Analysis of Batteries or Supercapacitor as an Energy Storage for Sound Energy Harvester System

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Abstract: This study focuses on the concept analysis of the suitability of batteries or supercapacitor as an alternative storage device in low power electronic devices. Sound wave was utilized as a source of energy for charging the supercapacitor, and a piezoelectric Q220-A4-503YB was used as the energy transducer. A respectable performance of piezoelectric in terms of the output force and voltage was found to be at an operating frequency of 68 Hz with an input source of 96 dB sound intensity level. Based on the experimental work, the supercapacitor is more efficient as a storage device for low power source when compared to batteries due to the charging current. The charging time of the 0.22 F supercapacitor for either in Villard or Dickson is higher when compared to others. The charging time of the supercapacitor with the voltage regulator of 0.5 W and 1.0 W by the Villard multiplier is longer as compared to the Dickson multiplier, which produced an output voltage of 9.817 V and 9.647V respectively. From the study, it is proven that the speed of delivery voltage can be stored in supercapacitor with higher capacitance would be have longer time when in term of process charging and discharging as compared to lower capacitance.

**Keywords** : Batteries, energy harvesting system, noise, piezoelectric materials, supercapacitor, sound wave

## 1. Introduction

The field of power harvesting has experienced significant evolution over the past few years due to ever-increasing needs and desire to produce portable and wireless electronic with prolonged lifespan. An energy harvesting system is critical as the process is associated with the capability of capturing, converting, storing and delivering energy in a form that can be used to provide the power needed by the system it serves and is therefore considered energy-free. Energy harvesters exploit efficient renewable and environmental energy sources, including solar(1)-(2), wind(3)-(4), acoustic(5)-(6), thermal(7), heat(8), hydro-energy(9), ambient vibration energy(10)-(11), temperature gradient(12), magnetic energy(13) and mechanical vibration(14); all of which have attracted the growing attention of wide range of engineering specialties.

Unfortunately, output power of vibration and acoustic energies are lower than solar and wind energy. This becomes the main issue for wide practical application of vibration and acoustic energy harvesting. However, vibration and acoustic energy exhibit several special advantages than solar and wind energy. Firstly, harvesting vibration and acoustic energy is not limited by weather and time. Vibration energy largely exists in motions from vehicle and airplane, human body, operating machine, etc. And acoustic energy can be easily found in noise from traffics, airplane engine,

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stadium, etc. Ubiquity of vibration and acoustic energies will provide a great number of opportunities to allow us to utilize vibration and acoustic energy. Most importantly, storage of vibration and acoustic energy over a period of time may be significant.

Then, the extracted energy is converted into usable electric energy to power a battery**-**less system to overcome the frequent battery replacement problem. As the piezoelectric-based micro-energy harvesting system is starting to replace the use of conventional battery systems, the use of micro-energy harvesting system has increased dramatically in recent years. The ambient sources of energy harvesting produce mechanical energy which is then converted to electrical energy using a transduction mechanism, such as electromagnetic (inductive)(15)-(17),

electrostatic (capacitive)(18)-(19), or piezoelectric(20)-(21). These piezoelectric cantilevers also deliberated as useful transduction mechanism to convert the available vibrational energy from the surrounding into a functional form to power small size electronic devices in current studies as shown in Table 1.

Table 1: Maximum energy density of three types of vibration

transducer (22)-(23).

|  |  |
| --- | --- |
| Transducer | Energy density  (mJ/cm3) |
| Piezoelectric | 35.4 |
| Electromagnetic | 24.8 |
| Electrostatic | 4.0 |

Other advantages of energy harvesting system is that the expenses and problems involved during the changing of the batteries occasionally can be reduced. To harvest energy such as ambient vibration, such harvesters mechanism are commonly designed to work at one frequency, i.e. their resonant frequencies, and produce maximum output voltage when the resonant frequency matches the ambient vibration frequency of the sources. This is the reason piezoelectric transducers are chosen in this research, as it is the most efficient device to implement such energy transformation and harvesting.

Recent researches cited above had focused on developing optimal energy harvesting structures(24)-(25). Nevertheless, the electrical outputs of these devices are often too small to power up electrical devices directly. Consequently, the methods of collecting and storing parasitic energy are also one of the important keys to acquire self-powered systems. Sodano et al.(26) investigated several piezoelectric power harvesting devices and methods of accumulating energy by utilizing either a capacitor or a rechargeable battery. Ottman et al.(27) developed several highly efficient electrical circuits to store the generated charge as well as introducing it to the load circuit.

The piezoelectric has the ability to receive any vibration and convert them into electrical signal, as well as having the capacity of energy storage devices. Thus, this has attracted many researchers to implement circuits and systems to convert pressure and vibrations into electrical power as well as extending the overall lifespan of the system. Jamal et al.(28) illustrated the possibility of developing piezoelectric energy to harvest acoustic energy using electrochemical storage devices. The harvesting system was composed via sound generator amplifier. An electroacoustic absorber and Electrochemical Double Layer Capacitors (EDLC) were experimentally tested. The EDLC charged quickly but discharged slowly due to the larger value in farad as compared to capacitors or batteries(29). The experimental results showed that EDLC was able to deliver high-pulsed currents which caused the charging powers to be in the range from a few mW up to several tens of mW. The energy efficiency of the whole system ranged from 5 % up to 35 %.

Shahriat et al.(30) used multiple piezoelectric to produce sound energy that was then stored in a supercapacitor before being used to charge EDLCs via piezoelectric devices. In that particular study, the device was used to charge a 9 V electrochemical cell. Abeywardana et al.(31)-(32) proposed that while piezoelectric materials require low current in an energy harvesting system, a supercapacitor enables a significantly fast charging process as well as a higher amount of energy storage. This is done by increasing the current up to mA range, which can be used to power up external devices. This feature could be an alternative solution and can be proposed to produce electrical power via energy harvesting system. The demand for energy harvester system to run well depends on an established storage device. It needs to be able to have a full range of voltages instead of a defined potential.

