Solar Energy Harvesting for
Wireless Sensor Network (WSN)

by

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16487

Dissertation submitted in partial fulfilment of the requirements for the

Bachelor of Engineering (Hons)

(Electrical and Electronic Engineering)

FYP II JANUARY 2015

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CERTIFICATION OF APPROVAL

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Approved by,

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TRONOH, PERAK

JAN 2016

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the

original work is my own except as specified in the references and acknowledgements,

and that the original work contained herein have not been undertaken or done by

unspecified sources or persons.

(SUGANTI A/P SENIVASAN)

ABSTRACT

Wireless Sensor Networks are successfully used in the current times to many applications and systems. Generally, this WSN are powered by batteries which constrains the extensive use of WSN due to its finite resource structure. Therefore, the idea of energy harvesting technique is considered to ensure a longer lifespan of operation time for the WSN. Solar energy harvesting is being the most effective method for WSN placed outdoor under presence of sunlight due to its highest power density. In this project, solar harvesting using low-powered Maximum Power Point Tracker (MPPT) is designed to ensure better efficiency from solar panel. MPPT used is based on integrated circuit (LTC3105). Besides, usage of rechargeable batteries is included to ensure constant power to WSN at all times. This is because; power through solar harvesting is limited to only the day time under the presence of sun. DC-DC converter is used to ensure sufficient power to the WSN from the battery. WSN used in this project is IRIS mote. This is a prototype based project, thus the design of component used for power management is expected to demonstrate effectiveness and efficiency of solar harvesting to extend the battery life. The result of charging the battery through solar panel and discharging of battery to WSN will be studied and plotted in graph for discussion.

ACKNOWLEDGEMENT

Firstly, I would like to dedicate this column to thank all the involved parties who have been my support throughout my final year project preparation. Throughout this period, the main person that I would like to thank is my supervisor, Dr. Micheal Drieberg who has been my tremendous support. He has been giving ideas on how to improve my project execution and his inputs are inarguably helped me a lot to achieve what it is today.

Besides, I would like to acknowledge the support of my family which has been one of the important factors in me completing my final year project successfully. They have been supporting me in completing my degree in anyways possible, be it in terms of morale or financial.

Last but not least, I would like to express my gratitude to my fellow friends and classmates and lab technicians who have been a great help for me to complete this project with a success. I would like to once again thank everyone who is involved in completing this project, whether directly or indirectly. Your kind cooperation is forever appreciated.

TABLE OF CONTENTS

LIST OF TABLES **PAGE**

LIST OF FIGURES **PAGE**

1. INTRODUCTION

1.1 Background

Wireless Sensor Networks (WSN) being the latest trend to study the environmental changes and variable. WSN consist of sensor motes, transmitter and receiver network to pass data to main control unit. WSN varies from simple environmental temperature sensors to complex system with combination of thousands different sensors working in parallel to generate data from oilfield. [1] Figure 1 describes how the sensors work to transmit the data to the main CPU

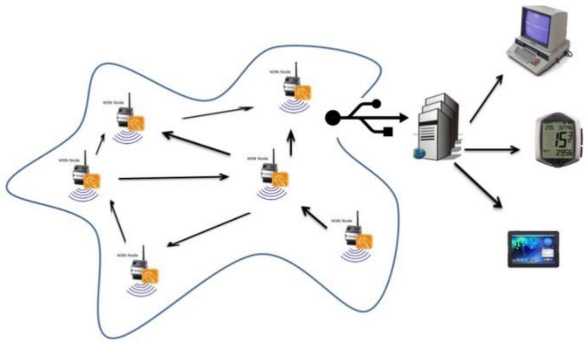

Figure 1: Architecture of WSN.

WSN requires a continuous supply of power to function. Currently the uses of batteries are available to power these WSN. One biggest drawback to this design is the difficulty to replace new batteries especially for constrained situation such as tall tower, or long bridge maintenances. Therefore, more research and studies are conducted to move the source to renewable energy like the generation through solar energy as the suitable medium because it is the most abundant and non-contaminated renewable energy. [2] Using rechargeable batteries and renewable sources to power the rechargeable batteries is the most efficient way to avoid the troublesome of changing the non-rechargeable batteries when the charge capacity is drained out.

1.2 Problem Statement

Problem statement of this project is to study the process of powering energy to motes of WSN. WSN consist of small motes of sensors which detect the changes or specific variable and transmit the changes through a networking system to a control panel. An example of WSN which will be used in this project is an IRIS mote WSN. This WSN is used to monitor buildings through temperature, vibration, speed and others. There are two modes of operation for WSN; active mode and sleep mode. Active mode is when the WSN is turned ON and the data detected is transmitted through the designed network, while sleep mode is when the WSN is turned OFF and no data is collected or transmitted. It is important to have a continual source of power for WSN. As per the case of this project, the required voltage is in the range of 2.7V to 3.3V and required current is roughly 25mA during the active mode. [3]

One major problem using batteries is to replace it time to time especially for extreme cases like environmental sensors placed at a very tall tower or buildings. [1] Besides that, replacing batteries at remote areas or frequent disaster accruing areas are difficult. Furthermore, changing batteries to a new one requires of man power and is more costly especially for the WSN which requires frequent batter replacement. Usage of renewable source to power a non-renewable battery will increase the life span of the input source to WSN.

1.3 Objective

- To develop a solar energy harvesting system that is integrated with wireless sensor motes.
- To evaluate the effectiveness of this system in terms of its efficiency, robustness and network lifetime

1.4. Scope of study

The scope of this project is focused to solar harvesting technique for current development of WSN. WSN is a very large development consisting from simple single functional sensor like a speed trap to very complex system consisting of many thousands of sensors and networks working at a time. However in this project, the scope of study will only cover the simpler WSN that is used in outdoor building or security; namely IRIS mote WSN. Since the WSN used is specified, thus the calculation and circuits values are referred to the data sheet of IRIS mote WSN

Since the WSN is power by solar harvesting, the process of power flow is only focused from electrical energy converted from solar by PV cell to the delivered inputs of WSN. The study includes the understanding of power managements and power conditioning, such as the use of a MPPT and DC-DC converters. Besides, other covered area is the storage which is the usage of a battery or supercapacitor. The factors affecting the efficiency, life span and properties of batteries or supercapacitor are included in the study to be able to maximize the power.

2. LITERATURE REVIEW

Wireless Sensor Networking (WSN) is a technological device used to sense changes in an environment and transfer the information through a communication network for analysis. Basically, WSN consists of smart sensor nodes which measure the difference in a variable such as temperature, light, sound, vibration and chemical. From a bigger picture, WSN are classified to two group namely structured that have fever nodes of sensors and unstructured that consists of more sensors. [4]

WSN is connected to physical environment through sensors which are programed with information and management system. Sensors perform monitoring, automation and some even control solution for changes detected. Application of WSN is widely spread from agriculture, healthcare, electro-mechanical studies, nanotechnology, military application and many more fields. The application of WSN depends on several requirements like frequencies, environment, range and size of network, battery-life, reliabilities as well as topology. [4] A large number of small self-powered nodes are used to gather information or to detect special events and communicate in a wireless fashion. WSN needs to communicate in order to handle their processed data to a base station which is the control unit. Data collected from sensors are channeled through a communication system from a transmitter to a receiver. Transmitter transmits the data, while receiver collects the data and makes path to control unit to process. Sensors are positioned along with transmitter. Both transmitter and receiver are powered separately.

The working mechanism of WSN is based on its duty cycle. Duty cycle in this context is the percentage of active mode in operational period [14]. The greater the duty cycle, the longer the active mode of WSN, thus more power is consumed. During the off duty cycle, the WSN will conduct the sleep mode as an attempt to conserve power. The Graph shows the relationship of current drawn from WSN and duty cycle.

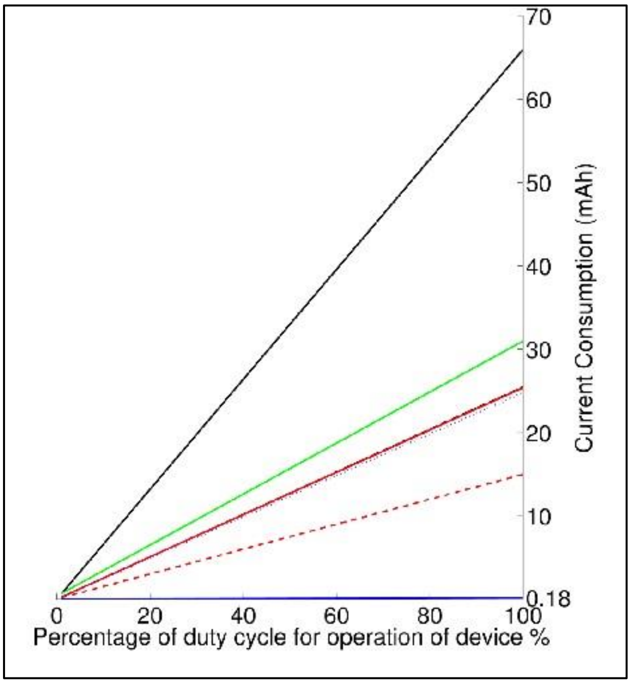

Figure 2: Graph of current drawn by WSN versus duty cycle of WSN [16]

Harvesting energy from renewable source is more conventional and is always available. Examples of renewable energy for low powered applications are vibration, solar, radio frequency, temperature difference and few more. From a survey, compared to all the renewable harvesting techniques, solar energy has the highest production of power, provided that the WSN is placed outdoor and under the presence of sunlight. Table 1 summarizes the average output of power from several renewable harvesting techniques. [5] However, harvesting energy from solar has its drawbacks, mainly, uncertain weather conditions and presences of impurities in air that affects the efficiency or the performance to generate power. [6]

Table 1: Output power from several renewable harvesting techniques. [5]

Energy Source	Harvested Power Levels
Vibration/Motion	
Human	$4uW/cm^2$
Industrial	$100uW/ cm^2$
Temperature Differential	
Human	$25uW/ cm^2$
Industrial	$1\text{-}10\ mW/ cm^2$
Light	
Indoor	$10uW/cm^2$
Outdoor	$10mW/cm^2$
RF Energy	
GSM	$0.1uW/cm^2$
Wi-Fi	$1uW/cm^2$

Solar harvesting is done through photovoltaic (PV) cells consisting of silicon which converts light energy to electrical energy. Suitable PV cells are suggested based on energy demands, output voltage and current, operating conditions and required size of panel. In this project, the power requirements are based on the IRIS mote WSN. Deciding on the solar panel depends on few main factors such as the power requirement for the overall system, type of suitable panel and size of the solar panel needed. In the case of understanding the power requirement, it is important to study on the total power needed by the system and comprising loses throughout the system including losses by solar panels. The rated output from solar panel must be greater than the total required power by the system. Next is the type of solar panel, namely Monocrystalline, Polycrystalline, thin film, hybrid and few more. The consideration on types of solar panel depends mainly on the efficiency, and power requirement. Generally, crystalline type panel, to be more specific Monocrystalline has the higher efficiency which is about 15-20%.

The most important element of a PV panel is the current-voltage curve describing the output power from the solar panel (P = IV). The IV curve is plotted through measuring the current as a function of voltage produced from the solar panel [7]. The main parameters on this curve are open circuit voltage (V_{OC}) and short circuit current (I_{SC}). Figure 2 is an example of IV curve showing (V_{OC}) and (I_{SC}). Through the IV curve, the maximum operating point of energy can be calculated. An efficient output will be when the current and voltage are operating at the peak point known as maximum power point (MPP) [8].

Maximum power point is measured by multiplying the current and voltage generated, then plotting another curve which is the power-voltage (PV). The blue line in Figure 3 is the PV plotting. The peak point on the PV panel will show the maximum voltage from the panel.

