# Development of Multiple-Input Power Management Circuit for Piezoelectric Harvester

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ABSTRACT

*This paper discusses the multisource input from the piezoelectric (PZT) generators to the power management circuit (PMC) of the energy harvesting system. It discusses the structure of the PMC starting from the AC-DC full bridge rectifier circuit and the structure of the storage circuit of the power management circuit itself. The AC-DC rectifier circuit was compared with separated AC-DC rectifier, series and parallel connection to choose the best performance output and structure. The storage circuit was also compared between traditional method and switch circuit. This paper also describes the designing circuit of the PMC from the software and fabricating it to PCB board circuit. The PMC was tested by connecting 4 input PZT generators which were harvested from the vibration and connected to the application electronic load circuit such as microcontroller and sensors to complete it as an energy harvesting vibration based system. The performance test was conducted by testing it in a laboratory and field test at one of the cooling fan power stations which provides continuous vibration from the motor. Two methods of testing were conducted to measure the performance of the PMC which were laboratory test and field test at the vibrating motor of cooling fan in power station. The 70% of the efficiency was recorded for both laboratory test and field test from the PMC. The output power of the PMC is 1.94mW and the input power is from the multisource input PZT. Author also makes a comparison between the performances of the PMC with other previous designs.*

**Keywords:** *Piezoelectric, Power Management Circuit, Broadband, Efficiency.*

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## Introduction

One of the efforts to increase the versatility and robustness of energy harvesting system is by utilizing multiple inputs from energy harvester [1]-[3]. The effort to combine multiple inputs of source power devices to power storage has started but with large scale power generation systems [4]-[9]. These studies focused on stand-alone generation system with low power generation from the source which had different challenges such as low power levels, small overall size and mass constraints.

This work examines harvesting the power from multiple input powers from PZT bimorph generator. The issue is addressed by using multiple input power PZT bimorph generator scheme of sizes. For energy harvesting applications such as stand-alone conditioning monitoring system, the mass and the volume of the system must be reduced to make the systems minimally intrusive in their environment. This will result in very small power outputs.

Therefore, this study is one of the efforts to reduce the size of the energy harvesting system which will propose the passive multisource energy harvester AC-DC rectifier energy harvester. When an array of the multisource from the PZT bimorph generator is used to power single device, the power must somehow be combined in an efficient manner in a multisource topology. Figure 1 shows the power from the harvesting generator (4 input multiple PZT bimorph generator) through AC-DC rectifier circuit, into the energy storage circuit, and to the electronic components being powered. Figure 1 also shows the power management control system flow of the power from the storage circuit.

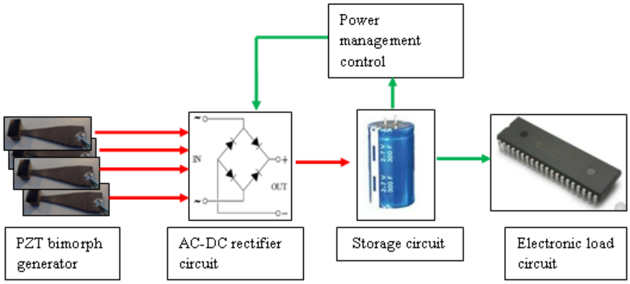


Figure 1: Multiple input power source circuitries connected to power up single device.

Passive circuits represent multisource topology as no power is used by the power management controls. This work examines the use of passive circuit topologies for combining the power from multiple PZT bimorph generator energy harvesters onto a single storage super capacitor. This work will study the two types of the passive circuit from 4 separate standard harvesting circuits as shown in Figure 2. Two types of the passive circuit will be compared during combination of the 4 inputs power. The first is the passive-series circuit of the AC-DC rectifier as in Figure 3. The second type of the passive circuit is the passive-parallel circuit of the AC-DC rectifier as in Figure 4.

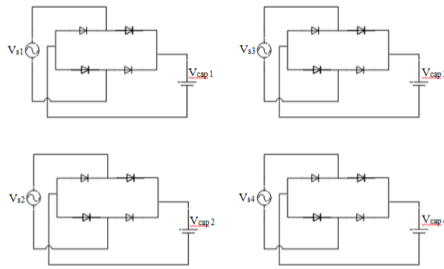


Figure 2: Four separate standard energy harvesting circuit.