The general idea of this research is to harvest sound wave energy in a new way via piezoelectric strips. Nowadays, there is a lot of noise due to surrounding bustling metropolitan cities and road traffics. All these noise could add up to a huge potential to be used as energy resources. The current growth rate of population produces a lot of noise from honking of cars as well as other voices(33)-(36). These could be used as an advantage by converting the noise into electrical energy. Noise energy could be converted into useful forms of energy by using a transducer. This is done by using a transducer that converts vibrations from sound or noise into electrical energy. This raw energy will then be converted and conditioned into a more usable energy storage device which could be applied to a load.

The medium to harvest sound energy for this research was a single piezoelectric strip, which is totally different as compared to previous research with double or multiple piezoelectric strips. The specific piezo-strip used was the model Q220-A4-503YB. This strip was selected out of convenience without any further specific operations. Several considerations include piezoelectric materials which are capable of producing high voltages, but are generally very low currents (often 10‟s – 100 V and in the range of nA-µA). Therefore, the piezoelectric transducer selected in this work is very promising for low power applications operating at a low resonant frequency as the environmental vibration sources. Difficulties may arise if the energy output from a single strip is too low to switch on the converter section. This may result either from a threshold voltage cutoff or from a very low current generated from the piezoelectric material.

There are two main purposes of this experiment. The first is to conduct an analysis and study on the suitability of energy storage devices (batteries and supercapacitor) on the charging time spent on piezoelectric transducer where the source of energy is from sound. Secondly, this study also considered the effect of voltage regulation on the supercapacitor. The effect due to the presence of voltage regulator in the supercapacitor on energy harvester circuit would also be examined. This is to investigate the different charging time required for the supercapacitor to be fully charged. In addition, the voltage regulator would be investigated if it could either fix a constant DC output voltage or block the AC ripple voltage before entering the supercapacitor. Besides the well-known renewable energy sources such as solar, vibration, mechanical, wind and turbine, sound could also be converted into electrical energy. In this work, the usage of ambient noise would be proposed as a suspension source to generate energy which is then stored in a supercapacitor or batteries for low voltage applications.

## 2. Methodology

Fig. 1 shows the experimental test setup for the piezoelectric transducer on energy harvesting system. The complete system consisted of a few major components including a wooden box, function generator, a piezoelectric energy harvester, a loudspeaker and an oscilloscope. The wooden box was used to prevent unwanted disturbance effect inside sound vibration of piezoelectric for testing purposes; however, the sound level meter and multimeter would pick up the sound level of speaker and output power generated through effective piezoelectric transducers mechanism.

The sound level meter was placed in the vicinity of the energy harvester (EH) inside an acoustic chamber. The chamber was made of wood absorber of dimension L= 86 cm, W=50 cm and H=51 cm, so that the sound level could be controlled and repeated all the time during experiments. The piezoelectric transducer was clamped close to the loudspeaker. The loudspeaker played the role of input source and its specifications are depicted in Table 2. Through the loudspeaker, sound wave was propagated through space and was picked up by piezoelectric transducer. The loudspeaker was connected to the function generator for amplitude control purpose. The vibrating frequency could also be controlled by the function generator. The sound level meter was used to measure the level of sound produced at the energy harvesting and the sound intensity was varied by adjusting the amplitude of function generator or by varying the distance to produce the intended level.

The vibration of piezoelectric transducer produced the electrical energy in the form of a.c. voltage. The induced voltage, output voltage waveform and the resonant frequency from the generator were measured and observed on the oscilloscope through Channel 1 and Channel 2. The frequency responses of EH sinusoidal waveform was evaluated. For power response, rms output voltage measurements were performed using a multimeter.



Wooden box

Observed by

Measure

d

by



Sound wave

(

loudspeaker

)



Piezoelectric

transducer



Voltage multiplier

)

Villard & Dickson

(



Voltage regulator



Batteries



Without

voltage

regulator



Supercapacitor



Function

generator



Loudspeaker



Piezoelectric



Sound level

meter (dB)



Oscilloscope



Multimeter

The total power across the piezoelectric transducer was calculated.

Fig. 1. The experimental setup for the piezoelectric transducer in energy harvesting system

Table 2. Specifications of 6.5” size loudspeaker.

|  |  |
| --- | --- |
| Nominal Impedance | 4 ohms |
| Speakers Sensitivity | 92 dB |
| Frequency Response | 40 Hz – 20 kHz |
| Nominal Music Power | 55 Watts |
| Maximum Music Power | 250 Watts |

In this paper, a transducer model Q220-A4-503YB was used to harvest sound waves and to convert them into useful electrical energy. The parameter values of the piezoelectric variations transducer (PVT) are summarised in Table 3. Experimentally, the sound wave from the loudspeaker was utilised as a function of sound source. Piezoelectric, which was used as an energy transducer, was placed at various distances in front of the speaker and was connected to the harvesting circuitry. The piezoelectric transducer model Q220-A4-503YB which was activated at 68 Hz had accomplished a maximum power response of 33.133 dBuW at a sound level of 96 dB. This level is comparable to the sound level for ambient environment; which is between 50-100 dB.

Table 3. Piezoelectric vibration transducer parameters.

|  |  |  |
| --- | --- | --- |
| Parameters | PVT | Unit |
| Piezo material | 5A4 | E |
| Weight | 9.5 | grams |
| Stiffness | 245 | N/m |
| Capacitance | 260 | nF |
| Resonant frequency | 68 | Hz |
| Free deflection | ± 1260 | 𝜇𝑚 |
| Blocked force | ± 0.31 | N |

## 3. Energy Harvesting System

Referring to the block diagram for harvesting circuit conception in Fig. 2, it can be categorized into a few parts; AC-DC converter that is the voltage multiplier (Villard and Dickson), voltage regulator and energy storage devices.

