

## Conceptual Design of Harvesting Energy System for Road Application

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### Abstract

Energy harvesting becomes more and more important in our life. It refers to the practice of acquiring energy from the environment which would be otherwise wasted and converting it into usable electric energy. For this, every kind of energy can be exploited such as solar, wind or strain and kinetic energy. The idea is to propose a conceptual design that will carry out a suitable energy harvesting conversion to be applied for road application. However, harvesting energy using piezoelectric generators has been chosen for this project. The project is conducting a simulation analysis using a piezoelectric generator based on a model by S Roundy et al. The data applied from a 15 mm x 3.2 mm x 0.14 mm single layer piezoelectric bending element which produce 950  $\mu\text{W}$  with a  $1.727\text{e6 Nm}^{-2}$  of input stress. The simulation is done using MATLAB-Simulink-SimPowerSystems.

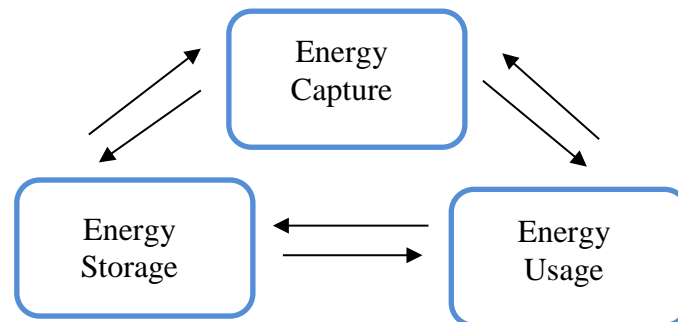
Keywords: Energy harvesting, piezoelectric generator

### 1.0 Introduction

Energy has always been a most important thing for the development of economy and social growth in country. There are two long-term energy challenges are being faced. One of them is undertaking climate change by mitigating Carbon Dioxide ( $\text{CO}_2$ ) emissions and the other one is ensuring a secure clean and affordable energy. As we can see, the usage of fossil fuel for power generation grows each year. These alternative sources are defined as renewable energy. In Malaysia, we are quite familiar with solar panel or photovoltaic which convert the sun's energy into electrical energy by using a solar cell(s). Recently, renewable energy also comes from non-natural resources which used another technique of energy harvesting. Energy harvesting or power harvesting refers to the practice of acquiring energy from the environment which would be otherwise wasted and converting it into usable electric energy [1].

Energy can also harvested from ambient environment such as mechanical, thermal, light, electromagnetic and also human body to replace traditional sources. Moreover, thermal energy due to temperature gradients and ambient vibrations constitute some of the major sources of energy that has a lot of potential for being harvested. Generally, the first energy harvesting procedure is capturing the energy (resources), storing

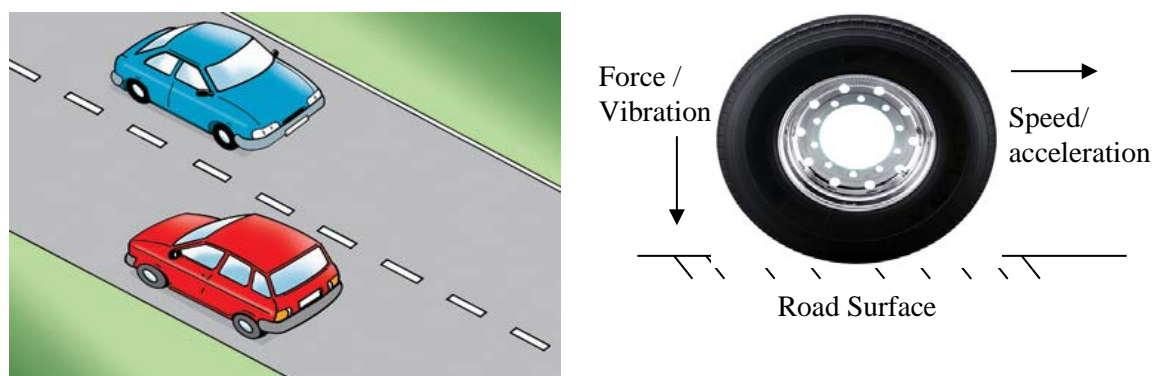
of energy using batteries or other kind of system, and finally the energy will supply power to nearby grid or system as shown in **Figure 1**.



**Figure 1: Energy Harvesting Principle**

## 2.0 Energy Harvesting for Road Application

The conceptual design in engineering is the generation of design alternatives or design concepts and the supporting analysis to determine the feasibility of each alternative [2]. Energy harvesting from pavements is a new research territory and encompasses techniques that somehow use the same principals that could be used in general building engineering regarding the materials usage. Some of these technologies are recently applied to be used to harvest energy from the road.