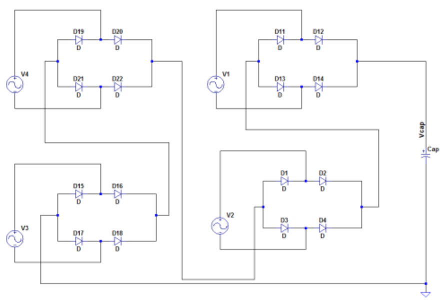

Figure 3: Series connection AC-DC rectifier circuit.

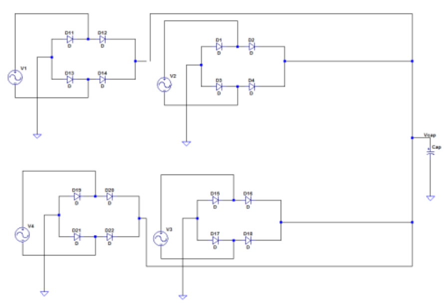

Figure 4: Parallel connection AC-DC rectifier circuit.

The aim of this work is to select the best AC-DC rectifier circuit and charging circuitry. This power management energy harvesting circuit focuses on the implementation of 4 different resonance frequencies as an input source to the power management circuit. By combining multiple input powers source from energy harvester or generator source to power one system, it can increase the viability of potential designs as solutions of many applications. These multiple input power source is combined as passive circuit topologies for a multiplicity of PZT bimorph generator as a multisource energy harvester solution which produces AC voltage.

Two comparison charging circuits are discussed which include the direct super capacitor charging circuit (normal super capacitor charge circuit) and switch mode super capacitor charge circuit. The verification of the comparison focuses on the performance circuit and user friendly for the end user. During charging of the super capacitor, it is important to show how much value of the voltage it is charging to the end user to know. This work also discusses on the verification experimental comparison items between two super capacitor charge circuits.

## Multi-source AC-DC connection

The circuit performance comparison of Figure 2, Figure 3 and Figure 4 are conducted by simulation and experimental. LTspice simulations from Linear Technology are used to run the circuit performance evaluation. The simulations reported herein examine the interactions of multiple input PZT bimorph generators and how this affects the performance of the extracted power of and stored in the super capacitor storage device.

The proposed passive AC-DC rectifier circuit was experimentally investigated using two test setups. The first test is to investigate the effect of passive series and parallel AC-DC rectifier circuit to the extracted power and stored in the super capacitor storage device as shown in Figure 5.

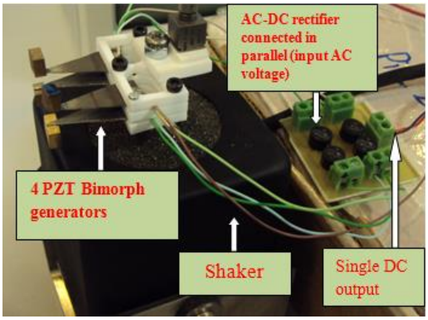


Figure 5: Experimental setup to test the connection PZT bimorph generator connected in parallel to the AC-DC rectifier circuit.

The powers were calculated at the extracted power from the PZT bimorph generator at the super capacitor storage device at various rectified DC supply voltages ranging from 0 to 30 V. Each test was repeated at 4 peak resonance frequencies 47Hz, 49Hz, 53Hz and 57Hz (4 PZT bimorph generator have own each peak resonance frequency). The voltage and current across the super capacitor were measured as to calculate the extracted power.

The time was taken to identify which type of the passive connection can give less time taken for the super capacitor to fully charge. The less time taken from the super capacitor to fully charge is better.Table 1 shows the test parameter properties that were used during simulation and experimental verification for passive circuit comparison between passive series and passive parallel circuit for AC-DC rectifier in multiple input sources.

