The Design of Operational Amplifier for Low Voltage and Low Current Sound Energy Harvesting System

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Abstract. The objective of this paper is to design a combination of an operational amplifier (op-amp) with a rectifier used in an alternate current (ac) to direct current (dc) power conversion. The op-amp was designed to specifically work at low voltage and low current for a sound energy harvesting system. The goal of the op-amp design with adjustable gain was to control output voltage based on the objectives of the experiment conducted. The op-amp was designed for minimum power dissipation performance, with the means of increasing the output current when receiving a large amount of load. The harvesting circuits which designed further improved the power output efficiency by shortening the fully charged time needed by a supercapacitor bank. It can fulfil the long-time power demands for low power device. Typically, a small amount of energy sources were converted to electricity and stored in the supercapacitor bank, which was built by 10 pieces of capacitors with 0.22 F each, arranged in parallel connection. The highest capacitance was chosen based on the characteristic that have the longest discharging time to support the applications of a supercapacitor bank. Testing results show that the op-amp can boost the low input ac voltage (~3.89 V) to high output dc voltage (5.0 V) with output current of 30 mA and stored the electrical energy in a big supercapacitor bank having a total of 2.2 F, effectively. The measured results agree well with the calculated results.

1. Introduction
The field of power harvesting has experienced significant evolution over the past few years due to the growth of ever-increasing demand to produce portable and wireless electronic devices with prolonged lifespan [1]. The limited time span of a battery limits the reliability of a device. An alternative to conventional batteries for the energy source can be considered in providing maximum energy to prolong the lifespan of an electronic device.

The purpose of energy harvesting systems is as a simple, inexpensive alternative source for charging, towards improving a self-powered devices by reducing the dependency on the conventional copper cables and troublesome battery. Energy harvesting is a process where the ambient waste energy was captured and converted into usable electricity. This process was proposed previously and related research has been highly developed. A variety of ambient sources such as solar [2], thermal [3],
acoustic noise [4], acoustic energy [5], nuclear power [6], wind [7], and mechanical vibration [8] have been studied as an additional energy supplies for the last decades.

With the increasing of serious polluted environment and resources shortage problems, the renewable energy attracts so much attention, especially for sound wave energy harvesting system, due to its wide availability. However, the power, the voltage, and the current produced by piezoelectric materials are far too small and lower than the power of most electronics applications. In addition, the piezoelectric harvesting system can produce a high level of output energy only when it generates resonance with external vibration excitation. This usually requires energy harvesting circuit to modulate the output power, which leads to a relatively large energy loss due to the switch control circuit. Eventually, it greatly affects the competence of energy harvesting system. Accordingly, the methods of collecting and storing parasitic energy are also the key to acquiring self-powered systems. Subsequently, op-amp was introduced alternatively as ac-dc converter circuit to increase the amount of energy generated by the energy harvesting device.

