified into two types. They are Horizontal Axis Wind Turbine (HAWT), Vertical Axis Wind Turbine (VAWT) [9]**.** The HAWT has higher output efficiency than the VAWT but it is not feasible to be used on a train because it would increase the drag and inherently increase the fuel consumption. Therefore, it can be used only when the train is stopping and where the drag is actually appreciable. But the operating time of the turbine would be very less. To overcome the hurdles, the VAWT is used as its blades are set to rotate in the plane vertical with respect to the ground level. By this way, it faces less drag. Moreover, VAWT is preferred more because it can handle tumultuous windy conditions and it can also operate on winds coming from any direction. So a constant regulation of the turbine is unnecessary. Compared to the HAWT its efficiency is less but it can be oper-ated during the running time. Therefore, it can be set to operate for a longer period. So the average output efficien-cy of a VAWT is much more than a HAWT making it preferable. Furthermore, VAWTs can be of two types: Dar-rieus Wind Turbines, Savonius Wind Turbines. Darrieus wind turbine is usually preferred for achieving wind en-ergy because it has a higher efficiency than its counterpart does. It is also lighter in weight, making it reasonable for rooftop use. But the only drawback is that it requires initial torque to start whose effect is of course offset by its higher efficiency and light-weight.

Positioning of the Turbines on Train

Though most proposals forwarded indicate the setting of the turbine on the top of the train, it is not appropriate because it would definitely increase the frontal area of contact creating greater drag. The trick here would be to utilize the physical phenomena of vortex shedding which occurs when a body moves through a fluid. As the body moves through the fluid, a pressure difference is created between the frontal surface (where the pressure is highest) and the adjacent lateral surface (where the pressure is lowest). This pressure difference creates a vortex, which revolves. This revolving vortex can be used to spin the turbine continuously. And thus a constant speed of revolu-tion is maintained. The fig-7 below shows the vortex shedding that occurs for the particular case.

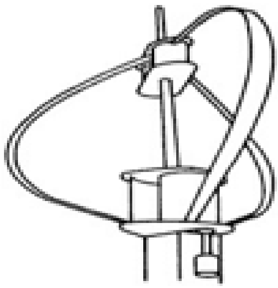

Fig. 6 Darrieus type VAWT

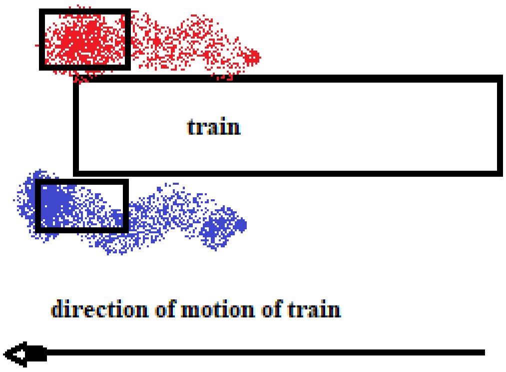

Fig. 7 Top view of train indicating position of turbines

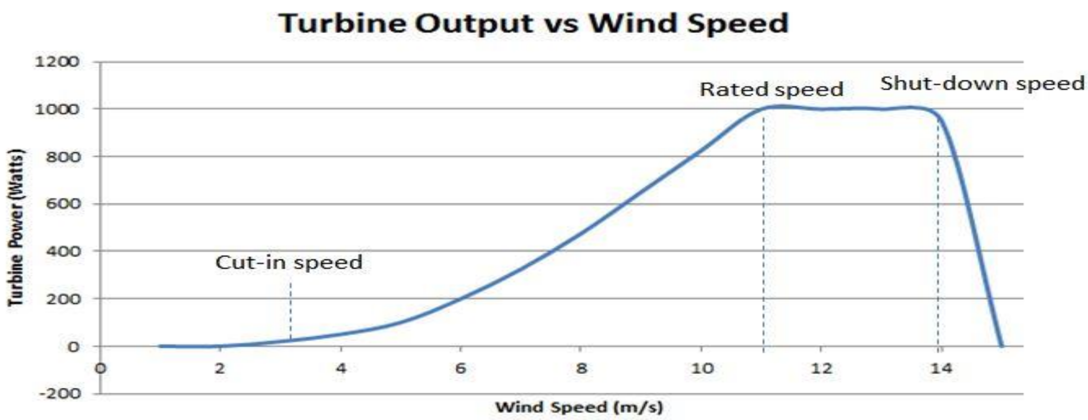

Fig. 8 Performance curve of Darrieus wind turbine [13]

