Design and Implementation of a Fuzzy Logic PWM Charge Controller for the Photovoltaic Systems
تصميم و تنفيذ منظم شحن لمنظومة فوتوفولتية بإستخدام المنطق المبهم ذو النبضات المتغيرة السعة

Eid Gouda, A. Abdelhaleim and S. S. Eskander
eid.gouda@yahoo.fr

الملخص

للبطاريات دروراً هاماً في المنظومة الفوتوفولتية حيث أنها تستخدم لتخزين الطاقة المولدة من الخلايا الشمسية ثم تقوم بتغذية الحمل. يقترح هذا البحث تصميم وتنفيذ منظم شحن للبطاريات يعمل علي زيادة عمرها الافتراضي بالاضافة الي تشغيل الخلايا الشمسيه عند نقطة القدره العظمي وذلك لإستغلال كل الطاقة المتاحة من المنظومة الفوتوفولتية. تتحقق هذه الأهداف من خلال التحكم في مداخل و مخارج منظم الشحن بحيث يعمل هذا المنظم علي منع حدوث الشحن الزائد أو التفريغ التام للبطاريات. أيضاً يقوم بتنظيم جهد الخلية الشمسية ليقترب من جهد البطاريات بإستخدام المنطق المبهم وبالتالي ينظم تيار شحن البطاريات بحيث يمنع إرتفاع درجة حرارتها وتبخر الحمض بداخلها مما يسمح بالاستفادة من سعة البطاريات المستخدمة بشكل تام. لذلك يزيد هذا المنظم من إستغلال الطاقة المولدة من المنظومة الفوتوفولتية و يقلل من تكلفة إنشاءها مما يحسن الإعتمادية علي المنظومة الفوتوفولتية.

Abstract

Charge controller is the device which is connected between the photovoltaic (PV) modules, DC batteries and loads. This paper proposes the design and implementation of a charge controller which is capable to protect the lead acid batteries in the PV system from overcharge and undercharge states. Moreover, this charge controller is designed to make the battery voltage near the PV voltage at the maximum power point (MPP) for the PV modules. Also, the designed charge controller uses the fuzzy logic Pulse Width Modulation (PWM) control, in order to make use of the full capacity of the lead acid batteries in the system. Therefore, this proposed design improves the reliability of the PV system and reduces its total cost.

1. Introduction

All the energy produced by a PV array is supplied to the load and stored in the battery bank. During periods of strong sunlight, the batteries may be fully charged much of the time. During the night, electrical loads supplied from battery bank. Therefore, reliable energy storage system is important in a stand-alone PV system. The energy storage allows the user to find electrical energy at any time of a day.

A charge controller device plays an important role in PV system. It is used to regulate the flow of current from the PV array into the battery bank, and from the battery bank to the various loads. The main tasks of the charge controller can be summarized in following points:

- Protection against battery overcharging and excess discharging and accidental short-circuits.
- Automatic selection of charging rates, depending on the estimated State of Charge (SOC) of the battery bank.
- Prevention of reverse current at night for the PV array.
- Display of important parameters such as battery voltage, estimated SOC, and warning of impending load disconnection [1]-[3].

There are two types of charge controller. The first type is a series controller which includes two power semiconductor switches. The first switch is connected in series with PV modules to control the charging current. The other switch is

connected in series with the load to control the discharge current.

The operation of a shunt controller depends also on two power switches. Here, the switch, which controls the charging current, is connected across the PV array rather than in series with it. Therefore, when the switch is open, the battery receives charge. When the switch is closed or short circuiting the PV, the charging current becomes zero. The shunt switch needs a larger heat sink and must carry the full short - circuit current of the PV module. In practice series charge controller is used in general more than shunt controllers on the market [4], [5]. Therefore, this paper will focus on the design of a series charge controller.

Artificial intelligence techniques can improve the performance of the charge controller in the photovoltaic system. There are many types of artificial intelligence techniques. Firstly, artificial neural network technique can learn from training cases and captures relationships among input data. Secondly, case-based rule technique solves a problem by recalling similar past problems, so it requires similar past cases. Moreover, swarm intelligence technique involves simple agents which are collectively solving a problem by local interaction. In addition, genetic algorithms are a search technique mimicking natural selection. This algorithm evolves a set of potential solutions towards a global optimum. Another technique is the fuzzy logic. This technique applied to many environmental problems because they can handle imprecise and incomplete data [6]-[8].

