The Journal of Instrumentation, Automation and Systems

Embedded System Design of a Maximum Power Point Tracking Controller for Traffic Light System Powered by Photovoltaic

Riza Muhida†, Arko Djajadi‡, Nor Hilmi Mohamad§, and Ari Legowo§
†Surya University, Indonesia
‡Swiss German University, Indonesia
§International Islamic University Malaysia, Malaysia

Abstract—Photovoltaic traffic light system is a significant application of renewable energy source. The develop the system use solar energy as an alternative effort of local authority to reduce expenditure for paying fees to power supplier which the power comes from conventional energy source. Since photovoltaic modules still have relatively low conversion efficiency, an alternative control of maximum power point tracking (MPPT) method applied to the traffic light system. MPPT is intended to catch up the maximum power at daytime in order to charge the battery at the maximum rate in which the power from the battery is intended to be used at night time or cloudy day. MPPT is actually a DC-DC converter that can step up or down of voltage in order to achieve the maximum power using Pulse Width Modulation (PWM) control. Based on experiment, we obtained the used MPPT voltage of operation at 16.454 V, this value had error 2.6% compared with maximum power point voltage of PV module which is 16.9V. Based on this result the MPPT control work was successfully deliver the power from PV module to battery maximally.

Keywords—Embedded system, traffic light, photovoltaic, Maximum Power Point Tracking (MPPT).

I. Introduction

PHOTOVOLTAIC pedestrian light system is a significant application of photovoltaic source. The development of the system as an alternative for local authority to reduce expenditure for paying fees to power supplier where the power comes from electric generator. Many research institutions around the world have developed these systems as contribution to society and thus will accelerate the initiatives to adopt solar energy as an alternative source for power supply. Since the photovoltaic pedestrian light system is expensive to build, it should be operated at their maximum output power levels, using a technique control in order to work efficiently [[1]-[7]].

The main objectives in this project is to design a traffic light system powered by photovoltaic and to obtain the maximum power from PV energy output to charge the battery and to operate the system.

Corresponding author: Riza Muhida (e-mail: riza.muhida@surya.ac.id).
This paper was submitted on November 14, 2015; revised on November 21, 2015; and accepted on December 4, 2015.

II. Overall System Description

A. Diagram of Overall System

Figure 1 below shows the general layout of the electrical system. This system consists of PV module, MPPT, battery, traffic light lamp, push button switch for pedestrian, relay unit, voltage regulator and PIC microcontroller.

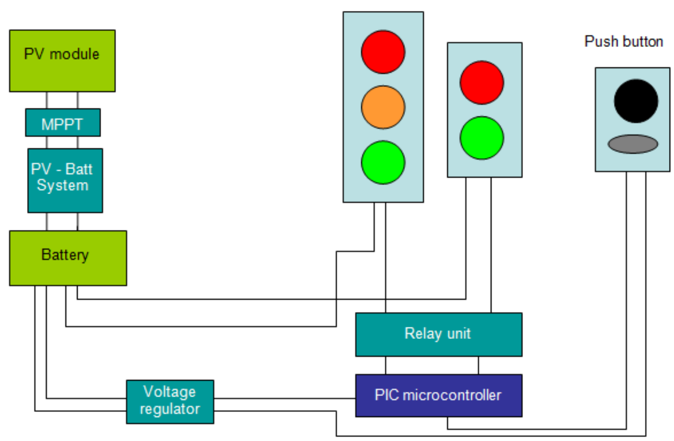

Figure 1 Schematic diagram of traffic light system powered by photovoltaic

Traffic light lamp in this experiment uses LED type; the LED-based lamps consist of an array of LED elements arranged in various patterns. When viewed from a distance, the array appears as a continuous light source. LED-based lamps have numerous advantages over incandescent lamps; among them are: much greater energy efficiency, much longer lifetime between replacements, brighter illumination with better contrast even in direct sunlight, the ability to display multiple colors and patterns from the same lamp. Individual LED elements can be enabled or disabled, and different color LEDs can be mixed in the same lamp, much faster switching. **Figure 2** shows LED traffic light that is used in this experiment.

The solar module selected for this prototype is polycrystalline silicon type. **Table I** shows characteristic of this PV module.

