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Electromagnetic Energy Harvester Techniques

Converting Vibration Energy into Electrical Energy

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Abstract — **The study of this thesis shows the development of electromagnetic energy harvester with DC to DC converter circuit which is used to harvest vibration energy and convert into electrical energy. Different types of electromagnetic harvesting methods were reviewed to understand the advantages and disadvantages of electromagnetic energy harvester application. Experiment were carried out to understand the harvestable output voltage which is generated from vibration, and the limitations of this project with different factors which affects the performance of the energy harvester has been reported.**

Keywords— **Electromagnetic, energy harvester, energy scavenger**

I. INTRODUCTION

Energy scavenging or energy harvesting is a method used to harvest the energy which can be found in sound, heat, vibration or light. Researches have been carried out extensively on energy harvesting devices as an alternative to replace batteries. Among the renewable energy resources, mechanical movement specifically vibration has been widely studied because the electromagnetic energy harvesting has potential and it is widely available. In large scale power generators such as wind-turbines, hydroelectric and fossil-fuel power plants, kinetic energy is converted into electrical energy. However, in small power generators it is not well known because the harvested electromotive force (EMF) is very small in value. Since vibration energy is in abundance, harvesting the energy from vibration and converting it into electrical power is more suitable for usage of low-power consumption devices and wireless sensors.

Vibration can be produced from heavy vehicle on the road, as well a running electric motor. However, the most intense vibration are produced by from when there are many vehicles and also when natural disaster such as earthquake occur. Although these vibration may cause discomfort for many, the energy produced can be harvested and used for micro-powered electronics sensors and devices. Apart from harvesting its energy, it can also be calibrated to be used as a safety warning device to alert others by detecting strong vibration that can indicate natural disaster. The aim of this project is to create an electromagnetic energy harvester that uses vibration from the environment and later convert the energy harvested into useful electrical energy. The electrical energy produced can have various uses such as to retrofit battery operated devices that consumes small power such as wireless sensors or micro powered electronic devices. Aim of this project, is to design an electromagnetic energy harvesting device which could be used as an alternative to power portable electronic devices which needs primary cell batteries as power source. Instead of vibration energy wasted in the environment, this electromagnetic energy harvester can be used to harvest the vibration energy and convert the energy into a more useful electrical energy.

II. LITERATURE REVIEW

Since crucial devices such as sensors have been more efficient and smaller in size it acquire own device for power up as well as requiring lesser power to function, techniques such as vibration energy harvesting is essential to be used for these kind of application. Very small batteries have to be made for these devices and the issue of less storage capacity can be reduced if a device can be made for constantly charging the battery.

Vibration energy harvesting exists in few different types. The type chosen mostly depends on the environment the vibration energy which is present, and the availability of the energy itself. The different types are further discussed below. Normally, the devices used in vibration energy harvesting are either piezoelectric, electrostatic or capacitive and electromagnetic. However electromagnetic harvester is more commonly used because construction of electromagnetic materials is easier to be obtained compared to piezoelectric material which is mostly unavailable.

A. Piezoelectric Energy Harvesting

This energy harvesting method involves deformation or straining piezoelectric material in order to convert mechanical energy into electric energy. It can be achieved by creating an electric field, subsequently a drop in voltage across the field by causing charge separation across the piezoelectric material when the material is deformed. The drop in voltage and the stress applied are almost proportional. This method involves an oscillating system with a mass (piezoelectric) at one of the ends and a cantilever beam structure. The voltage that is produced depends on the time and strain, thus creating an irregular current. A voltage around 2 to 10 Volts can also be produced in systems where piezoelectric materials are subjected to stress or compression.

The crystal lattice flowing through the system will be separated from the electric charges by the piezoelectric material. The vibration applied may induce voltage across the material if the piezoelectric material had not been short circuited. The system will not require any external voltage for excitation purposes because the induced voltage induced

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within the system will be high enough. However the issues will be the unavailability of the material, a lot of voltage impedance, high voltage leakage and the fact that sometimes production of voltage may decrease because the material depolarizes easily.

This is usually used for vibration energy harvesting whenever compression or stress is available around, for example the vibrations produced from human body movement such as walking can be beneficial to deform the material thus creating voltage when placed inside a shoe. Piezoelectric Transducer, (PZT) is among the other piezoelectric materials which is the most efficient because it converts 80% of the mechanical energy in which it receives and converts into electrical energy.

B. Electrostatic Energy Harvesting

Dielectric material is used by an electrostatic energy harvester to create the phenomenon of electrostatic induction. An appropriate dielectric material that is able to hold the voltage semi permanently after being charged to a high voltage on its surface would be an electret. Electrets are present in various applications, for example air filters and condenser microphones.

