Photovoltaic Low Voltage DC-DC Buck Converter for Maximum Power Point Tracker (MPPT)

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Abstract
Utilization of renewable energy is a good potential approach to overcome environmental issues. Clean energy sources such as solar arrays, wind generators and others have drawn wide interest in both research and industry fields. However, solar energy attracts much attention because it can be used for powering varieties of appliances. Conversion of solar energy into electricity has no running cost due to freely available, improves generation of electricity, and reduces pollution due to fossil fuels. The efficient conversion of photovoltaic (PV) energy is feasible with Maximum point Tracking (MPPT) algorithm and a DC-DC converter. A MPPT is employed for extracting the utmost power from the solar PV module and transferring that power to the load. The voltage available from the PV module is variable and to get a stable voltage from solar panels, DC-DC converters are required for constant power production. This study used a synchronous buck converter as an interface between PV module and the load. The buck converter functions as a solar charge controller to step down the PV voltage to charge a 12V lead acid battery. The analysis was performed by collecting the voltage and current data from PV panel in different atmospheric conditions and the output voltage gain from buck converter. The efficiency of proposed buck converter is compared with the previous proposed traditional buck converter. The analysis shows that the efficiency of the proposed buck converter is 91.9% and it is improved compared to the traditional buck converter.

Keywords: Photovoltaic, DC-DC buck converter, MPPT

1.0 Introduction

Nowadays, environmental problem is a common issue. Utilization of renewable energy is a good potential approach to overcome the problem. As the times go by, the demand of power is increasing progressively and on the opposing the resources used for power generation are becoming insufficient. Apart from the reason of insufficient resources, the approaches used for power generation by fossil fuels are not even environment friendly and they dedicate an ultimate reason for global warming and greenhouse effect. Therefore, clean energy sources such as solar arrays, wind generators and others have drawn wide attention in both research and industry fields. However, solar energy attracts much attention because it can be used for powering varieties of appliances. Conversion of solar energy into electricity has no running cost due to freely available, improves generation of electricity, and reduces pollution due to fossil fuels.

Photovoltaic (PV) are best known as a technique for generating electric power by using solar cells to transform energy from the sun into a current of electrons. The PV effect states to photons of light exciting electrons into a higher state of energy. It allows them to perform as a charge carrier for an electric current. The PV effect was first experimental by Alexandre-Edmond Becquerel in 1839 (Botti & Vidal, 2013). The term PV indicates the unbiased operating mode of a photodiode. The mode operating in which current through the device is entirely due to the transduced light energy. Practically all PV devices are some types of photodiodes.

The output power of solar panel depends on solar temperature, irradiance, and the load impedance. The load impedance is depending on application, while the solar irradiance and temperature are dynamic. Therefore, the solar panel required an online algorithm which dynamically computes the operating point. The efficient conversion of PV energy is possible with a Maximum Power Point Tracking (MPPT) algorithm and a DC-DC converter. A MPPT is used for extracting the maximum power from the solar PV module and transferring that power to the load (Pakkiraiah & Sukumar, 2016). There are several MPPT algorithms such as Perturb and Observe (P&O), Incremental Conductance, Fuzzy Logic Control, Neural Network, and others. A DC-DC converter perform as an interface between the load and PV module as it transfers maximum power from the PV module to the load. The voltage which is available from the PV module is variable and to obtain a stable voltage from solar panels, DC-DC converters are required for constant power production.

There are mainly three converters namely Buck, Boost and Buck-Boost converters which can be used for either increasing or decreasing the voltage. However, this project used a synchronous buck converter as an interface between PV module and the load. The buck converter is a step-down DC-DC converter with an output voltage is lower than the input. The operation of the buck converter is simple, with an inductor and two switches that control the inductor. It rotates between connecting the inductor to voltage source to store energy in the inductor and discharging the inductor into the load.

The paper is organized as follows. In Section 2.0, the problem statement of the study is presented. The objective of the study is then stated in Section 3.0. The literature review and methodology are presented in Section 4.0 and 5.0. Then, in Section 6.0, results and discussion are provided to verify study. Finally, conclusions of this study are given in Section 7.0.

2.0 Problem Statement

PV is made up of solar cells which are wired together into a module. An amount of these cells can be assembled to produce a much higher voltage. The variation of the PV panel power is due to the change of irradiation and temperature because of climatic change is analyzed by developing the mathematical model of PV panel (Nayak et al., 2017). The output voltage acquired from the PV panel is a DC voltage. For a low power application, a DC-DC converter is employed to step-up or to step-down the output DC voltage according to the load requirements. The main function of DC-DC converter in PV system is as intermediate power processor that changes the voltage and current levels so that PV array able to extract maximum power (Choudhary & Saxena, 2014). However, total conversion efficiency is very low. The load impedance is depending on application, while the solar irradiance and temperature are dynamic. Therefore, the solar panel required an online algorithm which dynamically computes the operating point. The efficient conversion of PV energy is possible with MPPT algorithm and a DC-DC converter. The conventional buck converter produced low efficiency due to conduction and switching losses of the diode (Ali et al., 2014). Therefore, a synchronous buck converter is proposed by replacing the diode with a second MOSFET to increase the efficiency of the converter.