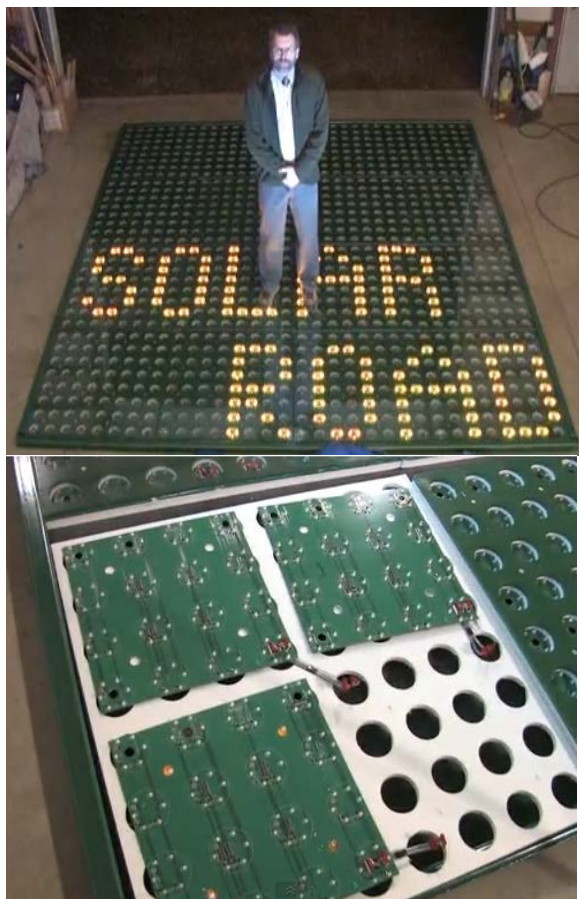


**Figure 2: Energy Harvesting from Road Pavement**

Vehicles such as cars, bus, lorries are the main ‘user’ on the road. When every vehicles moving, it will release energy in the form of force or vibration direct to the road surface. An energy harvesting system will capture these energies and convert it into an electrical energy.

## 2.1 Solar Energy

Solar energy is one of the most popular and well-known renewable energy due to its primary source of energy: The Sun. A solar roadway is a series of structurally engineered solar panels that are driven upon [3]. The idea is to replace current petroleum-based asphalt roads, parking lots, and driveways with solar road panels that collect energy to be used by homes and businesses, and ultimately to be able to store excess energy in or alongside the solar roadways. The United States Department of Transportation (USDOT) solar road is the prototype of an energy generating road that has been fitted with 'structurally-engineered' solar panels (**Figure 3**).



**Figure 3: Solar panel by Solar Roadways**

In direct sunlight at midday, the power density of solar radiation on the earth's surface is roughly  $100 \text{ mW/cm}^2$ . Researchers at the Korea Institute also investigated several approaches to harvest solar energy from asphalt pavements. It should be noted, however, that current thin film solar cells are difficult to use in surfaces that receive vast

mechanical load cycles and environmental conditioning could cause premature corrosion and wear. [4]

## 2.2 Wind Energy

Wind power is the conversion of [wind energy](#) into a useful form of energy, such as using: [wind turbines](#) to make [electrical power](#), [windmills](#) for mechanical power, wind pumps for [water pumping](#) or [drainage](#), or [sails](#) to propel ships. We know that every passing car on the highway will lead to the emergence of significant wind movement. Designed by Pedro Gomes, the E Turbine is an idea a series of small circular turbines would be placed along the median of a highway that would use the wind created by passing cars to generate electricity from the wind energy.



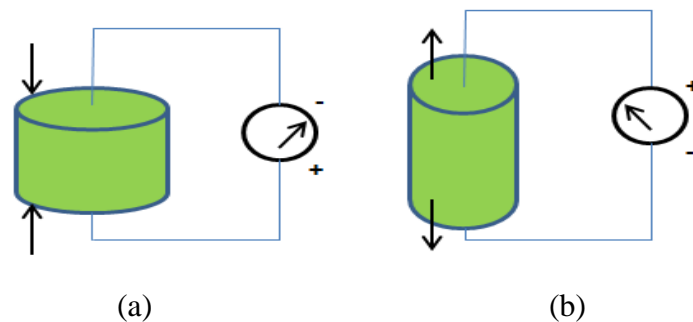
**Figure 4 : E Turbine concept by Pedro Gomes [5]**