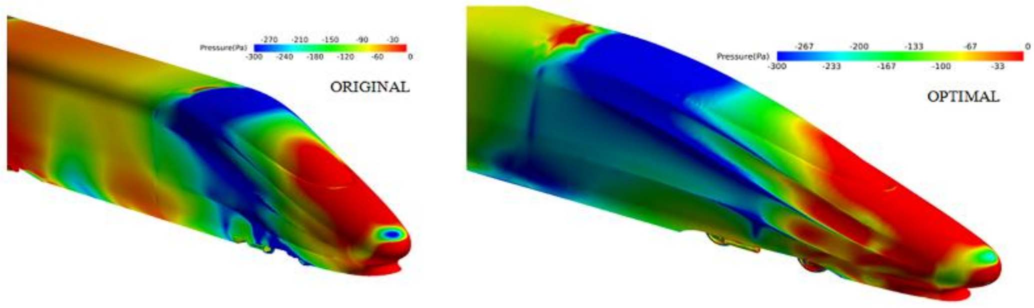

Fig. 9 Pressure distribution near head-coach for optimal and original design [14]

The blue and red portion indicates where the vortex is created. In addition, the boxed marked region is where the turbines are to be placed for maximum efficiency. The dimensions of the ducts also play an important role in controlling the speed of the intake air. The smaller the inlet port, higher is the speed of intake air due to high nozzle pressure. The relation between duct size and wind speed is illustrated in fig-8 and it is observed that wind velocity is maximum when duct size is 0.5 and for maximum velocity power is maximum.

Power Calculations for Darrieus Type Turbines

The basic working principle of a wind turbine is to convert the wind energy into mechanical energy, and then converting the rotating mechanical energy into electrical energy via an alternator [10]. The power generated by a turbine is proportional to the cube of the wind speed. The expression can be given as follows: [11]

$$P_t = C_p C_v A \rho v^3 \tag{1}$$

Where, P_t = output power from turbine expressed (watts), C_p = power coefficient (a parameter of the turbine), Cv= opening effectiveness (depends on the venting system), A= area covered by the blades of the turbine (m^2), v= velocity of the wind (ms^{-1}), ρ= density of air (kgm^{-3}) [12]. The average electric train consumes about 5 kWh per kilometre and the general values of constants like C_p and C_v are chosen to be equal to be 0.4 and 0.55 respectively.

The area covered by the turbine blades is considered to be 2-meter cube and the density of air is 1.23kgm-3. So, by solving equation (1) we have,

$$v^3 = Pt \big/ Cp.Cv.A.\rho \quad v^3 = 5000 \big/ (0.4\times0.55\times2\times1.23) \quad v = \sqrt[3]{9238.72} \quad v = 20.9ms^{-1} \quad v \approx 75.54kmh^{-1}$$

From the calculations, it is seen that for the turbines to produce enough energy to run the train, the wind speed must be minimum of 75kmh-1. But the above calculations provide the theoretical base for the possibility, which may not be feasible in practical life due to the various non-ideal behaviour of the turbine and even the system itself.

Conversely, we can calculate the power that we are generating via the turbines if we can determine the speed of air that the turbine is facing when the train is moving at a particular speed. The drag force can be measured using sensors like the FLEXIFORCE sensor. Thus, we know the values of all other parameters and calculate the value of the velocity of air. The equation is [11],

$$Fd = \frac{1}{2}\rho u^2 CdA \tag{2}$$

Where, Fd= Drag force of the wind, ρ= Density of the drag fluid (air), u= Flow velocity relative to the velocity of the air, A= Frontal area of contact of the force sensor, Cd= Drag coefficient. From equation (2), we can find the required expression for wind velocity as,

$$u = \sqrt{\frac{2Fd}{\rho CdA}} \tag{3}$$

Aerodynamic Shape Optimization

To provide the maximum performance, it is also necessary to consider the additional wind drag introduced by our proposed wind turbines. Wind drag means the unwanted hindrance to a moving body produced by air. All the turbines will produce some amount of drag resulting slower the train speed. Moreover, wind drag is a key issue as it increases the fuel consumption. Aerodynamic shape optimization of the train coaches can be a good solution here. Surely, the train will not lose its speed rather have optimized maximum speed. We will utilize computational fluid dynamics (CFD) in the coach shape design. A previous study on high-speed train showed such type of utilization [14]. Fig. 10 shows pressure distribution over the head coach before and after aerodynamic optimization. The blue area represents the least amount of drag whereas maximum by red. It is clear that the drag is reduced after optimization.

PIEZOELECTRICITY BASED ENERGY HARVESTING

Recently there has been developing enthusiasm for harvesting the energy of pressure and mechanical vibrations to generate electricity. Piezoelectric materials have enormous potential to become plainly a beneficial source of energy collecting on account of their temperament of changing over mechanical energy into electric energy and the straightforwardness at which they would more be able to promptly, than different materials, be coordinated into a -framework [15,17].