3.0 Objectives

The purpose of this study is to analyze an Arduino-based Photovoltaic (PV) with low voltage DC-DC synchronous buck converter. The analysis is to identify the maximum power point voltage (Vmpp) of the PV module at various atmospheric conditions, to calculate the efficiency of the PV panel and the synchronous buck converter, and to compare the proposed buck converter with the conventional buck converter.

4.0 Literature Review

Ba et al. (2018) proposed a comparative study of different DC-DC converter for ideal PV system. The paper showed when and how to choose the type of DC-DC converter for optimization process. The study observed that the DC-DC converter type can be specified in the optimization process of a standalone PV system. The Boost converter type is used if the direct coupling voltages responses are higher than MPP responses. While a Buck converter type is applied if the direct coupling voltages are lower than the MPP. Otherwise, Buck-Boost converter type is used to increase and decrease the voltage. The paper concluded that the Buck-Boost converter and the Bay-pass diode for photovoltaic cell are two essential elements in order to have a more effective and better robust MPPT optimization in PV system.

PV cells convert sun light into electricity, but it has disadvantages in terms of cost, intermittency, and low photo-conversion efficiency. The current-voltage characteristics of the PV cells depend on temperature and solar insolation level, which lead to the variation of the maximum power point (MPP). Thus, Salman et al. (2018) designed a microcontroller-based battery charge controller with MPPT for harvesting the maximum power obtainable from the PV system under given insolation and temperature conditions. It is designed to improve the PV system efficiency and increase the lifetime of the battery. The study stated that among different MPPT techniques, perturb and observe (P&O) technique offers excellent results and thus is used. This study involves the design of MPPT charge controller using DC-DC buck converter and a microcontroller. A prototype MPPT charge controller is analyzed with a 200W PV panel and lead acid battery. The results indicated that the designed MPPT controller increases the efficiency of the PV panel when compared to conventional charge controllers.

The selection of DC-DC converter required to track the maximum power of PV array to enhance the utilization of solar power (Nayak et al., 2017). This study proposed a PV system mostly used for cooking and heating applications to simplify the model and reduce the maintenance cost. Since the battery has not been used, DC-DC converter selection is an important factor of the PV system in standalone applications. The proposed system is designated based on maximum power transfer theorem which is dependent relative on load resistance. Different load resistance is measured for maximum power point tracking (MPPT) with different converter topologies. It has been observed that buck-boost converter is the most suitable for any load resistance connected in the PV system. It also observed that malfunction of tracking of maximum power occurs if DC-DC converter is not matched with the load resistance. From the study, it is obvious that a buck-boost converter is suitable for tracking maximum power for any load resistance connected to the PV system. However, the Buck converter is used when the load resistance is smaller than the internal resistance of PV array. While Boost converter is used in the vice versa condition. The study concluded that the selection of voltage or current as the output of the MPP tracker is an important element for generating pulses to control the DC-DC converter, or else the system becomes unstable.

Ramki and Tripathy (2015) reviewed an analysis of different DC-DC converter. The study discussed the analysis in terms of efficiency, complexity, and computational time. An Incremental Conductance (INC) MPPT algorithm is applied to evaluate the performance of every single DC-DC converter. The study found that the buck-boost DC-DC converter is more suitable for MPPT. The buck-boost converter also can be used for grid integration via an inverter by increasing the PV voltage to the desired level. The analysis simulated with incremental conductance MPPT algorithm. The power obtained from the PV array under high resistance is more than the resistance at MPP. Under this situation, the buck converter fails to obtain maximum power. However, other converters extracted almost the maximum power. Among the DC-DC converter, boost converter works better. The performance of various DC-DC converter under low resistance value is lower than the resistance at MPP. In this situation, buck converter works better.

In another study, Sanjeevikumar et al. (2015) presented a topology of PV power generation system with simple MPPT algorithm in voltage operating mode. The power circuit involves of high output voltage DC-DC boost converter which increases the output of PV panel. The study investigated a DC-DC boost converter to overcome the limitation of traditional DC-DC boost converters. The traditional DC-DC boost converters has a low efficiency, output limitation, and involve more sensors with complicated control algorithm. The DC-DC boost converter proposed by the researchers applied with an additional parasitic component to offer high output voltages for increasing the PV power generation. The proposed power system circuit significantly improves the high output voltage by a simple MPPT closed loop proportional-integral (P-I) controller. It involves only two sensors for feedback needs. The complete algorithm is developed in MATLAB software. The study concluded that the power circuit with DC-DC boost converter produced a higher performance of the output voltage compared to the conventional DC-DC boost converter. Other than that, the power circuit overcomes the parasitic effects and decreases ripples at the output waveforms.

A PV system associated with a buck converter and IC algorithm for extracting maximum power at various environmental conditions is proposed by Choudhary & Saxena (2014). The function of DC-DC converter in PV system is like an intermediate power processor that changes the current and voltage levels where the maximum power can be extracted from the PV panel. By changing the voltage and current level, the system converts a given fixed load to a variable load. The results achieved at different environmental conditions are found to be acceptable. Incremental conductance MPPT algorithm responds in very fast manner and the accuracy is higher as it reaches to a steady state very quickly.