Fig. 2. Block diagram of energy harvesting system.

## 4. Harvesting Interface Circuitry

**4.1** **Dickson and Villard voltage multiplier as the AC to DC converter circuits** The study introduced Dickson and Villard due to the output voltage produced by piezoelectric is low. In addition, it acts as the AC to DC converter circuits of the supply voltage and this could improve the overall power efficiency. Dickson and Villard multiplier circuit was introduced as it is much more efficient as compared to the bridge. It is capable of increasing the output voltage to double or triple amount, depending on the number of stages required. Besides, the Villard and Dickson circuit has a simple composition consisting of a diode and a capacitance. Both multiplier circuits are intended for low voltage purposes. Thus, it could convert both lower as well as higher voltages.

The maximum input voltage provided by a piezoelectric transducer to the converter was 3.89 V, which was efficiently converted and amplified by Villard and Dickson to 9.817 V and 9.647 V respectively. The circuit for Villard and Dickson voltage multipliers are as shown in Fig. 3(a) and Fig. 3(b) respectively. They had the same function as the rectifier where only the positive portion of the ambient signal was used. Schottky diodes (1N5711) are widely used in Dickson voltage multipliers due to their lower forward conduction voltage, larger saturation current, lower junction capacitance and small series of resistance. The purpose of small voltage drop will allow the lowest voltage of sound wave to be harvested.

In this experiment, this circuit could produce a steady potential of approximately 10 V greater than the applied input voltage. However, due to the existence of series connection to the coupling capacitances, the high coupling voltage drop would occur in this configuration.

|  |
| --- |
| **4.3** **Supercapacitor and batteries as energy storage devices for energy harvesting system** One of the objectives for this research was to ensure that the energy storage device could accept a wide range of voltages instead of a certain fixed voltage. Batteries (BRC 18650, 4000 mAh) and supercapacitor were proposed as the energy storage candidates. They had been analysed and studied based on the advantages and disadvantages prior to selecting the best alternative for this research. Supercapacitor, which is also well-known as electric double-layer capacitor, is an electrochemical capacitor with relatively high energy density. It is usually hundreds of times greater than lithium-ion battery. Lithium-ion battery is a type of rechargeable battery where the ion moves from the negative electrode to the positive electrode during a discharge and vice versa during the recharging process.  The supercapacitor can be charged and discharged virtually  \*\*Remarks: unlimited number of times. Aside from the fact that the  (a)Villard multiplier: C2=C8=22uF, C6=C7=2.2uF, supercapacitor can be charged very quickly due to their low |

D3=D4=D7=D8=1N5711

(b)Dickson multiplier: C1=C4=10uF, C3=2.2uF, C5=1000uF,

D1=D2=D5=D6=1N5711

Fig. 3. Voltage multiplier circuits; (a) Villard multiplier and (b) Dickson multiplier.

**4.2** **Voltage regulator designed as a voltage stabilizer component** The proposed usage of a voltage regulator in this research was to function as a voltage stabilizer, designed to automatically stabilize a constant voltage level before being charged. The proposed voltage regulator was used with three voltage rating; 4.7 V, 5.1 V and 7.5 V since rectification and multiplication voltage multiplier Villard and Dickson had produced maximum output voltage of 9.817 V and 9.647 V respectively, which is below 10 V. Therefore, the voltage rating of voltage regulator in the experiment should not exceed the value of voltage multiplier circuits in order to avoid the effect on output performance efficiency. The power of voltage regulator 0.5 W and 1.0 W were chosen based on piezoelectric transducer which was categorised as low power source with maximum power response of 33.133 dBuW.

There were two types of different power voltage regulator with three different voltage values used as shown in Table 4. A voltage regulator circuit is affordable in terms of cost. It can be used to change or stabilize the voltage level according to the necessity and design of the circuit. A voltage regulator is used for three reasons:

1. To regulate or vary the output voltage of the circuit
2. To maintain the output voltage at a constant desired value despite of variations in the supply voltage or the load current
3. To act as a protection for short circuits, current limiting circuit, thermal shutdown and over voltage

Table 4. Types of voltage regulator.

|  |  |  |
| --- | --- | --- |
|  | Power of voltage regulator | |
| 0.5 W | 1.0 W |
| Voltage rating |  |  |
| 4.7 V | 4.7 V |
| 5.1 V | 5.1 V |
| 7.5 V | 7.5 V |

internal resistance, which is also known as ESR, they have the disadvantage of being discharged too fast. Table 5 shows a few different types of ESR as well as the fared value of supercapacitor. In addition, Table 6 presents the official specifications of Li-ion battery, where both energy storage had been tested.

Table 5. Specifications of supercapacitor value and ESR.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Capacitance | 0.01 F | 0.022 F | 0.047 F | 0.1 F | 0.22 F |
| ESR (ohm) | 300 | 20 | 200 | 8 | 6 |
| Voltage rating | 5.5 V | 11 V | 5.5 V | 11 V | 11 V |
| Capacitance tolerance | +80%,  -20% | +80%,  -20% | +80%,  -20% | +80%,  -20% | +80%,  -20% |
| Lead spacing | 5.08 mm | 15 mm | 5.08 mm | 10.2 mm | 15 mm |
| Capacitor terminal | Radial leaded | Radial leaded | Radial leaded | Radial leaded | Radial leaded |
| Capacitor case style | Coin | Coin | Coin | Coin | Coin |

Table 6. Battery BRC 18650 Specifications.