The recent research cited above focused on developing optimal energy harvesting structures. Nevertheless, the electrical outputs of these devices in many cases were too small to supply power to any electrical devices directly. Jamal et al [9] investigated sound energy harvesting devices and the methods of accumulating energy by using multiple piezoelectric transducers stored in multiple supercapacitors. It was then summed up and amplified through adder LM 324 op-amp and voltage multiplier circuits. The resultant electric power was used to charge a rechargeable 9 volts dc battery and charged within half an hour. Ali Far [10] developed a highly efficient ultra-low current and low voltage rail-to-rail input-output class of an AB amplifier for energy harvesting system. A rail-to-rail input output amplifier with new floating minimum current source was also proposed, which operates under low Vdd (drain) as low as ~0.6 V, amplifier consumes 330 nA current, gain of 78 dB and improves amplifier's dc and ac response. Kyriakos et al [11] proposed the possibility of harvesting the wasted heat in a power amplifier (PA) by using thermoelectric generator (TEG) from 1 Watt, 2.45 GHz class-E power amplifier circuits, and converting them to DC electrical power. The PA circuit was built using microstrip technology and the generated heat and temperature distribution on the PA circuit board were evaluated. Consequently, the harvested output power of 1.015 mW, 1.31 V and 3.1 mA with 10dB gain was measured, respectively. Fahmi et al. [12] reported that a class-D RF power amplifier has been cultivated into wireless energy transfer module for solar energy harvesting system. The class-D radio frequency (RF) power amplifier has been used as the driving circuit for transmitted coil switching to obtain the desired frequency level of power source with nearly 99% efficiency, theoretically. Madhuri et al. [13] suggested that direct ac-to-dc power converter was offered for efficient energy harvesting from a low voltage inertial micro generators. The main target was signal generator, followed by a high-current buffer, used to measure the micro generator output voltage. The buffer can be examined by using a power op-amp in voltage follower mode. The pulse signal produced by the pulse width modulation (PWM) was fed to the two buffers that can be enabled by external signals. The comparators in the polarity detector unit enabled the appropriate buffers to produce a gate pulses that control the MOSFETs of the boost and buck–boost converter during appropriate half cycles. The converter was successfully operated to directly increase the low ac voltage (400 mV) to a high dc voltage (3.3 V).

The general idea of this paper was to develop an op-amp specifically to harvest low voltage and low current produced by sound wave energy. Difficulties may arise if the energy output from a single strip is too low to turn on the converter section. This may be resulted from a threshold voltage cut-off, or may also be resulted from the very low current generated from the piezoelectric material. Thus, effective solution by using the op-amp as an active harvesting circuits is necessary. The system was experimentally studied by using single piezoelectric strips in a sound energy harvesting system. The raw energy will then be converted and conditioned to something more usable. The general block diagram for this process is shown in Fig. 1. The material used to harvest wind energy for this paper were the piezoelectric strips. The specific piezo-strip used was a Q220-A4-503YB, with dimensions of 31.8 x 66.7 mm. The strip was chosen for its convenience more than for specific performance, under
the consideration that piezoelectric materials are capable in providing high voltages, but generally consumed very low currents (often 10’s – 100V and in the range of nA-μA).

There are many types of energy storage systems. Currently, batteries which are an example of mature technology, are widely used for its reliable performance and availability. However, it has a few drawbacks, such as short charging/discharging, time providing only small amount of power density, and short life cycle [14]. On the other hand, supercapacitors have larger power density, smaller capacity and long life cycle [15]. Therefore, in this research, sound energy harvesting storage system combined the characteristics of the op-amp and the supercapacitor bank was introduced. The storage system was controlled by power electrical converters to charge or discharge in harmony, which not only guarantees the quality of the sound energy harvesting system, but also improves the overall performance of the energy storage system, extending the life cycle of the energy storage system and reduces the costs incurred. The calculated output voltage and power of the piezoelectric plates match well with the experimental data. The simulation results were then compared with the experimental data for validation purposes. The comparison agreed well with each other and the deviations were acceptably small for design purposes.

![Energy Harvesting System](image)

**Figure 1.** Energy Harvesting System.

### 2. Methodology
The methods used for the energy harvesting system was categorised into few parts, as follows. Firstly, the experiment started with the development of the op-amp which was to amplified the low voltage and low current sound energy harvester. The op-amp was designed with variable gain to be able to switch based on output voltage required. Secondly, for better gain of op-amp in this research, the single piezoelectric was selected to run the op-amp as a harvesting circuit. Then, the minimum gain will be chosen based on the target output of supercapacitor bank which is 5.0 V. Thirdly, the minimum gain of the op-amp with single piezoelectric was measured and analysed with single piece supercapacitor charging time with difference capacitance and finally, the highest capacitance of a supercapacitor will be considered into building the supercapacitor bank due to the longest discharging time or vice versa.