In this paper, a fuzzy logic charge controller is designed for the photovoltaic power system because the availability of sun light is randomly varying. In the conventional controller, the system should be modeled to provide adequate control. But the fuzzy logic charge controller provides an effective solution for measurements of uncertainties present in this varying PV system. The proposed controller depends on single input buck converter and fuzzy logic control. It recognizes the SOC for battery bank. Then charge controller generates suitable control pulses for its power switches to perform its required tasks.

This paper is divided into 5 main sections. An introduction was represented in section 1. The design steps of each component of the proposed charge controller such as the used batteries, switches, gate driver circuit, protection circuits will be shown in section 2 in details. The control system, and microcontroller coding will be located in section 3. The most important section of this paper will be found in sections 4 and 5 where the implementation of the charge controller and results discussion will be analyzed. Finally a conclusion will be found in section 6.

2. Charge Controller Design

The design of charge controller is closely related to the PV array and the DC batteries. As shown in figure 1, the main components of the charge controller are power switches, driver circuits, control system, and protection devices. Therefore, this section will discuss the design of these elements.

2. 1. DC Batteries

Deep cycle lead acid battery is the main component in the PV systems. The deep cycle battery is designed to discharge between 45% and 75% of its capacity, depending on the manufacturer and the construction of the battery [9]. In the market, these batteries usually have the 12V, and 100Ah specifications. Therefore, the DC voltage of the storage system may be 12V or its multipliers.
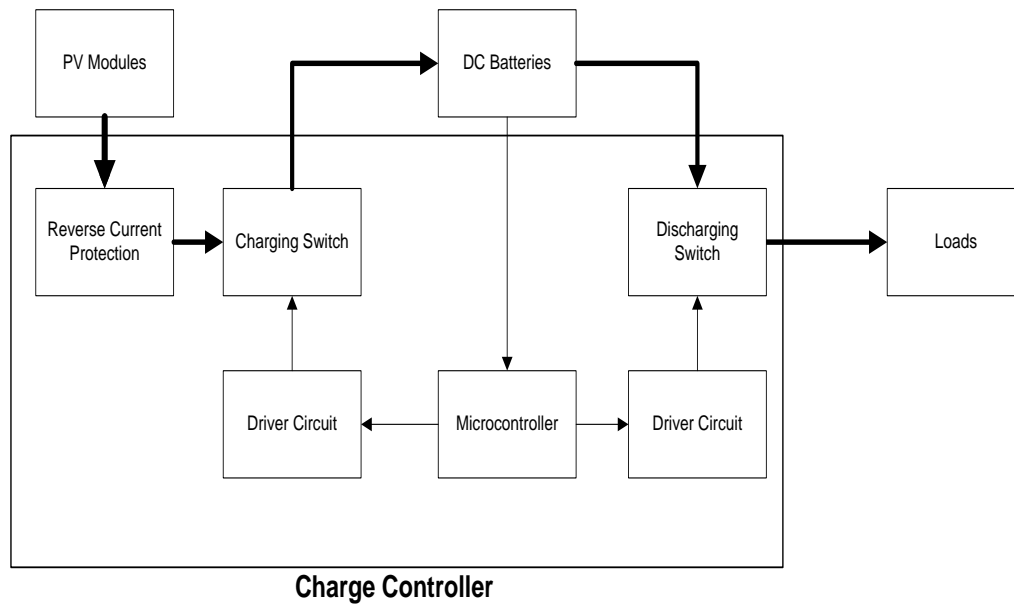
Charge Controller

Figure 1 Block Diagram for the Charge Controller within the PV System

In the designed system, The DC system voltage is 24 V in order to operate the PV modules near the maximum power point. The PV modules have I/V characteristics shown in figure 2, where $V_{o.c}$ equals to 34.2 V as stated in the datasheet. The shaded region in the figure specifies the location of maximum power point at any solar radiation. The shaded region is near to 24 V [10]. Therefore, the proposed charge controller should have a rated voltage of 24V.
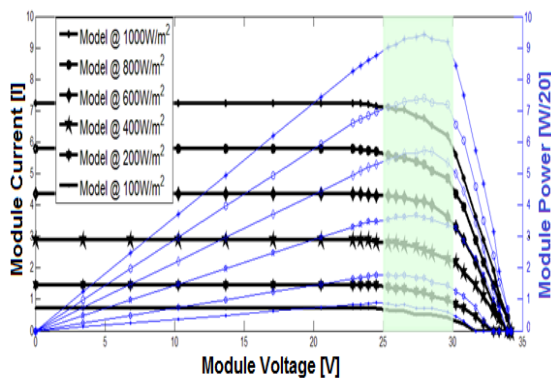
Figure 2 Characteristics Curves of PV Module Used in the Proposed System