The basic arrangement of a vibrational harvesting system using an electrets in an electrostatic induction. This works by induction of positive charges on one movable and one fixed electrode whenever negative charges are applied on electrets. Some of the positive charges produced will be moved from the fixed to the movable electrode when an external vibration displaces the movable electrode plate towards the direction of the arrow causing production of current using an external load. The gap of the structure reduces causing increase in the current, the constant and voltage of the electrets.

C. Electromagnetic Energy Harvesting

The magnetic field is used to create electric energy in this process. A magnet could be placed to oscillate inside a coil or a mass which it can be used to oscillate in a magnetic field while being wrapped within a coil. Basically, voltage induction by Faraday's law is applied in this system whereby the coil is put through different quantities of magnetic flux.

An amplifier circuit needs to be used as the voltage produced is small as low as 0.1V in some cases. In order for voltage to be induced, certain factors have to be taken into account for adjustments such as the number of turns in a coil (increased turns will cause increased cutting together with the lines of the magnetic field), altering the mass of the solenoid or even the diameter of the wire used to form the coil. However the size may limited as when these parameters are to be considered for developing this harvester. Besides that, another crucial factor is, external voltage sources are not needed to initiate voltage generation. Commonly used sources are vibration from wind and mechanical vibration where typically cantilever is used to harvest energy from mechanical energy.

III. METHODOLOGY

Resonance based micro generators have been used by many researchers as a choice due to its properties such as large displacements internally and ability to attract higher amounts of energy from the surrounding environment. It is rather difficult to obtain a flux gradient that is high enough by just using a single structure of magnet added by the fact that linear vibration is rather limited. The design of this particular study consists of a simple arrangement with a cylindrical structure using two magnets to obtain a higher flux gradient.

A. Design Of Electromagnetic Energy Harvester

The two magnets are placed in opposite directions axially and the micro-generator's mechanical section is designed by tuning the moving mass (m) and spring constant (k) in order to match the ambient vibration frequency which is dominant with the oscillating system's resonance frequency. The EMF obtained for the micro-generator (V_i) is as follows,

$$V_i = \mathrm{n}\frac{\partial\Phi}{\partial t} = \mathrm{n}\frac{\partial\Phi}{\partial z}\frac{\partial \mathrm{z}}{\partial t} = (n)\left(\frac{\partial\Phi}{\partial z}\right)(z') = K_e z' (1)$$

Whereby, n represents the number of turns in the coil, Φ represents the flux linkage in each turn, and z represents the micro-generator's internal displacement.

The Ke factor, is an electromechanical constant that only depends on the generator design. The following methods can be used to achieve the range of EMF needed:

(i) Increasing the n, number of turns or

(ii) Changing the symmetrical structure (∂Φ/∂z)

Therefore, the size of the coil should satisfy the requirements of the EMF design in order to construct and electromagnetic generator. The micro-generator can be displayed as a generic spring damper where by it can calculated as,

$$mz(\mathrm{t}) + \mathrm{kz(t)} + \mathrm{D_{total}z'(t)} = \mathrm{my}(t)\ (2)$$

Whereby, z(t) represents the generator system's internal vibration and y(t) represents the ambient vibration. Dtotal is the damping element which is in control of the extraction of the energy in the system, consisting of two elements: (i). (Dm), Mechanical damping, and, (ii). (Delectrical), Electrical damping.The extracted electrical power is derived as,

$$F_{elec} \times z' = (D_{electrical} z')z' = V_i \times i\ (3)$$

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Whereby, i represents the current flow in the coil and F_{elec} represents the force for electrical damping. The F_{elec}, force for electrical damping is derived as,

$$F_{elec} = n\frac{\partial \Phi}{\partial z} \times i = K_e \times i \ (4)$$

As indicated in equation 1, only the generator construction and design is responsible for the value of Ke, an electromechanical constant. When an effective resistance, R_{load} is connected to a generator which includes coil resistance, the current i obtained is shown below,

$$i = \frac{Vi}{R_{load}} = \frac{K_e z'}{R_{load}} \ (5)$$

B. Energy From Electromagnetic Damping

The impedance given by the inductance from the coil is negligible when compared to the resistance of the coil considering the low input frequencies. By combining the equations (3), (4) and (5), the damping element value, $D_{electrical}$ is obtained as shown below

$$D_{electrical} = \frac{F_{elec}}{z'} = \frac{K_e i}{z'} = \frac{K_e^2}{R_{load}} \ (6)$$