Table 1: Test parameters properties.

| Property | Simulation | Experiment |
|---|---|---|
| **Acceleration set for shaker** | - | 0.25g |
| **Input voltage** | $16V_{rms}$ | Generate from PZT (maximum voltage generate $16V_{rms}$) |
| **Peak resonance frequency (Hz)** | 47, 49, 53, 57 | 47, 49, 53, 57 |
| **Internal capacitance (25nF)** | Single = 25<br>Series = 6.25<br>Parallel = 100 | Single = 25<br>Series = 6.25<br>Parallel = 100 |
| **Storage super capacitor** | 1mF | 1mF |
| **Voltage fully charge** | 8V DC | 8V DC |

## Storage comparison charging circuit

For simplicity, consider the piezoelectric generator after full bridge rectification as a fixed voltage source with varying source resistance as a function of the vibration. The rectified equivalent model for the power management circuit is shown in Figure 6. The power output from the piezoelectric energy harvester can be expressed as in Equation (1):

$$P_{source} = \left[(V_{source})\left(\frac{V_{load}}{R_{source}}\right)\right]\left[1 - \frac{V_{load}}{V_{source}}\right] \quad (1)$$

Figure 7 illustrates the relationship between the piezoelectric generator source power and the load voltage for a constant Vsource and Rsource. From

[5], it is evident from Figure 7 that maximum power transfer will occur when the load voltage is half of the source voltage (Vload = Vsource / 2).

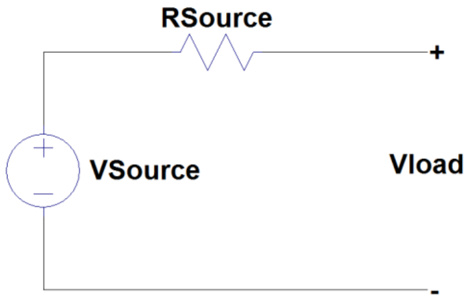


Figure 6: Simplified equivalent model of the rectified piezoelectric generator.

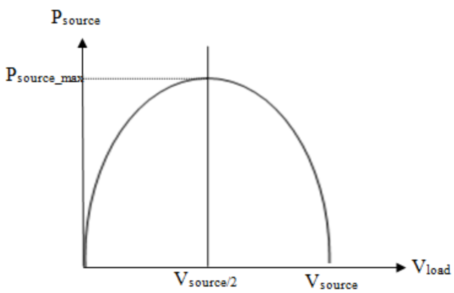


Figure 7: Piezoelectric generator source power as a function of the load voltage.

## Charging super capacitor directly and switch mode super capacitor circuit

The easiest and cheapest way to charge a super capacitor from the full bridge rectifier is to connect a capacitor in parallel across the output terminals (Vload in Figure 8). To keep the voltage over the super capacitor within specification, a zener diode with the cut-off voltage 16V is used as shown in Figure 10. The cut-off voltage will clamp input voltage from the rectifier if it is over 16V as to maintain stable input voltage charge to super capacitor.

With minimal circuitry and assuming an ideal storage capacitor, the only loss incurred is the reverse leakage current through the zener diode. But when an initially discharged capacitor is connected across the output terminals, the energy harvester is biased at 0V and essentially sources no power. Although the capacitor will charge, the power transfer efficiency is nearly 0% at Vload = 0V and at Vload = Vsource (refer Figure 7). Charging an ideal capacitor and assuming zero losses through zener diode, the power transfer efficiency will follow the parabola as depicted in Figure 9 reaching 100% at Vsource/2. The circuit in Figure 7 has a further limitation in which it does not provide the end user with operation information. Levels of vibration can vary significantly on a single motor. For example, an energy harvester may produce 10mW on the side of a motor but 0.5mW on the top of the same motor. To simplify installation and optimize charge times, it is important to provide the end user with an indication of how much power is being generated.

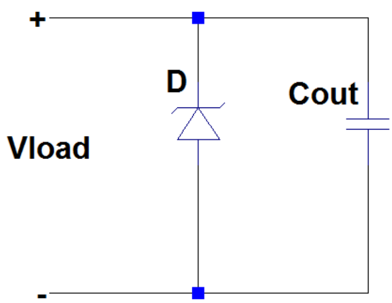


Figure 8:  Charging a super capacitor with minimal charging circuitry.