2. 2. Power Switches

Figure 3 shows the electric circuit of series-type charger controller which has two power switches. The designed charger controller uses a P-channel MOSFET as a charging switch in order to be controlled by a simple driver circuit, where the charging switch is used to control the charging current for the battery bank. On the other hand, the discharging switch is N-channel MOSFET for the same reason. The purpose of the discharging switch is the prevention of excessive discharge of the battery bank by disconnecting the load. MOSFET switches have many advantages:

- High switching capability that is the operational frequencies up to 1 GHz.
- Simple protection circuits and voltage control.
- Easy paralleling for increasing current-handling capability.
- The capabilities of MOSFET can reach up to 10kVA, 1000 V, and 200 A [11], [12].

These advantages of MOSFETs will allow the designed charge controller to have a current rating up to 30 A and to use PWM for controlling the charging current of the DC batteries.
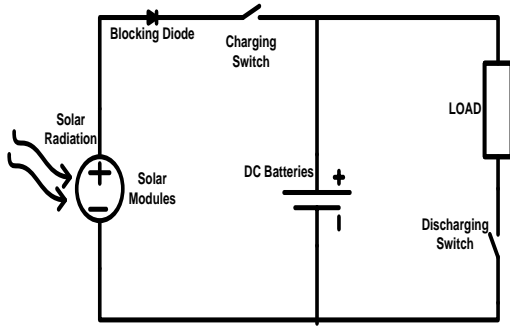
Figure 3 Circuit of Series Charge Controller Type

2. 3. Snubber Circuit Protection

Snubber circuit is an additional circuit used to reduce stress on the power semiconductor switches. It limits the peak voltage across the semiconductor switch during turn-off. Snubber circuit has many configurations. The simplest snubber circuit for MOSFETs is the RC snubber circuit as shown in figure 4 [13]-[14]. Designing of snubber circuit for MOSFET switches can be simplified as follows [15]:
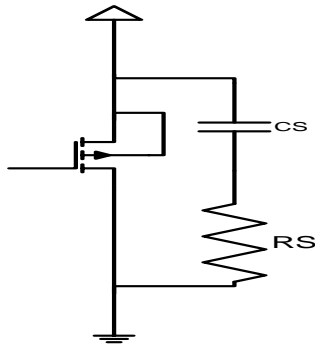

Figure 4 Schematic Diagram of the Snubber Circuit

- The resistance value is chosen to allow the flow of load current without voltage overshoot after the switch opens. The resistance value calculated from equation (1) depending on Vo and I. Vo is off voltage across the switch after it opens and I is on current before the switch opens.

$$R_s \leq \frac{Vo}{I} \leq \frac{24}{30} \leq 0.8 \qquad (1)$$

- The resistance will dissipate the energy stored in the snubber capacitor, ½*Cs* Vo^2, for each voltage transition regardless of the resistance. The capacitance will be chosen to cause the 7-watt resistor to dissipate half of its power rating, 3.5 watts. For two times f_s

transitions per second, the resistor will dissipate 3.5 watt then:

$$3.5 = (½\ CsVo^2) * (2fs) \qquad (2)$$

Where f_s = switching frequency = 5K Hz

$$C_S = \frac{3.5}{f_s\ V_o{}^2} = 1.2\ \mu F \qquad (3)$$

2. 4. Driver Circuits

There are two driver circuits in the proposed design of the charge controller. Both circuits are shown in figure 5 and figure 6. They use two NPN transistors and one PNP transistor to amplify the 5 V microcontroller control signal into 12V for the gate of the power MOSFETs. The NPN transistor turns the MOSFET switch ON, while the PNP transistor turns it OFF.

There is a resistance between the gate and source of the MOSFETS. This resistance is designed from equation (4) based on the allowed collector current in a datasheet of used transistors Q1P, Q2N, Q3N, and Q3P.

$$R1P, R1N, R2P, and\ R2\ \ equals \frac{12\ V - V_{ce(sat)}}{10\ mA}$$

$$= \frac{12 - 0.2}{10 * 10^{-3}} = 1180\ \Omega \qquad (4)$$

Similarly R3P and R3N are calculated from equation (5).