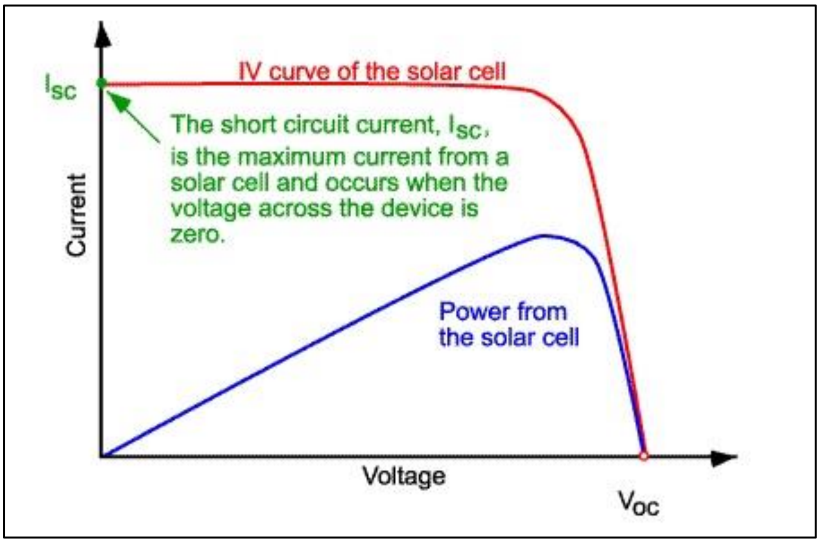

Figure 3: IV curve [7]

One best solution to ensure the operating voltage and current at the MPP was to use a Maximum Power Point Tracker (MPPT) as the control measure after harvesting power from PV cells. MPPT is an electronic device that maximizes the output power produced by the PV module. MPPT is divided to two parts; power electronics controller, consisting of DC-DC circuits and a major control system to ensure solar harvested at optimal level. For the DC-DC control part, if the circuit is a buck converter, the excess voltage produced by solar panel will be converted to output current. Converting the excess voltage to current will reduce the voltage lost and maximizes the output power. Solar panels produce greater module voltage compared to battery voltage during cooler days due to high discharge from battery. Therefore the battery current will be greater during short days or with less sun radiation. [9]

MPPT has few tracking technique, mainly indirect and direct method. Indirect methods consist of fixed voltage method and fractional open circuit method while the direct methods are perturbed and observe as well as incremental conductance. Firstly, the Fixed Voltage Method which is done manually by adjusting the maximum power voltage (V_{MPP}) according to the average calculation on IV curve based on the weather of the specific place. This method is considered inaccurate for fluctuating weather conditions. Next is the Fractional Open Circuit Voltage (indirect); measured by the formula "$V_{MPP} = k * V_{OC}$", where the value of constant k varies from 0.7 to 0.8V. V_{OC} is measured by temporarily turning off the circuit and the value recorded will be multiplied to the constant value to estimate the V_{MPP}. Drawback to this design is the need to turn off the circuit every now and then to estimate the V_{MPP}. This problem is however solved by using pilot cell, a separate cell from solar panel that is used to measure the V_{OC}. Perturb and Observe method is a more efficient way of finding V_{MPP} through self-adjustment by the MPPT itself. It tracks several points on voltage curve on the IV graph and position itself at the maximum power value possible through incremental and decremental algorithm. Similar algorithm is used for Incremental Conductance however rather than measuring the power; conductance (I/V) is measured. One available MPPT IC which is used to power rechargeable batteries and supercaps as well as harvesting solar is LTC3105. [10]

Another important component in the solar harvesting is the storage which is either a rechargeable battery or a supercapacitor. Mostly used storage is rechargeable batteries due to high capacity available. The important properties of rechargeable batteries are as in Table 2. [11]

Table 2: Properties of rechargeable batteries [11]

Cell type	Ni-Cd	Ni-MH	SLA	Li-ions	Polym.-Li
Energy density (Wh/Kg)	50	75	30	100	175
Life cycle (charges-discharges)	1500	500	200-300	300-700	600
Self-discharge (charge % at time)	60% 4 months	15% 1 month	60% 24 months	40% 5 months	8% 1 month
Nominal voltage (V)	1.25	1.25	2	3.6	2.7

To increase the efficiency of solar harvesting, a switched mode circuit can be used, whereby the energy from solar harvesting is directly powered to WSN and extra energy is used to charge the renewable battery during the presence of sunlight. During the absence of solar energy, switch will activate the battery to power the WSN. [12] In this way, the battery will not consistently go through charging and discharging, thus the lifespan of the battery can be sustained longer. The DC-DC controller which acts as the charger will be less stressed. However, one factor that is needed to be considered is the switch time from solar power to battery power during the absence of sunlight. The switch time should not affect the continual function of WSN. The diagram at figure 4 shows the circuit for switched-mode battery power as the back-up for solar harvesting.

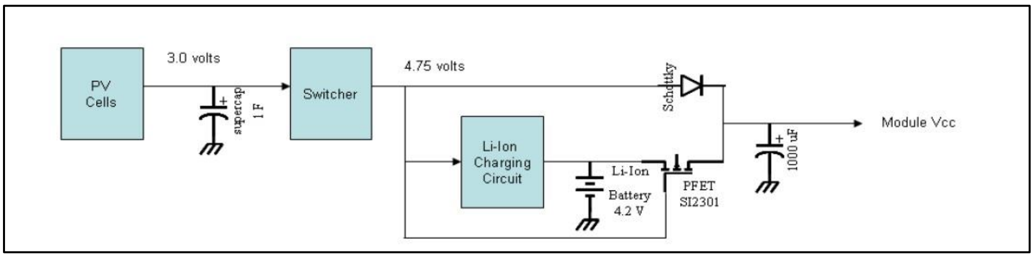

Figure 4: Block diagram of switcher circuit [12]

To further enhance the circuit, low- voltage cutout circuit can be used. A low-voltage cutout acts like a guard to check the limit of minimum voltage to enable the circuit. During the start up under the presence of low sun light, DC-DC converter circuit during the boost mode will draw more current, thus the output current to WSN is approximately zero. The cutoff circuit will allow the voltage and current across panel to certain level before the circuit can be connected. When the current and voltage are sufficient to ensure DC-DC converter to run, cutoff will allow the circuit to be connected. Once the illumination of sunlight reduces below the minimum limit, the cutoff circuit will be activated and the switcher circuit will be turned down, thus the WSN will be powered by battery. [17]

3. METHODOLOGY

3.1 Research methodology

Following are the steps taken in the project;

1) Research and understanding

   Using Internet as the basic medium, first step was to understand the literature review on the topic and conceptual ideas on the project. Many references of journals and websites was used to understand WSN and its powering mode, process of solar harvesting, power conditioning or power management. From the knowledge gain, proper block diagram of the working flow of project was designed. Figure 5 describes the flow of electronic components in this project in a block diagram. The important components in this project are WSN, solar panel, MPPT control, DC-DC converters, and battery for storage.

Figure 5: Component block diagram

2) Experimental Setup

For the experimental setup, material identification was critical. During this part of project, types of solar panels, WSN, MPPT and converters used in the project are confirmed. The power requirements are analyzed and tabulated in Table 3. The performance of a WSN is based on either the active or sleep mode. During the active mode, WSN transmit signal to detects stimulus and receives the data through a receiver. However, during the sleep mode, the receiver and transmitter of WSN are temporarily turned off and no stimulus will be detected. Thus the current consumption during the sleep mode is only drawn by the processor which is about 8uA, whereas during the active mode, current drawn by processor, transmitter and receiver are 8mA, 17mA and 16mA respectively. Thus the maximum current drawn by WSN during the active mode is 25mA, which is during the transmitter functions. Assuming the percentage of duty cycle for WSN in this project is 5% in 1 hour, thus the calculation of duration of active mode and sleep mode for an hour as well as the power consumption is as follows;

$$\boldsymbol{duration\ of\ active\ mode = 5\% \times 60s = 3s} \quad \textbf{(1)}$$

$$\boldsymbol{duration\ of\ sleep\ mode = 95\% \times 60s = 57s} \quad \textbf{(2)}$$

Power drawn by WSN for 1 hour;

$$\boldsymbol{[3s \times active\ mode\ power] + [57s \times sleep\ mode\ power]} \quad \textbf{(3)}$$

$$\boldsymbol{(3 \times 82.5) + (57 \times 0.0264) = 249mWH} \quad \textbf{(4)}$$

Current drawn by WSN for 1 hour;

$$\boldsymbol{[3s \times active\ mode\ current] + [57s \times sleep\ mode\ current]} \quad \textbf{(5)}$$

$$\boldsymbol{(3 \times 25) + (57 \times 0.008) = 75.4mAH} \quad \textbf{(6)}$$

The power generated by solar is transferred to WSN through battery. The rechargeable batteries used in this project are Nickel Metal-Hydride (NiMH). NiMH range is various capacities from 1300 to 3500mAh, but for this project, two NiMH batteries with capacity 1500mAh are available to be used in this project. Therefore it is important to consider the battery (NiMH) efficiency. Charging efficiency of NiMH is typically 66% [16], which means for every 75.4mAH current to WSN from battery, will be replaced by 108.7mAH current from solar to the battery.

The maximum power required will then be multiplied by performance ratio factor, which are about 1.3 ratios to include coefficient of losses in the overall system [20]

Table 3: Tabulation of calculated power requirement

Description	Voltage (V)	Current (mA)	Power (mW)
Active mode (max power drawn when transmitter and processor active)	**3.3**	**25**	**82.5**
During sleep mode	**3.3**	**0.008**	**0.0264**
Power required by battery considering the output to WSN (duty cycle 5% for 1 hour)			**249**
Maximum power including losses	**249m x 1.3**		**323.7**
Total power required (for 1 hour)			**~400**

The total power required including losses and extra power to charge battery is about 0.4W. Thus, the solar panel chosen for this project is MC-SP0.8 with output power of 0.8W which is more than sufficient to power the whole system.

Next, MPPT controller is used in this project to allow possible maximum output power. MPPT control is implemented using an integrated circuit from Linear Technology, namely IC LTC3105. It is a Step-Up DC-DC converter with MPPT controller. Figure 6 shows the LCT3105 circuit configuration when it will be connected to solar panel.

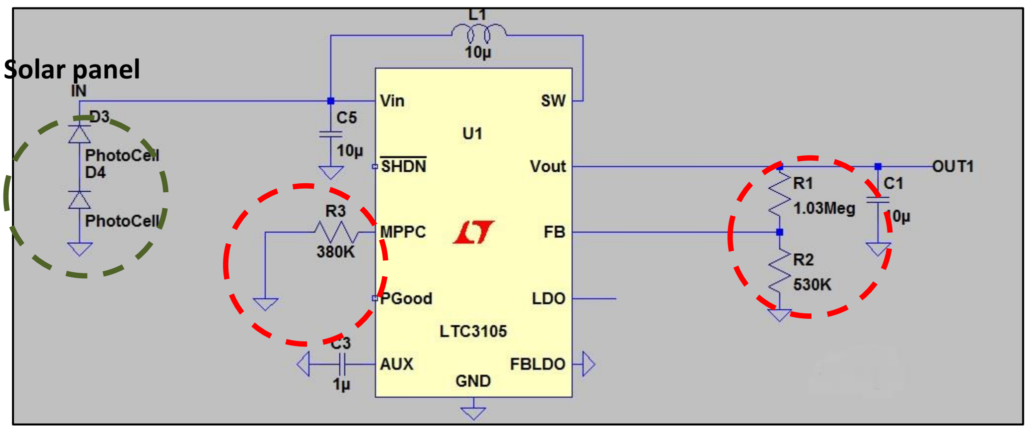

Figure 6: Circuit configuration of LTC3105

The resistors R1 and R2 are adjusted to set the value for the DC-DC converter. The calculated values for the R1, R2 are shown as follows;

$$\boldsymbol{Vout = 1.104V \times \left(\frac{R1}{R2} + 1\right)} \tag{7}$$

Output of solar panel is roughly 3V while expected voltage output from the converter is 3.2V and assuming R1 as 1M ohms;

$$\boldsymbol{3.2 = 1.004V \times \left(\frac{1M}{R2} + 1\right)} \tag{8}$$

Thus the value for R2 is roughly 530k ohms.

For the MPPT controller, the maximum voltage possible is first determined through the study of MC-SP0.8 solar panel data sheet. Maximum power point tracking is implied through LTC3105, which controls the inductor current to maintain the input voltage from solar panel. MPPT control circuit regulates the inductor current to adjust the input voltage. When the value of input voltage is greater than the MPPT voltage, inductor increases the current to ensure to pull the input voltage to MPPT value. Similarly, as the input voltage reduces below MPPT voltage, inductor current is reduced to rise input voltage to reach the MPPT value. From the data sheet, the value of V_{MPP} is determined as 3.85V. The IV curve of MC-SP0.8 panel is shown in Figure 7 below. After knowing the value of V_{MPP} and setting the current constant to (1×10^{-5})A, the value of V_{MPP} is calculated for LTC3105.

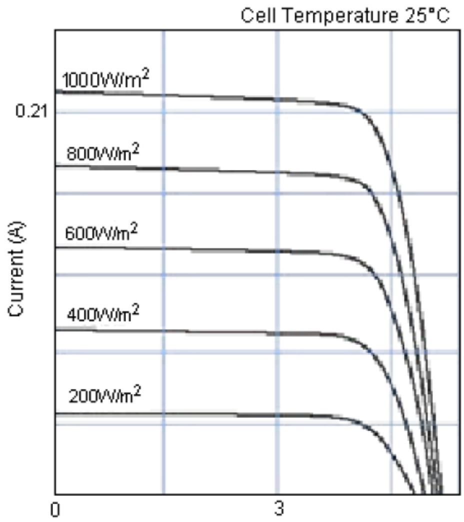

Figure 7: IV curve of MC-SP0.8 solar panel [19]

$$\mathbf{Vmpp} = (\mathbf{1} \times \mathbf{10^{-5}})\mathbf{A} \ \times \mathbf{Rmpp} \qquad \textbf{(9)}$$

$$\mathbf{Rmpp} = \frac{\mathbf{3.85}}{(\mathbf{1}\times\mathbf{10^{-5}})} = \mathbf{3.85}\boldsymbol{M}\Omega \qquad \textbf{(10)}$$

Output from LTC3105, which is set to 3.2V will be connected to the rechargeable batteries for continuous charging by solar panel. WSN will be powered from the rechargeable batteries. Thus to ensure a constant voltage output, another DC-DC converter is used.