The more complex and costly of the two circuits discussed here is shown in Figure 11. The buck converter mode circuitry is functioned to eliminate the limitations of the standard charging circuit as in Figure 10. The circuit in Figure 11 consists of the components comprising of a P-Channel MOSFET (M1), smoothing capacitor (C1-C3), storage capacitor (Cout), and control circuitry driving the PMOS gate, where in this case the buck converter will use feed-forward to optimally regulate the input voltage (Vload) in Figure 11.

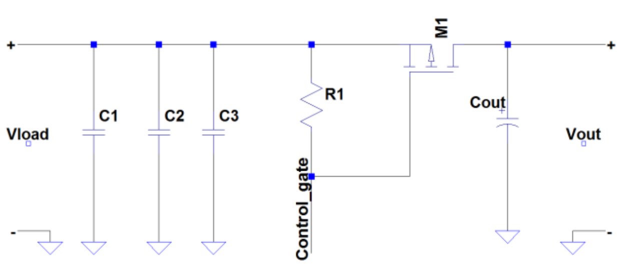


Figure 9:  Using buck converter discontinuous mode to charge a super capacitor.

## Power management circuit design

Figure 10 shows the proposed power management energy harvesting circuit vibration based system. The harvester device produces an AC voltage and therefore it needs to be rectified to DC voltage before it is possible to charge the capacitor. The circuit contains AC-DC rectifier circuit, energy storage device, comparator circuit and DC-DC regulator circuit. The schematic design of the power management circuit is shown in Figure 11. By using LT Spice software, the schematic design was scathed and simulated for the performance result. There are advantages in using this software because its library contains all the devices that are used in this design. Block I shows the 4 AC-DC full-bridge rectifier circuits which are inputs from the piezoelectric AC voltage. Block II shows the storage capacitor device with circuit interfacing. The storage capacitor is using 2.2mF. This block functions to store the input power from the energy harvester before starting to distribute it to the electronic application devices. The output from storage device is then connected to the comparator circuit mentioned as block III in Figure 11. LTC1540 comparator device from Linear Technology is used for the comparator circuit. Meanwhile, block IV shows the DC-DC step-down regulator device. The LT1934 DC-DC step-down device from Linear Technology is used to regulate the output voltage from the storage capacitor and connected with the block V which is energy latching circuit before it is connected to the application circuit such as sensor, microcontroller and RF module, while the wireless communication circuitry consists of an encoder chip and a wireless transmitter chip.

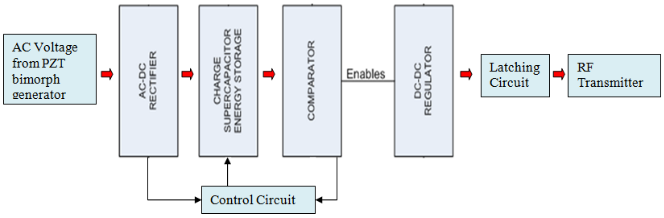


Figure 10: Block diagram proposed power management energy harvesting circuit.

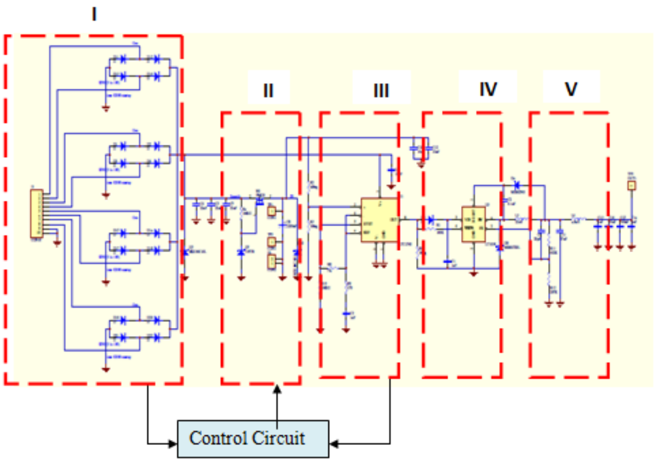


Figure 11: Schematic circuit for the power management circuit with the control circuit.