$$R3P, and\ R3N\ = \frac{5\ V - V_{BE}}{10\ mA} = \frac{5 - 0.7}{10 * 10^{-3}}$$

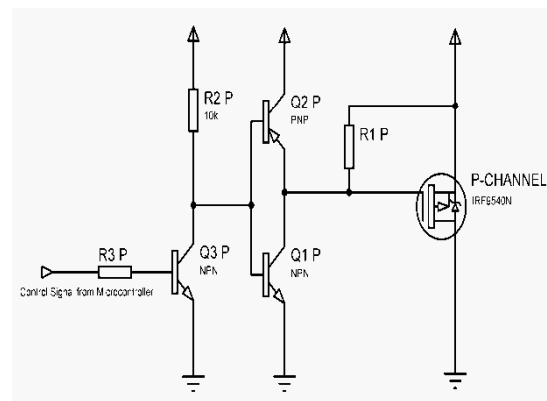$$= 330\ \Omega \qquad (5)$$

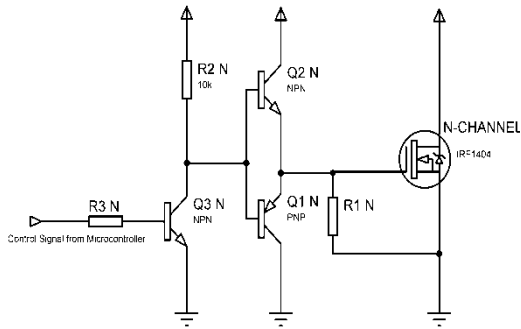*Figure 5 Schematic Diagram of the Driver Circuit for P-channel MOSFET*

Figure 6 Schematic Diagram of the Driver Circuit for N-channel MOSFET

2. 5. PV Module Reverse Current Protection

To prevent PV module reverse current at night, a blocking diode is included between the PV array and the DC batteries as shown in figure 3. The diode allows current flow from the PV array to the battery bank and blocks the flow of a current in a reverse direction.

2. 6. Charge Controller Protection Fuses

There is a fuse connect in series with the battery bank. This fuse has a rating of 30 A. The purpose of the fuse is to avoid the damage for the batteries and charge controller, when there is a short circuit on the batteries, or when the load exceeds the rating of the charge controller.

3. Charge controller

Figure 7 shows the diagram of the proposed charge controller. This control system consists of microcontroller, voltage sensors, and LEDs. Firstly, the microcontroller is a main element in the charge controller. Microcontroller is programmed to generate the control signals for the charge controller switches. Also, microcontroller displays the status of the system through two LEDs. The green LED indicates the state of charging. On the other hand, the yellow LED shows that the load is connected to the batteries. Finally, there is a voltage sensor which consists of potential divider resistances to measure the voltage of battery bank. These resistances divide the

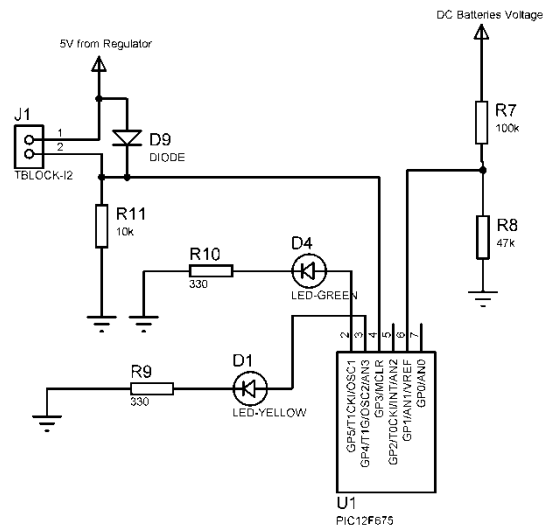voltage of battery bank in order to be suitable for microcontroller.

Figure 7 Schematic Diagram of the Microcontroller Circuit

3. 1. Microcontroller PWM Coding

The proposed charge controller can simply prevent the excess discharging of the battery by disconnecting the load. But, during the charging of the battery, it operates as a buck converter for PV module voltage according to the state of charge for the lead acid batteries. The proposed design uses PWM control for the P-MOSFET switch. Microcontroller controls the duty cycle of the control signals in order to change the output voltage from the PV modules. Consequently, it regulates the charging current for the batteries.
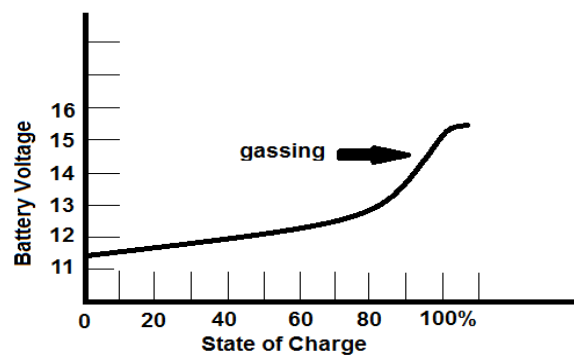