In this experiment, a transducer model Q220-A4-503YB was used to harvest and convert the sound waves into a useful electrical energy. The sound wave energy system was accumulated from a loudspeaker. Piezoelectric, which was used as an energy transducer, was placed at various distance from the speaker and was connected to the harvesting circuitry. The specifications of loudspeaker are shown in Table 1. The piezoelectric transducer model Q220-A4-503YB was operated at 68 Hz and accomplished a maximum power response of 33.133 dBuW at sound level of 96 dB. This level is in the range of the sound level for ambience environment; which was between 50-100 dB.

Figure 2 shows the experimental setup used for the characterization of sound energy harvesting. The loud speaker was installed in a wooden box and connected to a function generator. During in-lab testing, instead of energy harvester, a function generator was used to provide input voltage waveforms with various amplitudes and frequencies. Oscilloscope was used to observe the input and output voltage signals for different frequencies and amplitudes. Sinusoidal waveform was provided as an input throughout the in-lab characterization.
Figure 2. The experimental setup for the characteristics of the piezoelectric transducer harvester on sound wave.

Table 1. Specifications of 6.5” 2-way loudspeaker.

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

2.1 Energy Harvesting System/Harvesting Interface Circuit

The block diagram for the harvesting circuit concept as shown in Fig. 3 can be categorised into a few parts, operational amplifier (op-amp), rectifier circuit, and energy storage devices. Piezoelectric (PE) transducers are commonly utilised to produce high output voltage and low output current. The utilisation of the op-amp instead of comparator provides lower power dissipation and improves power extraction capability of the piezoelectric harvesters. Energy conversion efficiency varies according to the op-amp and bridge rectifier. Performance optimisation of the op-amp and bridge rectifier is required to maximize the energy conversion efficiency.

Figure 3. Schematic representation of the op-amp.

2.1.1 Operational amplifier (non-inverting)

The feature of non-inverting amplifier is an op-amp circuit configuration which produces an amplified output signal. The output signal of a non-inverting op amp was in-phase with the input signal applied. In other words, a non-inverting amplifier behaved like a voltage follower circuit. A non-inverting amplifier also used negative feedback connection, but instead of supplying the entire output signal back to the input, only a small part of the output signal voltage was fed back as an input to the inverting input terminal of the op-amp. The high input impedance and low output impedance of the non-inverting amplifier makes the circuit ideal for impedance buffering applications. Fig. 4 illustrates the LM 358N pin configuration.
The LM 358N is a dual single supply op-amp. As a single supply, it eliminates the need for a
dual power supply, thus simplifying the design and basic application usage. LM 358N consists of two
independent, high gain, internally frequency compensated op-amp which were designed specifically to
operate from a single power supply over a wide range of voltage. The LM 358N is a dual op-amp,
which means there are two op amps in one integrated circuit (IC). One op amp consists of a non-
inverting input, and another one consists of voltage follower. LM 358N is also one of the types of op-
amp. The LM 358N has around 30 mA current out.

![Image]

**Figure 4.** LM 358N pin configuration.

### 2.1.2 Operational amplifier (voltage follower)
The main purposes of a voltage follower are:
1. To provide a high impedance input which isolates the amplifier's output from the circuit it was
attached to.
2. To provide a low impedance output to provide high current output and/or high bandwidth for a high
 capacitive load.

Voltage follower, also known as buffer amplifier, is a device which connects high impedance
circuit to low impedance circuit. The gain of voltage follower is unity i.e. $A_v = 1$. Voltage follower =
Unity gain.

In voltage follower, the output signal is the same as the input signal. It is a device having high
input impedance and low output impedance. Thus, voltage follower acts as a unity gain buffer to avoid
loading effects in the circuit driving it.

The main reason the voltage followers were used was that they draw small amount of current,
without disturbing the original circuit, and provide the same voltage signal as the output. They act as
isolation buffers, isolating the circuit providing the least disturbance to the power of the circuit. When
the circuit has a very high input impedance, only small amount of current is drawn from the
circuit. According to ohm's law, current, $I=V/R$. Thus, the greater the resistance, the less current is
drawn from a power source. As a result, the power of the circuit was unable to affect the supplied
current on a high impedance load.