The DC-DC buck boost converter is used to adjust input voltage to WSN is always the same regardless the output from NiMH battery. The DC-DC converter finalized for this project is another integrated circuit by Linear Technology, namely LTC 3530. LTC 3530 is a wide input ranged buck-boost converter which provides synchronous rectification up to 96% efficiency. The output of converter can be fixed by connecting a resistor divider from feedback pin to output pin.

$$\boldsymbol{Vout} = \mathbf{1.215}\boldsymbol{V} \ \times \left(\frac{\boldsymbol{R1}}{\boldsymbol{R2}} + \mathbf{1}\right) \qquad \textbf{(10)}$$

Assuming R1 as 1M Ω , based on the calculation, R2 is 576K Ω.

The circuit connection diagram of LTC3530 is as follows;

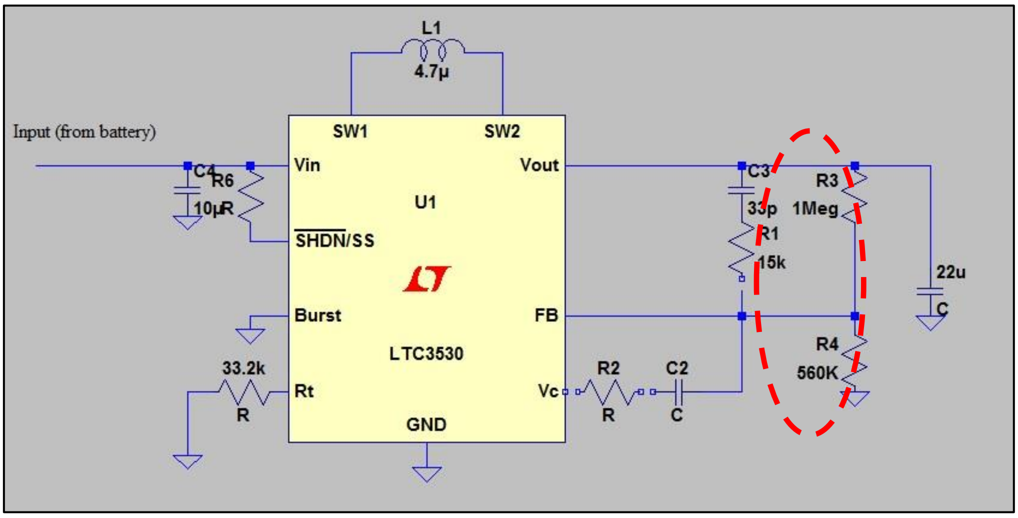

Figure 8: Circuit configuration of LTC3530

The output of the converter is adjusted to 3.3V, which will be connected to WSN. The shutdown pin will be connected to input voltage to ensure the pin is always turned on. LTC3530 is internally control by four-switch control method and depending on the control voltage, the IC will operate in either buck, buck/boost or boost mode. In this project, LTC3530 will be mainly operating in boost mode.

The list of finalized components is bolded in the block diagram as shown in Figure 9. This arrangement describes the power flow from solar panel to the WSN while using battery as the storage for the system during the night and conditions without the presence of sunlight.

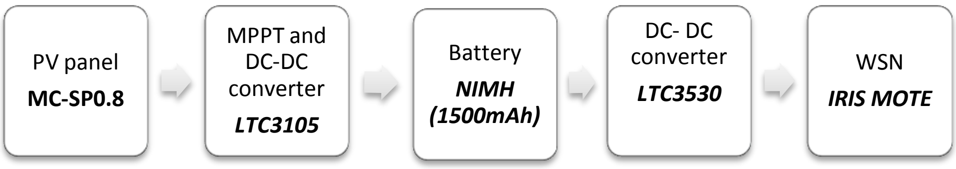

Figure 9: Flow of the components

3) Hardware implementation

The next step of the project is the hardware implementation which is to purchase the finalized components and carry out sufficient testing. Testing will be first carried out with separate components and the reading of each test will be recorded. This step is important to ensure each component are working correctly, moreover this testing is more reliable due to less complication in the design. After testing each component separately, solar panel and LTC3105 will be integrated. The output from LTC3105 will be studied. Once the output is matched as required, the other components will be integrated as a whole and more testing will be performed. All the connection will be done on a breadboard first during the testing process. Successful connection on the breadboard will then be designed on PCB. The component schematic for overall solar harvesting system is shown in Figure 10.

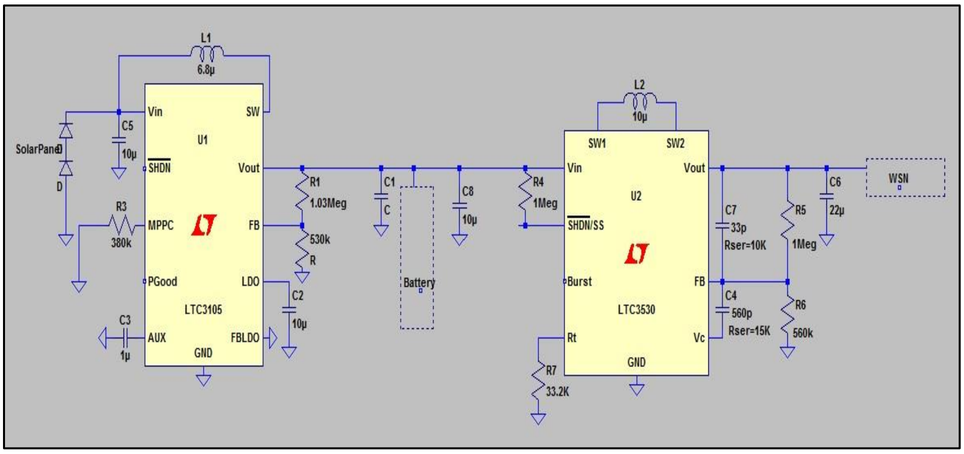

Figure 10: Schematic of total solar harvesting circuit

4) Experimental Work and Analysis

Another important part of this project is the analysis of data. The finalized design will need and the testing results will be interpreted. The result will be compared to the theories. Tabulated results will be plotted to a graph and discussed.

5) Report Writing

Compilation of all research findings, literature reviews, experimental works and outcomes into a final report.

3.2 Project Key Milestone

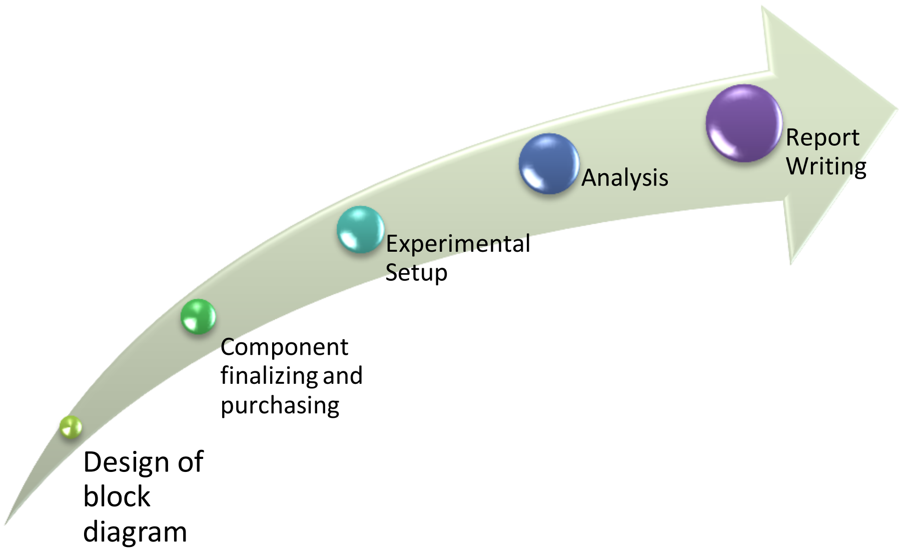

Figure 11: Project Key Milestone

3.3 Gantt Chart

Table 4: Gantt Chart of Project Planning

		Number of weeks											
		1	2	3	4	5	6	7	8	9	10	11-13	14
1.	Testing LTC3105	■	■	■	■	■							
2.	Prototyping LTC3105 and LTC3530			■	■	■	■	■	■				
3.	Recording outputs (voltage and current)							■	■				
4.	Analyzing results and plotting graphs							■	■	■			
5.	Designing PCB schematic							■	■	■			
6.	Prototyping switcher circuit									■	■		
7.	Designing complete PCB schematic										■		
8.	Poster presentation preparation											■	
9.	Technical report writing											■	
10.	Pre SEDEX preparation											■	
11.	Final report writing											■	
12.	Viva preparation												■

4. RESULT AND DISCUSSION

To validate the methodology discussed, few levels of experiment have been conducted. Firstly, to test the solar panel and the outputs at several time periods. This experiment is conducted to ensure the solar panel isn't defective. Next, is the testing on IC LTC3105. There are two major function of LTC3105 which is to perform MPPT control and buck or boost the converter to fixed output voltage of 3.2 to charge the battery. Each of these functions is carried out in experiment 2 and 3 respectively. All the results are tabulated and discussed sections below.

4. 1 Testing the solar panel

Solar panel bought was MC-SP0.8 and the output tested is tabulated in Table 5. However, the expected output under the presence of good radiation of sunlight according to datasheet is as follows;

Expected voltage : 4.8 V

Expected current : 0.23 A

Table 5: Tested result during peak hours

Time	Position of solar panel	Voltage (V)	Current (A)
11-12 Pm	**Parallel to ground (under good sunlight)**	**4.5**	**0.27**
	Panel tilted at 20^o from ground (under good sunlight)	**4.5**	**0.25**
	Panel tilted at 45^o from ground (under good sunlight)	**4.6**	**0.23**
	Parallel to ground (under shade)	**4.5**	**0.10**
	Panel tilted at 20^o from ground (under shade)	**4.5**	**0.10**
	Panel tilted at 45^o from ground (under shade)	**4.3**	**0.09**
1-2 Pm	**Parallel to ground (under good sunlight)**	**4.7**	**0.30**
	Panel tilted at 20^o from ground (under good sunlight)	**4.7**	**0.30**
	Panel tilted at 45^o from ground (under good sunlight)	**4.7**	**0.28**
	Parallel to ground (under shade)	**4.5**	**0.10**
	Panel tilted at 20^o from ground (under shade)	**4.6**	**0.10**
	Panel tilted at 45^o from ground (under shade)	**4.5**	**0.10**

Highest irradiance of sunlight hits the solar panel during the peak hours of a day which is ranging from 11am to 3pm. From the observation, solar panel is left on the ground to ensure highest irradiance of solar energy.

4. 2 Testing LTC3105 for MPPT function

MPPT is the function of detecting maximum point on IV curve of a solar panel and ensuring that the panel is working at the maximum point. MPPT ensures operation of system at the maximum power. The configuration of MPPT control can be referred to Figure 6. For this project, the MPPT voltage is set to 3.8V. Thus, input voltage above the MPPT voltage will be reduced while input voltage lesser than MPPT voltage will be increased to ensure maximum operation of solar harvesting. MPPT is activated by connecting a resistor and diode from MPPC to ground. To disable the MPPT, MPPC pin is connected to ground directly.

Figure 12 is the circuit placement to test and compare the MPPT function of LTC3105. The circuit connection on the left is the connection with MPPT enable mode, while connection circuit on the right is the connection of MPPT disable mode. Both the circuits are placed under the same irradiance of sunlight; tested and collected reading from Arduino at the same time. Table 6 is the result of testing the LTC3105 for both with and without MPPT operation.

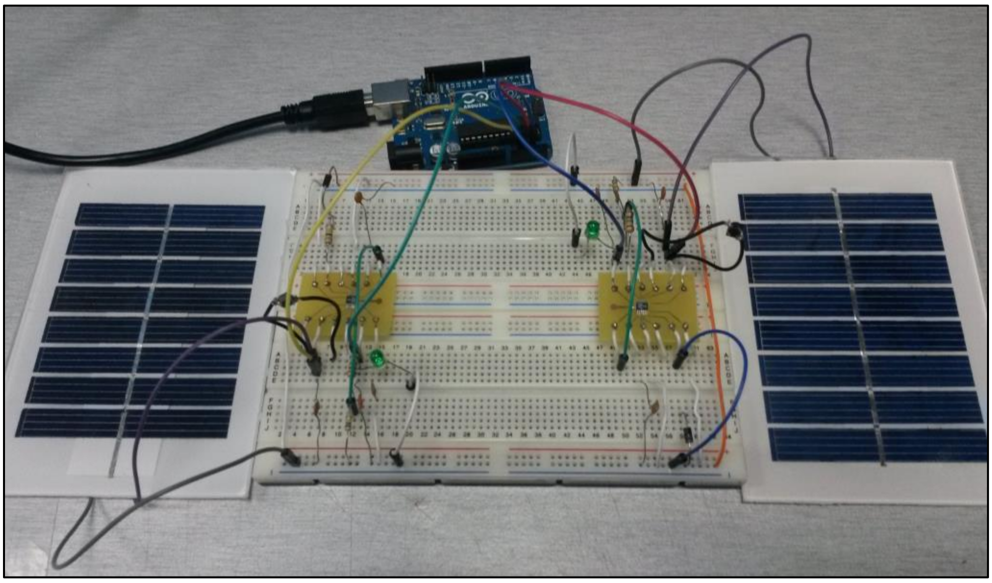

Figure 12: Circuit position to test MPPT enable and MPPT disable

Table 6: Tabulated results of current and voltage when MPPT enable and disable

Time	MPPT enable			MPPT disable		
	V_{IN}	I_{IN}	Power	V_{IN}	I_{IN}	Power
9am	3.36	224.00	752.64	2.02	134.67	272.03
10am	3.74	249.33	932.51	2.74	182.67	500.51
11am	3.63	242.00	878.46	3.39	226.00	766.14
12pm	3.64	242.67	883.31	3.61	240.67	868.81
1pm	3.71	247.33	917.61	3.52	234.67	826.03
2pm	3.59	239.33	859.21	2.98	198.67	592.03
3pm	3.51	234.00	821.34	2.48	165.33	410.03
4pm	3.48	232.00	807.36	2.05	136.67	280.17

As observed from the result tabulated, operating power of LTC3105 is at maximum with MPPT enable. From the experiment conducted, the system is operating at different irradiance of sunlight throughout the day. At 9am, the irradiance of sunlight is low, and LTC3105 is observed to operate almost V_{OC}. However, the current is low at lower irradiance of sunlight causing power to be low. Power is the multiplication of voltage and current. During late morning and afternoon, which is around 10am up to 3pm, the IC operated at higher irradiance of sunlight. Input voltage of MPPT enable is still maintained close to maximum voltage, whereas current harvested is greater. Power being directly proportional to current and voltage, is also high during this period.