|  |  |
| --- | --- |
| Battery Type: | 18650 Rechargeable battery |
| Material | Li-ion battery |
| Capacity | 4000 mAh |
| Size | 6.5 cm length - 1.8 cm diameter |
| Voltage rating | 3.7 V |
| . Rechargeable times | Up to 1800 times |
| Advantages | |
| -No memory effect  -Environmentally friendly  -Over charge and discharge protection circuit | |

To develop the charging supercapacitor from sound wave energy, an approximate calculation was based on the following parameters:

Total charge stored, *Q* in the capacitor was calculated using:

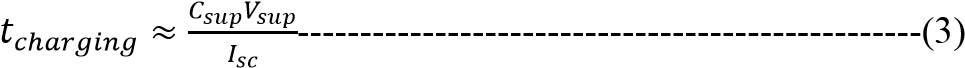
𝑄 = 𝐶𝑉-----------------------------------------------------------------(1) Total energy stored, *E* in the capacitor was calculated using:

𝐸 = 𝑄𝑉-----------------------------------------------------------------(2)

Where Q is charge (in coulombs), V is voltage required and C is capacitance.

The time needed to charge the supercapacitor to a voltage of

𝑉𝑠𝑢𝑝 using the diode charger can be approximated using Equation (3).



Where 𝐶𝑠𝑢𝑝 is capacitance of supercapacitor, 𝑉𝑠𝑢𝑝 is the voltage of supercapacitor and 𝐼𝑠𝑐 is the short circuit current.

All supercapacitor have voltage limits. While the specification of supercapacitor can be made to withstand high voltage rating as presented in Table 5, the supercapacitor was confined to 5.5-11.0 V. To get higher voltages, several supercapacitor were connected in series. But according to Ohm Law‟s, when the supercapacitor are in [serial connection,](http://batteryuniversity.com/learn/article/serial_and_parallel_battery_configurations) this reduces the total capacitance and increases the internal resistance or vice versa. The next step was to observe the time constant of the circuit: the amount of time it takes for voltage or current values to change approximately to certain value from their starting value to their final value in a transient situation. In a series RC circuit, the time constant is equal to the total [i](https://www.allaboutcircuits.com/textbook/direct-current/chpt-1/resistance/) in ohms multiplied by the total capacitance in farads in Equation 4. At the same time, when internal resistance ESR increases, time of charging also increase proportionally.

Total time constant, 𝜏in the capacitor is calculated using;

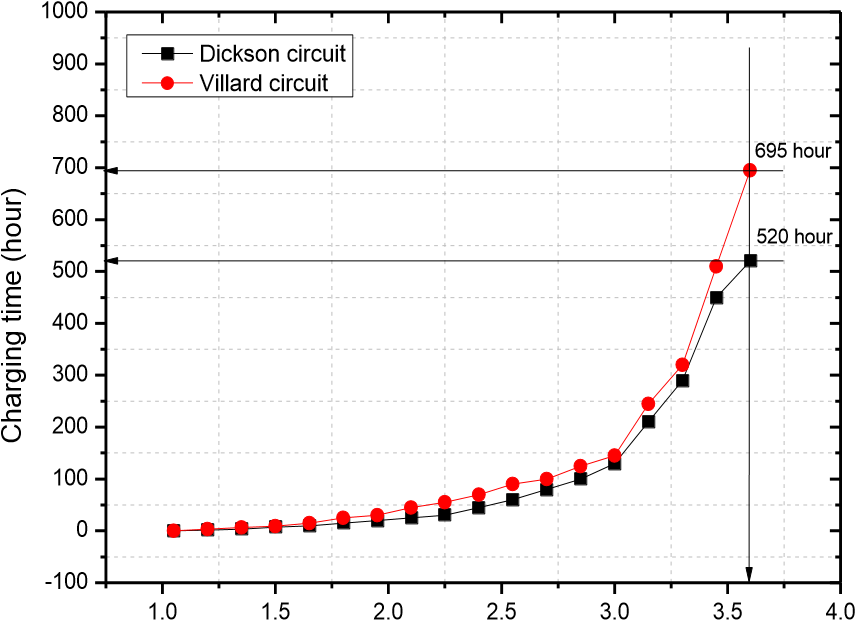
𝜏 = 𝑅𝐶-------------------------------------------------------------------(4)

Where R is internal resistance (in ohm), and C is capacitance.

## 5. Results and Discussions

**5.1** **Analysis on the charging time of lithium ion batteries and supercapacitor on piezoelectric transducer without voltage regulator** Fig. 4 and Fig. 5 show the relationship between the charging time of supercapacitor and batteries without connecting the piezoelectric transducer and multiplier circuit to the voltage regulator. The output voltage for Dickson was 9.647 V and for Villard was 9.817 V. From Fig. 4, the result demonstrated that charging time for Dickson and Villard circuits with batteries to achieve 3.6 V (rating voltage of 3.7 V) would be more than 500 hours. From the experimental results, it was also found that the battery charging time for Villard was more than 600 hours. This was longer when compared to Dickson, which took more than 520 hours. The reason for the longer time required to fully charge the battery was due to the low power density and low charging current. The characteristics of battery over supercapacitor are that it has high specific energy but weak power density. A battery with weak power density is the ability of the battery to take on or deliver and charge lower compare to a supercapacitor with high power density. Power density units are W/kg. On the other hand, the advantage of batteries with high energy density is the capacity of the battery to store energy. High energy density battery can store a lot of energy, which will then be available to the device for longer period of time compared to a low energy density battery. Thus, it is not applicable as storage devices for lower power sources.

Batteries charging time vs voltage



Voltage (v)

Fig. 4. Experimental results of charging time with voltage multiplier Dickson and Villard circuit on batteries as storage device.