Figure 2 LED traffic light (left) and LED pedestrian light (right) are under testing in lab

TABLE I CHARACTERISTICS OF PV MODULE

Item	**Results**
Manufacturer	KYOCERA (Japan)
Model	KC120-1
Standard Irradiance / Cell temperature	1000 W/m^2 (AM 1.5) 25 °C
Maximum power	120 W
Voltage at maximum power	16.9 V
Current at maximum power	7.0 A
Open circuit voltage	21.5 V
Short circuit current	7.45 A

TABLE II CHARACTERISTICS OF BATTERY

Item	**Results**
Manufacturer	MSB
Model	MSL 12-40
Voltage	12 V
Capacity	40 Ah
Dimensions	195 × 165 × 170 mm
Weight	10.0 kg

Figure 3 Sealed lead acid battery

To store the electric energy from PV module we use a battery. Battery is a device that converts chemical energy contained in active materials directly into electrical energy by means of an electrochemical reaction. Batteries used in PV lighting system must be rechargeable. Characteristic of battery used in this experiment is shown in **TABLE II** and **Figure 3**.

The optimal type of battery for PV traffic light is a deep-cycle (or deep discharge) battery which most of its energy can be repeatedly drained and recharged. The maximum depth of discharge for low-maintenance (sealed) batteries is 30%. The maximum depth of discharge is a measure (in percentage) of the amount of energy that can be drained from the battery during the cycle, without damaging the battery. Batteries should generally be located in a weather resistant, non-metallic enclosure in order to prevent corrosion.

The main controller used to control the sequence of traffic light and reading battery level as well is PIC microcontroller 16F877A. In another word, we can say that it is the brain of the system. In order to give instruction to this kind of microcontroller, we need to do programming according to the sequence needed. To achieve this, we need its software (PIC C compiler) and PIC programmer kit. In this PIC, there are also module for displaying characters in LCD and reading analog input.

Basic wiring of PIC microcontroller is shown in **Figure 4**.

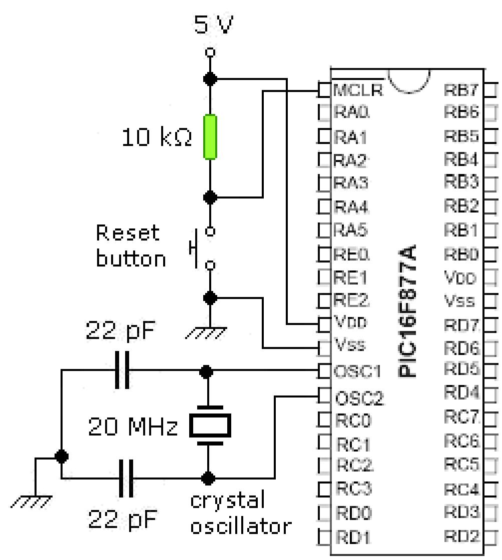

Figure 4 Basic connection of PIC microcontroller

Because PIC microcontroller (or small scale circuit) needs only small amount of voltage, voltage regulator are required to regulate the voltage coming from PV cell. In this system, we have chosen LM7805 which provides 5V supply. In order to have further stabilized voltage, the capacitors are required to filter high frequency (as shown in the following voltage regulator schematic diagram) because digital devices are very sensitive with small change of voltage. Basic wiring of regulator for PIC microcontroller is shown in **Figure 5**.

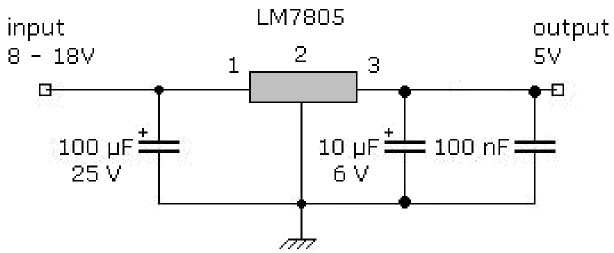

Figure 5 Basic connection of regulator for PIC microcontroller

To control voltage of Traffic light lamp using PIC microcontroller we use a relay. It is very crucial to isolate one circuit electrically from another, while still allowing the first circuit to control the second. One simple method of providing electrical isolation between two circuits is to place a relay between them, as shown in the circuit diagram in **Figure 6** below. A relay consists of a coil which may be energized by the low-voltage circuit and one or more sets of switch contacts which may be connected to the high-voltage circuit.