For the experiment with MPPT disable, input voltage and current depends directly on irradiance of sunlight, where during the peak day, voltage and current harvested is highest. Power is at maximum during the peak. During off peak hours, both current and voltage are lower, and the power is also low. Therefore the difference in power during peak and off peak periods is distinctive.

Enabling MPPT operation allows the IC to adjust the input current and voltage to work at maximum power possible. Setting MPPT voltage to 3.8V, the input voltage is adjusted by reducing the current through inductor. By this way, the operating power of LTC3105 can be maintained at maximum. Figure 13 describes the input voltage of solar harvesting during MPPT enable and disable mode.

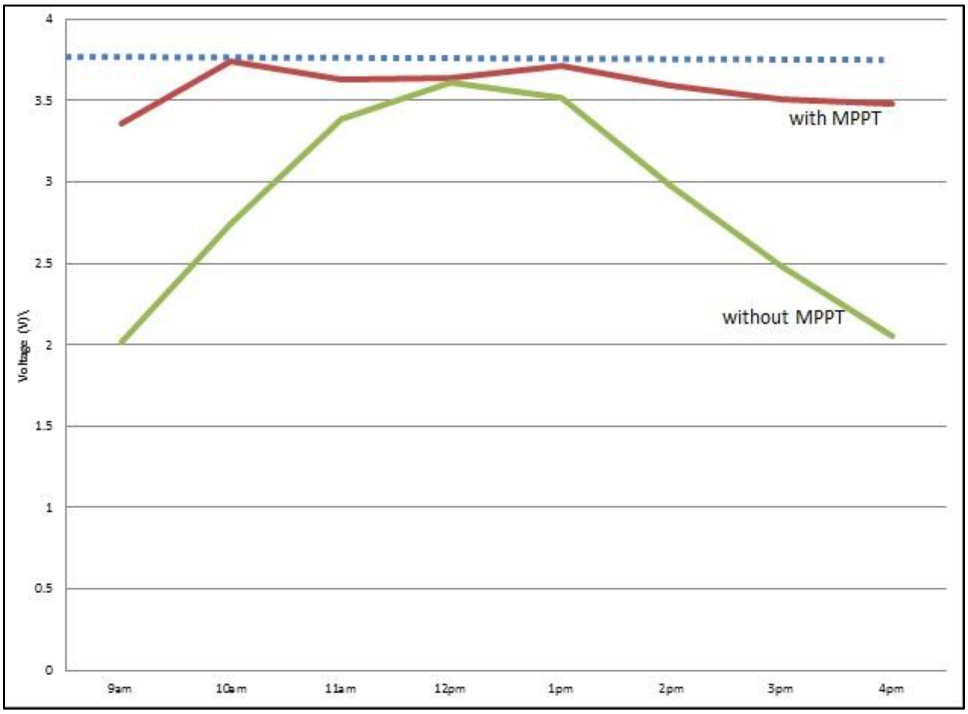

Figure 13: Graph of input voltages vs time for MPPT enable and disable

During MPPT enable mode, the voltage observed to be operating at the range of V_{MPP} under the presence of high irradiance of sunlight. After 5pm, the solar panel operates at lower irradiance level, and affects the operating voltage and current of MPPT.

From the tabulated result, operating current under the presence of low radiance of sunlight is low and high during the peak hours, applies to be the same for both MPPT enable and disable. As discussed earlier, for MPPT enabled mode, current is adjusted through inductor to maintain the voltage at V_{MPP}, and ensures the harvesting at maximum. Graph of current is plotted in Figure 14.

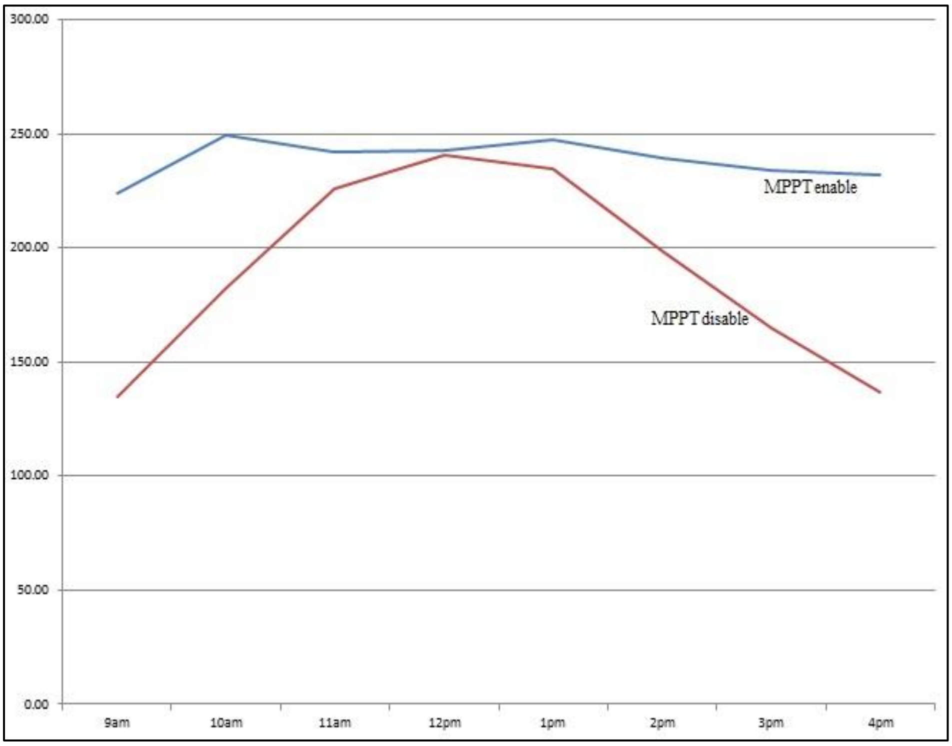

Figure 14: Graph of input currents vs time for MPPT enable and disable

Figure 15 shows the operating power of LTC3105 during the MPPT enable and disable mode. To simplify the comparison curve of power; MPPT control enables the IC to maximize the power harvested by ensuring the voltage operation at almost $V_{MPP.}$ Therefore the power maximized by controlling the MPPT voltage.

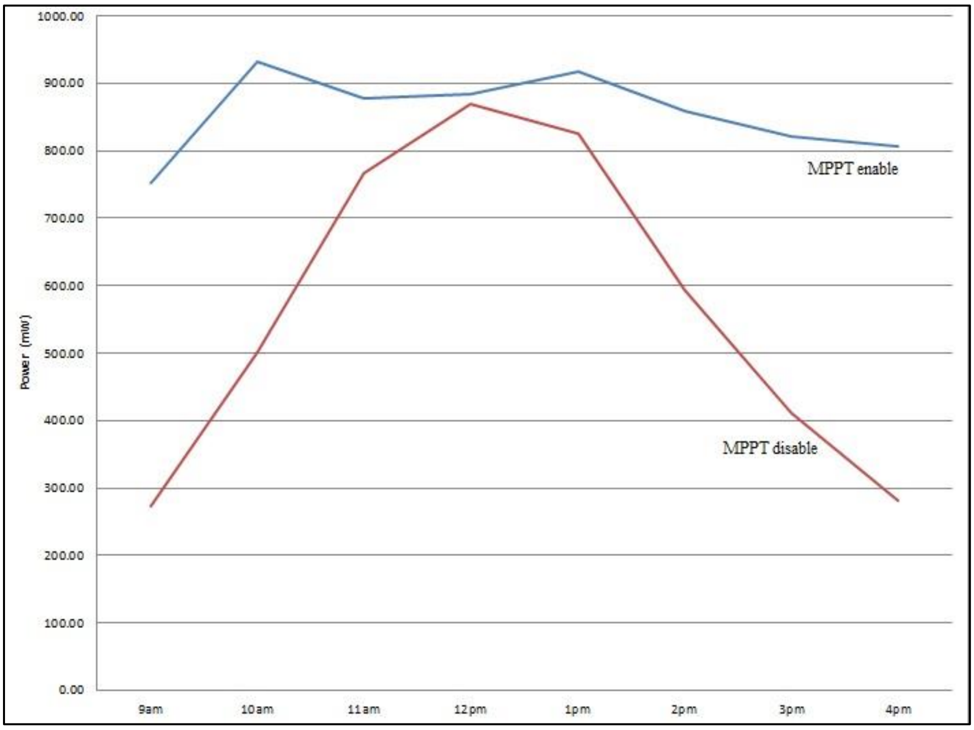

Figure 15: Graph of input power time for MPPT enable and disable

4. 3 Testing LTC3105 for DC-DC controller

The DC-DC controller function in LTC3105 is set to buck the input to provide constant output of 3.2V to the battery. DC-DC converter is programmed through resistor divider which sets output voltage to 3.2V and connected to battery. The LTC3105 is left connected to solar panel and battery for about 10 hours. Arduino controller is programmed to track the values of voltage and current at several time intervals. The average results of voltage and current at each time is tabulated in Table 7.

Table 7: Average values of voltage and current recorded at several time intervals

	Output from solar panel		Measurement of Battery	
Time	**Voltage (V)**	**Current (mA)**	**Voltage (V)**	**Current (mA)**
8.00	**2.82**	**11.80**	**2.54**	**184.64**
9.00	**3.86**	**25.81**	**2.67**	**249.81**
10.00	**4.22**	**99.32**	**2.83**	**174.25**
11.00	**4.06**	**104.59**	**2.77**	**111.33**
12.00	**4.20**	**102.88**	**2.82**	**162.92**
1.00	**4.09**	**109.55**	**2.71**	**149.34**
2.00	**3.80**	**87.13**	**2.69**	**214.51**
3.00	**3.76**	**61.78**	**2.73**	**141.40**
4.00	**3.54**	**25.15**	**2.66**	**97.95**
5.00	**3.72**	**15.18**	**2.59**	**95.04**
6.00	**1.73**	**3.70**	**2.47**	**172.78**

From the result tabulated, highest voltage and current is measured during late morning till the mid-day which is from 10a.m. till 3p.m. Maximum hours of solar harvesting is estimated about four to five hours a day in average. Besides that, IC LTC3105 is considered to operate at steady-state conditions as the output from solar panel works in a quite narrow voltage window centered at $V_{MPP,}$ which is about 3.8V. LTC3105 is set to operate as buck converter, where output from solar panel (roughly 3.8V) is used to supply charge to batteries (roughly 3.2). Graph 16 shows the input and output curve of DC-DC converter of LTC3105.

Output voltage of LTC3105 will be depending on the NiMH batteries, whereby during the mid-day, batteries will be charged thus the voltage will gradually increase until it is fully charged. However, during the absence of sunlight, charges from the batteries will not be replaced, therefore the voltage will experience reducing curve. Figure 17 shows the difference in output voltage of LTC3105 which represents the battery voltage as discussed.

