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Design Analysis of Piezoelectric Cymbal Transducer (PCT) Array for Roadway Energy Harvesting System

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Abstract: The shortage resources of non-renewable energy have leads to the invention of piezoelectric energy harvester. The piezoelectric energy harvester manages to convert the axle loading from travelling vehicles into useful electrical output where it can used for power up the street lamp or sensor. In this paper, the array configurations of Piezoelectric Cymbal Transducer (PCT) with the conditioning circuit for roadway energy harvesting application is examined for its energy harvesting capabilities. Simulation studies using COMSOL FEA (Finite Element Analysis) simulation software has been carried out to find out the suitable array configurations of PCT that is capable to produce higher electrical output. The PCT design model comprises of eight PCT structures arranged in array configurations and placed in structural steel protective cover. A resistive load is connected in parallel with PCT model to examine the harvested power from the PCT. This study has found out that the array configurations with the utilisation of damper in various resistive load has significant corresponding effects on the power generation of PCT. A total generated power of 109 mW has been obtained from PCT array model with the utilisation of damper embedded in asphalt pavement under 30 kN load across 20 kΩ resistive load at frequency of 100 Hz. A conditioning circuit is designed to ensure the electric output is feasible to power up load such as street lamp. The conditioning circuit consist of rectifier, boost converter and energy storage is designed in Proteus Design Suite software. It has been discovered that the conditioning circuit managed to boost the input power to the output power by a ratio of 1:2. These results suggest that PCT array model with conditioning circuit managed to be implemented as energy harvester in roadway application.

Keywords : Piezoelectric, COMSOL, Cymbal Transducer

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1. Introduction

Electrical energy is one of the most essential elements in human's life. Over the years, enormous amount of innovation is being created to boost up the demand of electricity. According to the Malaysia's Energy Commission, Energy Information Administration [1], about 46 percent of electrical energy is generated from natural gas and around 41 percent is from coal and only 1 percent is from the renewable energy. When fossil fuels are burned, they cause bad consequences to the environment. Malaysia is aiming for sustainable development by 2020 [2], thus more renewable energy projects should be implemented in the country. Engineers have found alternative ways for electrical energy resources in recent decade and one of the more environmentally friendly way is through the piezoelectric transducer.

Generally, piezoelectric uses crystal to convert the mechanical energy into electrical energy. Conventional piezoelectric based energy harvester is basically divided into two types which are high frequency type (cantilever) and low frequency type (cymbal). Cymbal piezoelectric harvests energy from compression such as roadways and pavement, while cantilever type harvests energy via vibration such as railway and bridge [3]. Most of the ambient energy is currently being wasted; lost as heat, light, tide or other impractical forms. Thus, engineers are trying hard to collect and to convert these energies into electricity as one of the efforts to enhance the renewable energy resources.

Aiming for the better sustainable development by 2020, Malaysia can utilise the piezoelectric energy harvesting system in its roadways. Due to the increasing number of vehicles in Malaysia, buddle of kinetic energy due to the compression of vehicle tyres are wasted. The kinetic energy from the vehicles can be converted into electrical energy and can be used for street lighting and other miscellaneous applications where this will help in cost savings and also help to heading towards the cleaner environment.

Cymbal piezoelectric transducer is one of the most promising alternative ways to harvest such wasted energy owing to its weather independency feature [4]. Cymbal transducer holding a piezoelectric layer in the middle and can directly be placed in the pavement with the protective case [5]. The cymbal piezoelectric can improve the ceramic energy output efficiencies as the structure of the piezoelectric is subjected to both vertical and horizontal stresses [6]. This project intends to investigate the array configuration of cymbal piezoelectric in order to produce high electrical energy and to propose appropriate method in amplify and store electrical energy generated from the cymbal piezoelectric.

2. Materials and Methods

The research works presented in this project are conducted in COMSOL Multiphysics and Proteus design suite software environments in order to obtain the required result data. The overview block diagram for this research is illustrated in Figure 1.