The control circuit in Figure 11 consists of 3 components placed sequentially: op-amp differential amplifier (MAX4419), low power comparator (MAX981) and pulse generator (MAX919). The control circuits detect and track the rate of voltage changing rather than magnitude as to detect the peak magnitude of the voltage across the PZT bimorph generator. Once the instance negative rate of change voltage is detected, the op-amp and comparator trigger the pulse generator to generate a pulse with duty cycle and period fixed by passive resistors. The comparator is designed after the op-amp amplifies the small outputs power across it. The total power consumption of the control circuit is 400 µW. Comparator circuit is functioning to control on the switching storage super capacitor circuit.

## Multisource AC-DC connection

Two multisources topology of the AC-DC rectifier circuit were studied to combine the power from the multiplicity of piezoelectric energy harvesters, series and parallel. The performance of the two circuits was compared using separate energy harvesting for each piezoelectric device. Table 2 concludes the performance of the two circuits. Parallel connection for the multisource piezoelectric energy harvester gives good efficiency compared to the series connection of the multisource piezoelectric energy harvester input power. Power efficiency is the most important performance criteria that need to be considered in any energy harvesting systems.

Table 2 lists the time t(sec) for the storage super capacitor in Figure 5 to fully charge and the average power of energy storing from the experiment and simulation for the three cases at each peak resonance frequency. From Table 2, it is noted that 4 multiple different frequency input connected in passive parallel circuit generates the largest charging current to storage super capacitor and the most efficient to charge the energy storage super capacitor with 1mF. From Table 2, the passive parallel connection of the AC-DC circuit just needs a short time to fully charge the storage super capacitor. Therefore, from the Table 3, it can be concluded to choose the passive parallel AC-DC rectifier circuit as the circuit connection for the multiple input PZT bimorph generators.

Table 2: Performance comparison between passive series and parallel AC-DC rectifier circuit.

| Freq | Con. Of PZT | $V_{DC}$ after rectified (experiment only) (V) | Experiment | | Simulation | |
|---|---|---|---|---|---|---|
| | | | t (sec) fully charge (8.2V) | Average power (mW) | t (sec) fully charge | Average power (W) |
| **47Hz** | Single | 11.5 | 120 | 1.25 | 84 | 1.43 |
| | In series | 17 | 450 | 0.76 | 419 | 0.84 |
| | In parallel | 11.85 | 30 | 2.5 | 28 | 2.35 |
| **49Hz** | Single | 10 | 240 | 1.05 | 201 | 0.93 |
| | In series | 16 | 978 | 0.65 | 942 | 0.62 |
| | In parallel | 10.6 | 60 | 1.918 | 50 | 1.9 |
| **53Hz** | Single | 10 | 160 | 1.25 | 120 | 1.05 |
| | In series | 18 | 845 | 0.67 | 811 | 0.73 |
| | In parallel | 11.7 | 40 | 2.38 | 37 | 2.3 |
| **57Hz** | Single | 9.85 | 200 | 1.25 | 189 | 1.15 |
| | In series | 16 | 850 | 0.56 | 820 | 0.67 |
| | In parallel | 11.05 | 50 | 2.618 | 46 | 2.75 |

Table 3: The criteria to select the best connection for multiple input power from PZT.

| | Single connection | In series | In parallel |
|---|---|---|---|
| **Circuit complexity** | 1) Need 4 storage super capacitor<br>2) More complex | 1) Need 1 storage capacitor.<br>2) If one connection broken, all the circuit not funtion | 1) Need 1 storage capacitor.<br>2) If one connection broken, the rest circuit still can funtion. |

| | | | |
|---|---|---|---|
| **Small size circuit** | Need more space and connection | Medium | Medium |
| **Charging time to fully charge** | Slow | Very slow | faster |
| **Power stored in capacitor** | Low | Very low | higher |
| **Efficiency (percentage output power strored to the input power generate by PZT)** | Low | Very low | higher |

*In this case the number of multiple input PZT is 4 pieces.