The electricity generated could then be used to power highway and street lights, information and warning signs, or even emergency phones set up along the road. Currently, the E Turbine remains a concept without any immediate plans to begin implementing them despite getting attention by becoming a finalist in several competitions. The concept is using a [Vertical-axis wind turbines](#) (or VAWTs) which have the main rotor shaft arranged vertically. The key disadvantages include the low rotational speed with the consequential higher [torque](#) and hence higher cost of the drive train, the inherently lower [power coefficient](#), and the difficulty of modelling the wind flow accurately and hence the challenges of analysing and designing the rotor prior to fabricating a prototype.[5]

## 2.3 Piezoelectric Generator for Road Application

This method alters mechanical energy into electrical energy by straining a piezoelectric material. Piezoelectric effect was discovered by J and P Curie in 1880. They found that strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field. This strain comes from many different

sources. For example, the sources could be from human motion, low frequency seismic vibrations and acoustic noise. Moreover, piezoelectricity has the ability of some elements such as crystals and some types of ceramics, to generate an electric potential from a mechanical stress [6].

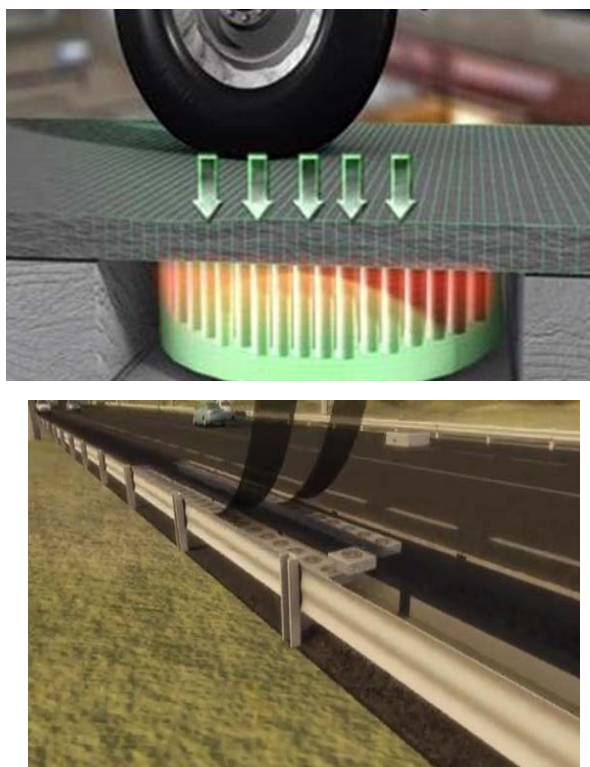


**Figure 5: a) Disk compressed: generated voltage has same polarity as poling voltage  
b) Disk stretched: generating voltage has polarity opposite that of poling voltage**

Mechanical compression or tension on a poled piezoelectric ceramic element changes the dipole moment, creating a voltage. Compression along the direction of polarization, or tension perpendicular to the direction of polarization, generates voltage of the same polarity as the poling voltage (**Figure 5(a)**). Tension along the direction of polarization, or compression perpendicular to the direction of polarization, generates a voltage with polarity opposite that of the poling voltage (**Figure 5(b)**).

The design proposes the placement of piezoelectric sensors beneath the road surface which would produce electricity from the vibrations caused by the movement of vehicles on the road. The technology works in this way: When a car or truck passes over pavement, the pavement vibrates slightly. By placing relatively inexpensive [piezoelectric](#) sensors underneath a road, the vibrations produced by vehicles can be converted into electricity.





**Figure 6: IPEG by Innowattech**

Innowattech [7] has conducted trials to demonstrate this energy at the Technion Institute of Technology in Haifa where a vehicle travelled over a road under which IPEG (Innowattech [Piezoelectric](#) Electric Generators) had been planted 6cm under the road level and at a distance of 30cm apart. The IPEGs (**Figure 6**) are [piezoelectric](#) crystals that can harvest mechanical energy created by changes in weight, motion, vibration and temperature, and convert it to electrical current.

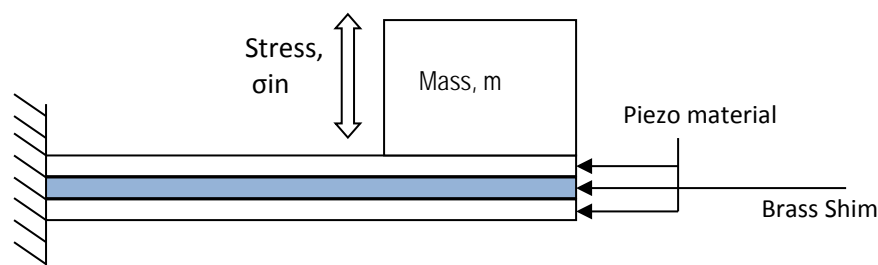
The energy harvested was stored in the electronic capacitors of the storage system. Innnowattech's claims of producing significant amounts of electricity, about 400 kWh from a 1 km stretch of generators along the dual carriageway (assuming 600 vehicles go through the road segment in an hour), enough energy to power 600-800 homes.