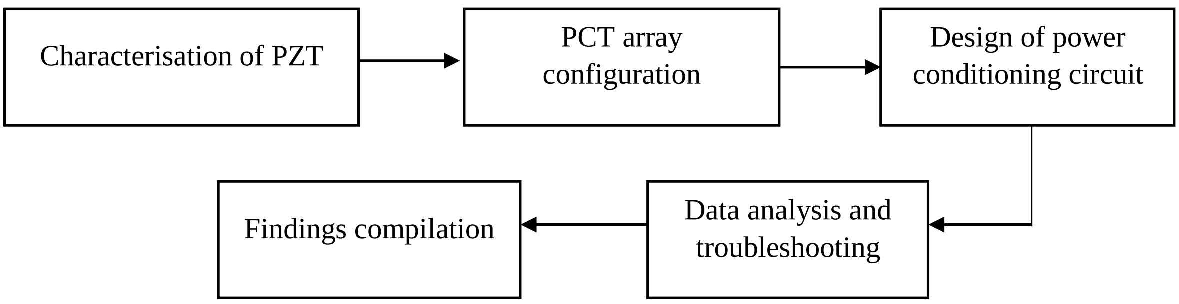

Figure 1: The block diagram of the project

The analysis works will be carried out to study the suitability of the piezoelectric transducer array's configuration as well as to design the power conditioning circuit. The tests on the modelling work will be conducted using 3D model of piezoelectric using COMSOL. The power conditioning circuit will be designed using PROTEUS software and the output voltage will be recorded and analysed.

2.1 Design of PCT array model in asphalt pavement

The design of the Piezoelectric Cymbal Transducer (PCT) that carried out using COMSOL multi-physics is shown in Figure 2 is according to the specification as proposed by Chua et al. [7]. Based on Figure 3, the pavement model is designed using two block geometry which is located on top of the PCT model and at the bottom of the PCT model. Both of the pavement blocks having a height of 60 mm. The material used for the pavement is asphalt material. The sizing characteristics for each of cymbal transducer element are stated in Table 1.

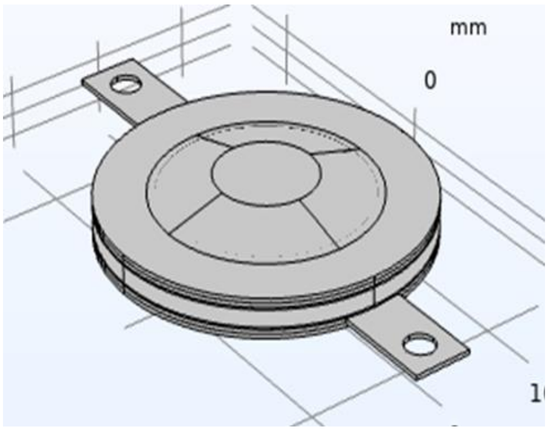

Figure 2: The PCT structure model

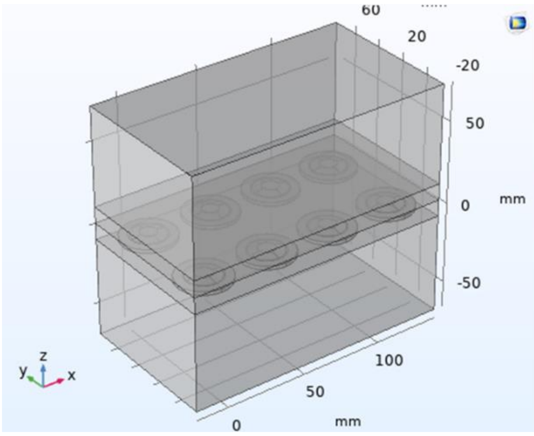

Figure 3: The PCT array model in asphalt Pavement

Table 1: Measurement of PCT parameter

Parameter	Dimension	Measurement (mm)
Total diameter (mm)	Φ	32
Cavity base diameter (mm)	Φ_e	22
Apex/End cap diameter (mm)	Φ_d	10
Piezoceramic (PZT) thickness (mm)	t_p	0.3
Cavity height (mm)	h	2
End cap thickness (mm)	t_c	0.3
Slip ring thickness (mm)	t_{sr}	0.015

2.2 Design of power conditioning circuit

The power conditioning circuit which contains of rectifier, boost converter, super capacitor as energy storage and also the load resistance is designed using Proteus Design Suite is shown in Figure 4.