5.0 Methodology

Figure 1 illustrates the block diagram of the system. The voltage sensor senses the voltage coming from the PV panel and from the battery. ACS712 is a current sensor used to sense current from the PV panel. Voltage and current sensor senses by the voltage and current sensor will be feeds to the Arduino. The buck converter functions as a solar charge controller to step down the PV voltage to charge a 12V lead acid battery. The load MOSFET used to control the load. During night, the load MOSFET will ON to enable the load. There are three LED represents as an indicator of the battery state of charge. It indicates whether the battery is fully charge, normal voltage, or low voltage. The LCD displays the parameter of the PV panel, battery parameter, and load status.

The signal involved in the study is power signal and control signal. As shown in Figure 1, the power signal labelled with red line, while the control signal labelled with blue line. The power signal present at two conditions.

i. PV panel → Fuse → Current Sensor → MOSFET Q_1, Q_2, and Q_3 → Inductor → Battery
ii. Battery → Fuse → Load → MOSFET Q_4

The control signals present at two conditions as well.

iii. Signal from different sensors to the Arduino
iv. Signals from the Arduino to the MOSFET drivers, LED, and LCD display

The voltage sensor senses the solar panel and battery voltage. Then, it feed the output voltage to Arduino Analog pin A0 and pin A2. The voltage sensor is implemented by using a voltage divider circuits which is R1, R2, and R3, R4. Arduino's Analog inputs can be used to measure a DC voltage between a range of 0 and 5V. It can be measured by using the standard 5V analog reference voltage. However, the range can be increased by using two resistors to build a voltage divider. The used of the voltage divider is to decrease the voltage being measured to fix the range of the Arduino Analog inputs. Equation 1 and 2 shows the relationship between input voltage and output voltage by considering voltage divider resistance circuit.

$$V_{out} = \frac{R_2}{R_1+R_2} \times V_{in} \qquad \text{(Eq. 1)}$$

$$V_{in} = \frac{R_1+R_2}{R_1} \times V_{out} \qquad \text{(Eq. 2)}$$

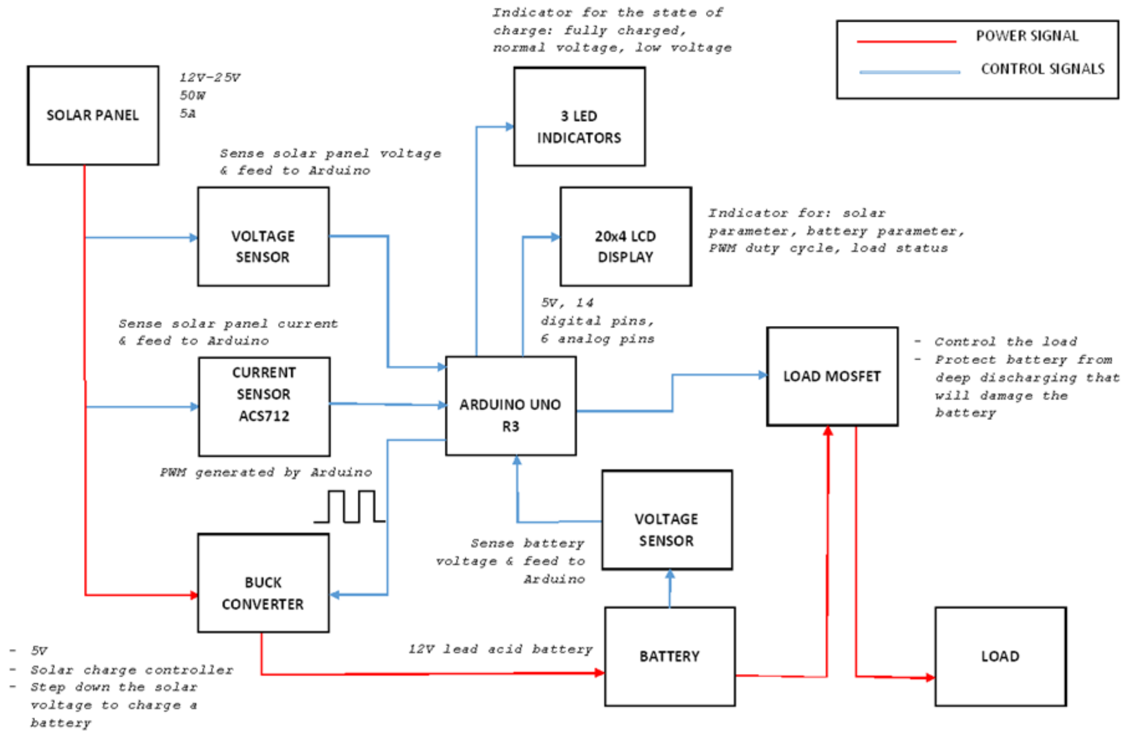

Figure 1: Block diagram of the system

In this study, I used a Hall Effect current sensor, ACS 712. It is used for measuring the current. The current of the current sensor is 5A. The ACS 712 sensor sense and read the current value and convert it into a suitable voltage value. The value that links the current and voltage measurements is called sensitivity. The ACS 712 sensitivity is 185mV/A where the sensor can measure a positive and negative current that range between -5A to 5A. It needs a 5V power supply and the middle sensing voltage is 2.5V when there is no current.