Therefore, the micro-generator's electromechanical coefficient and the generator's connected resistance are responsible for the values of electrical damping. $D_{electrical}$ the coefficient for electrical damping consumes power consisting of useful electrical power and loses in the coil. The generator develops input power in this case is derived as shown,

$$P_i = \frac{V_p^2 D^2}{4 f_s L}\beta$$
$$where\ \beta = 2\int_0^{2\pi} sin^2\,\theta \left[1 - \frac{sin\,\theta}{Vo/Vp}\right]^{-1} d\theta \ (7)$$

Whereby, $\theta = 2\pi \cdot t/T_i$ and L represents the boost inductor. It was observed that, the parameter β is closer to unity for higher step up ratios (Vo ⩾ Vp). A design whereby the coil inductance can be related to the needed value of boost inductor can be created using this equation. Loses experienced in circuit parasitic of low power or low voltage converter. The output diodes and boost inductor's resistance are the cause of the main loses within the circuit.

C. DC To DC Step Up Converter Circuit

Assuming V_f represent the forward voltage drop in the diode and R_{ind} represents the inductor's resistance and R_{ds} represents the ON-state resistance. Below shows the conduction loses obtained in the circuit,

$$P_{loss} = I_i(rms)^2 \cdot R_{ind} + I_{sw}(rms)^2 \cdot R_{ds} + 4.V_f \cdot I_{diode}(avg) (8)$$

Whereby, I_i represents input current, Isw, is switch current and Idiode representing the diode current. The peak for the input current can be defined as shown below, considering k_{th} which is the switching cycle for the converter,

$$iPk = V_{ik} DT_s/L \text{ where } V_{ik} = V_p \cdot \sin(2\pi k \cdot T_s/T_i) \ (9)$$

The following formulae can be used to obtain the current fall time input,

$$d_f T_s = i_{pk} L/(V_o - V_{ik)} \ (10)$$

The design of the converter is in such a way that the conduction loss in the circuit will dominate the loss in switching. This is normally caused by switching frequencies that are low compared to the increase and decrease of values in semiconductor device, and when coil impedance causing high resistive parasitic in the circuit

A low switching frequency is chosen to maintain micro-power operation by enabling the use of low power operation amplifiers (op-amps).

The switching loss in transistors occur because of the finite time needed for the current to rise then drain to source voltage and become zero in the transistor. The current increases slowly from zero decreasing the power lost during the switching instant during the Discontinuous Conduction Mode (DCM). In case of continuous conduction mode for boost converters, the voltage across the switch is only the input voltage during turn on as opposed to the voltage of output. The switching cycle can be shown as below, considering kth to be the switching loss over general and τ to be the switch's transition time.

$$P_{ik} = \frac{V_{ik} i_{pk} \tau}{2T_s} \text{ where } i_{pk} = V_{ik} \cdot \tau/L \ (11)$$

The switching loss can be shown as below when the summation over the whole line circle is done.

$$P_{sw} = \frac{V_p^2 \tau^2}{4T_s L} \ (12)$$

The switching loses of the diode is also reduced since reverse recovery effect is absent when the converter operates in Discontinuous Conduction Mode (DCM). The loss because of body diode capacitance is reduced for Schottky diodes as well. Lastly, (7), (8) and (12) can be used to estimate the output power.

$$P_{output} = P_{in} - P_{loss} - P_{sw} \ (13)$$

D. Software Simulation

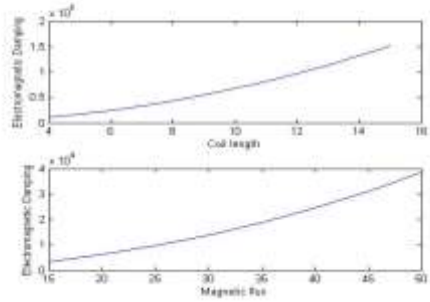

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Figure 1: Electromagnetic Damping against Coil Length and Magnetic Flux

In order to calculate voltage generated by the relative movement of coils and magnets and to simulate the magnetic fields that were generated by coils and magnets, MATLAB models were designed.

The graph above in Figure 1 illustrates how magnetic flux and varying the coil length can affect electrical damping. Similar patterns of graph was shown during the simulation carried out for both variation as the electrical damping increases when there was an increase in magnetic flux and coil length. Low damping values are required in order for the generator to be constructed.

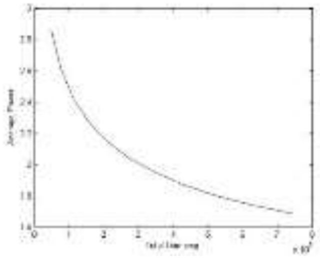

Figure 2: Electromagnetic Damping against Average Power

A graph was obtained with maximum power when the damping ratio was varied. The maximum power achieved decreases as the damping ratio is increased. Thus, for designing purposes, a low damping value was aimed.