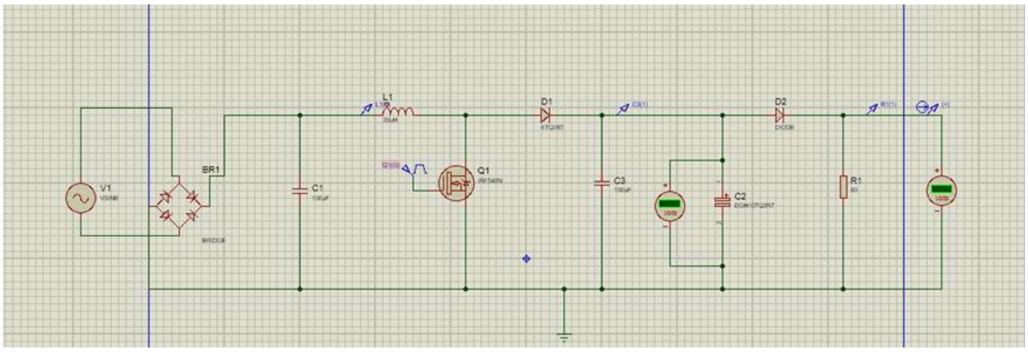

Figure 4: The power conditioning circuit

The rectifier is to convert the alternating current (AC) input into a direct current (DC) output and filtered using a capacitor filter with a value of 100 µF. The boost converter which contains of transistor IRF540N, an inductor with a value of 39 µH and a 100 µF capacitor is then used to step up the input voltage. The energy will store in a super-capacitor before the energy is transmitted to the load resistance.

2.3 Mathematical analysis of the cymbal transducer

The piezoelectric is a device that generate electrical energy with an applied mechanical stress which involve the deformation of material of piezoelectric. Direct piezoelectric effect is occurred when the external stress applied onto crystal mesh disturbed the charge balance. This will cause the electric charge carrier to transfer the energy and creating a current in the crystal. The changes in the electric field, the electrical displacements, or mechanical stresses and strains are linearly related. The relation can be shown by the following equations [8]:

$$T_{ij} = C_{ijkl} S_{kl} - e_{kij} E_k \qquad \text{Eq. 1}$$

$$D_i = C_{ijkl} S_{kl} - e_{kij} E_k \qquad \text{Eq. 2}$$

where, T_{ij} is the stress, S_{kl} is the strains, D_i is the electrical displacement, C_{ijkl} is the constitutive relationship, e_{kij} is the piezoelectric effect and E_k is the clamped permittivity. The derived Equations (2.3) and (2.4) show the strain-charge relationship of the piezoelectric effect in order to model an electricity energy harvester. The equation also define the conversion from mechanical to electrical effect by the piezoelectric materials.

$$S = \left[s^E\right]T + \left[d^t\right]E \qquad \text{Eq. 3}$$

$$D = \left[d\right]T + \left[\varepsilon^t\right]E \qquad \text{Eq. 4}$$

where, E is the force field strength, ε^t is the permittivity of the fabric underneath a relentless electric field, d is the matrix for direct electricity, d^t is the matrix for reverse electricity effect and t denotes the matrix operation. For direct piezoelectric, use the equations to deduce the following co-efficient:

$$d_{ij} = \left(\frac{\partial D_I}{\partial T_j}\right)E = \left(\frac{\partial S_i}{\partial E_j}\right) \qquad \text{Eq. 5}$$

$$e_{ij} = \left(\frac{\partial D_i}{\partial S_j}\right)E = \left(\frac{\partial T_i}{\partial E_j}\right)S \qquad \text{Eq. 6}$$

The energy is an exceeding electricity material is designed as energy stored in an exceeding condenser. Thus, the subsequent equation is derived:

$$W_{33} = \left(\frac{1}{2}\right)Q_{33}V_{33} \qquad \text{Eq. 7}$$

Where Q_{33} and V_{33} are described as:

$$Q_{33} = d_{33} F_{33} \qquad \text{Eq. 8}$$

$$V_{33} = \frac{T}{WL} F_{33} g_{33} \qquad \text{Eq. 9}$$

3. Results and Discussion

This section presents the outcomes from the design of PCT model and power conditioning circuit. Initially, the electrical output from the PCT array model is analysed in Section 3.1. The effects of the PCT array model is compared to the single PCT. The effectiveness of hard rubber damper implement on the PCT array model is analysed and its improvement in electrical output are discussed in Section 3.2. The performance of PCT array model embedded in asphalt pavement is then discussed in Section 3.3. Section 3.4 composes the outcomes from the power conditioning circuit simulation works that enhancing the electrical output of the PCT array model. The proposed design of the power conditioning circuit has made the PCT array model more feasible to be implemented in real roadway application.