The core component of a buck converter is a MOSFET. It is important to choose a right MOSFET according to the circuit operation. There are several basic parameters for selecting a right MOSFET.

i. Voltage Rating – V_{ds} of a MOSFET should be larger than 20% or higher than the rated voltage.
ii. Current Rating – I_{ds} of a MOSFET should be larger than 20% or higher than the rated current.
iii. ON Resistance (R_{ds} ON) – Select a resistor with low ON resistance (R_{on})
iv. Conduction Loss – Depends on R_{ds} (ON) and the duty cycle and keep the minimum conduction loss.
v. Switching Loss – It occurs during transition phase. It depends on voltage, current, and switching frequency. Try to maintain it minimum.

In the study, the maximum voltage of PV panel is 11.88V and the maximum current is 0.95A. I have chosen IRFZ44N MOSFET. According to the datasheet, the MOSFET have enough value of V_{ds} and I_{ds}. It also has a low R_{ds} (ON) value.

A MOSFET driver allows a low current digital output signal from an Arduino to trigger the MOSFET gate. It produces a high current drive input for the MOSFET gate. MOSFET have a large stray capacitance between the gate and the other terminals. It must be charged or discharged each time the MOSFET is switched ON or OFF. A transistor requires a particular gate voltage to switch ON. The gate capacitor must be charged to the required gate voltage for transistor to be ON. To OFF the transistor, the charge must be dissipated.

When a transistor is switched ON or OFF, it does not immediately switch from a non-conducting to a conducting state. It may transiently support both high voltage and conduct a high current. When gate current is applied to a transistor, a certain amount of heat is generated which can burn the transistor. Therefore, it is important to keep the switching time short to minimize a switching loss. The circuit that drives the gate terminal should be capable of supplying a practical current so the stray capacitance can be charged quickly. The best way to do this is to use a MOSFET driver. I am using an IR2104 half bridge driver. The driver takes the PWM from the Arduino and drives the two outputs for High and Low Side MOSFET.

The Arduino is a microcontroller board based on the ATmega328. It has 14 digital input and output pins, 6 of the pins can be used as PWM outputs, 6 analog inputs, a USB connection, a 16 MHz ceramic resonator, an ICSP header, a power jack, and a reset button. It contains everything needed to support the microcontroller. It can be connected to a computer with a USB cable or power it with an AC-DC adapter or battery to get started. In the study, I chose an Arduino UNO R3 as a microcontroller. The Arduino UNO R3 differs from all boards because it does not use the FTDI USB-to-serial driver chip. The specification of Arduino UNO R3 shown in Table 1.

Table 1: Specification of Arduino UNO R3

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)
Clock Speed	16 MHz
Length	68.6 mm
Width	53.4 mm
Weight	25 g

In this study, an I2C LCD display is chosen. It is a 20x4 char LCD used to monitor the PV panel, battery, and load parameters. It is chosen because of its simplicity compared to basic LCD display. It only needs four wires to interface with the Arduino. It has a V_{cc}, GND, SDA, and SCL terminals. The

LCD display connected with a push switch to control the LCD back light. Back light of an LCD display consumes a lot of power. Then, the push switch will control the back light. By default, the back light will be in OFF condition. If the users press the switch, the back light will ON for 15 seconds before it goes OFF. The LCD has been programmed to display in three columns. Column 1 displays the PV panel voltage, current, and power. Column 2 displays battery voltage, and charger state. Column 3 displays PWM duty cycle, and load status.

LEDs are used to indicate the level of battery voltage. I used three different colors of LEDs. Red, green, and yellow LEDs. Red LED indicates a low voltage, green indicate normal voltage, and yellow LED indicate fully charged battery. The range of the battery voltage is programmed as follows.

i. Fully charged battery (Yellow) – Vbat > 14.1V
ii. Normal voltage (Green) – 11.9V < Vbat < 14.1V
iii. Low voltage (Red) – Vbat < 11.8V

The schematic diagram of the system is shown in Figure 2. Power coming from the PV panel and the voltage sensor sense the PV voltage. The output goes to Arduino pin A0. The power from PV panel cannot goes directly to the battery until MOSFET Q1 is ON. The switching of Q1 is done by PWM signals from Arduino. The charge controller will check the PV panel voltage and compare it with the battery voltage. If the PV voltage is higher than the battery voltage, then Arduino will starts sending PWM signals to MOSFET Q1 to charge the battery. If the PV voltages lower than the battery voltage, PWM signals will not send by Arduino. When Q1 is ON, power goes to the battery and charging process starts. MOSFET Q5 used to drive the load. During night, a pulse will be sent to the MOSFET Q2 to enable the load. If the battery was too low, the load will be disconnected to prevent deep discharging of the battery.