### **3.0 Piezoelectric Bimorph model**

Piezoelectric materials can be used as a means of transforming ambient vibrations into electrical energy that can be stored and used to power other devices. The energy produced by these materials is, in many cases, far too small to directly power an electrical device. However, if the material is use in a large scale and in a collective power (storage), it is shown that the small energy is just a turning point to harvest slightly large electrical energy (Innowattech).

In this research we are using piezoelectric bender generators. A bending element could be mounted in many ways to produce a generator. One of the ways is connecting two piezoelectric beams that are separated by a shim which also called the piezoelectric bimorph [8]. **Figure 7** shows

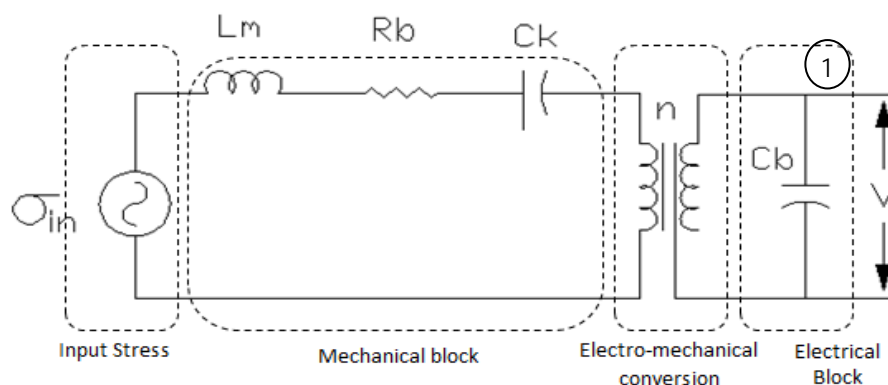
that a two layer piezoelectric mounted as a cantilever beam with a mass placed on the free end. This type is chosen for two reasons. First, for a given force input, the cantilever configuration results in the highest average strain, and the power output is closely related to the average strain developed in the bender [9]. Piezoelectric also preferred as they efficiently convert mechanical stress or strain to an electrical voltage or charge without any additional power.



**Figure 7: A two layer piezoelectric material mounted as cantilever**

### 3.1 Equivalent Circuit of Energy Conversion

A convenient method of modeling piezoelectric elements such that system equations can be easily developed is to model both the mechanical and electrical portions of the piezoelectric system as circuit elements. The electromechanical coupling is then modeled as a transformer. An equivalent circuit for the bender system in **Figure 7** is shown in **Figure 8**.



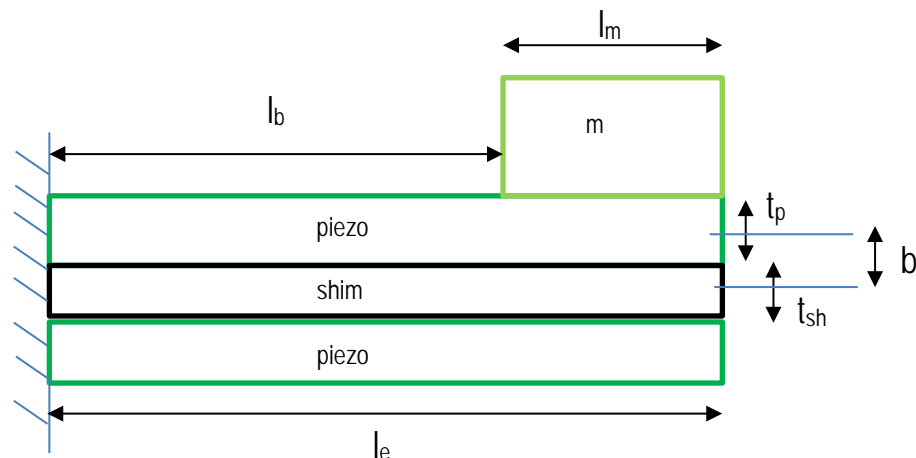
**Figure 8: Equivalent circuit for piezoelectric bender generator (PBG) [14]**

The mechanical element in Figure 1 are represented in the equivalent circuit. The equivalent inductor,  $L_m$ , represents the mass or inertia of the generator. The equivalent resistor,  $R_b$ , represents mechanical damping. The equivalent capacitor,  $C_k$ , represents the mechanical stiffness.  $\sigma_{in}$  is an equivalent stress generator that represents the stress developed as a result of the input vibrations.  $n$  represents the equivalent turns ratio of the transformer.  $C_b$  is the capacitance of the piezoelectric bender.  $V$  is

the voltage across the piezoelectric device. Transformers are characterized by a turns ratio that relates voltage on one side to voltage on the other side. In this case, stress on the mechanical side is related to voltage on the electrical side.