### 2.1.3 Rectifier as ac-dc converter signal
The rectifier is unique because its formation allows the negative portion of the input signal to follow
the same current path as when it does during the positive input signal. The intention of using rectifier
is to convert the AC signal from the output op-amp into dc power. The energy was then stored in the
energy storage such as battery or supercapacitor bank. The full wave bridge has the same function as
the half wave in the sense that only the positive portion of the ambient signal was used. To improve
the extraction capacity, schottky diodes 1N5711 were widely used in rectifier due to their low forward
conduction voltage ~0.45 V, large saturation current, low junction capacitance, low substrate leakage,
very fast switching and small series resistance which was in good agreement with the theoretical
values. The purpose of small voltage drop will allow as minimum as possible the voltage of the sound
wave to be harvested.
2.1.4 Supercapacitor as energy storage device

The supercapacitor can be charged and discharged virtually with unlimited number of times. Aside from the fact that the supercapacitors can be charged very quickly due to their low internal resistance, which is known as ESR, they can also quickly be discharged. Table 2 organised a few different types of ESR and Farad value of a supercapacitor, which has been tested.

To develop the charging of supercapacitor from sound wave energy, an approximate calculation was based on the following parameters [14-16]:

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 \( V_{sup} \) using the diode charger can be approximated based on Equation (3).

\[
t_{diode} \approx \frac{C_{sup} V_{sup}}{I_{sc}}
\]  
(3)

Where \( C_{sup} \) represents capacitance of supercapacitor, \( V_{sup} \) represents the voltage of supercapacitor to be store and \( I_{sc} \) represents the short circuit current.

Figure 5. The schematic circuit of supercapacitor bank.

Supercapacitors have many advantages. For instance, they maintain a long life cycle, which can be cycled hundreds of thousands of times with minimal change in performance and are offset by their low energy density. A supercapacitor’s lifetime spans 10 to 20 years, and the capacity might reduce from 100 % to 80 % after 10 or so years. On the other hand, supercapacitors with their low equivalent series resistance (ESR), provide high power density and high load currents to achieve almost instant charge in seconds.

The requirement for this paper is the efficiency of energy storage device. It needs to be able to accept a wide range of voltages instead of a fixed voltage. Storing the energy and accumulating it to a usable energy level had become a problem that needed to be solved. One end of the circuit was connected to a supercapacitor bank. The supercapacitor bank in Fig. 5 was charged completely so that it can recycle the electrical power by converting them into mechanical energy and vice versa. Hence, it
can be used in case of power failure and in situations where reduction in electricity (by switching off the supply) expenditures is needed. The entire process mentioned in the design occurs only after the supercapacitor bank was fully charged. The supply was then cut off automatically from the device and finally the device operates by the used of supercapacitor bank.

### Table 2. 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 case style | Coin | Coin | Coin | Coin | Coin |

### 2.2 Principal of operational op-amp

In this study, the LM 358N was used to design the op-amp and also as comparator to the supercapacitor bank system. In Fig. 6, the completed schematic circuit of op-amp with bridge is presented. An op-amp was used as harvesting circuit for sound energy harvester and was categorised into two stages. First stage is voltage follower and the second stage is non-inverting op-amp. In Fig. 6, there was no gain for the first stage (voltage follower), in fact consists of two resistor function as voltage divider where, there are R4= 1 kohm connected between terminal input to op-amp (+) input and R3 = 100 kohm connected between op-amp (+) to ground on the input of (+) op-amp. This construction allows the op-amp do drop the voltage by about 0.01 %.