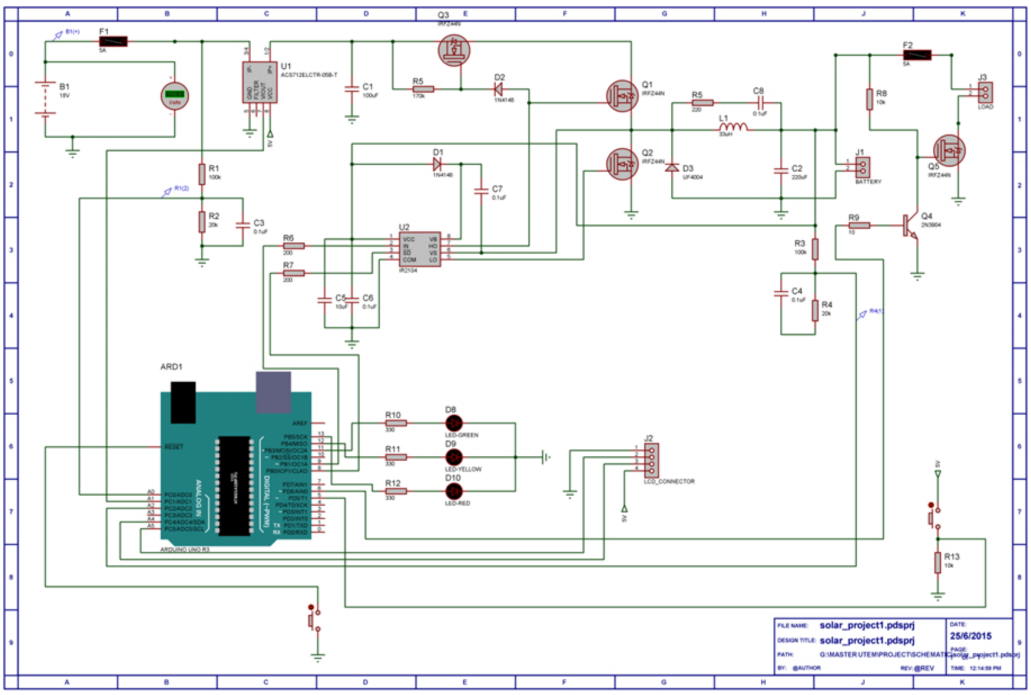

Figure 2: Schematic diagram of the system

The input power connector to the PV panel is the terminal JP1 and terminal JP2 is the output connector to the battery. The third terminal JP3 is the connection for the load. F1 and F2 are the 5A safety fuses for overcurrent protection.

The buck converter is made up of a synchronous MOSFET switches, Q_2 and Q_3. The energy storage devices consist of inductor L_1 and capacitors C_1 and C_2. The inductor smooths the switching current and C_2 smooth the output voltage. Capacitor C_8 and R_6 are snubber network. It is used to cut down the ringing of the inductor voltage produced by the inductor switching current. The third MOSFET, Q_1 is inserted to allow the system to prevent the battery power from flowing back into the PV panel at night. Q_1 turns ON when Q_2 is ON from voltage through D_1. R_1 drains the voltage off the gate of Q_1 so it turns OFF when Q_2 turns OFF.

The diode D_3 (UF4007) is an ultra-fast diode. It will start conducting current before Q_3 turns ON. It is used to make the converter more effective. The IC IR2104 is a half bridge MOSFET gate driver. It runs the high and low side MOSFET using the PWM signal from the pin D9 Arduino. It can be closed with the control signal of pin D8 Arduino from the Arduino on pin 3. D_2 and C_7 are element of the bootstrap circuit. It produces the high side gate drive voltage for Q_1 and Q_2. The Arduino software keep on track of the PWM duty cycle and never lets 100% or always on. It controls the PWM duty cycle at 99.9% to keep the charge working.

There are two voltage divider circuits involving of R_1, R_2 and R_3, R_4 resistors to determine the PV panel and battery voltages. The output from the voltage divider feeds the voltage signal to pin A0 and pin A2 of Arduino. The ceramic capacitors C_3 and C_4 are applied to remove high frequency spikes. The MOSFET Q_4 is used to monitor the load. The driver for the MOSFET is comprises of a transistor and R_9, R_{10} resistors. The diode D_4 and D_5 are TVS diode. It is applied for over voltage protection from PV panel and load. The current sensor ACS712 senses the current from the PV panel and feeds it to pin A1 of Arduino.

The three LEDs are attached to the digital pins of the Arduino and operate as an output interface to display the battery charging state. Reset switch is used if the code gets stuck. The back light switch is to control the back light of LCD display.

Arduino version 8 software is chosen to write and simulate the coding of the system. Firstly, the charge controller will check the PV panel voltage and compare with the battery voltage. If it is the PV panel voltage is greater than the battery voltage, the Arduino will starts sending PWM signals to the Q_1 MOSFET to charge the battery. When the PV panel voltage is lower than the battery voltage, the PWM signals will not be send by the Arduino.