### 3.2 Analytical Model

A mathematical model of the bimorph piezoelectric was defined by Roundy et al., which allows better estimation of the amount of power that is able to generate from a vibration source [10]. As with purely electrical circuits, the systems in **Figure 8** are then determined using Kirchhoff's current law and Kirchhoff's voltage law. Summing the currents at node 1 in **Figure 8**, we will have

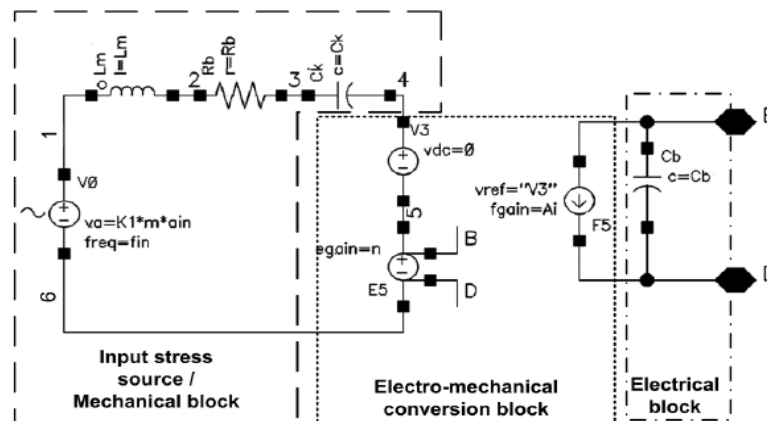




Where  $m$  is the proof mass and

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be identified. Thus, we decided to use the SPICE model by Luigi Pina et al., to realigned into MATLAB-Simulink-SimPowerSystems. **Figure 10** shows the SPICE schematic subcircuit of the piezoelectric electromechanical model.



**Figure 10: SPICE schematic subcircuit of the piezoelectric bender generator electromechanical model.**

This model defines  $n$  as the equivalent voltage transformer ratio, which given by

will also execute the same value to maintain or determine the approximate value which can represent the energy harvesting system. Note that the bimorph prototype is made of two layers of PZT-5H (lead zirconate titanate) with a brass center shim. The center shim is an economical approach to produce a rugged actuator [11]. The data used as below:

| Parameters | Value                              |
|------------|------------------------------------|
| $l_e$      | 6.5 mm                             |
| $l_m$      | 8.5 mm                             |
| $l_b$      | 1.5 mm                             |
| $t_p$      | 0.14 mm                            |
| $t_{sh}$   | 0.1 mm                             |
| $w$        | 6.7 mm                             |
| $\zeta$    | 0.012                              |
| $Y$        | $5.0 \times 10^{10} \text{ N/m}^2$ |
| $f$        | 120 Hz                             |
| $m$        | 7.71 g                             |
|            | $2.5 \text{ ms}^{-1}$              |

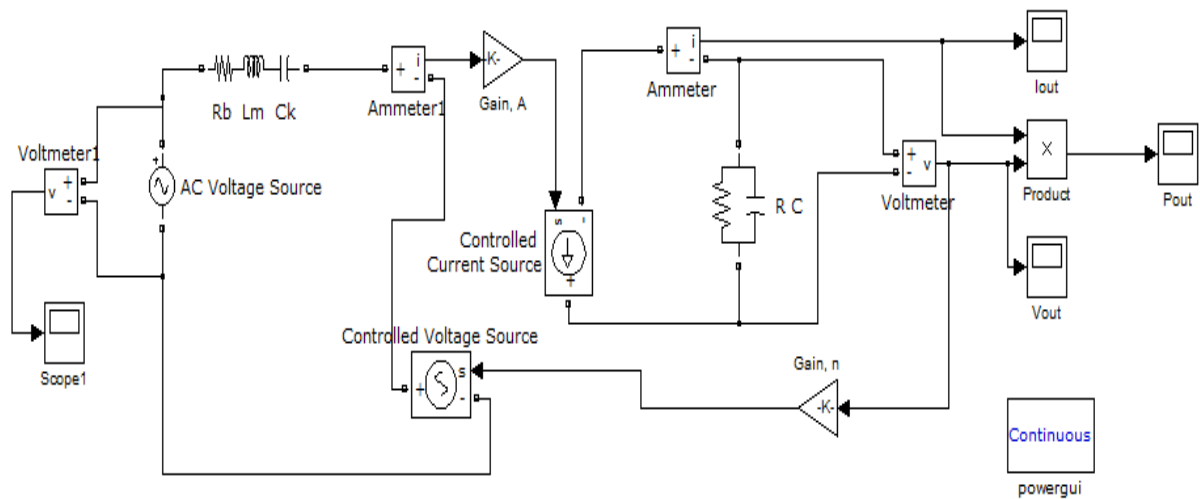
**Table 1: Parameters use for determination of electrical elements in equivalent circuit**