Storage comparison charging circuit

The performance, advantage and disadvantage of two power management circuits were investigated. Below 2mW of source power from piezoelectric generator which is the simplest and cheapest solution charging super capacitor directly achieves the best performance. But the results show that the buck converter switch discontinuous charge circuit performance at input power source levels of above 1mW is the least comparable to the charging of super capacitor directly. From the performance testing of both circuits, the advantages by using switch mode charging circuit shows the indication of whether the capacitor is charging and the indication of how fast it is charging. Besides that, by using switch mode charging circuit, it requires no external power sources to trigger the switch of the circuit if compared to the charge by direct charge. Therefore, if operation information is required, and the complexity and cost can be afforded, the switch mode charge circuit is the best solution for input power source power levels of above 1mW.

The power transfer efficiency for the buck converter discontinuous mode to charge a super capacitor as in Figure 9 is measured at 500µW, 1mW and 2mW. The efficiency charging of the capacitor as in Figure 8 is calculated using Equation (3). The results are depicted in Figure 14 to 16. Figure 14 shows that charging super capacitor directly yields the best efficiency at 500µW if compared to the switch mode charging circuit. At these low input power levels, the buck converter discontinuous charge super capacitor faces suffer due to its relatively high circuit losses.

$$Efficiency = \left(\frac{P_{out}}{P_{Source}}\right)(100) \tag{2}$$

$$= \left[\left(\frac{{V_{out}}^2}{R_{out}}\right) \div \left(\frac{{V_{source}}^2}{4(R_{source})}\right)\right](100) \tag{3}$$

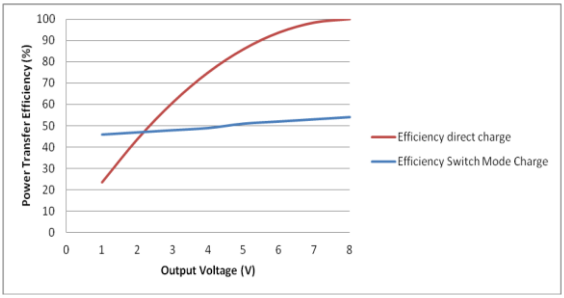


Figure 12: Power transfer efficiency at an input power 500µW.

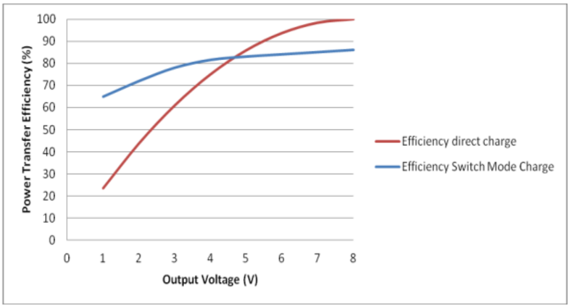


Figure 13: Power transfer efficiency at an input power 1mW.

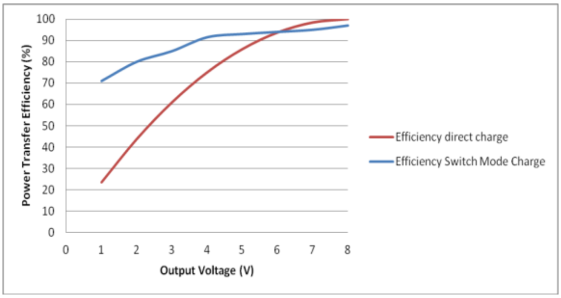


Figure 14: Power transfer efficiency at an input power 2mW.

At the source power of 1mW in Figure 13, the buck converter discontinuous charge super capacitor is the best at the low output voltage levels. At the source power of 1mW level too, the efficiency of the buck converter discontinuous charge super capacitor circuit improves close to the 90% maximum. As expected, the buck converter discontinuous charge super capacitor further improves the efficiency at an input power of 2mW. The initial super capacitor charge time from 0V to 8V for the 2 circuits is measured. The normalized results are provided in Figure 15. The normalized super capacitor charge time from 3.6V to 8V for the two circuits are shown in Figure 16.