Then, the Arduino will check the battery voltage. If the battery voltage was below 14.1V, the battery will be charged in boost mode. It means that the battery will be charged with maximum amperage. The boost mode of charging will be done by sending PWM signals with 95% of duty cycle. When the battery voltage reaches above 11.9V, the charging mode will turn as absorption mode from boost mode. It is done by changing the duty cycle from 95% to 10%. The absorption mode will keep the battery fully charged. A pulse will be sent to the Q_2 load MOSFET to enable the load during night. If the battery was too low and reaches to 11.8V, the load will be disconnected to prevent deep discharge of the battery.

6.0 Result and Discussion

Data collected from various atmospheric conditions in order to obtain a value of temperature, voltage, current, and power of the PV panel. Data collected during sunny day, cloudy day, and when raining. Table 2 and Table 3 shows a data collected on 3rd and 4th of January 2018 during sunny day. From the table, it is clearly shown that during both days the temperature was between 27°C to 30°C. On the 3rd January, the maximum voltage of PV panel, V_{mpp} was 16.50V and the maximum current produced was 0.80A. During that day, the maximum power produced by the PV panel was 6.71W. When the PV panel produced the highest power, the V_{mpp} at that time was 11.0V and the current was 0.61A. On 4th January, the V_{mpp} was 16.50V and the maximum current produced was 0.72A. During that day, the maximum power produced by the PV panel was 5.86W when. At the highest power produced, the V_{mpp} at that time was 9.77V and the current was 0.60A.

Table 2: Data on 3rd January 2016 during sunny day

Time	Temperature (°C)	Voltage, V (V)	Current, I (A)	Power, P (W)
0800	27	0.00	0.80	0.00
0815	27	1.90	0.78	1.48
0830	27	2.50	0.77	1.93
0845	27	3.30	0.75	2.48
0900	28	5.00	0.72	3.60
0930	28	5.80	0.65	3.77
0945	28	6.00	0.65	3.90
1000	28	7.00	0.65	4.55
1010	29	8.90	0.63	5.61
1025	29	9.80	0.62	6.08
1030	29	10.56	0.62	6.55
1045	30	11.00	0.61	6.71
1100	30	12.70	0.49	6.22
1115	30	13.70	0.44	6.03
1120	30	14.00	0.42	5.88
1130	30	14.50	0.39	5.66
1140	30	15.10	0.35	5.29
1145	30	15.70	0.27	4.24
1150	30	15.90	0.21	3.34
1200	30	16.00	0.15	2.40
1205	30	16.30	0.04	0.65
1210	30	16.50	0.01	0.17

Table 3: Data on 4th January 2016 during sunny day

Time	Temperature (°C)	Voltage, V (V)	Current, I (A)	Power, P (W)
0800	27	0.00	0.72	0.00
0830	27	0.85	0.69	0.59
0845	28	3.90	0.68	2.65
0900	29	4.70	0.66	3.10
0930	29	6.79	0.65	4.41
1000	30	9.77	0.60	5.86
1015	30	11.00	0.50	5.50
1045	30	12.80	0.44	5.63
1100	30	13.77	0.36	4.96
1115	30	14.49	0.29	4.20
1125	30	15.00	0.25	3.75
1140	30	15.80	0.21	3.32
1205	30	16.10	0.16	2.58
1240	30	16.35	0.12	1.96
1300	30	16.44	0.09	1.48
1315	30	16.50	0.00	0.00

During cloudy day, the data was collected on 6th January 2016. The data represented in Table 4. On that day, the sun was not so bright with a temperature between 25°C to 27°C. The maximum power produced by the PV panel is 3.99V with a voltage and current of 7.67V and 0.52A. During that day, the V_{mpp} that extracted by the PV panel is 11.89V.

Table 4: Data on 6th January 2016 during cloudy day

Time	Temperature (°C)	Voltage, V (V)	Current, I (A)	Power, P (W)
0800	25	0.00	0.69	0.00
0830	25	0.09	0.67	0.06
0900	25	1.93	0.64	1.24
1000	25	3.00	0.62	1.86
1030	26	5.33	0.57	3.04
1100	26	5.89	0.56	3.30
1115	26	7.00	0.53	3.71
1145	26	7.67	0.52	3.99
1200	26.5	8.00	0.47	3.76
1245	26.5	8.99	0.44	3.96
1300	26.5	9.09	0.38	3.45
1330	26.5	10.55	0.33	3.48
1345	26.5	10.89	0.28	3.05
1400	26.5	11.00	0.24	2.64
1415	27	11.34	0.11	1.25
1430	27	11.89	0.00	0.00

The PV panel able to extract power when there is no sun light or during rainy day. As shown in Table 5, the data are collected on 7th January 2016 when there is raining. From the table, it shows that the V_{mpp} that can be extracted by PV panel during rainy day is 2.75V. Even though the V_{mpp} is low, the PV panel still extract power from the environment. The maximum power produced by the PV panel during that day is 1.29W with the voltage and current of 2.75V and 0.47A.