All the values are refer to [12] in order make sure the data is valid as possible as it can. Then, these parameters will give us the value of the equivalent circuit element in **Table 2**. The bimorph is set to operate in parallel.

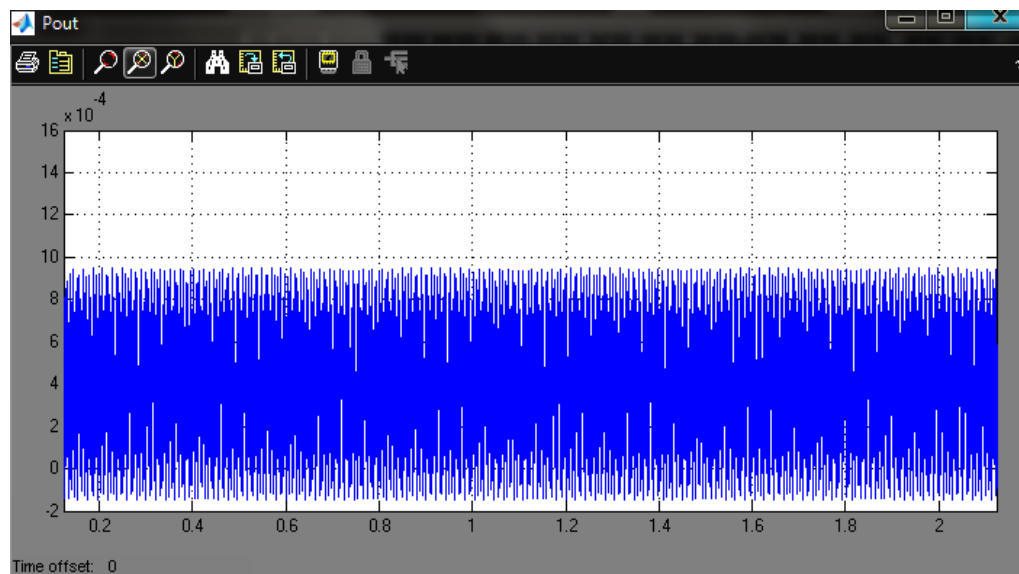
| Circuit Element | Value  |
|-----------------|--|
| $\sigma_{in}$   | $1.1727 \times 10^6 \text{ Nm}^{-2}$         |
| $R_b$           | $2.0622 \times 10^6 \text{ Nm}^{-2}\text{s}$ |
| $L_m$           | $9.4501 \times 10^4 \text{ kgm}^{-1}$        |
| $C_k$           | $2 \times 10^{-11} \text{ N}^{-1}\text{m}^2$ |
| $C_b$           | $10 \times 10^{-9} \text{ F}$                |
| $n$             | $114286 \text{ Nm}^{-2}\text{V}^{-1}$        |
| $A_i$           | $-665.6 \times 10^{-6} \text{ NmV}^{-1}$     |