In this project, SPDT relays with 5V-rating have been chosen because the relay voltage is supplied by output of PIC microcontroller. Even though every output pin already produced 5V (for high state), but it is still insufficient to energize the relay due to the low current output. Therefore, transistors are required to amplify the current for energizing the relays.

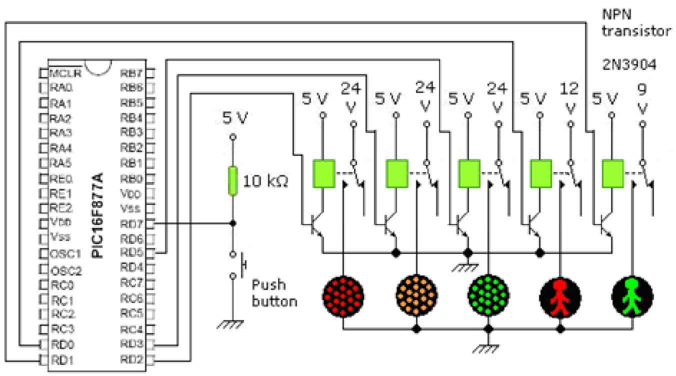

Figure 6 Basic connections of PIC microcontroller, relay, and lamp

B. Control Mechanism of Traffic Light

Flow chart of control mechanism for traffic light system is shown in **Figure 7**. The main controller used to control the sequence of traffic light and reading battery level as well is PIC microcontroller 16F877A. In another word, we can say that it is the brain of the system. In order to give instruction to this kind of microcontroller, we need to do programming according to the sequence needed. To achieve this, we need its software (PIC C compiler) and PIC programmer kit. In this PIC, there are also module for displaying characters in LCD and reading analog input.

C. PV Battery Charging Circuit

This design implements a charger for a lead-acid battery as a sub-function in a microcontroller whose main function can be any more complex task. Furthermore, PIC microcontroller gets its power from the same battery. The charging process is gradual and uses so little processor time and therefore it does not disturb the PIC microcontroller primary task - controlling sequence of lighting. Diagram of connection and charging between PV and battery are shown in **Figure 8** and **Figure 9**.