An electrical potential is appeared (voltage) across the sides of a crystal when it is subjected to mechanical stress. This phenomenon is known as piezoelectricity. The charges in a piezoelectric crystal are balanced at normal condition though they are not symmetrically arranged. The effects of the charges are cancel demolished, leaving no net charge on the crystal faces. If the crystal is squeezed, charges then out of balance. As a result, the effects of the charges no longer cancel one another out and net positive and negative charge is appeared on opposite crystal faces. Therefore, voltage is produced and it is called piezoelectricity.

Energy harvesting from piezoelectric materials depends on many factors. In recent years' piezoelectric energy harvesting technology has been broadly researched [18-21]. The generation of electricity can be performed through various topologies and for efficient design the best one need to be chosen illustrating quantitative data analysis. Most conventional harvesters work effectively just when the excitation frequency is very near to resonant frequency of the generator and the bandwidth is excessively thin, making it impossible to use in surrounding environment [20]. Therefore, we have to select such type of methodology in which excitation frequency is very close to resonant frequency for the generator.

A new design was initiated of broadband energy harvester employing multiple piezoelectric bimorphs (PBs) with a range of thicknesses of piezoelectric layers [22]. Connecting ten PBs serially, it was observed that maximum output power varied from 25 μW to about 60 μW. Further, in an ultra-wide-band width energy harvester was designed using the nonlinear stiffness of a doubly clamped micro-electro-mechanical system (MEMS) resonator [23]. On the basis of the piezoelectric cantilever, the monomer on the broadband technology of an array was focused on previous researches. For making it suitable to various environment, the broadband harvesters are disadvantageous for complex structure. Piezoelectric diaphragm array is used to increase the energy harvesting [24]. Considering several parameters with negligible deviations, the array of the piezoelectric units is connected in parallel. An equivalent model for a single piezoelectric unit is illustrated in the fig. 12 [25]. For attaining large deflection, the rim at each metal plate with a width of 3 mm is clamped by two organic glass holds. At resonant frequency, an energy harvester can generate maximum electric power. An appropriate initializing stress can decrease the resonant frequency and will eventually enhance the output power. For this purpose, in this model, several masses were attached to the top of the piezoelectric plates before the process of measurement [26-27].

From fig- 13, it is observed that generated power is at mill watt range. On the contrary, in fig-14 generated power is in microwatt range. Therefore, by analysing the data and graphical representation, we conclude to a point that implementing circular diaphragm based energy harvester array [24] is more efficient for harvesting energy using piezoelectric materials than previous models such as energy harvesting using multiple bimorphs in [22].

Table-1 Piezoelectric diaphragm array disk specifications [24]

Metal plate of composite disk		Piezoelectric ceramic disk	
radius	thickness	radius	thickness
20mm	0.2mm	12.5mm	0.2mm

Table-2 Outcome of piezoelectric circular diaphragm array based structure at $R_L = 11k$ [24]

Pressure stress	frequency	Power
0.8N	150Hz	21MWatt

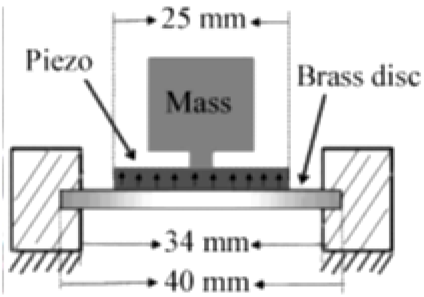

Fig. 10 The detail of single circular

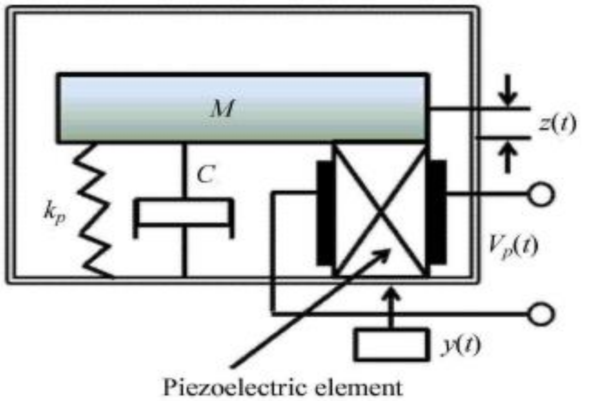

Fig. 11 Simplified equivalent model for the single piezoelectric unit in the array structure