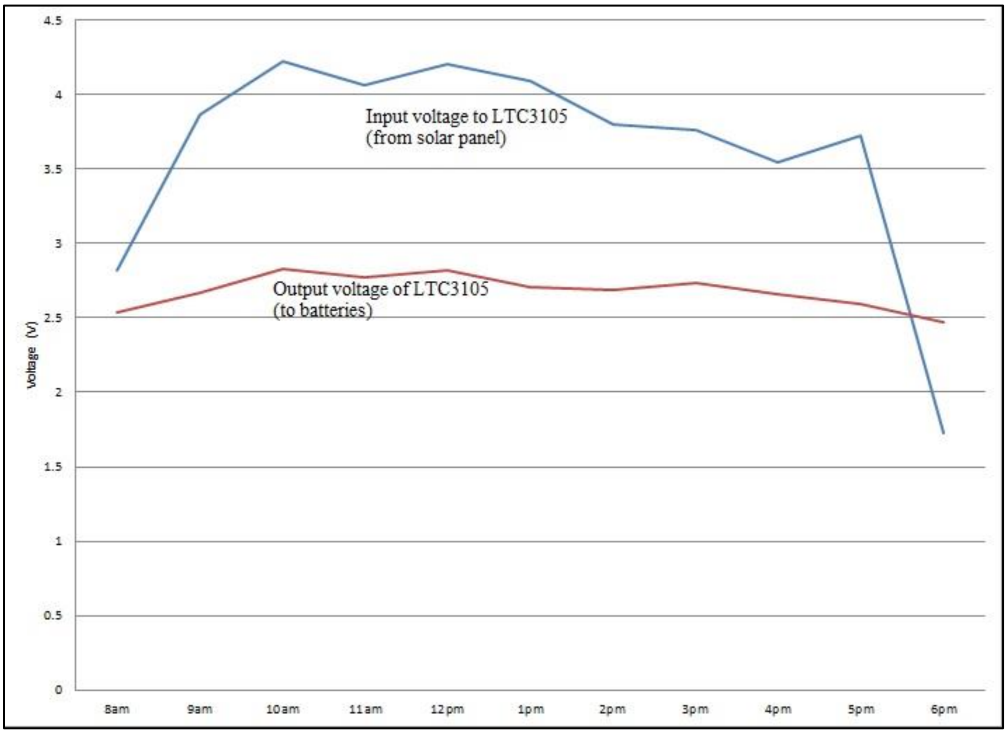

Figure 16: Graph of input and output voltage vs time for LTC3105

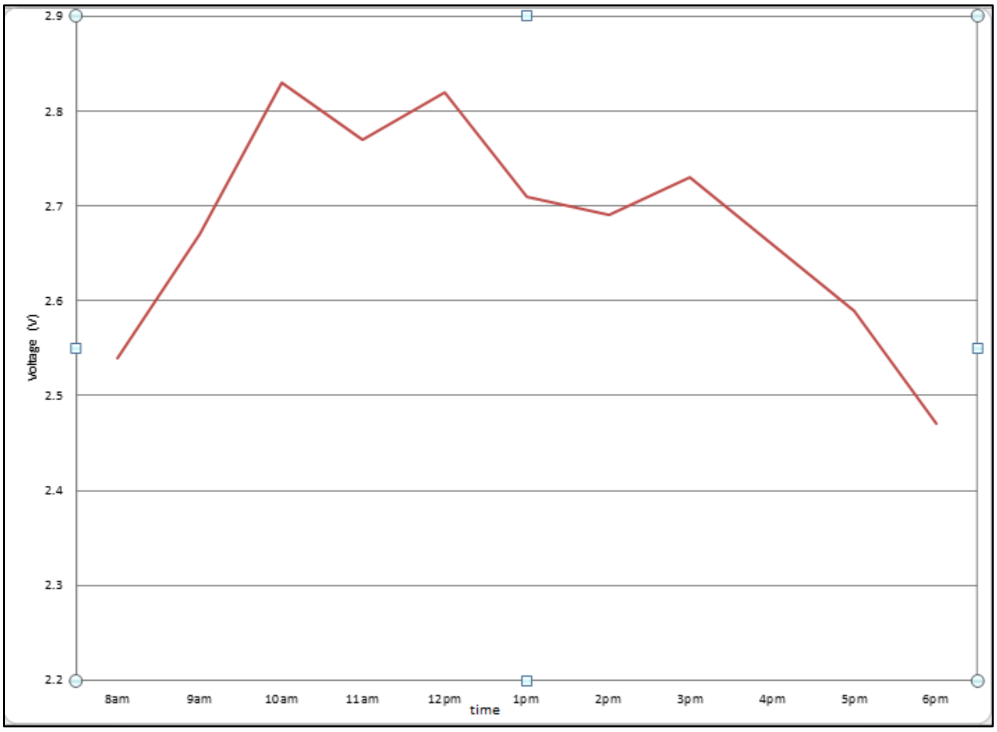

Figure 17: Graph showing enlarged curve of battery voltage

4. 4 Testing LTC3530

LTC3530 is a synchronous DC-DC converter. In this experiment LTC3530 is used as boost converter to increase the voltage to WSN. Output voltage from battery which is about 2.4V will be boost to about 3.3V. Two LEDs are connected in series as the output for LTC3530 used for testing. Voltage across the LEDs are measured as the output voltage as show in Figure 18. Figure 18 is the circuit connection and result of DC-DC boost from battery voltage.

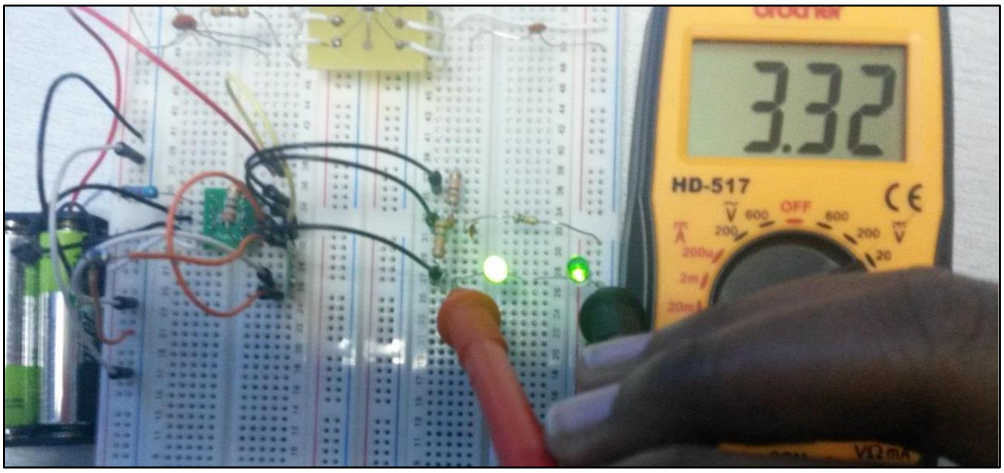

Figure 18: LTC3530 connection and result of boost configuration

Circuit connected as in Figure 18 is also connected to Arduino to measure average input and output of LTC3530. The results are tabulated in Table 8. From the result tabulated, the output voltage to WSN is in the range from 2.87 to 3.79, which is still under the operating range of WSN Iris used in this project. The average voltage output of LTC3530 from the result tabulated is 3.34V. However, the power efficiency of overall circuit is about 65%.

Table 8: Tabulated results of input and output of LTC3530

$V_{BATTERY}$ (V)	$I_{BATTERY}$ (mA)	$P_{BATTERY}$ (mV)	V_{OUT} (V)	I_{OUT} (mA)	P_{OUT} (mW)
2.36	114.00	269.04	3.51	30.79	108.07
2.30	244.00	561.20	3.76	82.76	311.18
2.81	98.00	275.38	2.79	89.12	248.65
2.87	114.00	327.18	2.87	92.70	266.05
1.92	293.00	562.56	3.32	76.41	253.68
2.64	212.00	559.68	3.41	76.57	261.10
3.52	326.00	147.52	3.37	81.62	275.06
2.37	179.00	424.23	3.75	92.05	345.19
2.95	148.00	436.60	3.32	91.23	302.88
2.64	196.00	517.44	3.35	81.62	273.43
2.64	**192.40**	**408.08**	**3.35**	**79.49**	**264.53**

4. 5 Testing the overall performance of Solar Energy Harvesting

Circuit is connected with all the components as discussed in methodology part. Figure 19 shows the component connection on breadboard.

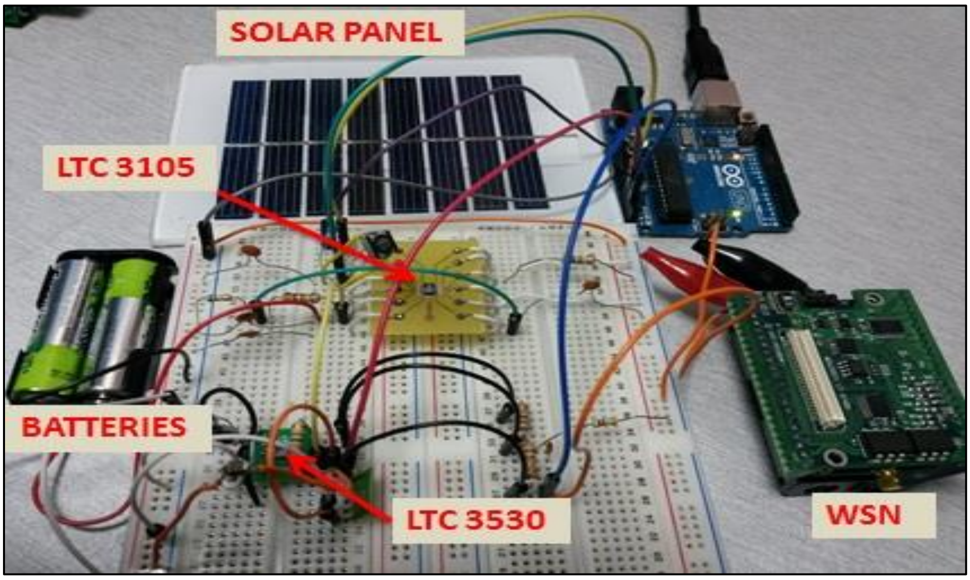

Figure 19: Complete connection of components for solar harvesting for WSN

The circuit is connected to solar and readings of voltages in between components (solar panel, LTC3105, batteries, LTC3530, WSN) are measured at specific intervals of time throughout a day. Voltages measured at points on circuit are illustrated as in Figure 20. The data collected are recorded.

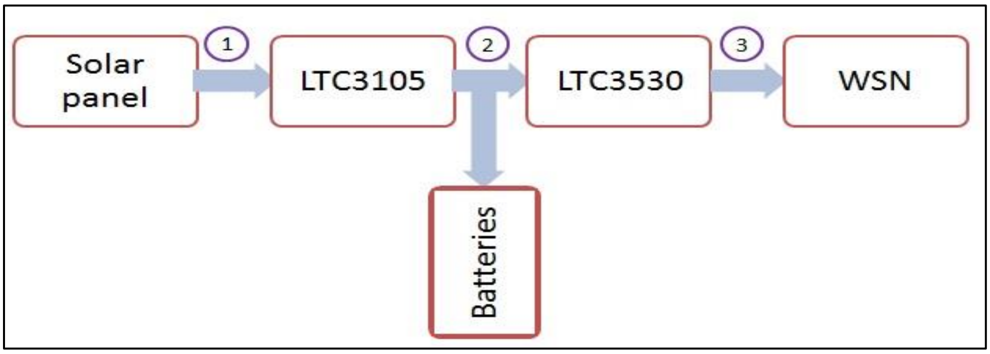

Figure 20: Points at which voltages are measured during solar harvesting for WSN

The WSN is programmed to work under high power and duty cycle is adjusted to 2 seconds, whereby every two second, WSN will be sensing, transmitting and receiving data on temperature of surrounding. The WSN is set to work frequently to ensure study on longevity of WSN in shorter duration of time. Testing of circuit was carried out under two different condition; under presence of sunlight and another under the shaded region or absence of sunlight. Results obtained are tabulated in Table 9 and 10.

Table 9: Tabulated results of voltages and currents under presence of sunlight

Under Presence Of Sunlight					
V1	**I1**	**V2**	**I2**	**V3**	**I3**
3.71	104.59	2.65	142.88	3.11	29.44
3.67	109.55	2.09	238.52	3.12	40.73
3.94	87.13	2.59	101.70	2.96	17.95
3.58	214.51	2.67	98.36	2.96	18.15
3.74	141.40	2.57	148.67	2.98	24.60
3.87	249.81	2.25	307.01	2.94	43.22
3.99	174.25	2.59	212.47	2.23	28.61
3.87	162.92	2.77	222.00	2.89	29.52
3.97	214.59	3.02	271.04	2.92	46.16
3.98	141.17	2.67	269.16	2.82	40.73
4.03	97.95	2.78	98.76	2.87	18.29
4.37	111.33	2.59	142.03	2.96	25.55
3.69	249.81	2.78	142.09	3.01	25.55
3.71	172.78	2.65	77.41	2.79	29.70
3.83	302.77	2.76	68.21	2.79	31.00
4.35	259.72	2.63	92.73	2.52	28.15
3.93	262.92	2.80	107.00	2.90	27.72
3.80	241.04	2.63	122.60	3.02	43.31
3.89	**191.54**	**2.65**	**89.56**	**2.88**	**30.47**

Table 10: Tabulated results of voltages and currents under absence of sunlight

Under Shaded Area, Absence Of Sunlight					
V1	**I1**	**V2**	**I2**	**V3**	**I3**
1.18	1.95	2.27	119.47	2.36	16.29
1.18	1.88	2.22	78.99	2.36	28.15
1.18	2.24	2.21	62.45	2.39	28.15
1.19	2.27	2.11	195.50	2.36	21.72
1.20	2.12	2.14	111.33	2.38	18.15
1.21	1.99	2.24	184.64	2.36	19.01
1.22	2.72	2.10	95.30	2.33	8.72
1.22	2.72	2.28	266.10	2.43	46.16
1.21	2.43	2.22	108.61	2.43	21.72
1.22	2.55	2.23	244.38	2.39	40.73
1.20	2.72	2.19	306.83	2.44	54.31
1.22	2.72	2.16	171.07	2.36	32.72
1.19	2.72	2.24	101.60	2.39	25.43
1.19	2.72	2.28	127.60	2.35	33.58
1.18	2.59	2.26	119.47	2.34	40.73
1.17	2.62	2.14	184.60	2.33	21.72
1.17	2.38	2.12	118.70	2.41	46.16
1.17	2.57	2.14	184.60	2.48	40.73
1.19	**2.44**	**2.20**	**154.51**	**2.38**	**30.23**

Results tabulated from experiment 1 which the circuit is tested under the presence of sunlight, indicates the presence of solar produces current and voltage to charge up the battery and supply energy to power WSN. Voltage and current 1 are the measurements indicating power from solar panel. Average voltage from solar panel is about 3.89V, set to V_{MPP}. Voltages and currents 2 are measurements indicating power from the battery. Power from battery is conserved and maintain at above nominal, average about 2.65V.