The data collected from the various atmospheric conditions above can be summarizing as illustrated in Table 6. From the collected data, the efficiency and the total loss of PV panel can be calculated.

$$\text{PV panel efficiency} = \frac{V_{out}}{V_{in}} \, x \, 100\% \qquad (3)$$

$$\text{Total loss} = (I \, x \, V_{bat}) - 10W \qquad (4)$$

Table 5: Data on 7th January 2016 during rainy day

Time	Temperature (°C)	Voltage, V (V)	Current, I	Power, P (W)
1400	27	0.00	0.70	0.00
1410	27	0.55	0.69	0.38
1425	26.5	1.12	0.55	0.62
1445	26	1.14	0.55	0.63
1455	26	1.20	0.55	0.66
1505	25.5	1.25	0.55	0.69
1515	25.5	1.40	0.49	0.69
1530	25	1.90	0.49	0.93
1540	25	2.53	0.47	1.19
1555	25	2.75	0.47	1.29

Table 6: Summary of data collected from various atmospheric conditions

Date	Weather	Vmpp (V)	Power (W)	Temperature (°C)	PV panel efficiency (%)	Total loss (W)
03/01/2016	Sunny	11.0	6.71	30	92.6	2.68
04/01/2016	Sunny	9.77	5.86	30	82.2	2.8
06/01/2016	Cloudy	7.67	3.99	26	64.6	3.76
07/01/2016	Raining	2.75	1.29	25	23.1	4.36

The second method of analysis is to compare the proposed buck converter with the previous conventional buck converter. For 10W PV panel, an assumption of conventional buck converter and synchronous buck converter are shown in Table 7.

Table 7: Assumptions of conventional buck converter and synchronous buck converter

Conventional buck converter	Synchronous buck converter
Capacitor loss: 0.12 W	MOSFET Rectifier: 0.01 W
MOSFET Loss: 0.3 W	Input capacitor loss: 0.12 W
Diode Loss: 0.47 W	MOSFET Loss: 0.30 W
Inductor Loss: 0.15 W	Inductor Loss: 0.15 W
Output Capacitor Loss: 0.01 W	Output Capacitor Loss: 0.01 W
Total losses: 1.05 W	Total losses: 0.59 W
Efficiency: 90.5%	Efficiency: 94.4%

From Table 7, it is clearly shown that the efficiency of a synchronous buck converter is higher than a conventional buck converter. In the study, I compared the result from proposed synchronous buck converter with three previous works of conventional buck converter. Table 8 shows a result obtained from previous conventional buck converter. Thus, a result from proposed synchronous buck converter illustrated in Table 9.

Table 8: Result of conventional buck converter

Reference	Power (W)	Efficiency (%)
Microchip	10	90.5
(Satif et al., 2018)	3	87
(Altamimi & Khan, 2017)	20.06	88

Table 9: Result of proposed synchronous buck converter

Date	Weather	Power (W)	Efficiency (%)
03/01/2016	Sunny	6.71	91.9
04/01/2016	Sunny	5.86	90.9
06/01/2016	Cloudy	3.99	87.1
07/01/2016	Raining	1.29	68.6

By referring to Table 8, the highest efficiency that can be achieved with a conventional buck converter is 90.5%. According to Table 9, it is clearly shown that the proposed synchronous buck converter obtained higher efficiency compared to the conventional buck converter. The design gave an efficiency of 91.9%. The converter efficiency is calculated by using a formula.

$$\text{Converter efficiency} = \frac{P_{out}}{P_{out}+losses} \times 100\% \qquad (5)$$

The efficiency of a converter depending on the power produced. Higher power gives a better efficiency. Other than that, a high power is depending on the atmospheric temperature or solar irradiation. Higher temperature will produce a higher power that will result in high efficiency of the converter. The solar irradiation is varying throughout the day. As the solar irradiation varies, the voltage and current varies. The controller helps to sustain constant voltage and current although the solar irradiation is varying as represented in Figure 3. Temperature itself varies along with solar irradiation as illustrated in Figure 4. Although the temperature varies, the voltage and current are maintained constant with the application of the controller.