**Table 2: The value of circuit element**

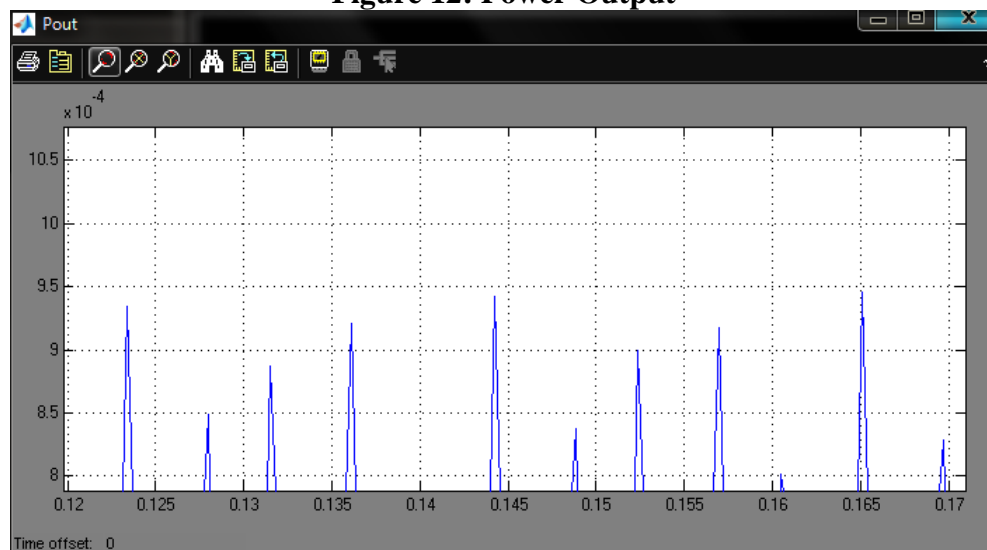
#### 4.1 Simulation using general equivalent circuit



**Figure 11: Simulation circuit with  $R_{load}$  of 125 k $\Omega$**



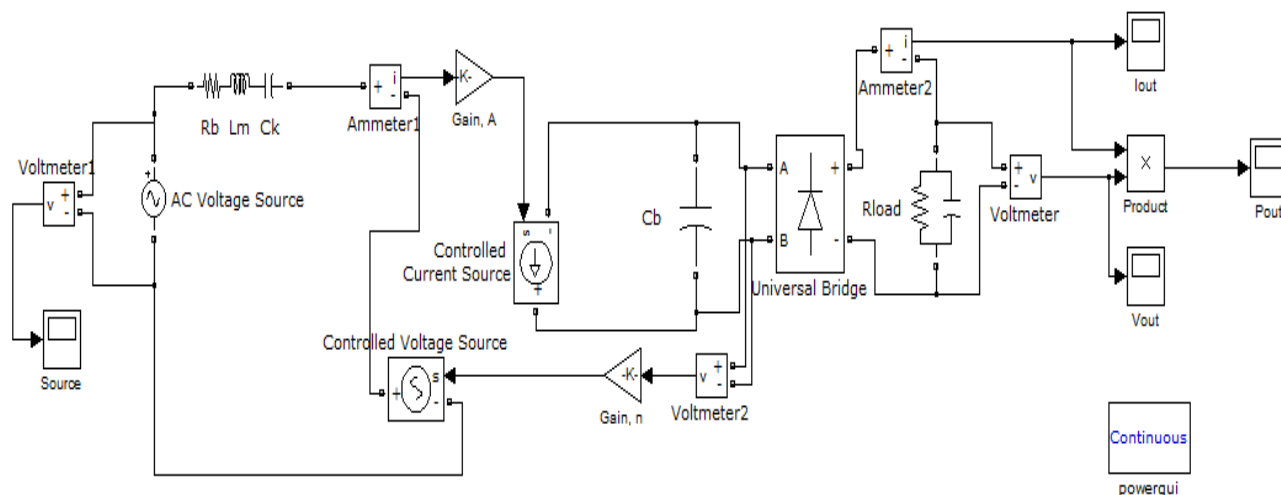
**Figure 12: Power Output**



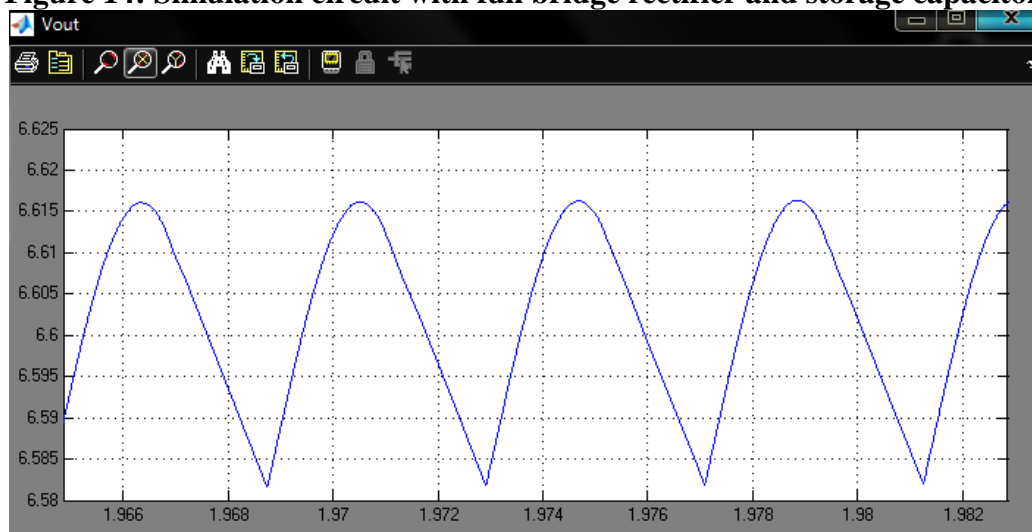
**Figure 13: Maximum Power Output  $\approx 950 \mu\text{W}$**