For experiment 2 where circuit tested under absence of sunlight, solar energy is insufficient to power the WSN not charge the battery. WSN is powered by the rechargeable battery, thus the voltage of battery reduces below the nominal voltage after turning on the WSN for about an hour. Voltage of battery reduces to about 2.2V in average. Graph in Figure 21 shows the comparison of battery voltage for presence and absence of sunlight.

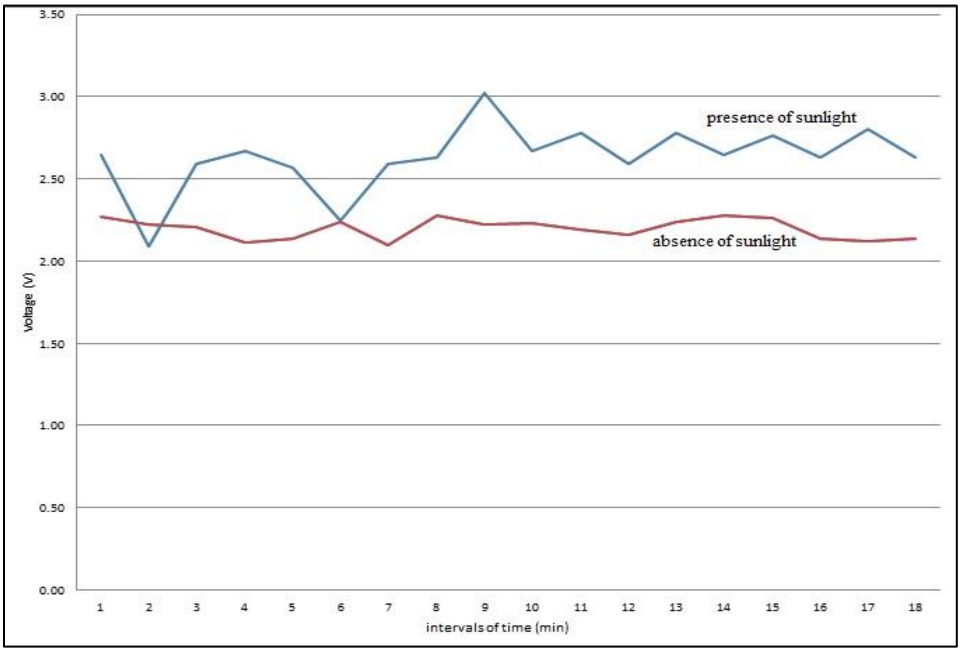

Figure 21: Graph of battery voltage comparison for circuit under presence and absence of solar harvesting

From this experiment, it is proven that the power from battery will run off eventually and needs replacements if is not recharged by energy harvesting. Solar energy is harvested to recharge the battery and ensure longer lifespan of WSN.

Experiment with overall circuit is also conducted for almost a day to study on the charging curve of the rechargeable battery by solar harvesting as well as to measure the efficiency of the system. The measurement of current at part two is split to three and current at each path is measured as shown in Figure 22. Result of the experiment of every hour is attached in Appendix while the average values are tabulated in Table 11.

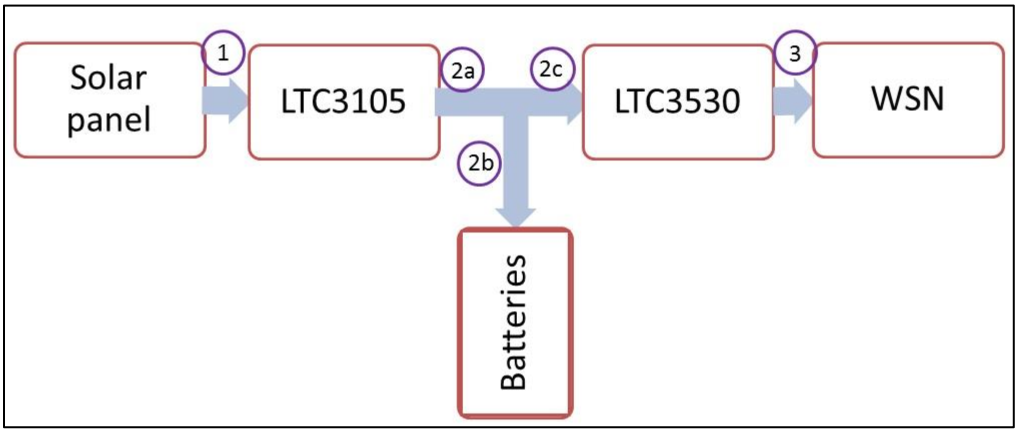

Figure 22: Points at which voltages are measured during solar harvesting for WSN

Table 11: Tabulated results of voltages and currents of system

TIME	V1(V)	I1 (mA)	V2(V)	I2A(mA)	I2B(mA)	I2C(mA)	V3(V)	I3(mA)
9.00am	3.75	86.35	2.29	59.16	6.63	35.53	2.23	21.22
9.30am	3.95	71.95	2.48	63.42	14.59	34.93	2.22	22.24
10.00am	3.97	92.13	2.3	70.04	12.03	33.27	2.22	28.57
10.30am	3.99	88.54	2.36	54.71	15.63	30.72	2.37	25.91
11.00am	4.13	95.61	2.61	40.64	10.59	30.75	2.59	29.11
11.30am	4.14	86.55	2.64	48.29	20.87	35.62	2.35	30.47
12.00pm	4.02	114.39	2.63	55.19	63.78	21.89	2.12	22.02
12.30pm	3.97	100.45	2.64	44.64	64.61	28.15	2.18	31.00
1.00pm	4.00	111.22	2.65	66.96	22.88	33.27	2.89	29.87
1.30pm	4.02	118.12	2.66	65.20	18.92	32.45	2.87	28.50
2.00pm	4.09	97.55	2.67	60.73	28.52	27.15	2.17	25.06
2.30pm	4.06	90.87	2.68	66.75	26.80	32.58	2.67	29.04
3.00pm	3.82	80.87	2.69	66.27	20.17	22.88	2.51	28.05
4.00pm	3.79	86.98	2.62	51.81	20.00	30.00	2.55	28.61
5.00pm	3.61	87.13	2.65	35.26	19.47	13.03	2.44	30.47
No presence of sunlight								
6.00pm	1.16	2.37	2.39	0.99	-16.04	20.48	2.38	26.04
7.00pm	1.18	3.62	1.80	-2.72	-15.38	26.80	2.17	33.01
8.00pm	0.68	3.39	1.62	-1.49	-22.36	21.35	2.28	21.64
9.00pm	0.72	2.61	2.09	-0.53	-23.53	19.10	2.15	21.82

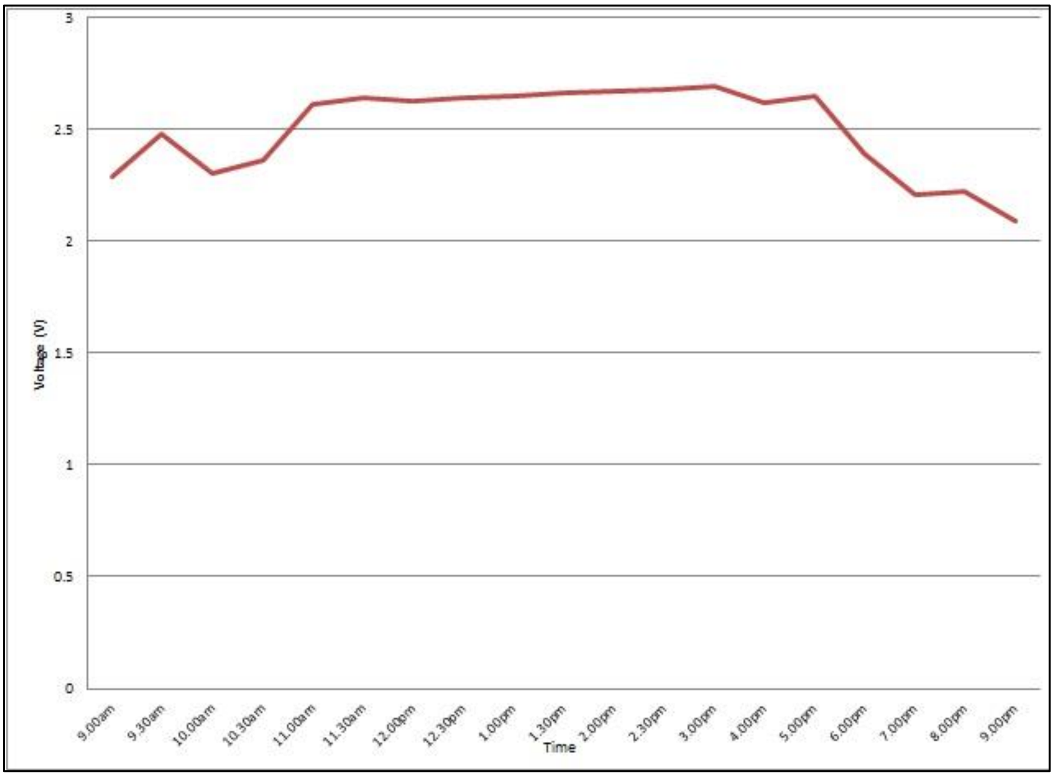

Figure 23: Graph of voltage curve of battery to study on result of solar harvesting

The charging curve of battery is shown in Figure 23. In the morning when there is presence of sunlight, solar energy is harvested and charges the battery. At afternoon, when the sunlight is brightest, the voltage of battery is measured at maximum and almost constant until evening. After 5pm, when the sun sets, absence of sunlight results in minimum solar harvesting. Energy from solar harvesting is insufficient to maintain the charges of battery, thus battery discharge to power WSN. The battery voltage curve degrades in value.

Efficiency is calculated by dividing output power over input power. Input power of LTC3105 is calculated by multiplying V1 and I1 while output power of LTC3105 is measure by multiplying V2 and I2A. Input power of LTC3530 is calculated by multiplying V2 and I2B while output power of LTC3105 is measure by multiplying V3 and I3. Calculated powers are tabulated in Table 12. From the average powers calculated, efficiency is measured. The efficiency of LTC3105 is about 38.5% while efficiency of LTC3530 is about 86.16% if measured by the average for half a day.

Table 12: Calculated result of input and output power

Pin LTC3105	Pout LTC3105	Pin LTC3530	Pout LTC3530
323.81	135.47	81.36	44.62
284.20	157.28	86.62	48.92
365.76	138.09	76.52	73.28
353.27	129.11	72.49	67.63
394.87	106.07	80.25	77.98
358.31	127.48	94.03	71.60
459.84	145.14	67.57	57.91
398.78	117.84	74.31	67.58
444.88	177.44	88.16	86.32
474.84	173.43	86.31	81.79
398.97	162.14	72.49	54.38
368.93	178.89	87.31	77.53
308.92	178.26	61.54	71.66
329.65	135.74	78.60	72.95
323.25	93.43	85.99	74.34
372.552	**143.73**	**79.57**	**68.56**

5. CONCLUSION

Renewable energy currently is being more focused and emerged by many professionals as the major source to applications. Using solar energy harvesting to supply continuous power to charge batter for WSN is a great method to overcome finite resource problem. To construct an effective harvesting technique, several factors are considered mainly on understanding the various components used, power management technique such as MPPT and DC-DC converters. Besides, usage of battery is important to store the charges and ensure the constant power to WSN during condition without the presence of sunlight. The overall idea of this project is to show the approach of harvesting solar energy in most efficient way and present the design with analysis and evaluation on the result.

This project can be improved since the overall system efficiency is only about 60%. One suggestion to follow up with this project is to consider alternate method for MPPT management. This is because LTC3105 is a MPPT controller with DC-DC converter which is mainly programmed to boost the voltage. However in this case, we require voltage to be constant or bucked to 3.2V. Although the IC is capable of handling buck conversion, the efficiency of system will be affected. Thus, it is recommended to improve power management by considering alternative for LTC3105. Besides that, the project can be further improved by designing switching circuit which is programmed to detect presence of sunlight and channel the harvesting energy to WSN while during the absence the switch will allow charge from battery to power WSN; similar to the concept of low-voltage switching.