3.1 Energy yield evaluation of PCT array model

Electric power generations of the PCT model with array configuration has been analysed using finite element analysis method as available in COMSOL. The frequency is varied from 10 Hz to 100 Hz in analysing the frequency response effect on electrical output. Figure 5 shows the output voltage varying with frequency of 10 to 100 Hz. Figure 6 shows the related output power.

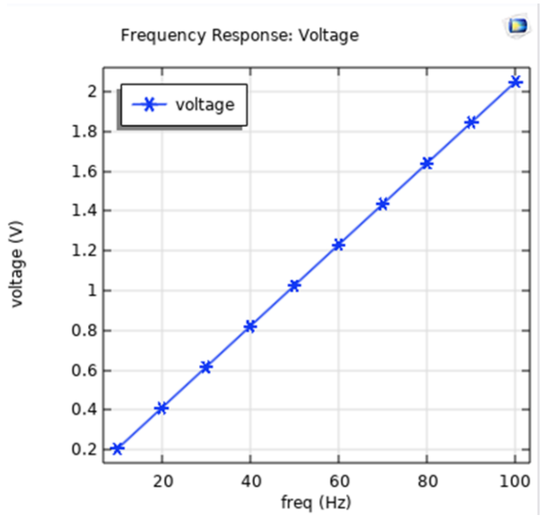

Figure 5: The output voltage versus frequency

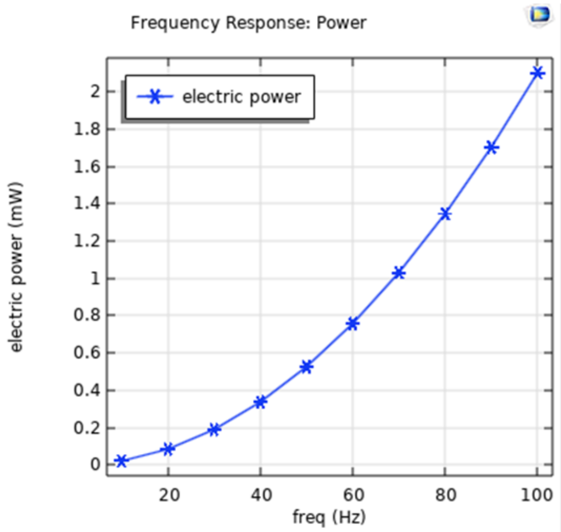

Figure 6: The output power versus frequency

From this data, it can be seen that the output voltage and the output power are exponentially increase to the input frequency. The results indicate that the maximum output voltage from the PCT model is 2.2 V while the maximum output power is at 2.1 mW both obtained at frequency of 100 Hz. This study has found that the frequency is significantly affects the electrical energy generated from the PCT model. These results are in aligned with the recent studies from Jiang et al. [9] which indicated that the maximum power that could be harvested is proportional to the input frequency. The initial objective of this project was is to improve the total energy yield of cymbal piezoelectric with proper array configuration. Based on the study on PCT array configuration, it is found that the PCT array model produced higher electrical energy compared to the single PCT model in a proportional frequency. The input frequency is represented with the speed of vehicles in real practise. The speed of the vehicles can converted to the time of compression. The compression exerted from the surface of the vehicle tire will cause the PCT model to generate an electric charge. The force applied needs to be evenly distributed on the PCT array model in maximising the output power. Thus, the time of compression can significantly affect the total energy yield. Therefore, it can be suggested that a higher frequency can definitely increase the PCT array model's output power.

3.2 Evaluation of total energy yield with damper

In order to analyse the electrical output of PCT array model with damper, the resistive load is varied from 10 kΩ to 50 kΩ. The frequency is maintained at 100 Hz and the total force is remained constant at 30 kN. The output power and output voltage from the varied resistive load is shown in Figures 7 and 8 respectively.