Figure 8 Typical Charging Characteristics of a 12 V Lead-acid Battery [16]

Figure 8 shows the relationship between the battery voltage and the state of charge for this battery. It shows that the overcharging occurs when the battery voltage reaches an upper set point, normally preset at about 14.5 V. Also, when the voltage falls to a lower set point, normally about 11.5 V, the state of charge is an excess discharge [17], [18]. Therefore, the algorithm of microcontroller's program will be as follow:

1- Read the voltage of the batteries (V_{batt})

2- If V_{batt} less than 22.5 V

  YES: Disconnect the load

  No: Connect the load

3- If V_{batt} more than 29 V

  YES: Disconnect the PV modules and go to step 1

4- Calculate the PWM duty cycle

5- Connect PV modules

6- Go to step 1

This algorithm can be shown as in the flowchart of figure 9.
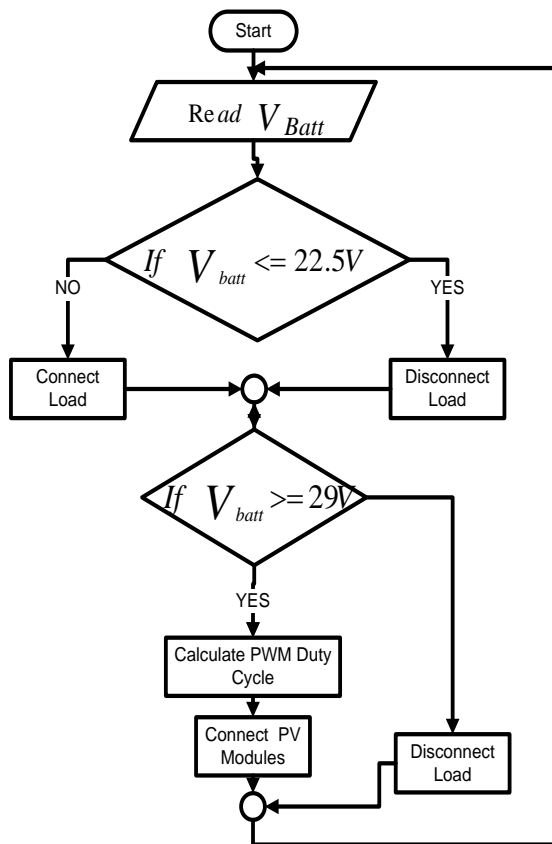
Figure 9 Flowchart of Microcontroller's Code

3. 2. Fuzzy Logic Control Loop

The microcontroller should change PWM duty cycle according to a required charging scheme shown in figure 10. In this scheme, charge controller provides an initial boost charge using all the available current, then, as the SOC approaches 100%, absorption charge will become at constant voltage and low current. This helps to keep the battery operation in top condition [19]-[21].
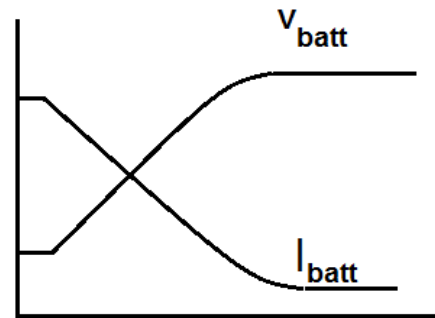

Figure 10 the change of the battery current (I_{batt}) according to the battery voltage (V_{batt})
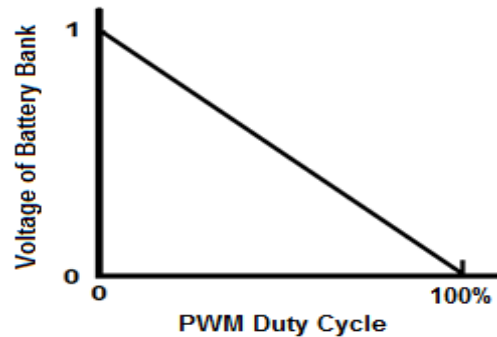

Figure 11 the Required Relationship between the Battery Bank Voltage and the PWM Control Signal.