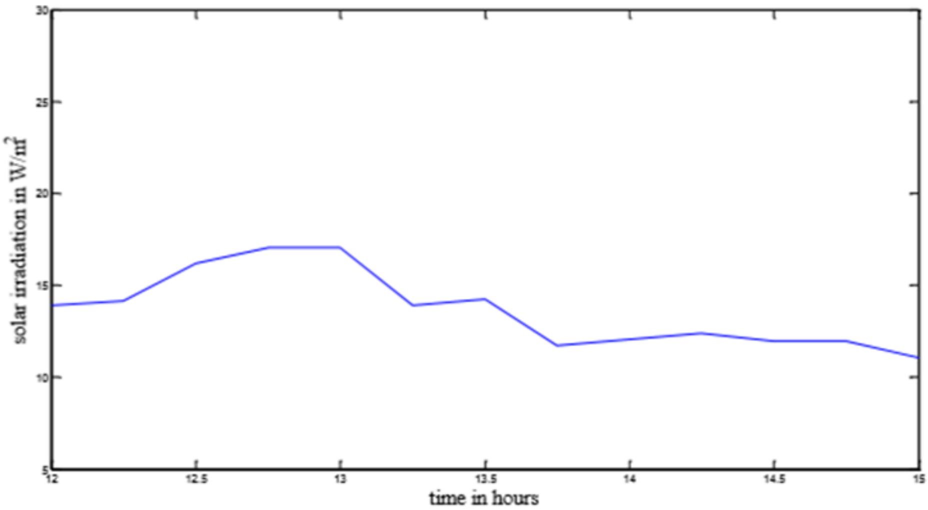

Figure 3: Solar irradiation performance

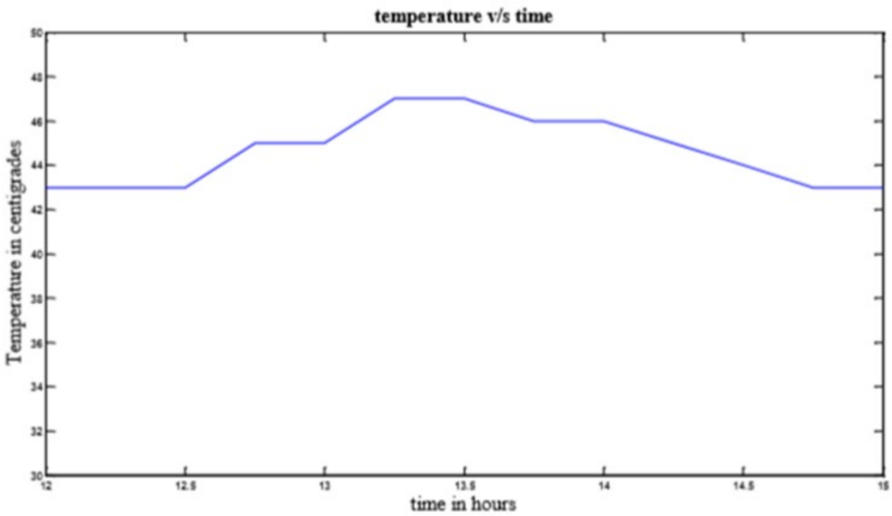

Figure 4: Temperature measurement

Figure 5 represents the comparison between conventional buck converter and synchronous buck converter topologies in terms of efficiency. Meanwhile, the voltage drops across MOSFET Q_2 in synchronous buck converter is lower than the voltage drops across the diode in conventional buck converter topology. Therefore, synchronous buck converter has low or less power dissipations. Besides that, the synchronous buck converter achieved higher efficiency compared to the conventional buck converter. From the Figure 5, it is obvious that, synchronous buck converter has a better efficiency than conventional buck converter. The efficiency of a synchronous buck converter at low load level is higher than non-synchronous buck converter. However, under a higher load level, the efficiency will depend on a duty cycle. However, the trade-off for better efficiency in synchronous buck converter is the cost for additional MOSFET used. MOSFET minimize the size of the area, but it has complex control because both switches should not operate simultaneously. Whichever simultaneous conduction could cause an overload and at the same time damage the system.

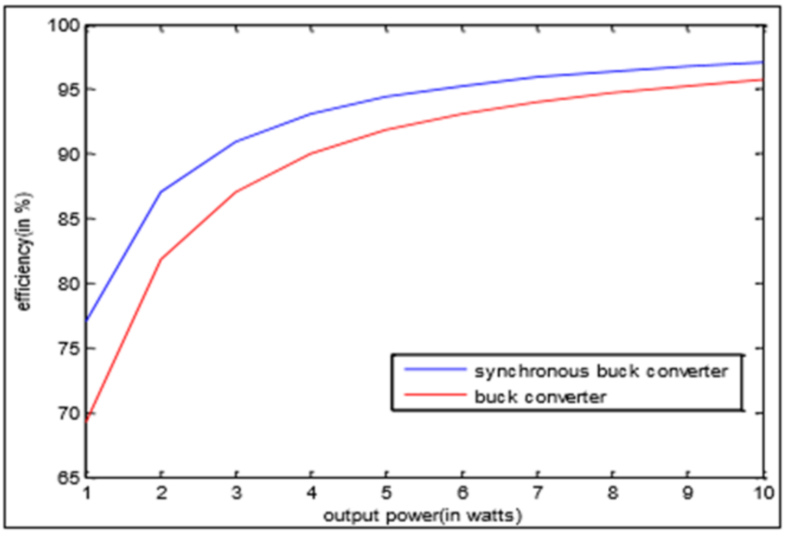

Figure 5: Efficiency comparison between conventional Buck Converter and synchronous Buck Converter

7.0 Conclusion

A PIC-based PV charge controller with DC-DC synchronous buck converter has been successfully. The PV panel is tested at various atmospheric conditions to obtain the Vmpp of the PV panel. The high efficiency synchronous buck converter controller is simulated in Proteus 8 software. The coding of Arduino UNO R3 is simulated in Arduino software. Further, the efficiency of the PV panel and the proposed controller is calculated. Moreover, a comparative study is made between previous conventional buck converter and the proposed synchronous buck converter in terms of efficiency. As a result, the proposed synchronous buck converter gives a 91.9% of efficiency and it is high in efficiency as compared to the previous conventional buck converter.

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