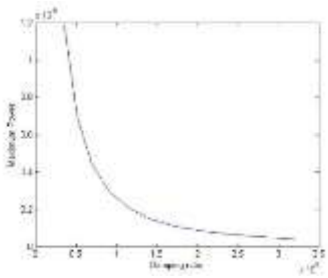

Figure 3: Maximum Power against Damping Ratio

Varying the coil's resistance enabled a graph of maximum power to be obtained. The maximum power obtained decreased as the resistance of the coil increased. A low coil resistance was aimed for designing purpose.

E. Block Diagram

It consists of input which is vibration from the environment, which excites the magnet. The energy from magnetic induction is converted into electrical energy by the energy harvester. The harvested energy it is then stepped up through DC to DC converter circuit. The amplified voltage is then available via Universal Serial Bus (USB) connection.

IV. Experimental Results

Some of relevant experiments are conducted in order to complete the functionality of the whole project. All results are carefully recorded for analytical purposes in the terms of theoretical and observation. The experimental that had been done to produce this paper are as below.

A. Experiment 1: Circuit Testing

Objectives: To investigate the output of DC to DC converter circuit with different input voltages. Result:

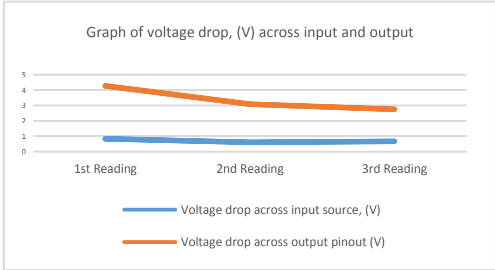

Figure 4: Graph of voltage drop across the input and output of the circuit

B. Experiment 2: Induced Voltage from Copper Coil with Magnet

Objectives: To investigate the induced voltage that can be obtained from the magnet induction. Result:

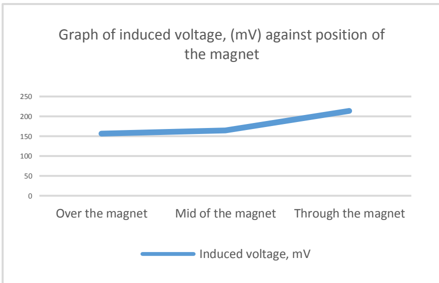

Figure 4: Graph of induced voltage against positions of the magnet

C. Experiment 3: Energy Harvesting Device on Coastal Road Highway Railing

Objectives: To investigate the harvested electrical energy from highway railing to observe the readings from road conditions. Result:

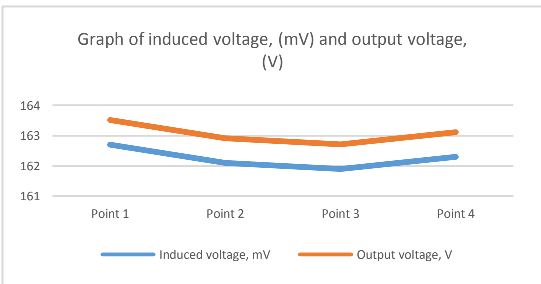

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Figure 5: Graph of energy harvested on coastal road

D. Experiment 4: Energy Harvesting Device on Different Road Conditions

Objectives: To investigate the harvestable electrical energy from vibration on car driving on different road conditions. Result:

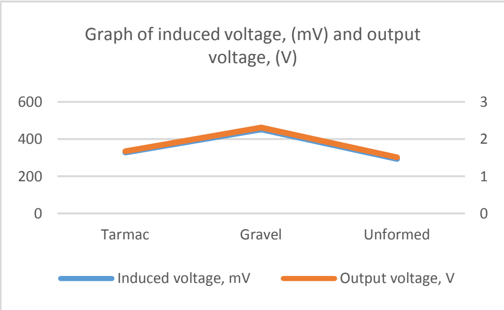

Figure 6: Graph of energy on different road conditions

V. CONCLUSIONS

In overall, electromagnetic energy harvesting is an effective method of generating energy from vibration. However, there are some weakness during development of this energy harvester whereby it was proposed to be applicable to generate energy from vibration to power wireless sensors. Based on the conditions that experiments were carried out, further methods should be considered so that energy harvesting is more practical. Based on the experiments carried out in this project, it can be concluded that designing the energy harvesting system varies according to different conditions. The factors that should be considered and could affect the performance of an electromagnetic energy harvesting device such as types of circuit designs which could harvest optimum electrical energy from minimal vibration energy, considering applicable area or environment condition for the application which can be used to harvest vibration energy, the different types or possible magnet positions and orientation that can be used to harvest vibration energy, combining various different types of energy harvesting methods into one device which could harvest vibration energy efficiently

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