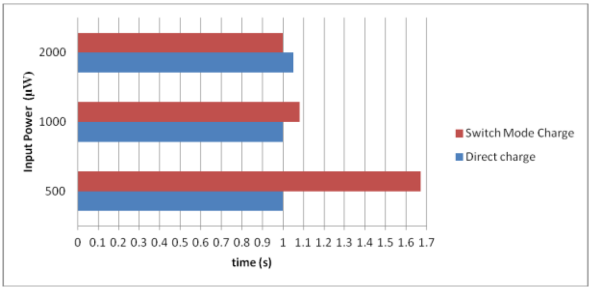


Figure 15: Initial super capacitor charge time from 0V to 8V

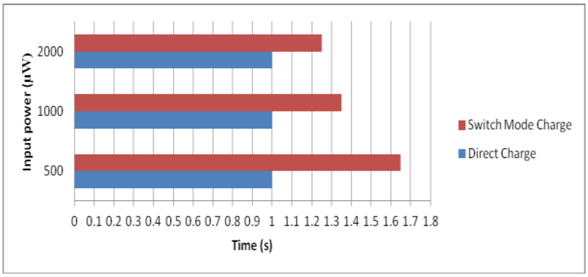


Figure 16: Super capacitor charge time from 3.6V to 8V.

<u>Performance testing of the power management circuit with the energy harvesting system</u>

Generally, the output voltage and power of the piezoelectric energy harvester are high, and a voltage regulation and control circuit is necessary to store energy into the capacitor device before transmitting it to the electronic application circuit. There is a difference in the time taken to fully charge the capacitor between laboratory test and field test as mentioned in Table 4. Based on Table 4, the charging time during field test is faster than laboratory test. It was due to the acceleration value in the field test which is higher compared to the laboratory test. In the laboratory test, the acceleration is set at 0.25g rms. The location to attach piezoelectric energy harvester to the vibration motor is different from the test. Higher vibration point or higher acceleration on the vibration motor was chosen so as to make the piezoelectric produce more power. However, sensor location point to be attached on the vibration motor must be specific at the critical point of vibration even though other points produce more acceleration value.

Lastly, the performance test is not comparable with other previous work for two reasons. First, the measurement tests were performed at different levels and second, the total power dissipation of the electronic circuits has not been considered in some configurations. To evaluate the performance comparison, we proposed the design criteria that will be compared and mentioned as in Table 5.

Table 4: Specification of the power management circuit test in laboratory

| | |
|---|---|
| **Harvester Frequency Range** | 40 – 60 Hz |
| **Input voltage** | 5V – 100V AC |
| **Voltage protection clamp** | 10V DC |
| **Time for initial super capacitor charge time** | 15 seconds (labaoratory)<br>5 second (field test) |
| **Power input** | 2.618mW (@ 47Hz) |
| **Power output** | 1.94mW (@ 47Hz) |
| **Efficiency** | 74% |
| **Power losses** | 0.678mW |
| **Output Voltage DC-DC** | 5V (to electronic application circuit) |
| **Operation system** | (i) Standalone system (powered by harvester)<br>(ii) Single supply voltage<br>(iii) Small scale size<br>(iv) AC-DC full bridge rectifier circuit |

## Conclusion

An AC-DC rectifier circuit and storage charging circuit for the power management circuit (PMC) was presented and demonstrated for harvesting energy from set of 4 vibrating piezoelectric generator. Three configurations of AC-DC rectifier circuit were compared to choose the best configuration for the multiple PZT generators. The parallel connection from the 4 AC-DC rectifiers is the best connection compared to the series connection and 4 separated AC-DC rectifier as shown in Table 2. The criteria used are indicated for each configuration as mentioned in Table 3.

The next important part in PMC is the capacitor storage circuit. This paper makes a comparison of the traditional capacitor charging circuit and the buck switch capacitor charging circuit. The power transfer efficiency, initial super capacitor charge time and super capacitor recovery time were the 3 criteria considered when comparing both the charging circuits. The traditional charging circuit or direct charge super capacitor circuit has a good performance at the initial super capacitor charge time compared to buck switch capacitor charging circuit, but the disadvantage is that the circuit cannot provide the end user information during charging period as to the circuit was charged.

The proposed PMC was then tested in the lab and field test. The PMC is then connected to the harvesting system containing 4 input PZT generators and electronic application load to test its performance. The PZT generators have 4 different frequencies which are 47Hz, 49Hz, 53Hz and 57Hz. The proposed PMC gives 74% efficiency at the 2.618mW input from the PZT generators. The output power is 1.94mW.

## Acknowledgement

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