In Fig. 5, the calculation result of Dickson circuit demonstrated that 0.01 F resulted in 131 s and the 0.22 F resulted in 5,747 s. As for Villard circuit, the supercapacitor with 0.01 F resulted in 141 s and the 0.22 F resulted in 6,187 s. Next, the proposed circuit was implemented and experimented. It was discovered that Dickson circuit with 0.01 F supercapacitor required a charging time of 280 s as compared to 0.22 F that required 7,880 s when the same voltage of 9.647 V was applied. At the same time, for Villard circuit, charging time was 295 s for 0.01 F as compared to 8,500 s for 0.22 F. The charging time for Villard was longer than Dickson. This was because the output voltage for Villard was 9.817 V, which was higher when compared to Dickson at 9.647 V.

Villard and Dickson circuit without voltage regulator:

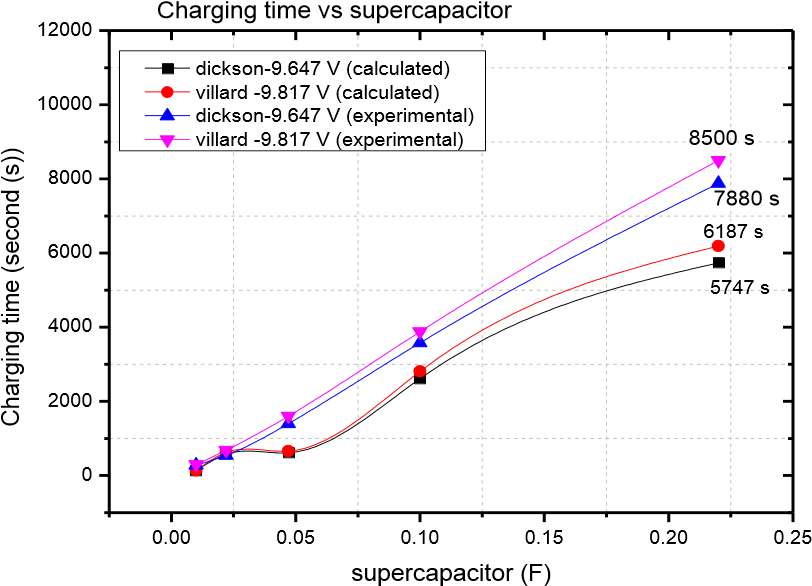


Fig. 5. Calculated and experimental result for supercapacitor charging time without voltage regulator 0.5 and 1.0 watt.

Overall, the results illustrated that the charging time for harvesting circuits were directly proportional to the voltage of the supercapacitor and multiplier. The experimental results for both Dickson and Villard circuits presented that charging time required by supercapacitor was longer as compared to the results from calculation. It may be due to current losses which happened between cable connections. The lowest current value and the longest time taken by supercapacitor to be fully charged may be due to the smaller power being delivered to it. It was also noticed that a smaller value of supercapacitor would result in a shorter charging time of circuit.

**5.2** **Analysis on the charging time of supercapacitor on piezoelectric transducer with voltage regulator** Graphs in Fig. 6 until Fig. 9 show that the relationship between charging time and supercapacitor values for Villard and Dickson circuit were directly proportional to each other. The increase in charging time applied corresponded to the increase in value of the voltage regulator. Both calculated and experimental graphs demonstrated that the charging time of supercapacitor by piezoelectric and voltage multiplier circuit with voltage regulator was longer compared to the circuit without voltage regulator as shown in previous results in Fig. 5.

The calculated charging times for both circuits were implemented and shown in Fig. 6 and Fig. 8. The charging time of Villard and Dickson circuits in 4.7 V, 5.1 V and 7.5 V overlapped with each other for voltage regulator 0.5 W and 1.0 W. However, Fig. 7 shows that the experimental result using Villard circuit with 7.5 V/0.5 W voltage regulator required a longer time as compared to voltage regulator with 7.5 V/1.0 W. This was similar with the circuit connected to 5.1 V/0.5 W and 4.7 V/0.5 W voltage regulator that required longer time as compared to 5.1 V/1.0 W and 4.7 V/1.0 W. Fig. 9 shows the charging time using Dickson circuit with 7.5 V/0.5 W voltage regulator. It was demonstrated that it required a longer time as compared to the circuit with voltage regulator of 7.5 V/1.0 W. The same trend could be observed for 5.1 V/0.5 W, 4.7 V/0.5 W, 4.7 V/1.0 W and 5.1 V/1.0 W voltage regulator. Thus, the overall calculated and experimental results showed that the circuit with 7.5 V voltage regulators required a longer time as compared to the circuit with 4.7 V and 5.1 V voltage regulator. Hence, the analytical research work had considered a better result than the calculated research work. Nevertheless, several assumptions were made for the analytical works as compared to the calculated ideal ones.

When the capacitor value increased, the required charging time for the supercapacitor would also increase as well for both theoretical and experimental case study. Besides that, the charging time for the circuit with 7.5 V voltage regulator required a longer time as compared to the 5.1 V and 4.7 V for both Villard and Dickson. For the circuit with 0.5 W voltage regulator, the charging time for both Dickson and Villard circuit was larger as compared to the circuit with 1.0 W voltage regulator. This may be due to the fact that more current was released by a 1.0 W voltage regulator as compared to a 0.5 W voltage regulator.

A higher charging current would increase the speed for charging the supercapacitor. The result also proved that the charging time of supercapacitor with voltage regulator was longer as compared to those without voltage regulator. The purpose of the voltage regulator was to produce a constant voltage level for the charging supercapacitor. Nevertheless, a voltage regulator would also be a trade-off between stability and the speed of the response towards any changes. A supercapacitor with voltage regulator would require a longer charging time due to the fact that the circuits had reduced the input voltage. Besides, there was an increase in the load current and the regulation element was commanded. This was up to a point where the circuits tend to produce a higher output voltage and vice versa. By reducing the input voltage, input current for the larger period would be drawn until the effect on charging time would become longer.