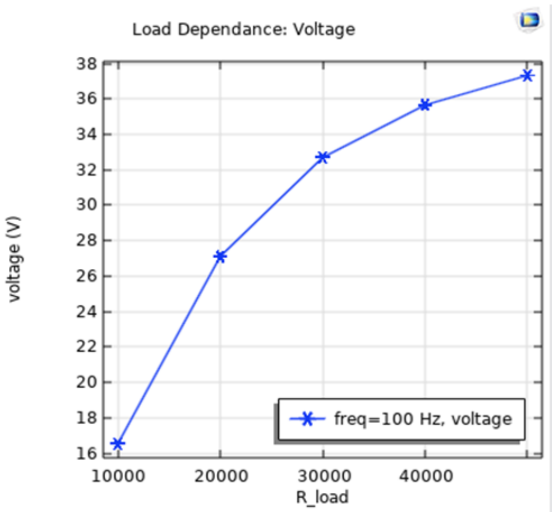

Figure 7: Output voltage from load resistance

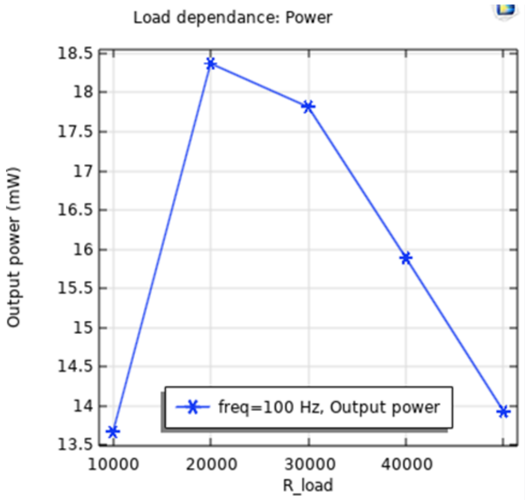

Figure 8: Output power from load resistance

Figure 7 shows the clear trend of increasing output voltage in response to the resistive load with maximum voltage of 37 V. Further analysis has showed that the output power is at 18.4 mW at 20 kΩ resistive load. The output power is decreasing after 20 kΩ of resistive load. Interestingly, this correlation is related to the analyses of the optimum resistive load of the PCT model. This study indicate that an output power can be increase by applying the damper on top of the PCT model compared to the previous simulation results. These results are reflected Lu et al. [10] works, that higher voltage can be generated in piezoelectric with shock absorber compared to direct piezoelectricity. This result can be explained by the fact that the hard rubber damper can provide elasticity and damping which acts as a spring and damper. The damper has eventually enhance the effectiveness of the suspension on the PCT model. The high resilience of hard rubber can limit the amount of pulling up and thus increase the effect of PCT array model. Moreover, the damper also can protect the PCT array model from destroyed and increase the life expectancy of PCT array model in the pavement. This observation might support the hypothesis that utilisation of damper can improve the output power of the PCT array model.

3.3 Evaluation of the total energy yield in asphalt pavement

In order to estimate the capability of PCT array model embedded in asphalt pavement, the electrical output from the PCT array model has been analysed. The simulation is carried out by varying the resistive load from 10 kΩ to 50kΩ in determining the optimum generated output power. The output voltage and output power from simulation is shown in Figure 9 and Figure 10, respectively.