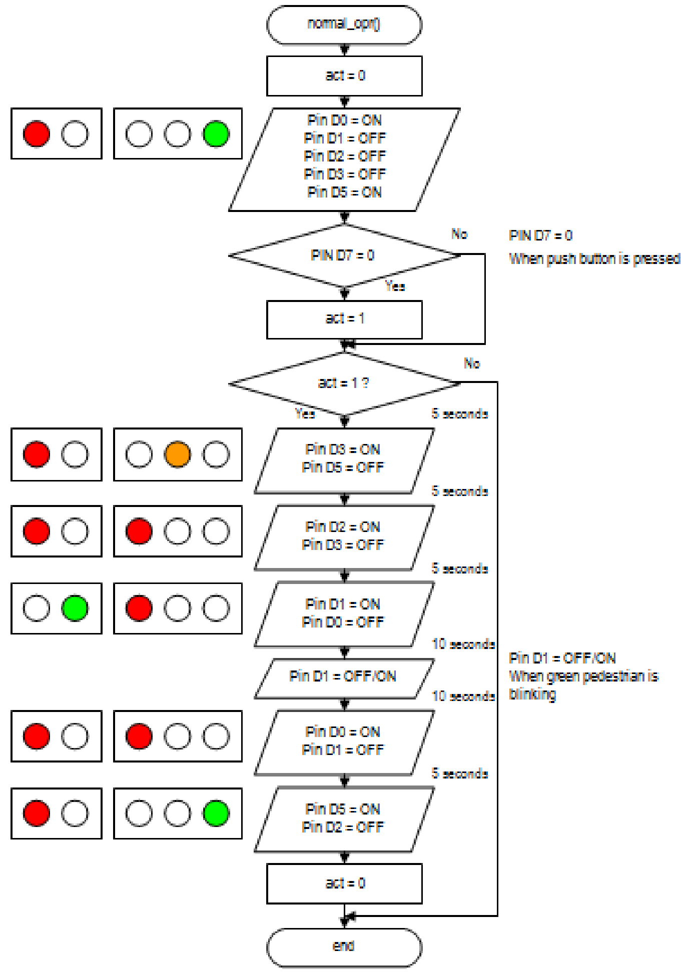

Figure 7 Control mechanism of Traffic light system

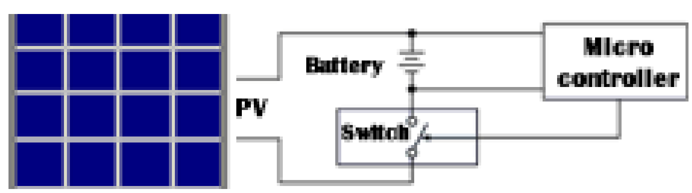

Figure 8 A PV-Battery charging diagram

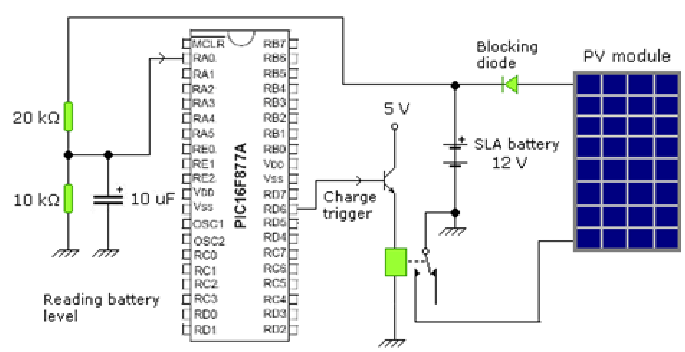

Figure 9 PV-Battery charging circuit

In the case, when the battery is being charged, power switch must be on until the voltage reaches the upper limit of charging. In the second case, when the battery is being discharging, the power switch must be off until it reaches the lower limit of discharging. The lowest limit can be configured in PIC microcontroller and the state of charge can be monitored by user using LCD.

Charging control mechanism is shown in **Figure 10**. If voltage of battery is over 14.5 V, switch of relay will be off, and if voltage of battery below 14.5V, the switch will be on.

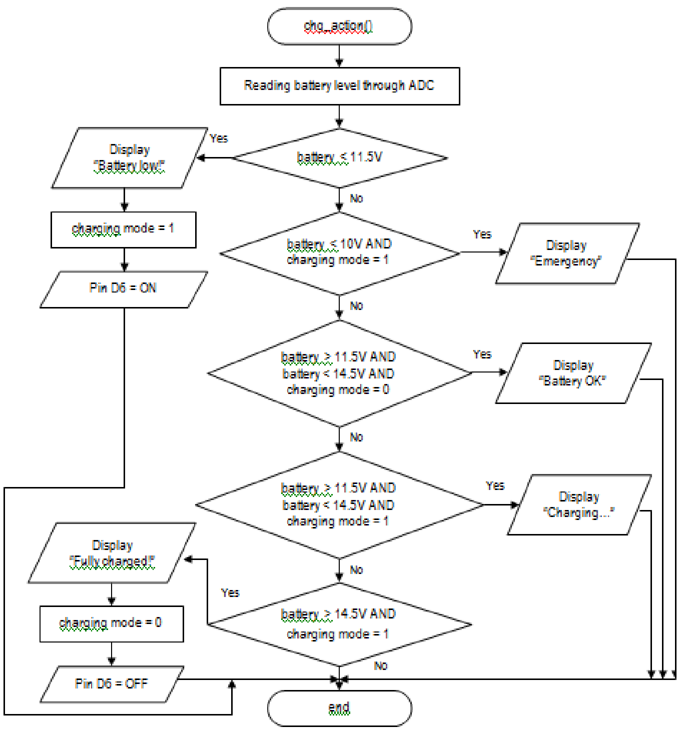

Figure 10 PV-battery charging control mechanism

III. Maximum Power Point Tracking Mechanism

A. Theoretical Approach

Electrical characteristic of voltage and current of solar module can be represented by the curve experimentally and can be mathematically expressed with curve identification.

$$i(v) = I_{sc} - I_d\left(\exp\left(\frac{ev}{kT}\right) - 1\right) \quad (1)$$

where $i(v)$, I_{sc}, I_d, Voc, k, T, e are current density flowing into load (A/m^2), short-circuit current density (A/m^2), dark (saturation) current density (A/m^2), open-circuit voltage (V), Boltzmann's constant (1.38 x 10^{-23} J/K), and absolute temperature (K), single electron charge (1.6 × 10^{-19} C), respectively.