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7. APPENDIX

9.00am

v1	i1	v2	i2a	i2b	i2c	v3	i3
4.17	86.89	2.16	-13.58	5.43	8.15	2.28	17.95
2.24	270.15	1.96	84.31	-2.27	43.45	1.95	18.15
2.1	16.29	2.04	8.15	24.44	40.73	2.59	19.01
3.99	141.2	2.06	98.15	16.29	16.29	2.48	32.72
3.95	135.77	1.96	87.02	2.72	46.16	1.83	28.15
3.69	18.23	1.98	54.31	35.3	54.31	2.39	18.15
4.06	46.16	2.02	32.58	-19.01	13.58	2.37	19.01
4.12	78.74	2.17	37.6	0	40.73	1.98	30.53
3.65	105.9	2.18	-38.01	0	29.87	2.52	21.72
4.06	92.32	1.87	84.18	16.29	57.02	1.82	19.01
3.87	19.01	2.19	2.72	-10.86	-5.43	2.31	18.15
4.1	89.66	1.98	68.15	2.72	8.15	2.66	19.01
4.32	70.6	2.46	29.87	16.29	5.43	2.13	19.01
4.19	38.01	1.69	-27.15	5.43	24.44	1.92	21.72
3.750714	**86.35214**	**2.051429**	**59.16429**	**6.626429**	**27.34857**	**2.230714**	**21.215**

9.30am

v1	i1	v2	i2a	i2b	i2c	v3	i3
4.15	57.02	2.41	43.45	16.29	46.16	2.36	19.95
3.76	19.01	2.53	29.87	13.58	0	1.85	22.11
4.05	24.44	2.47	28.15	2.72	13.58	1.82	19.01
4.06	32.58	2.52	15.43	0	2.72	2.43	32.72
3.72	32.58	2.49	-5.43	0	5.43	2.03	28.15
4.03	133.05	2.41	109.01	2.72	13.58	1.87	18.15
4.19	29.87	2.45	27.15	-32.58	5.43	1.91	19.01
3.96	260.67	2.48	128.74	-2.72	5.43	1.88	30.53
3.98	78.74	2.48	-27.15	-2.72	-10.86	2.18	21.72
4.08	86.89	2.42	84.18	32.58	81.46	2.65	19.01
3.84	228.09	2.48	133.58	62.45	16.29	2.39	18.15
3.84	8.15	2.54	19.01	10.86	16.29	2.34	19.01
3.93	51.59	2.52	35.3	19.01	16.29	2.54	19.01
3.74	38.01	2.43	-10.86	29.87	29.87	2.47	21.72
3.75	43.45	2.48	59.74	27.15	-27.15	2.48	22.03
4.14	27.15	2.55	-5.43	54.31	24.44	2.13	25.61
3.95125	**71.95563**	**2.47875**	**63.42125**	**14.595**	**14.935**	**2.208125**	**22.24**

10.00am

v1	i1	v2	i2a	i2b	i2c	v3	i3
3.98	219.94	2.2	148.88	43.45	-10.86	1.95	43.01
3.77	2.72	2.25	65.17	5.43	81.46	2.59	50.22
3.72	233.52	2.28	-5.43	-16.29	16.29	2.48	20.52
3.84	13.58	2.23	95.04	-19.01	16.29	1.83	32.72
4.1	2.72	2.23	95.04	-27.15	16.29	2.39	28.15
3.64	122.19	2.32	-2.72	13.58	29.87	2.37	18.15
3.99	76.03	2.34	67.88	38.01	-27.15	1.99	29.01
3.98	35.3	2.29	43.45	19.01	24.44	1.87	30.53
4.18	190.07	2.34	-8.15	29.87	16.29	1.91	21.72
4.09	19.01	2.34	24.44	8.15	40.73	1.88	46.16
4.21	57.02	2.4	95.04	2.72	46.16	2.18	21.72
4.04	40.73	2.34	78.74	24.44	54.31	2.65	19.01
4.24	157.49	2.33	89.61	19.01	19.01	2.39	18.15
3.92	119.47	2.32	93.58	27.15	2.72	2.34	19.01
3.978571	**92.12786**	**2.300714**	**70.04071**	**12.02643**	**23.275**	**2.201429**	**28.574**

10.30am

v1	i1	v2	i2a	i2b	i2c	v3	i3
3.98	219.94	2.2	48.88	43.45	-10.86	2.22	-2.73
3.77	2.72	2.25	65.17	5.43	81.46	2.12	62.55
3.72	233.52	2.28	-5.43	-16.29	16.29	2.6	15.02
3.84	13.58	2.23	95.04	-19.01	16.29	1.98	23.50
4.1	2.72	2.23	95.04	-27.15	16.29	1.82	29.61
3.64	122.19	2.32	-2.72	13.58	29.87	2.43	29.52
3.99	76.03	2.34	67.88	38.01	-27.15	2.03	36.16
3.98	35.3	2.29	43.45	19.01	24.44	1.87	19.01
4.18	190.07	2.34	-8.15	29.87	16.29	1.91	32.72
4.09	19.01	2.34	24.44	8.15	40.73	1.88	28.15
4.21	57.02	2.4	95.04	2.72	46.16	2.59	21.72
4.04	40.73	2.34	78.74	24.44	54.31	2.48	18.15
4.24	157.49	2.33	89.61	19.01	19.01	1.83	21.73
3.92	119.47	2.32	63.58	27.15	2.72	2.39	27.61
3.978571	**92.12786**	**2.300714**	**54.71071**	**12.02643**	**23.275**	**2.37**	**25.9084**

11.00am

v1	i1	v2	i2a	i2b	i2c	v3	i3
4.08	59.74	2.58	16.29	10.86	54.31	2	21.72
4.24	206.36	2.66	57.02	-5.43	8.15	2.13	18.15
4.12	46.16	2.62	21.72	21.72	-19.01	2.53	19.01
4.1	62.45	2.58	30.86	13.58	19.01	2.16	32.72
4.22	200.93	2.66	65.17	13.58	16.29	1.87	28.15
3.93	173.78	2.59	88.15	18.86	40.73	2.08	21.72
4.26	62.45	2.61	32.58	1.86	21.73	1.87	18.15
4.11	62.45	2.66	32.58	29.87	10.86	2.08	21.72
4.01	130.34	2.63	78.74	10.86	35.3	2.31	18.15
4.19	43.45	2.62	-2.72	10.86	29.87	2.24	19.01
4.2	35.3	2.58	10.86	16.29	16.29	1.94	33.05
4.07	78.74	2.61	-2.72	-5.43	0	2.24	16.11
4.09	13.58	2.6	40.73	-10.86	16.29	2.35	46.11
4.24	162.92	2.65	59.74	0	40.73	2.68	33.99
4.132857	**95.61786**	**2.617857**	**40.64286**	**10.59571**	**20.75357**	**2.591429**	**29.1104**

11.30am

4.18	190.07	2.65	64.17	5.43	46.16	1.91	32.72
4.15	48.88	2.6	38.01	-8.15	54.31	2.19	28.15
4.23	124.9	2.6	46.16	10.86	19.01	1.92	21.72
3.97	13.58	2.71	32.58	27.15	2.72	2.17	18.15
4.24	84.18	2.71	48.8	29.87	24.44	2.8	25.04
4.02	111.33	2.62	35.3	-8.15	40.73	2.64	20.19
4.22	179.21	2.7	27.15	38.01	8.15	2.45	33.05
4.1	46.16	2.63	10.86	32.58	-27.15	2.91	46.11
4.21	130.34	2.61	54.31	-8.15	21.73	2.18	19.63
4.24	27.15	2.61	95.04	-5.43	10.86	2.31	17.95
4.2	27.15	2.63	97.75	54.31	35.3	2.53	18.15
4.12	38.01	2.67	-5.43	35.3	29.87	2.49	24.6
4.16	119.47	2.68	-8.115	29.87	16.29	2.87	43.22
4.16	97.75	2.67	56.29	35.3	54.31	2.16	28.61
4.05	114.04	2.62	113.58	24.44	19.01	2.08	29.52
4.1	32.58	2.68	46.16	40.73	54.31	2.24	46.16
4.146875	**86.55**	**2.649375**	**48.28844**	**20.87313**	**25.62813**	**2.353125**	**30.47**

12pm

v1	i1	v2	i2a	i2b	i2c	v3	i3
3.83	21.72	2.7	-40.73	173.78	16.29	1.9	17.95
3.94	127.62	2.63	127.62	293.26	19.01	1.94	18.15
4.13	116.76	2.61	92.32	160.2	-8.15	1.8	24.6
3.97	16.29	2.59	-65.17	97.75	16.29	2.43	33.22
3.85	141.2	2.6	111.33	48.88	29.87	2.3	28.61
4.08	15.77	2.65	152.06	-127.62	16.29	1.93	29.52
3.84	51.59	2.65	-86.89	62.45	13.58	2.36	36.16
4.16	100.47	2.61	-97.75	331.27	24.44	2.38	21.72
3.97	184.64	2.64	-95.04	149.34	70.31	2.21	18.15
4.13	143.91	2.66	165.63	-76.03	24.44	2.17	19.01
4.05	195.5	2.61	181.93	173.78	-5.43	2.37	21.72
4.08	122.19	2.61	114.04	-111.33	27.15	1.79	18.15
4.17	92.32	2.62	59.74	13.58	29.87	2.07	19.01
4.16	271.53	2.66	13.58	-16.29	32.58	2.05	19.01
4.025714	**114.3936**	**2.631429**	**55.19071**	**83.78714**	**21.89571**	**2.121429**	**22.02**

12.30pm

v1	i1	v2	i2a	i2b	i2c	v3	i3
3.76	65.17	2.66	266.1	35.3	40.73	1.3	39.72
3.8	51.59	2.67	100.47	-10.86	19.01	2.13	28.15
3.78	21.72	2.6	46.16	48.88	38.01	2.22	21.72
4.04	32.58	2.61	-16.29	10.86	76.03	2.25	38.15
4	19.01	2.71	-59.74	54.31	32.58	2.45	35.01
3.79	200.93	2.65	-48.88	38.01	73.31	2.43	21.72
4.14	217.23	2.61	-2.27	10.86	29.87	1.88	18.15
4.13	38.01	2.61	86.89	2.27	35.3	2.15	19.01
3.92	19.01	2.65	-46.16	24.44	13.58	2.91	38.75
4.11	13.58	2.61	67.88	-19.01	73.31	2.45	17.95
3.97	157.49	2.64	95.04	2.72	48.88	2.64	18.15
3.77	2.72	2.66	46.16	-5.43	62.45	1.81	24.6
4.09	133.05	2.61	67.88	54.31	48.88	2.19	43.22
3.87	103.18	2.67	13.58	-19.01	24.44	2.35	28.61
3.77	195.5	2.6	10.86	16.29	29.87	1.92	29.52
3.88	141.2	2.7	70.6	43.45	27.15	1.94	46.16
3.92625	**88.24813**	**2.636498**	**44.64164**	**49.81281**	**32.31728**	**2.18875**	**31.005**

1.00pm

v1	i1	v2	i2a	i2b	i2c	v3	i3
3.97	66.32	2.73	43.45	40.73	73.31	3.11	29.44
4.08	141.2	2.62	67.88	46.16	5.43	3.12	40.73
4.11	78.74	2.68	13.58	24.44	46.16	2.96	17.95
4.09	62.45	2.67	81.46	8.15	43.45	2.96	18.15
3.66	135.77	2.63	54.31	5.43	21.73	2.98	24.6
4.07	100.47	2.65	56.29	8.15	8.15	2.94	43.22
3.98	234.92	2.59	0	0	0	0	0
3.76	127.62	2.73	86.16	57.02	84.18	2.89	29.52
3.78	24.44	2.62	5.43	19.01	2.72	2.92	46.16
4.22	222.66	2.61	127.15	10.86	13.58	2.82	40.73
4.16	24.44	2.62	5.43	19.01	5.43	2.87	18.29
4.2	114.04	2.62	92.72	16.29	10.86	2.96	25.55
4.05	29.87	2.67	29.87	32.58	2.72	3.01	25.55
3.91	149.34	2.66	16.29	32.58	8.15	2.79	29.7
4.002857	**111.2277**	**2.65**	**66.96**	**22.88643**	**23.27643**	**2.897143**	**29.87143**

1.30pm

v1	i1	v2	i2a	i2b	i2c	v3	i3
4.21	209.08	2.61	92.72	16.29	43.45	2.82	40.73
3.89	160.2	2.63	73.58	13.58	21.72	2.87	18.29
3.85	149.34	2.71	54.31	5.43	21.72	2.96	25.55
3.88	206.36	2.71	54.31	24.44	19.01	3.01	25.55
3.95	162.92	2.72	84.44	24.44	32.58	2.79	29.7
4.11	43.45	2.61	103.18	8.15	21.72	2.79	31
3.87	97.75	2.62	59.74	10.86	10.86	2.52	28.15
4.07	89.64	2.64	65.17	32.58	21.72	2.9	27.72
4.03	35.3	2.62	8.15	10.86	10.86	3.02	43.31
4.07	67.88	2.68	35.3	10.86	27.15	2.96	18.15
4.05	81.46	2.65	16.29	10.86	10.86	2.98	24.6
3.95	149.34	2.71	54.31	5.43	21.72	2.94	43.22
4.18	206.36	2.71	84.31	24.44	19.01	2.77	26.31
4.15	162.92	2.72	44.44	24.44	32.58	2.8	20.13
4.11	43.45	2.61	103.18	8.15	21.72	2.69	35.61
4.2	114.04	2.62	72.72	16.29	10.86	3.2	17.99
4.01977	**117.8893**	**2.655484**	**65.20645**	**19.04505**	**22.47376**	**2.87625**	**28.50063**