To achieve this charging scheme, figure 11 shows the required relationship between the battery bank voltage and the PWM control signal. This relationship can be achieved by the following fuzzy logic controller. Firstly, the difference between the measured value of battery bank voltage and the upper set point is calculated according to equation (6).

The percentage difference

$$= \frac{V_{upper\ set} - V_{batt}}{Max\ |V_{upper\ set} - V_{batt}|} \qquad (6)$$

The fuzzy logic controller depends on the membership functions in the figures 12, and 13. Moreover, the value of the duty cycle is controlled by using the fuzzy logic membership function shown in figure 13. Because the driver circuit invert the control signal of microcontroller, these membership functions shows that the output PWM duty cycle will increase as the battery voltage increase or the percentage difference decreases. The proposed fuzzy logic controller achieves the continuous change in the pulse width of the control signal in sympathy with the SOC, making use of the PV ' s output while at the same time protecting the battery and prolong its life time.
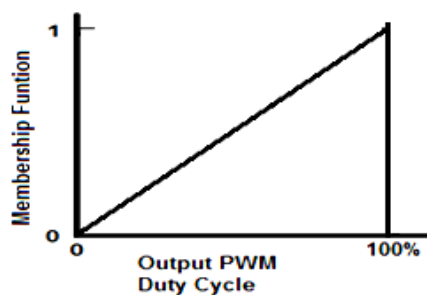

Figure 12 Input Membership Function

Figure 13 Output Membership Function

4. Implementation

The designed charge controller uses microcontroller PIC 12f675. This microcontroller is programmed by MikroC to generate the control signals for the charge controller switches [22].

- The designed circuit of charge controller is implemented on a Printed Circuit Board (PCB) by using PROTEUS DESIGN SUITE [23]. In this PCB, there are power terminals for connecting the battery bank, solar array, and load into the designed circuit. Also, the tracks of power circuit are designed with width 15mm, while the control circuit consists of 2 mm copper tracks in the designed PCB.
- Load can be controlled manually either by using push button on the PCB or through remote control switch.
- 5V Voltage regulator is used as a power supply to provide adequate and stable voltage for the microcontroller, and driver circuits.
- Heat sink is fixed to P-MOSFET in order to dissipate the generated heat on MOSFET.
- There is anti-parallel freewheeling diode across the load in order to eliminate the back electromotive force from the load.

5. Experimental Results and Discussion

The printed circuit board for designed charge controller is shown in figure 14. And, figure 15 shows the schematic diagram for this charge controller.
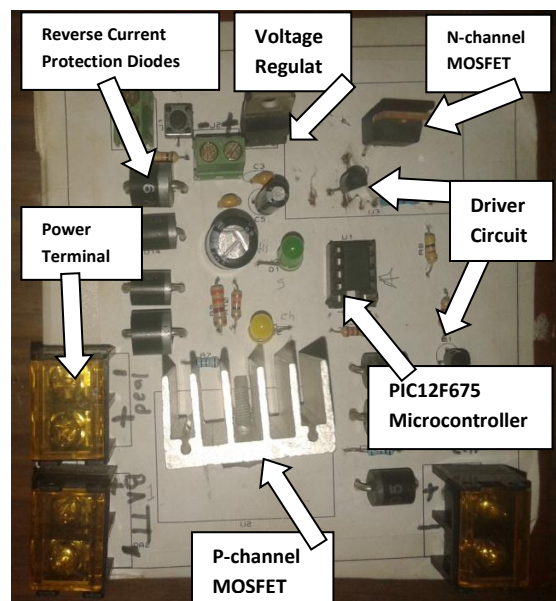