The maximum voltage across PV cell is achieved under open-circuit condition where $j(v) = 0$,

$$\begin{aligned}
0 &= I_{sc} - I_d\left(\exp\left(\frac{eV_{oc}}{kT}\right) - 1\right) \\
I_{sc} &= I_d\left(\exp\left(\frac{eV_{oc}}{kT}\right) - 1\right) \\
\frac{I_{sc}}{I_d} &= \exp\left(\frac{eV_{oc}}{kT}\right) - 1 \\
\frac{I_{sc}}{I_d} + 1 &= \exp\left(\frac{eV_{oc}}{kT}\right) \\
\ln\left(\frac{I_{sc}}{I_d} + 1\right) &= \frac{eV_{oc}}{kT} \\
V_{oc} &= \left(\frac{kT}{e}\right)\ln\left(\frac{I_{sc}}{I_d} + 1\right)
\end{aligned} \quad (2)$$

Power obtained from PV cell is

$$\begin{aligned}
p &= iv \\
p(v) &= \left[I_{sc} - I_d\left(\exp\left(\frac{ev}{kT}\right) - 1\right)\right][v]
\end{aligned} \quad (3)$$

The maximum power point is obtained by taking derivative of $p(v)$ and. $dp/dt = 0$.

$$p(v) = i(v)v$$

$$\frac{dp}{dv} = v\frac{di}{dv} + i(v)$$

$$\begin{aligned}
\frac{di}{dv} &= \frac{d}{dv}\left[I_{sc} - I_d\left(\exp\left(\frac{ev}{kT}\right) - 1\right)\right] \\
&= -\frac{d}{dv}\left[I_d\left(\exp\left(\frac{ev}{kT}\right) - 1\right)\right] \\
&= -\frac{d}{dv}\left[I_d \exp\left(\frac{ev}{kT}\right)\right] \\
&= -I_d\frac{d}{dv}\left[\exp\left(\frac{ev}{kT}\right)\right] \\
&= -I_d\left(\frac{e}{kT}\right)\exp\left(\frac{ev}{kT}\right)
\end{aligned} \quad (4)$$

$$\begin{aligned}
\frac{dp}{dv} &= v\left[-I_d\left(\frac{e}{kT}\right)\exp\left(\frac{ev}{kT}\right)\right] + \left[I_{sc} - I_d\left(\exp\left(\frac{ev}{kT}\right) - 1\right)\right] \\
&= -\left(\frac{I_d ev}{kT}\right)\exp\left(\frac{ev}{kT}\right) + I_{sc} - I_d\left(\exp\left(\frac{ev}{kT}\right) - 1\right)
\end{aligned}$$

$$0 = -\left(\frac{I_d ev}{kT}\right)\exp\left(\frac{ev}{kT}\right) + I_{sc} - I_d\left(\exp\left(\frac{ev}{kT}\right) - 1\right) \quad (5)$$

V_{MPPT} = v at $\frac{dp}{dv} = 0$ as shown in **Figure 11** as the power-versus-voltage curve.

In Dc-DC Converter, we can set V as a function of duty factor (D), as formulated as:

$$V_o = V_i D \tag{6}$$

where V_i, V_o, and D are voltage input of DC-DC converter, voltage output of DC-DC converter, and duty cycle of Pulse Width Modulation in switching MOSFET, respectively.

Therefore, changing of duty cycle will increase or decrease the output voltage.

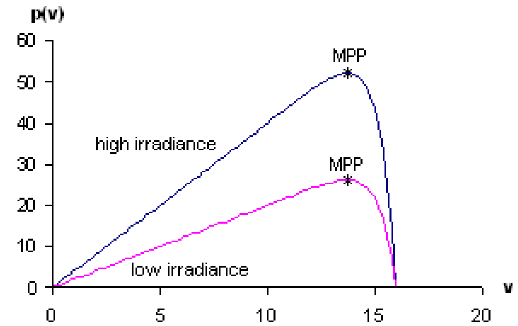

Figure 11 Characterstic of power-voltage of PV panel

B. DC-DC Converter

Stepping-down or stepping up the voltage needs adjustment of PWM connected to MOSFET as switch. In this case, according to investigation of electrical characteristics of current-voltage, we have decided to use step-down or Buck converter to implement DC-DC conversion. Actually, most of the MPPTs are usually using Buck converter

Diagram of DC-DC converter that used in this experiment is shown in **Figure 12**.