Similarly, as long as the highest output voltage was achieved, the regulation element would be charged to produce a lower voltage. Thus, it could be concluded that the charging time for circuit with 7.5 V voltage regulator would require a longer time as compared to the circuit with 5.1 V and 4.7 V voltage regulator. It could be summarized that a higher power of voltage regulator would require a shorter time.

Fig. 7 and Fig. 9 shows the experimental results for charging time testing under capacitance of 0.01 F and 0.047 F. It can be observed that Villard and Dickson circuit with 7.5 V/0.5 W voltage regulator required the shortest time as compared to voltage regulator of 7.5 V/1.0 W. Similarly, the circuit connected to 5.1 V/0.5 W and 4.7 V/0.5 W voltage regulator would require a longer time as compared to 5.1 V/1.0 W and 4.7 V/1.0 W. It is may be due to the types of capacitance where 0.01 F and 0.047 F have a voltage rating of 5.5 V. Thus, in order to achieve a voltage of 7.5 V, these two types of supercapacitor were required to be connected in series.

The series connection of these two supercapacitor had reduced the total capacitance and decreased the charging time required by the supercapacitor to fully charge the voltage balancing. Nevertheless, this would increase the internal resistance. Thus, it can be viewed from Fig. 6 until Fig. 9 that the relationship of capacitance was directly proportionally to charging time. But during charging time at the beginning, especially at capacitance 0.01 F and 0.047 F, it can be observed that a small approximated curve (circle shape) occurred before the charging time increase in straight line in the graph as shown. The situation was due to both capacitance only having a voltage rating of 5.5 V. In order to increase the voltage value to be bigger than the voltage regulated used in the test, the series connection is required in the circuits. In addition, the series connection for both the Villard and Dickson circuit increased the total voltage, reduced the overall capacitance and minimized the charging time for supercapacitor. The value of capacitance was directly proportional to the charging time, as shown in Equation (3) and Equation (4). So, when the total amount of capacitance was reduced, the time of charging into full charged super capacitance was also the shortest compared to other capacitance with the largest voltage rating of 11 V. Subsequently, capacitance with 0.022 F, 0.1 F and 0.22 F had maximum voltage rating 11 V, where a series connection was unnecessary for the circuit with voltage regulator of 4.7 V, 5.1 V or 7.5 V, which voltage rating is exceed its value of voltage regulator. At the end, the graphs show that the time of charging at capacitance with

0.022 F, 0.1 F and 0.22 F had increased linearly.

Villard circuit: Calculation result charging time vs supercapacitor

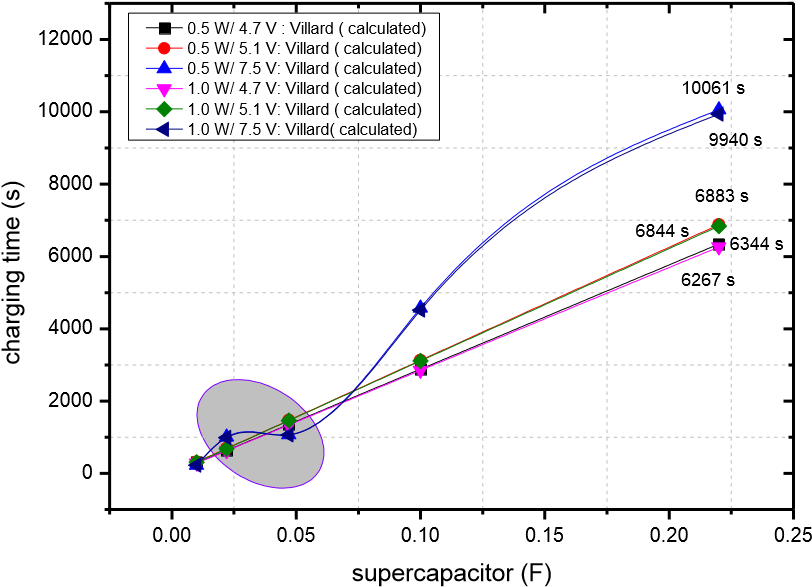


Fig. 6. Calculated result of Villard circuit charging time and supercapacitor.

Villard circuit: Experimental result charging time vs supercapacitor

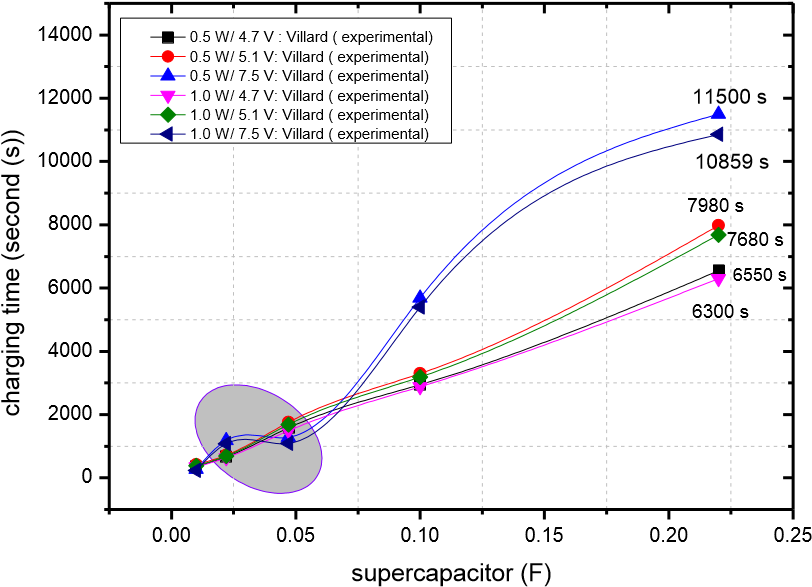


Fig. 7. Experimental result of Villard circuit charging time and supercapacitor.