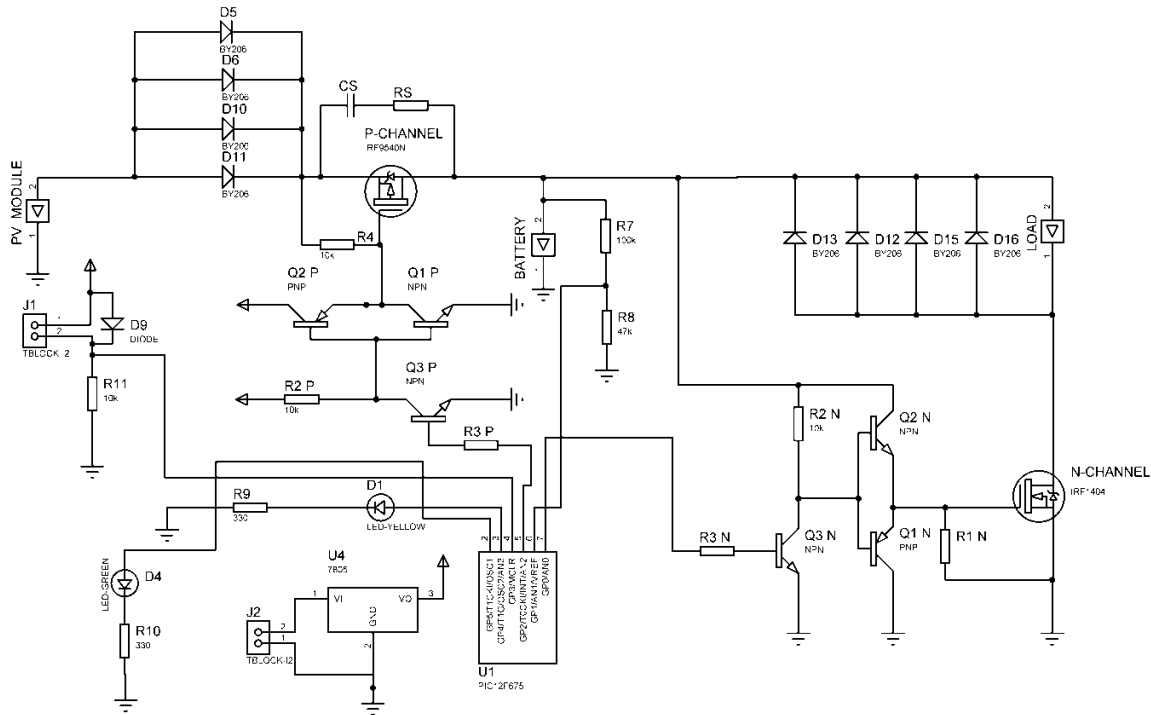*Figure 14 Photograph for the Designed Charge Controller*

Figure 15 Schematic Diagram of the Proposed Charge Controller

The following figures show the control signals for the P-channel MOSFET and the charging current at different state of charge for batteries. The charging current was measured by measuring the voltage across a series connected resistance between the PV module terminal and DC battery terminal. The value of this resistance is 5Ω.

Figure 16 displays that the control signal will be with zero duty cycle. This control signal causes the P-channel switch to conduct all available charging current (figure 17) from PV module to the battery bank because the state of charge for the battery bank is low.
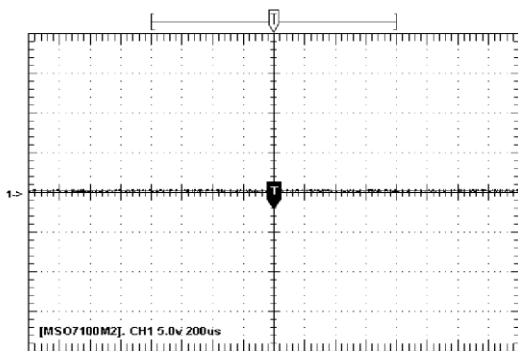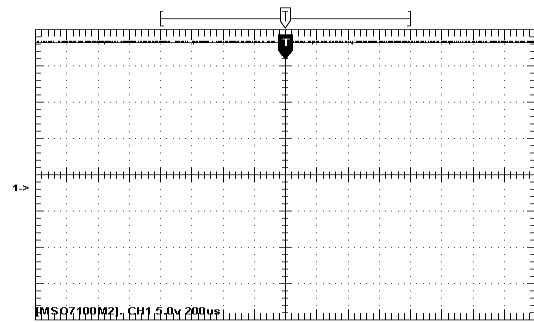

Figure 17 Waveform for charging current when battery voltage equals 22 V

As the state of charge increases, the duty cycle of control signal increases (as in figure 18) in order to decrease the charging current (as in figure 19).
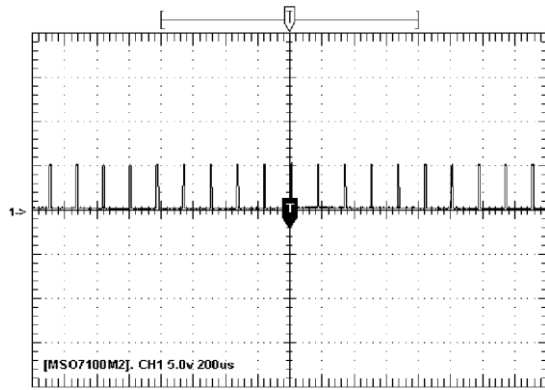