The gain of the non-inverting circuit for the op-amp was easy to identify. The calculation hinges around the fact that the voltage at both inputs was the same. This arises from the fact that the gain of the amplifier was exceedingly high. If the output of the circuit remains within the supply range of the amplifier, then the output voltage divided by the gain means that there is virtually no difference between the two inputs.

As the input to the op-amp draws no current, the current flowing in the resistors R4 and R3 is the same. The voltage at the inverting input was formed from a potential divider consisting of R4 and R3, and as the voltage at both inputs is the same, the voltage at the inverting input must be the same as the non-inverting input. This means that $V_{in} = V_{out} \times R4 / (R4 + R3)$. Thus, the op-amp gain is available to adjust based on experiment persistence and adjusting the maximum and minimum by shifting the resistance value on RV2.

The purpose of building up the voltage divider is to protect the op-amp (+) input. Therefore, resistor R4 functioned as to provide high impedance between terminal input and op-amp input (+). Hence, there will be no damage to op-amp in case terminal input is accidentally connected to higher voltage than the op-amp can handled.

Moreover, the important of resistor R3 is to make the op-amp input less sensitive to noise and pull down the op-amp input to ground if the terminal input is left floated (not connected to anything). Overall, the op-amp output will remain off even if the terminal input is left floated. If R3 was not used, the op-amp input will be very sensitive, and the op-amp input will floated (not pulled down to ground) when the terminal input is left floated, resulting in the undesired output produced by the op-amp output.

Initially, this application uses only one op-amp as non-inverting op-amp and is sufficient instead of using voltage follower. However, for this research, LM 358N op-amp was used, and this configuration pin contains two op-amp built in inside one IC in Fig. 4. In IC pin, let assume if one of
the op-amp left unused (floated), the overall circuit output performance will be affected. To overcome this problem, another op-amp acted as voltage follower was constructed with the advantage to amplify the current of the input for the output.

![Schematic Circuit of Op-Amp and Bridge](image)

**Figure 6.** The schematic circuit of op-amp and bridge.

### 3. Results and Discussion

#### 3.1 Designing op-amp with adjustable gain value

A single piezoelectric was tested with an op-amp to identify the most suitable performance by adjusting the op-amp variable gain in order to examine better gain. The minimum (min) gain of op-amp was chosen as the most suitable gain to achieve the experiment output of 5.0 V. To validate this method, the op-amp circuit was designed by using Proteus, where the prototype circuit was measured by using oscilloscope and implemented ac and dc voltage was measured by using multimeter. An observation on oscilloscope shows that CH1 represents AC voltage at signal input, CH2 represents AC voltage at signal output, and CH3 represents DC voltage at signal output from bridge. Fig. 7 until Fig. 10 depicted a comparison between simulation and experimental results for op-amp circuit voltage after amplified and rectification using conventional bridge circuit. Fig. 7 and Fig. 8 shows the simulation and experimental result, respectively for waveform signal from ac and dc voltage at minimum gain of op-amp. Whereas, Fig. 9 and Fig. 10 depicted the simulation and experimental result, respectively for waveform signal from ac and dc voltage at maximum (max) gain of op-amp. Overall, the results of experimental measurement and simulation are in good agreement with one another.

![Simulation Result Minimum Gain of Op-Amp](image)

**Figure 7.** Simulation result minimum gain of op-amp.

![Experimental Result Minimum Gain of Op-Amp](image)

**Figure 8.** Experimental result minimum gain of op-amp.
This paper provides comparative results of calculations between minimum and maximum gain on a non-inverting op-amp and gain of voltage follower. The maximum and minimum gain of op-amp is by considering the RV1 value of 5 kohm. Based on the calculation, the minimum and maximum gain of a non-inverting op-amp is 1.05 and 2.3 as explained in detail below.