2.00pm

v1	i1	v2	i2a	i2b	i2c	v3	I3
3.99	10.86	2.65	65.17	8.15	19.01		40.73
3.99	8.15	2.62	108.61	8.15	5.43	2.38	28.15
4.04	81.46	2.62	84.18	29.87	8.15	2.21	21.72
4.32	241.66	2.7	19.01	29.87	19.01	2.17	21.72
3.74	236.23	2.72	124.44	38.01	21.72	2.37	18.15
4.07	76.03	2.62	16.29	57.02	5.43	1.79	19.01
4.3	89.61	2.65	32.58	19.01	27.15	2.23	8.72
4.32	130.34	2.65	98.15	8.39	38.01	1.87	46.16
4.24	2.72	2.73	21.72	43.45	65.17	1.91	21.72
4.31	190.07	2.64	2.72	57.02	-16.29	1.88	19.01
3.99	16.29	2.74	54.31	32.58	76.03	2.18	54.31
3.71	143.91	2.65	13.58	-5.43	-5.43	2.65	32.72
4.28	2.72	2.68	84.18	16.29	38.01	2.45	18.15
4.09	135.77	2.75	35.3	57.02	78.74	2.15	19.01
4.099286	**97.55857**	**2.672857**	**60.73143**	**28.52857**	**27.15286**	**2.172308**	**25.061**

2.30pm

v1	i1	v2	i2a	i2b	i2c	v3	i3
4.13	95.04	2.65	-2.72	21.72	24.44	2.23	21.72
3.71	100.47	2.69	-5.43	21.72	5.43	2.89	19.01
4.12	122.19	2.67	84.18	8.15	16.29	2.92	54.31
3.67	127.62	2.63	106.29	16.29	10.86	2.82	32.72
3.99	59.74	2.73	57.02	43.45	67.88	2.87	18.15
4.08	116.76	2.75	46.16	54.31	78.74	2.98	19.01
4.03	67.88	2.64	2.72	21.72	73.31	2.94	8.72
4.22	81.46	2.73	38.01	46.16	10.86	2.77	46.16
4.03	122.19	2.66	82.58	13.58	32.58	2.8	21.72
4.07	32.58	2.64	105.9	13.58	21.72	2.69	19.01
4	40.73	2.65	40.73	8.15	38.01	3.2	54.31
3.96	46.16	2.67	-5.43	8.15	-2.72	1.79	8.72
4.2	84.18	2.63	10.86	10.86	48.88	2.69	46.16
4.1	2.72	2.71	54.31	10.86	70.6	3.2	21.72
4.05	146.62	2.75	21.73	51.59	16.29	1.79	54.31
4.2	114.04	2.64	35.3	54.31	84.18	2.22	29.71667
4.066106	**91.08899**	**2.675253**	**66.87682**	**26.85576**	**32.583**	**2.675**	**29.0411**

3.00pm

v1	i1	v2	i2a	i2b	i2c	v3	i3
3.53	119.47	2.55	84.18	16.29	24.44	2.45	27.72
3.44	84.18	2.56	51.59	2.72	8.15	2.64	43.31
3.83	8.15	2.55	89.61	13.58	13.58	2.81	18.15
3.92	54.31	2.58	10.86	2.72	19.01	2.19	24.6
3.68	152.06	2.56	62.58	40.73	-32.58	2.45	43.22
3.68	230.8	2.58	155.43	16.29	5.43	2.11	26.31
4.03	46.16	2.65	43.45	5.43	57.02	1.98	46.16
4.14	24.44	2.59	21.72	8.15	16.29	1.99	21.72
4.31	59.74	2.54	43.45	29.87	10.86	2.05	19.01
3.76	21.72	2.59	21.72	5.46	16.29	2.09	18.15
4.07	160.2	2.67	103.45	40.73	35.3	2.31	19.01
3.72	86.89	2.7	29.01	59.74	59.74	2.22	8.72
3.58	10.86	2.6	27.15	-2.72	48.88	2.41	46.16
3.81	73.31	2.58	13.58	43.45	38.01	2.70	30.53
3.821429	**80.87786**	**2.592857**	**66.27**	**20.17429**	**22.88714**	**2.516**	**28.055**

4.00pm

v1	i1	v2	i2a	i2b	i2c	v3	i3
3.58	19.01	2.57	65.17	19.01	-27.15	2.19	46.16
3.73	13.58	2.56	100.47	8.15	16.29	2.81	21.72
3.77	62.45	2.57	103.18	10.86	13.58	2.45	19.01
3.88	225.84	2.56	16.29	16.29	8.15	2.64	24.31
3.78	203.18	2.55	8.15	8.15	10.86	1.81	32.72
3.89	103.18	2.69	5.43	10.86	-5.46	2.99	28.15
3.59	97.75	2.62	2.72	8.15	32.58	2.35	21.72
3.79	73.31	2.6	86.89	8.15	27.15	2.69	18.15
3.63	160.2	2.69	5.43	40.73	19.01	2.81	19.01
4.19	70.6	2.6	16.29	13.58	10.86	2.22	8.72
3.71	214.51	2.65	5.43	54.31	43.45	2.41	36.16
3.69	16.29	2.59	86.89	24.44	5.43	2.70	21.72
3.71	19.01	2.61	78.74	13.58	27.15	2.71	19.01
3.94	19.01	2.72	114.04	32.58	5.43	2.64	4.31
3.71	27.15	2.64	10.86	-5.43	13.58	2.45	20.01
3.69	152.06	2.67	46.16	54.31	78.74	1.99	58.4
3.793594	**86.7838**	**2.618143**	**51.81258**	**20.01078**	**30.09539**	**2.55**	**28.61**

5.00pm

V1	I1	v2	i2a	i2b	i2c	v3	i3
3.68	0.59	2.73	2.75	10.75	-27.15	2.28	21.72
3.77	1.33	2.62	5.43	5.43	16.29	1.95	19.01
3.80	2.58	2.61	103.18	8.15	13.58	2.59	54.31
3.66	2.09	2.62	16.29	29.87	8.15	2.48	32.72
3.58	2.11	2.62	8.15	5.46	19.01	1.83	18.15
3.73	2.14	2.67	5.43	40.73	10.86	2.39	19.01
3.77	2.1	2.66	2.72	19.01	43.45	2.79	8.72
3.53	2.24	2.73	86.89	8.15	5.43	1.82	46.16
3.44	1.33	2.62	5.43	10.86	27.15	2.31	21.72
3.83	2.12	2.68	16.29	16.29	5.43	2.43	19.01
3.58	1.99	2.67	5.43	8.15	8.15	2.86	54.31
3.71	2.72	2.63	86.89	16.29	10.86	2.83	8.72
3.94	2.1	2.65	95.21	43.45	-5.46	2.43	46.16
3.71	2.28	2.59	12.14	54.31	32.58	2.33	21.72
3.69	2.22	2.59	12.14	22.56	27.15	2.39	54.31
3.61	**1.996**	**2.65**	**35.26**	**19.47**	**13.032**	**2.447333**	**29.71667**

6.00pm

V1	I1	v2	i2a	i2b	i2c	v3	i3
1.22	1.04	2.47	2.72	-21.72	32.58	1.83	21.72
1.09	1.98	2.42	-5.43	8.15	27.15	2.39	18.15
1.19	2.27	2.41	2.72	-16.29	19.01	1.79	19.01
1.18	2.12	2.48	5.43	-19.01	10.86	2.82	8.72
1.17	1.99	2.32	0.59	2.72	43.45	2.45	46.16
1.17	2.72	2.24	1.33	-35.43	2.72	1.66	21.72
1.12	2.72	2.33	0.99	-28.15	13.58	1.97	19.01
1.08	2.43	2.43	0.98	10.86	5.43	1.92	54.31
1.18	0.59	2.23	0.00	-22.72	10.86	2.13	32.72
1.18	1.33	2.21	-5.43	-62.72	24.44	1.83	28.15
1.19	0.99	2.22	2.72	-25.43	8.15	2.13	21.72
1.2	0.98	2.22	5.43	8.15	13.58	2.34	18.15
1.21	2.41	2.13	0.59	-16.29	19.01	2.33	19.01
1.11	2.43	2.19	1.33	5.43	43.45	2.39	8.72
1.11	0.59	2.2	0.99	-28.15	33.01	2.41	8.88
1.16	**1.745**	**2.39167**	**0.99**	**-16.04**	**20.485**	**2.380625**	**22.79313**

7.00pm

V1	I1	v2	i2a	i2b	i2c	v3	i3
1.18	2.72	1.98	2.72	-2.72	21.72	2.48	40.73
1.18	5.43	1.86	1.06	-13.58	5.43	2.39	28.15
1.19	-8.15	1.93	-2.72	-8.15	27.15	2.36	21.72
1.2	2.72	1.97	-8.15	-10.86	38.01	1.82	21.72
1.21	10.86	1.95	-1.13	-16.29	24.44	2.45	18.15
1.11	5.43	1.95	-5.43	-8.15	-5.43	1.66	19.01
1.22	2.72	1.76	-2.72	-16.29	27.15	1.97	8.72
1.22	10.86	1.88	0.01	-43.45	29.87	1.92	46.16
1.21	-2.72	1.74	-19.01	8.15	32.58	2.13	21.72
1.2	-8.15	1.72	2.72	-40.73	44.72	1.83	19.01
1.19	-2.72	1.69	-5.43	-10.86	2.72	2.13	54.31
1.18	16.29	1.66	2.72	-16.29	13.58	2.34	32.72
1.17	5.43	1.64	-5.43	8.15	5.43	2.33	18.15
1.21	8.16	1.62	0.00	-16.29	10.86	2.43	19.01
1.11	5.43	1.65	0.00	-43.45	38.01	2.33	8.72
1.180625	**3.620667**	**1.802**	**-2.72**	**-15.387**	**26.801**	**2.171333**	**25.2**

8.00pm

V1	I1	v2	i2a	i2b	i2c	v3	i3
0.77	16.29	1.64	0.98	-35.43	24.44	2.38	20.52
0.85	-5.43	1.59	0.00	-28.15	8.15	2.36	12.72
0.51	10.86	1.71	-1.13	-40.73	13.58	2.33	28.15
0.75	-5.43	1.62	-5.43	-16.29	19.01	2.43	18.15
0.86	10.86	1.66	-2.72	5.43	21.72	2.43	29.01
0.6	5.43	1.59	0.01	8.15	5.43	2.36	18.15
0.51	-8.15	1.66	0.01	-29.87	27.15	2.44	19.01
0.45	2.72	1.62	0.13	-22.72	38.01	2.36	22.72
0.77	-8.15	1.63	-2.72	-62.72	19.53	2.39	28.15
0.45	16.29	1.61	-8.15	-25.43	10.22	2.36	33.2
0.78	-5.43	1.61	0.99	8.15	32.58	2.92	26.31
0.52	10.86	1.58	0.98	-28.15	27.15	2.13	26.16
0.84	4.53	1.59	0.00	-40.73	19.01	2.83	21.72
0.71	13.58	1.59	-5.43	-16.29	10.86	2.13	10.1
0.74	-8.15	1.57	0.00	-10.58	43.45	2.34	10.56
0.680625	**3.378667**	**1.61875**	**-1.49**	**-22.36**	**21.353**	**2.384375**	**21.642**

9.00pm

V1	I1	v2	i2a	i2b	i2c	v3	i3
0.86	0.99	2.21	-5.43	-35.43	24.44	2.36	18.15
0.71	0.98	2.22	2.72	-28.15	8.15	2.38	19.01
0.66	5.43	2.22	5.43	-40.73	24.44	2.21	32.72
0.78	-8.15	2.13	0.59	-16.29	-5.43	2.17	28.15
0.75	2.72	2.22	1.33	5.43	27.15	2.37	18.15
0.79	-8.15	2.18	0.99	8.15	24.44	1.79	24.6
0.44	16.29	1.98	-2.72	-29.87	18.15	2.07	13.22
0.84	-5.43	1.99	-8.15	-22.72	13.58	2.05	26.31
0.75	10.86	1.97	-1.13	-62.72	19.01	1.8	16.16
0.84	4.53	1.99	-5.43	-25.43	20.55	2.43	21.72
0.72	13.58	2.04	0.59	8.15	30.61	2.3	19.01
0.6	-2.72	2.13	1.33	-28.15	-5.46	1.93	29.01
0.72	16.29	2.09	0.99	-40.73	32.58	2.36	30.53
0.6	5.43	2.11	0.98	-16.29	10.86	2.38	21.72
0.82	8.16	2.00	0.59	-28.15	43.45	2.33	8.88
0.725333	**2.606**	**2.09125**	**-0.5273**	**-23.528**	**19.10133**	**2.1531**	**21.82267**