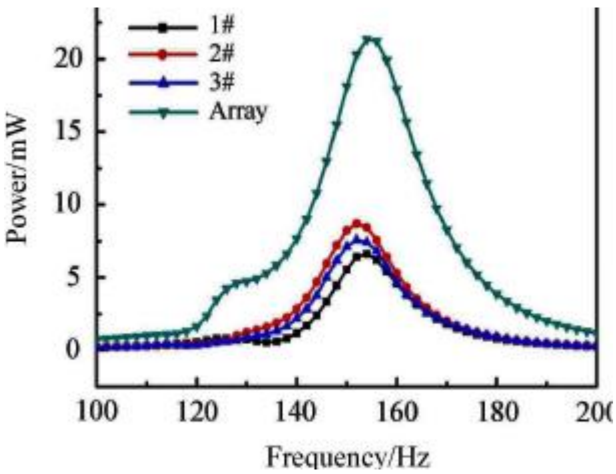

Fig. 12 Generated power using circular diaphragm array in parallel connection [24]

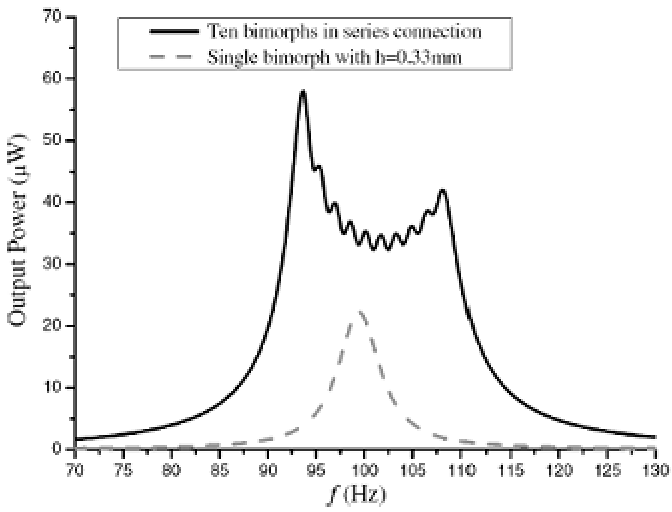

Fig. 13 Generated power level using multiple bimorphs [22]

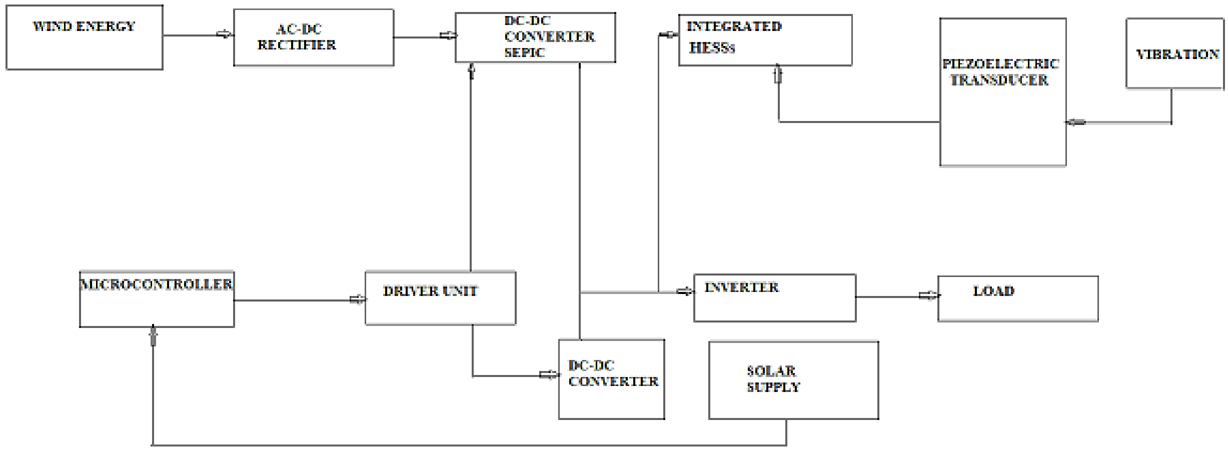

Fig. 15 Block diagram of the Proposed Model of the Integrated System for Energy Harvesting

ENERGY STORING SYSTEM

Different methodologies have been established for storing the harvested energy. Battery is used frequently for storing harvested energy. In the railway system, the HESSs plays a significant role which is the combination of traditional batteries and recently developed ultra-capacitors. HESSs takes the benefits of the high-energy storing capacity of batteries as well as the flexibility and capability of capturing high power density of ultra-capacitors. Ultra capacitors are advantageous with a higher life cycle and fast response than batteries. Integrated HESSs develops the energy storing system eradicating the individual disadvantages of batteries and ultra-capacitors [25].

CONCLUSION

Solar, wind and piezoresistivity based energy harvesting has been described with updated methodologies that ensures harvesting energy to a greater extent. Furthermore, using the Si-solar cell with 26% efficiency enhances power generation. Choice of Darrious type wind turbine and defining the proper positioning of the turbines accelerate wind energy conversion. Proposal for implementing circular diaphragm based energy harvester array paved the way of generating more power efficiently. The usage of integrated hybrid energy storing system executes regenerative braking and increases the reliability of the energy storing system.

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