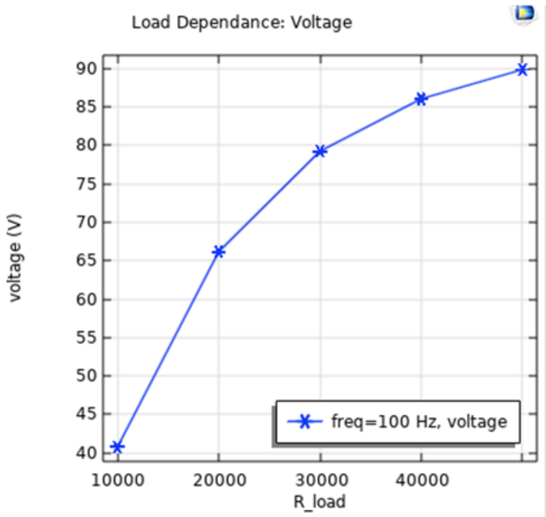

Figure 9: The output voltage from the load resistance

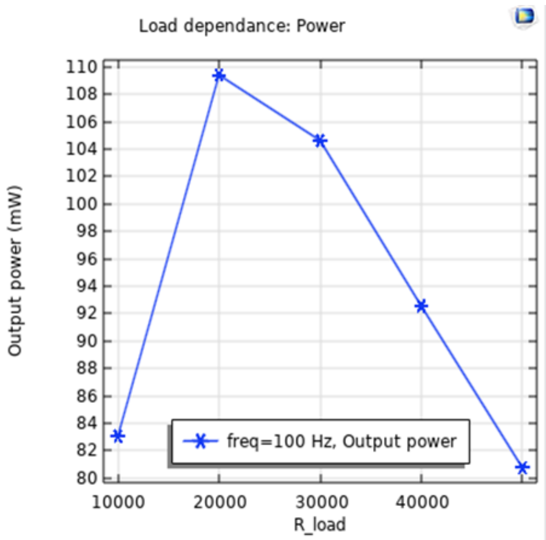

Figure 10: The output power from the load resistance

Figure 9 has shown the output voltage is exponentially increase to the resistive load while Figure 10 gives the highest output power at 20 kΩ. From this data, it can be seen that external electrical load resistance is one of the significant roles in determining the level of electrical power of the PCT array model in asphalt pavement. Comparing the result in Figure 10 and Figure 6, it shown that the PCT array model are capable to generate higher electrical output in asphalt pavement. This finding has also reported by B.C Kok et al [11]. In practical implementation of the PCT array model in asphalt pavement, the axles of vehicles aspects also need to be determined. Jiang et al. [9] have indicated that the passing vehicles with two axles can induce two power pulses. Based on the simulation analysis, the highest output power is 109 mW at 100 Hz frequency. Taking the pulse power produced from the two axles vehicle, the designed PCT array model might produce 0.218 W for one vehicle loading. Assuming the traffic volume is 2000 vehicles per hour, it can be estimated that the possible output power harvest from the PCT array model is about 436 W/ h. This amount of electrical energy is significant and can be stored in a battery to power up the road appliances such as street lamps.

3.4 Evaluation of output from power conditioning circuit

The performance of the power conditioning circuit to boost the output power from PCT array model is analysed. The input voltage is set to 65 V at a frequency of 100 Hz. The input voltage value was taken from the simulation of PCT array model in asphalt pavement using COMSOL. The resistive load is varied from 10 Ω to 100 Ω. The duty cycle set maintain at 75%. Almost all electronic equipment are in direct current (DC) basis. Thus, in order to utilise the AC voltage generated from the PCT array model, the rectifications process need to be considered. The first test is aimed to evaluate the waveform from the full bridge rectifier as shown in Figure 11.

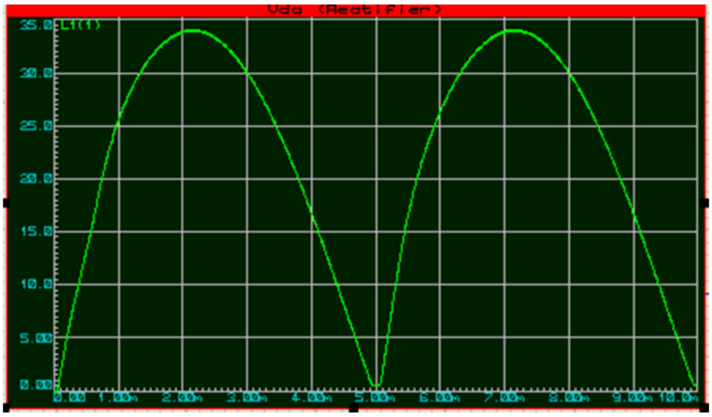

Figure 11: The waveform from the full bridge rectifier

Figure 11 shows that both half-cycle of a sine wave of AC waveform have been rectified. Significantly, the highest peak of the waveform is at 34.5 V. The value is then compared to the formula of the full bridge rectifier as follows:

$$V_{dc} = \frac{2V_p}{\pi} \qquad \text{Eq. 10}$$

where V_{dc} is output voltage in DC and V_p is peak voltage. The calculated output DC is 41.38 V while the measured output DC voltage is 34.5 V. There is only a slight difference between the calculated and measured value where the percent error is about 16.63%. Figure 12 shows the electrical output from the designed circuit.