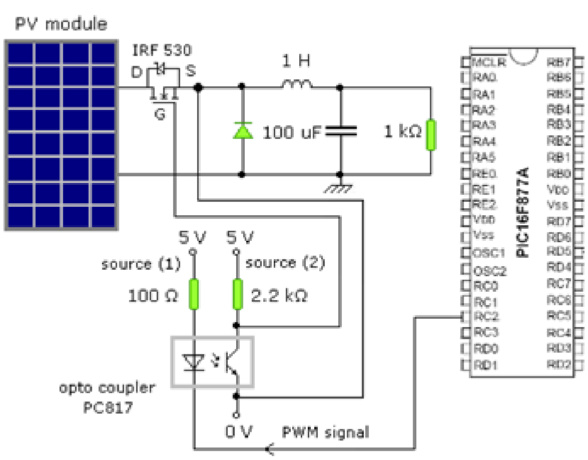

Figure 12 DC-DC converter for MPPT control

Switching DC-DC converter is more efficient at very high frequency. Therefore, using PIC, we can generate high frequency PWM. A very high frequency signal is generated, with amount of 2.4 kHz through pin C2.

For duty cycle adjustment, we need to know the maximum power obtained at particular voltage. This voltage can be either measured by investigating electrical characteristic or referring data sheet or specification provided by manufacturer.

According to the specification provided by the manufacturer (**TABLE I**), the maximum power is obtained at 16.9V at 1000 W/m2 irradiance with 25 C temperature. Because the load of system is almost constant, we can only fix the duty cycle according to the input and output voltage in which depend on the load. We have output voltage from PV module at certain load, and then the maximum power point voltage has been obtained. Then, duty cycle is the ratio of maximum power point voltage to output voltage from PV module at certain load. Mathematically, it can be expressed as the following:

$$D = \frac{V_{\text{MPP}}}{V_{\text{output}}} \tag{7}$$

For an instance, the output voltage from PV module is 18V and maximum power point voltage is 16V. Then, duty cycle = 16/18 = 0.89. In the algorithm, the signal is generated using the following algorithm:

```
setup_ccp1(CCP_PWM); // pin C2
setup_timer_2(T2_DIV_BY_16,127,1);  // 2.4 kHz signal
set_pwm1_duty(113);// 0.89 duty cycle
```

According the algorithm above, 113 is obtained based on duty cycle value which has been obtained previously, 113/127 ≈ 16/18.

IV. RESULTS AND DISCUSSION

A. Circuit Implementation

Figure 13 shows circuit of this experiment board consist of DC-DC converter, control circuit and relay.

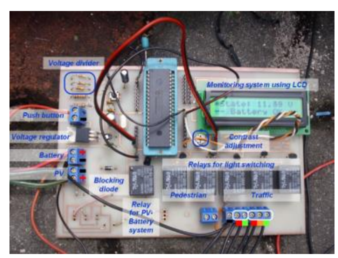

Figure 13 Experimental board

Figure 14 shows a traffic light lamp with a mounting PV module that was used in this experiment.

Figure 14 Traffic light lamp and PV Module

B. Measurement Method

After completing traffic light module installation and its control, performance analysis for power consumption have to be analyzed. These are involving measurement of voltage and current for both PV-Battery and Battery-Load.

For voltage and current analysis, it was suggested to take the reading for every 10 minutes for graph plotting purpose. There were two ways of measurement of these parameters; using data acquisition or multimeters. For voltage measurement, LABVIEW 7.0 is used with several hardwares:

- NI-PCI-6221 installed inside computer through PCI slot with provided driver software.
- NI-SCC-68 to be connected with to-be-measured source (attenuated source) or to be connected with direct source in between -10V and +10V.
- NC-SCC-AI01 for voltage attenuation due to the limited range of NI-SCC-68. The gain for this attenuator is 0.2. Therefore, 12V will display 12V x 0.2 = 2.4V.

For current measurement, there must have been a current to voltage converter with determined gain prior to attenuation using NC-SCC-AI01. However, the current-to-voltage package was unavailable. Designing the new one seemed to be difficult and required a lot of time to be spent. Hence, the manual way was suggested; using two multimeters with ammeter configuration. Then, the data containing four parameters were taken from the morning until evening and tabulated. After finishing tabulation, the data were plotted with four parameters versus time. **Figure 15** shows some components that used to measure the performance of this system.