Dickson circuit: Calculation result charging time vs supercapacitor

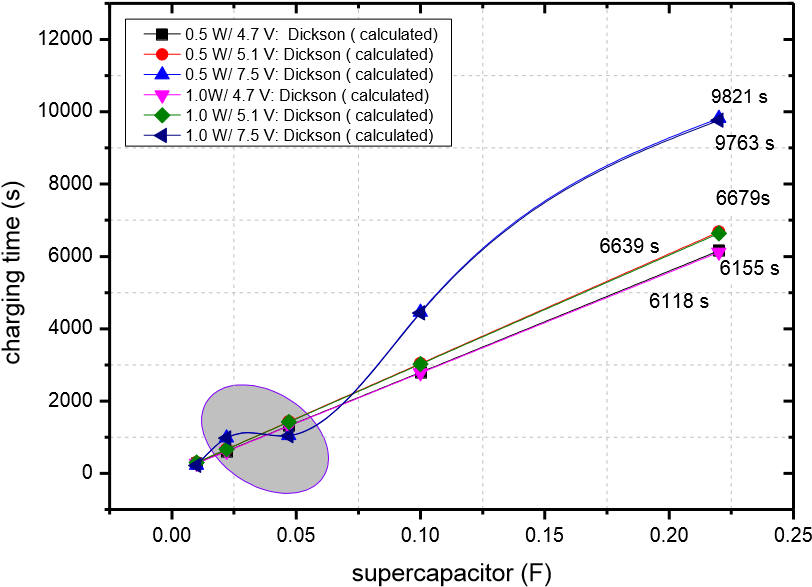


Fig. 8. Calculation result of Dickson circuit charging time and supercapacitor.

Dickson circuit: Experimental result charging time vs supercapacitor

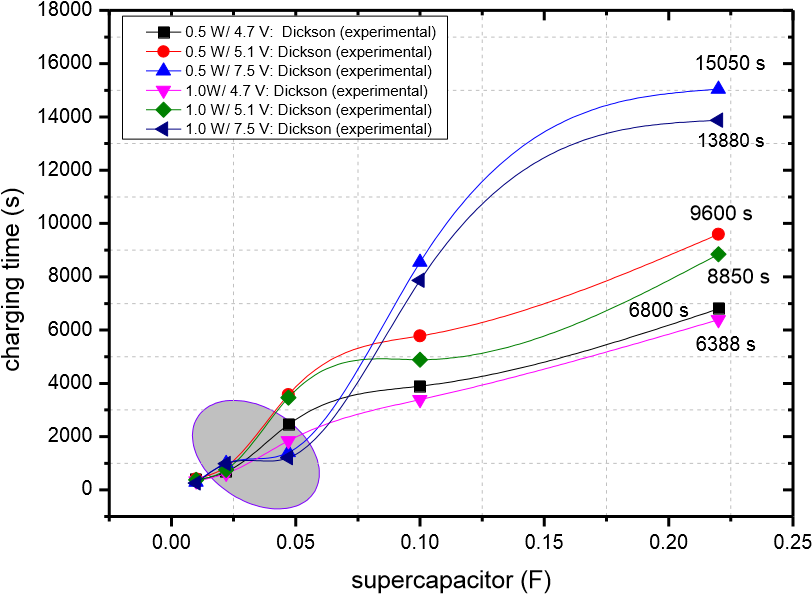


Fig. 9. Experimental result of Dickson circuit charging time and supercapacitor.

**5.3** **Analysis on the discharging time for supercapacitor on piezoelectric transducer** Fig. 10 shows the relationship of the discharge time and supercapacitor charged with different voltage regulator. The experiment was conducted via a small LED with supercapacitors which were fully charged. The graphs proved that the supercapacitor with the largest farad value would need a longer time to discharge, where the LED would be in OFF stage. Thus, it can be deduced that a higher farad value of supercapacitor would result in a longer life of LED in ON stage. Meanwhile, the supercapacitor which had a higher storage voltage value would also require a longer time to discharge. Thus, the increase in discharge time was proportional to the value of voltage regulator.

The supercapacitor with 0.01 F had a shortest lifespan of 20-40 s for LED to be ON stage. Nevertheless, the LED used for 0.22 F supercapacitor had a longer time which was 700-1,500 s. During the discharging process of the supercapacitors, there were two parameters which had to be considered. There was a drop in voltage due to internal resistance as well as due to capacitance. If it was discharging very fast, this meant that either the capacitance was very low or the material had a very high resistance.

The graph shows that the discharge time of supercapacitor depended on the amount of voltage storage and the LED load being applied on it. As a result, the smaller the ESR or resistance on the capacitance, the smaller the time constant. Thus, it would result in a faster charging and discharging rate for capacitor. The calculation and measurement results of the voltage discharge of the supercapacitor were compared and observed. The small approximate curve (circle shape) observed in the graphs for voltage regulator of 7.5 V and capacitance of 0.01 F and 0.047 F had a faster discharge time as compared to others due to the series connection in Fig. 10. This was due to the higher increase in voltage. However, it had reduced the total capacitance as well as decreased discharge time required as shown in Equation (3) and Equation (4).

The series connection had increased the ESR and this had resulted in a poor supercapacitor performance. Thus, the supercapacitor would become less „ideal‟. It would start to dissipate more power and some of the energy would end up being wasted as heat energy. A higher ESR value would reduce the maximum power. This would affect the total energy in the supercapacitor.