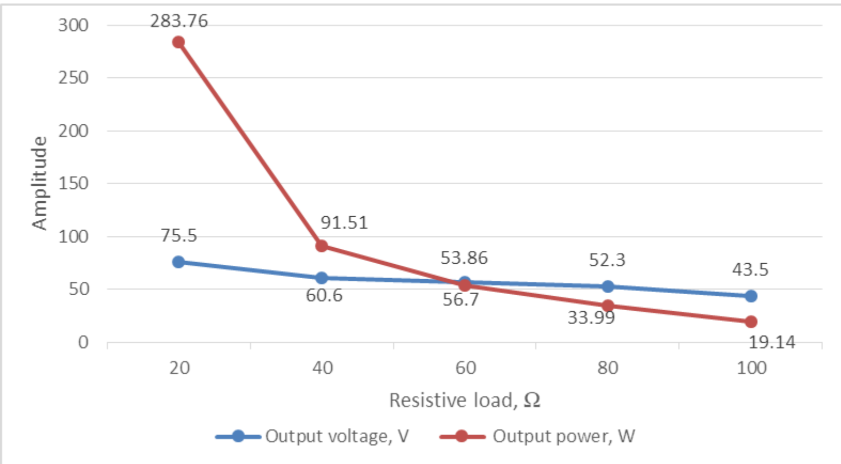

Figure 12: The output power and output voltage from the power conditioning circuit

In Figure 12, there is a clear trend of decreasing output power from power conditioning circuit with respect to linear resistive load. The highest output power is measured as the power delivered to the 20 Ω resistive load at the frequency of 100 Hz. The highest output voltage is 75.5 V. Based on the output voltage, it can be compared with the formula of output voltage from boost converter as follows:

$$V_o = \frac{1}{1-D} V_s \qquad \text{Eq. 11}$$

where D is the duty cycle and V_s is the input voltage. It was found that the calculated value of output voltage is 138 V. The percent error between the simulation result and the calculated value is about

45.3%. According to these data, we can infer that this proposed power conditioning circuit can increase the input voltage of PCT array model. The ratio of the output voltage to the input voltage is simplified to 2:1. This shows that the power conditioning circuit can boost two times the input voltage.

4. Conclusion

PCT array model with power conditioning circuit has been designed and demonstrated using COMSOL Multiphysics and Proteus Design Suite. The proposed PCT array model comprises of eight PCT that arranged in a structural steel platform. The study has examined the improvement in the total energy yield of the PCT array compared to a single PCT. The study of PCT array with hard rubber damper has also being carried out to increase the reliability of the PCT array model as implemented in asphalt pavement. One of the most significant findings from this study is that the proposed PCT array implemented in the asphalt pavement model has produced a maximum output power of 109 mW with an optimal resistive load of 20 kΩ at the frequency of 100 Hz under 30 kN force applied. It also found that the PCT array model with damper produced high electrical output compared to the PCT array without damper. A power conditioning circuit that comprises of full bridge rectifier, boost converter and energy storage has been designed in enhancing the output power generated from the PCT array model. The simulated designed circuit rectified the AC input voltage of 65 V, 100 Hz to 35.4 Vdc. The DC output voltage is then boosted up to 75.5 V. It is found that the proposed conditioning circuit has more than double of its input voltage. Thus, the objectives of this study in improving the total energy yield of cymbal piezoelectric with proper array configuration as well in designing the proper conditioning circuit for the PCT have been achieved. A limitation of this study is that the simulation result has not been compared to the experimental data from the real practice of PCT model in asphalt pavement. The total energy yield might be differ as experimental work can provide the empirical data while the simulation works cannot. In spite of its limitations, the study certainly adds to understanding the potential of PCT array with conditioning circuit applied in roadway as energy harvesting system.

Acknowledgement

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