Gain of non-inverting operational,

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = A_v = 1 + \frac{R_2}{R_1}
\]
\[
\frac{V_{\text{out}}}{V_{\text{in}}} = A_v = 1 + \frac{200}{4k}
\]
\[
A_v = 1.05 \text{ (Min gain)}
\]
\[
\frac{V_{\text{out}}}{V_{\text{in}}} = A_v = 1 + \frac{200 + (5k)}{4k}
\]
\[
A_v = 2.3 \text{ (Max gain)}
\]

Gain of Voltage follower,

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = A_v = 1
\]
\[
\frac{V_{\text{out}}}{V_{\text{in}}} = V_{\text{in}} = 1
\]

3.2 The testing of min and max value of op-amp with single piezoelectric

Table 3 tabulated the result of ac voltage at both signal input and output, dc voltage at signal output, as well as min and max gain of op-amp. The overall result obtained from theoretical calculation, simulation and experimental measurement were compared, ensuring a reasonable agreement to one another. The higher values of experimental data compared to both calculated or simulated were due to current losses or error in system setup during experiment. Furthermore, the theoretical calculation was more accurate compared to simulated research work, since more assumptions were involved in theoretical calculation as compared to simulated ideal ones. The min gain of op-amp was selected to fulfil the supercapacitor bank with total output voltage of 5.0 V. All experimental results were comparatively similar with the simulation results. As tabulated in Table 3, the experimental results of output voltage were much closer to the theoretical values, as predicted.
Table 3. Overall result of min and max gain value of op-amp in energy harvesting system.

| Single piezo | Calculation | Simulation | Experimental |
|--------------|-------------|------------|--------------|
|              | Min gain    | Max gain   | Min gain     | Max gain     |
| ac input     | 3.889 V     | 3.889 V    | 3.90 V       | 3.801 V      |
| ac output    | 4.043 V     | 8.855 V    | 4.084 V      | 8.00 V       |
| dc output    | 5.203 V     | 12.068 V   | 5.01 V       | 12.76 V      |
| Gain         | 1.05        | 2.3        | 1.040        | 2.105        |

ac input* - ac voltage at signal input
ac output* - ac voltage at signal output
dc output* - dc voltage at signal output

3.3 The testing of charging time on difference supercapacitance with single piezoelectric and min gain value of op-amp

Supercapacitors have been increasingly used recently to enhance the source with low voltage and low current as in sound energy harvesting. The main advantages of a supercapacitor are higher power density, longer cycle period and higher charging/discharging efficiency compared with the conventional battery. Supercapacitors are able to charge and discharge at a faster rate compared to batteries and have significantly larger charge capacity compared to conventional capacitors.

Initially, the experiment was carried out with single supercapacitor of different capacitance (Farad) to investigate which type of supercapacitor are suitable to be chosen to be utilised into a supercapacitor bank. From Table 4, it was observed that both theoretical calculation and experimental charging time for the 0.22 F capacitor was longer compared to the 0.01 F capacitor. However, the experimental charging time was higher compared to theoretical calculation due to the small losses between connections of components which lowered the charging current supplied. As a result, longer charging time is required due to small amount of current supplied.

Hence, the highest capacitance of 0.22 F for charge storage was chosen and emerged as an alternative to batteries in applications where the importance of power deliver surpass the total energy storage. Supercapacitors, on the other hand, were based on a different technology since they are electrostatic devices. The supercapacitors discharge performance is the result of a compromise with its power capability. They were classified into a virtually unlimited life cycle, a high power density due to the low internal resistance and a fast recharging phase. Whereas, the fast discharging criteria can be replaced by building the supercapacitor bank in which each supercapacitors were connected in parallel connection.