#### 4.2 Simulation using a Full Bridge Rectifier

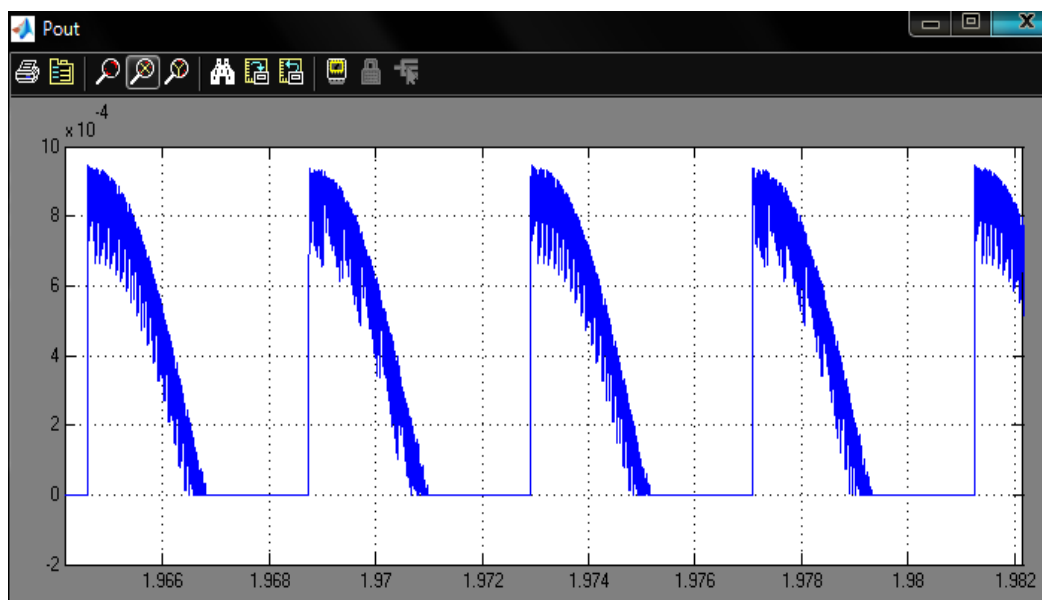
The source (input stress) is an AC source. For a piezoelectric generator, it has a DC power output. Thus, a full-bridge rectifier is use to convert the AC output into DC output. The second circuit also use a storage capacitor,  $C_{st}$ .



**Figure 14: Simulation circuit with full bridge rectifier and storage capacitor.**



**Figure 15: Voltage output Max  $\approx 6.6 \text{ V}$**



**Figure 16: Power output Max  $\approx 950 \mu\text{W}$**

## 5.0 Conclusion

We found out that, the result from MATLAB-Simulink-SimPowerSystems is almost equivalent to the SPICE model. The voltage output for a load of  $125 \text{ k}\Omega$  for SPICE model is also near  $6 \text{ V}$ . However, the current output has a different result comparing with the SPICE model. This can be determined by observing the power output. For SPICE model, the power output for  $125 \text{ k}\Omega$  of load is only about  $225 \mu\text{W}$ . Mathematically, this result is given by a different current value.

The project has identified the source of energy harvesting system for road application. Vibration driven by tyres (vehicles) is the major wasted resources to convert into electrical energy. We have chose an analytical model with the equivalent circuit by Roundy et al. and Luigi Pinna et al. , to estimate the energy conversion of mechanical resources and implement into a simulation environment. An attempt of using MATLAB instead of SPICE itself helps us to explore a new simulation environment for Power Systems.



## **6.0 Suggestion**

We found out that, technical reports on large scale of piezoelectric usage are seldom found in the power generation field. Future work would involve:

- i. Indepth analysis for the energy conversion using others applicable model
- ii. Analysis of energy from tyres (vehicles); force, vibration, frequency etc.
- iii. Compatibility of the energy to suit the piezoelectric generator; robust, resilience etc.
- iv. Experimental work for piezoelectric on road pavement; maintenance, environment etc.

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