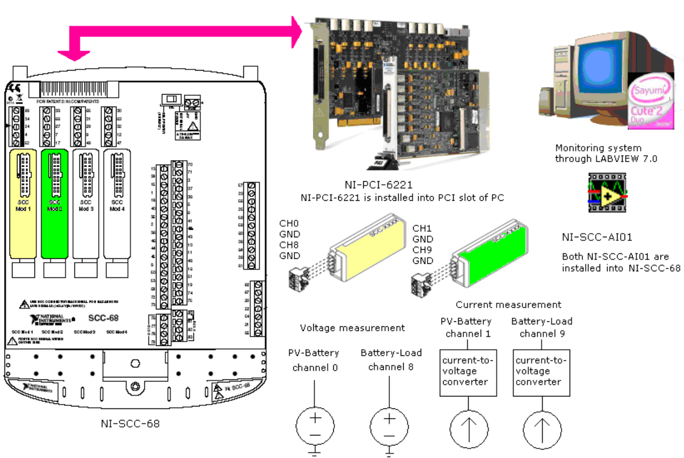

Figure 15 Measurement components using NI SCC-68

C. Battery Charging Performance

Figure 16 shows performance graph of battery charging system. We tested this battery charging circuit from 08.00AM until 7.15PM (we took data voltage and current of charging system circuit every 10 minutes).

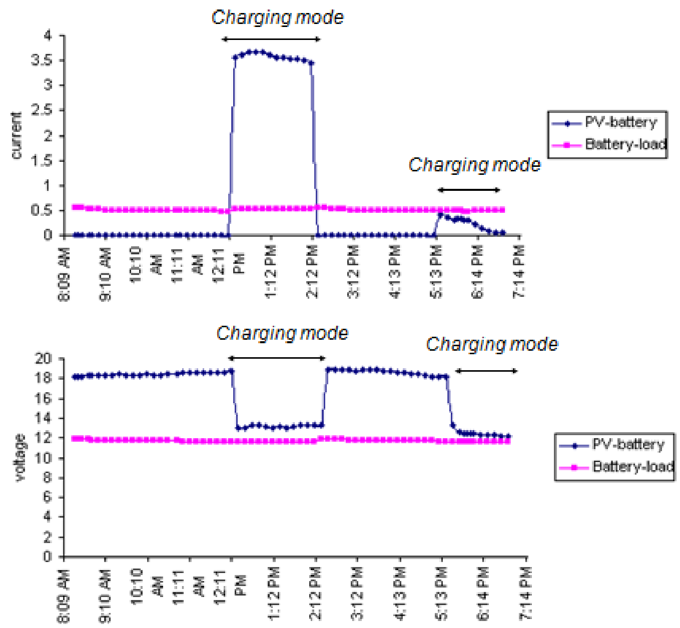

Figure 16 Performance of battery charging system

Based on **Figure 16** and programming flowchart in **Figure 10**, we can see that this charging system work very well. Where in the beginning of this experiment condition of battery in the full condition (voltage of battery more than 14.5V), if condition of the voltage of battery > 14.5V makes relay circuit cut off the current. When the voltage of battery below 14.5V the relay switch will ON and charging battery occurs, at the time 08.00 until 12.11AM the battery in full condition make the relay cut off, when at the time 12.11AM-2.12PM where the voltage of the battery bellow 14.5V make the relay ON and at this time we can see the current 3.5A delivered from PV module to Battery to charge the battery.

D. MPPT Performance

The experimental tests have been done for the MPPT. **Figure 17** shows output of generated pulse from Microcontroller as a feed pulse for MOSFET. This generated pulse we can be programmed as we desired as duty cycle of DC-DC Converter. For PWM control, the duty cycle is 0.866 with 2.4 kHz frequency. From theoretical analysis, we can obtain the expected output voltage, $0.866 \times 19\ V = 16.454\ V$ at maximum power.

Figure 18 shows the output voltage after filter of DC-DC converter, where we can keep output of DC-DC converter around 16.5 V. This voltage is a swing point of maximum power point of PV module. This method is known as MPPT technique uses Constant Voltage Control [7].

E. Testing of Overall System

We have tested the overall system of traffic light system powered by photovoltaic and MPPT for one day. Based on the test, the traffic light lamp, battery charging system, and MPPT work well as we have designed.