Table 4. Comparison of both experimental and theoretical calculation of the time charging required for different value of supercapacitance

| Supercapacitance (F) | Time charging (second) single supercapacitor |
|----------------------|---------------------------------------------|
|                      | Calculation | Experimental |
| 0.01                 | 1.67 s     | 15 s         |
| 0.022                | 3.67 s     | 30 s         |
| 0.047                | 7.83 s     | 60 s         |
| 0.1                  | 16.67 s    | 80 s         |
| 0.22                 | 36.67 s    | 110 s        |
3.4 The testing of charging time on different number of supercapacitors with single piezoelectric and min value gain of op-amp

The highest capacitor with value of 0.22 F was selected to construct the supercapacitor bank. The smaller the resistance or the capacitance, the smaller the time constant, the faster the charging and the discharging rate of the capacitor, and vice versa. Supercapacitor with the highest capacitance value has longer charging and discharging time required and vice versa. Due to slow discharging characteristic, it can hold the stored electrical energy for longer duration than the usual supercapacitor. Consequently, the output from multiple supercapacitor bank can be added easily. Table 5 presents the time needed to charge a supercapacitor bank having different pieces of 0.22 F supercapacitor. The results show that the number of supercapacitors was directly proportional to charging time needed. The more number of supercapacitors involved, the longer the duration needed in charging the supercapacitor bank.

With a continuous supply current of 30 mA, the supercapacitor bank (5.0 V) will be fully charged in less than 2 hours for each module. The total numbers of modules for supercapacitors used in this system were 10 modules, resulting in a total of 2.2 F connected parallel to one another. The system with supercapacitor shows significant enhancements compared with the used of battery. In Fig. 5, the LM 358N was used in supercapacitor bank as comparator to control both the green and the red LED condition. The green light in the supercapacitor bank will lit when it was fully charged. Whereas, the red light will lit when the total voltage was remain less than 5.0 V.

Supercapacitor with highest capacitance values per unit volume has the highest energy density compared to other capacitors. With their high capacitance values, supercapacitor can fill in the gap between capacitor and batteries. One important feature of supercapacitors compared to batteries is that it can be charged very quickly and discharge slowly due to the large value of Farad compared to conventional capacitor.

Table 5. Comparison on both experimental and theoretical calculations of the time charging required for different number of 0.22 F supercapacitor

| Number of 0.22 F supercapacitor (pieces) | Supercapacitor bank time charging (second) |
|------------------------------------------|--------------------------------------------|
|                                          | Calculation | Experimental |
| 2                                        | 73.34 s     | 230 s        |
| 4                                        | 146.68 s    | 458 s        |
| 6                                        | 220.02 s    | 686 s        |
| 8                                        | 293.36 s    | 900 s        |
| 10                                       | 366.7 s     | 1350 s       |

4. Conclusions

The topology combines an op-amp and a bridge converter to condition the positive input cycles, respectively. The topology successfully boosts the 3.89 V, 68 Hz ac to 5 V dc. The output voltage amplified to 5.0 V through an ac-dc converter and an op-amp voltage control. In comparison to rectifiers, this study employed the minimum number of passive energy storage components and achieved the maximum conversion efficiency. The output power and the output voltage are compared between all these topologies. The simulation results and experimental results were also compared. It was certified that the simulation results are in a good agreement with the experimental results. It was also proven that the op-amp was able to perform better than other ac-dc circuit, due to the simplicity and cost reduction criteria. An op-amp also capable to increase the output current to speed up the load charging time and improved the overall system efficiency up to 90 %.

Experimental and simulation results displayed that the supercapacitor bank was able to reduce the stress on the conventional battery power sources which has some drawbacks due to its higher volume
and a limited life cycle. Furthermore, using the op-amp, maximum energy harvesting can be implemented proficiently. Analysis of the op-amp was carried out. The recommended control scheme with the op-amp circuit was implemented and the bridge converter was successfully operated to directly step-up the low ac voltage to a high dc voltage as well. Future research can focused on investigating and utilized much more voltage for various other applications and the distortion on the input current can be reduced by designing a suitable circuit.

Acknowledgement
The authors would like to acknowledge University Malaysia Perlis and the Malaysian Ministry of Higher Education for providing the Fundamental Research Grant Scheme (FRGS Grant No: 9003-00561), which made this study possible to be conducted and successfully published.

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