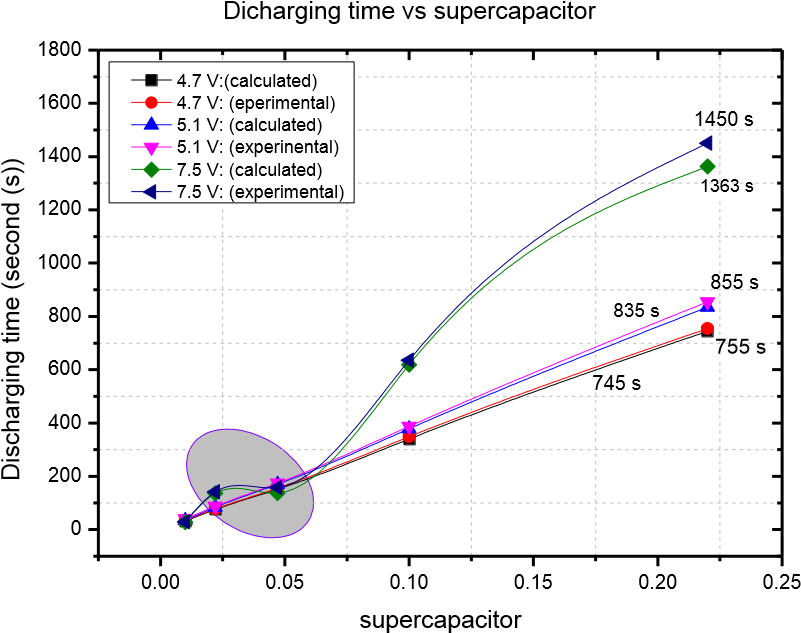


Fig. 10. Discharge time of fully charged supercapacitor under small LED.

## 6. Discussions

In principal, this study had determined an optimal performance for the designed energy storage device to act as a sound wave energy harvester system. The charging time of a battery was not ideal because the output current from the sound wave energy harvester system was too low. If the current was too small, it would make the batteries inefficient due to the longer charging time required. The efficiency of charging time required by energy storage devices would depend on the charging current. Thus, the supercapacitor with a higher power density would be the alternative for low voltage sources. Therefore, it could charge and discharge faster as compared to batteries.

Generally, a supercapacitor with a lower capacitance would have a higher charge value. Thus, it can discharge very quickly. The relationship between charging and discharging time in supercapacitance is almost comparable to each other. Charging time becomes larger when supercapacitor is in series connection; it will also increase the total voltage and internal resistance but will reduce the total capacitance. The same applies for the discharging process as well.

This problem of faster charging and discharging could be solved by building supercapacitor banks with higher capacitance. Each supercapacitor would be required to have 100 F of charge storage. They have to be placed in series or in parallel to achieve a maximum charge voltage or total capacitance. Therefore, supercapacitor with a lower capacitance would have a higher charge value. Thus, it can discharge faster. It was observed that the loading time of Villard and Dickson multipliers with voltage regulator was longer as compared to the charging time for multipliers without voltage regulator.

Thus, a faster discharge can be overcome as it turns out that supercapacitor would tend to “learn” to keep charging better over time. A longer period of exposure of supercapacitor to a voltage would lead to a lower discharge rate. The isolation barrier would require time to build up. This is due to the fact that these cells would be kept charged most of the time. Ideally, the mechanism for the supercapacitor to retain enough energy is by charging them all the time. Besides that, in this experiment, supercapacitors without voltage regulator were selected as a suitable charging method or storage device based on observation and results, which showed that they were able to charge and discharge at a faster rate. The reduced energy losses would have significantly larger charge capacity as compared to conventional batteries. Conventional batteries have the disadvantage of lower capacity of only a few thousand charge cycles, while supercapacitors have higher capacity of a few hundred thousand charge cycles.

## 7. Conclusions

This paper had presented an application where supercapacitors were determined to be more suitable for temporary energy storage device as compared to lithium ion batteries for sound wave harvesting system. The main shortcoming of supercapacitors in this research is due to the low energy density. The amount of energy a supercapacitor can store per unit weight is minimal. Besides, the charging rate is faster, particularly when compared to conventional batteries. Batteries have some drawbacks due to its higher volume and longer charging time. Besides, batteries store energy via chemical reaction. In addition, they are capable of high energy density, low self-discharge and the whole amount of energy is usable due to the non-linear discharge characteristic. Next, the calculated results of effect voltage regulator on supercapacitor charging time had matched well with experimental data. The calculated charged and discharge curves showed a good correlation with the experimental data across the whole range. In this paper, the research specifically discussed the use of ambient sound wave to generate energy in sound wave harvesting system. It would also improve the overall system efficiency by charging the supercapacitor with a voltage regulator. The calculation results were compared with the experimental data. The calculated and experimental results showed that the charging time for supercapacitor with voltage regulator were reasonably better as compared to the charging time of supercapacitor without voltage regulator. Thus, it is acceptable for small design purposes.

The experimental results showed that when the value of supercapacitor was larger, the time required for each supercapacitor to fully charge would also be longer. The results also proved that the overall charging time of supercapacitor for Dickson and Villard circuits with voltage regulator were longer speed of charging needed as compared to circuits without voltage regulator with a shortest speed of charging period. This may be due to the current losses in the voltage regulator circuit. In addition, the charging time would also become larger when the current value becomes smaller. This experiment also highlighted that the discharge time for supercapacitor with 0.22 F capacitance have the highest performance lifespan voltage where they can be stored, as compared to 0.01 F capacitance which time of charging and discharging is very fast in short period required. A higher capacity of capacitance value would result in a longer lifespan for the voltage to be stored. In contrast, a higher value of the multiplier circuit produced especially for Villard circuit would result in a longer time required to charge the supercapacitor. The experiment was performed with a single piezoelectric transducer as compared to other current research which arranged the piezoelectric transducer in array. The discharge performance of the supercapacitor is the result of compromising its power capability. They have a virtually unlimited life cycle, a higher power density due to the low internal resistance and a faster recharging phase. In this research, the fast discharge can be replaced by building a supercapacitor banks where each supercapacitor has to be connected in parallel connection.

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