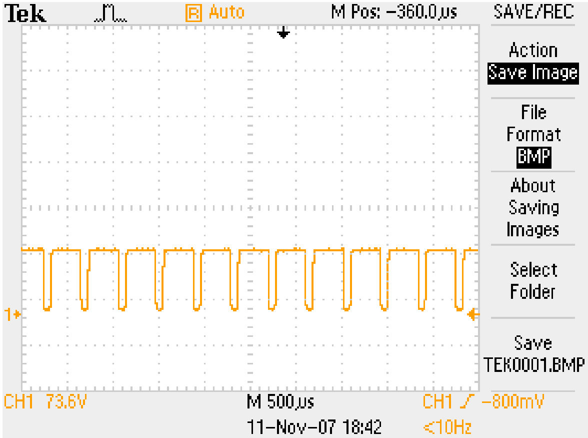

Figure 17 Generated pulse from microcontroller as a feed pulse for MOSFET

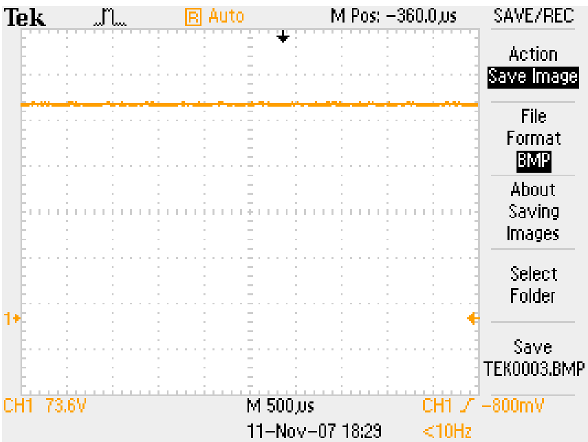

Figure 18 The output voltage output of DC-DC converter

V. Conclusion

In this paper we have presented the design and experimental of traffic light system powered by photovoltaic and MPPT. Based on experiment we can conclude that the MPPT, battery charging and lamp controller worked as we desired in design process. The output voltage of the DC-DC converter circuit from measurement showed value around 16.5 V. This voltage measurement is close to MPP voltage of PV module in the data sheet. This shows that MPP control worked to deliver a maximum power from PV module to battery.

References

[1] Shih-Hung Ko, Ru-Min Chao, "Photovoltaic dynamic MPPT on a moving vehicle", Solar Energy, Volume 86, Issue 6, June 2012, Pages 1750-1760. CrossRef

[2] F. Chekired, C. Larbes, D. Rekioua, F. Haddad, "Implementation of a MPPT fuzzy controller for photovoltaic systems on FPGA circuit", Energy Procedia, Volume 6, 2011, Pages 541-549. CrossRef

[3] Syafaruddin, Engin Karatepe, Takashi Hiyama, "Performance enhancement of photovoltaic array through string and central based MPPT system under non-uniform irradiance conditions", Energy Conversion and Management, Volume 62, October 2012, Pages 131-140. CrossRef

[4] Thomas Bennett, Ali Zilouchian, Roger Messenger, "Photovoltaic model and converter topology considerations for MPPT purposes" Solar Energy, Volume 86, Issue 7, July 2012, Pages 2029-2040. CrossRef

[5] Panagiotis E. Kakosimos, Antonios G. Kladas, "Implementation of photovoltaic array MPPT through fixed step predictive control technique", Renewable Energy, Volume 36, Issue 9, September 2011, Pages 2508-2514. CrossRef

[6] Nabil A. Ahmed, A.K. Al-Othman, M.R. AlRashidi, "Development of an efficient utility interactive combined wind/photovoltaic/fuel cell power system with MPPT and DC bus voltage regulation" Electric Power Systems Research, Volume 81, Issue 5, May 2011, Pages 1096-1106. CrossRef

[7] Riza Muhida, Minwon Park, Mohammed Dakkak, Kenji Matsuura, Akira Tsuyoshi, Masakazu Michira, "A maximum power point tracking for photovoltaic-SPE system using a maximum current controller", Solar Energy Materials and Solar Cells, Volume 75, Issues 3-4, 1 February 2003, Pages 697-706. CrossRef

[8] Minwon Park, Masakazu Michihira, Kenji Matsuura, "A novel MPPT control method using optimal voltage of PV with secondary phase-shift PWM control DC-AC converter", Proceeding of International Conference on Electric Power Engineering, 1999. PowerTech Budapest 99. CrossRef