Figure 16 Waveform for PWM control signal when battery voltage equals 22 V

Figure 18 Waveform for PWM control signal
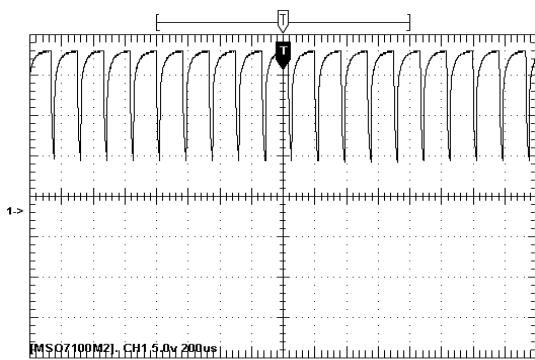*when battery voltage equals 24 V*

Figure 19 Waveform for charging current
when battery voltage equals 24 V

Similarly, figures 20, 22, 24 shows the change of the control signal according to the change in state of charge of battery bank until it becomes full charged. And figures 21, 23, and 25 are the waveforms of the charging current which are produced from these control signals.
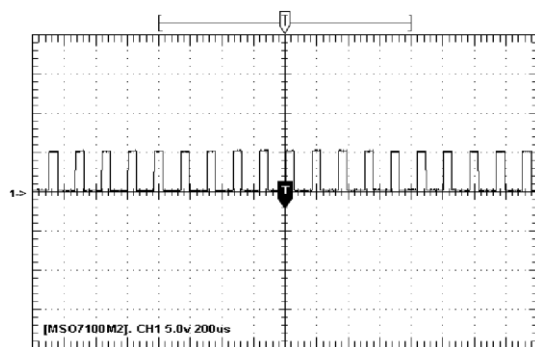

Figure 20 Waveform for PWM control signal
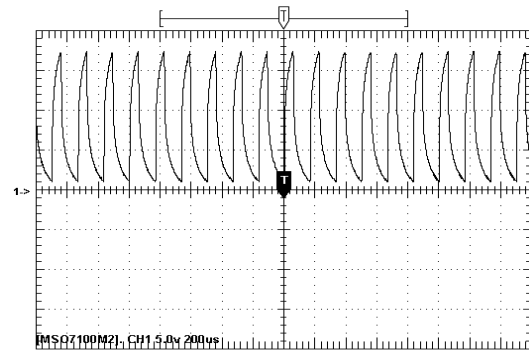*when battery voltage equals 26 V*

Figure 21 Waveform for charging current when
battery voltage equals 26 V

Figure 22 Waveform for PWM control signal
when battery voltage equals 28 V

Figure 23 Waveform for charging current when
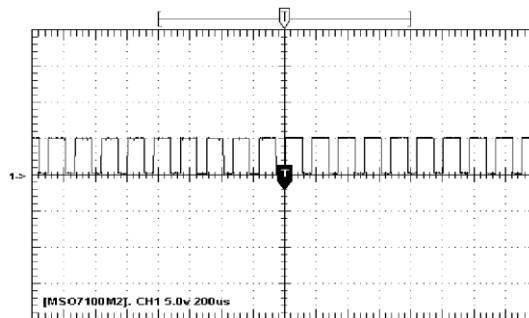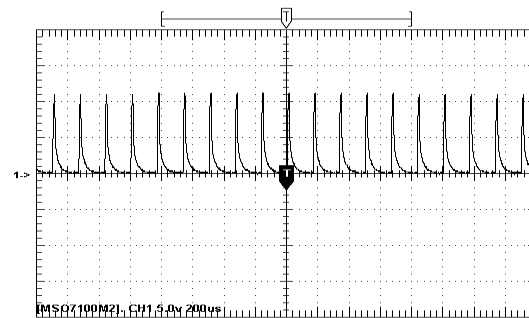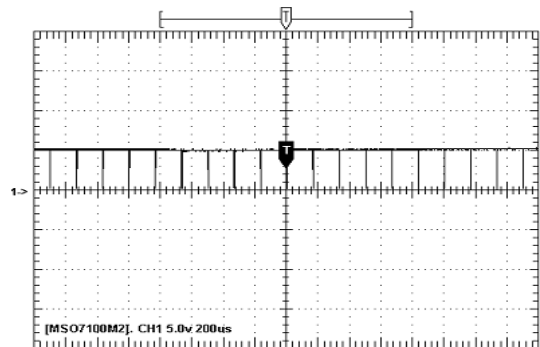*battery voltage equals 28 V*

Figure 24 Waveform for PWM control signal
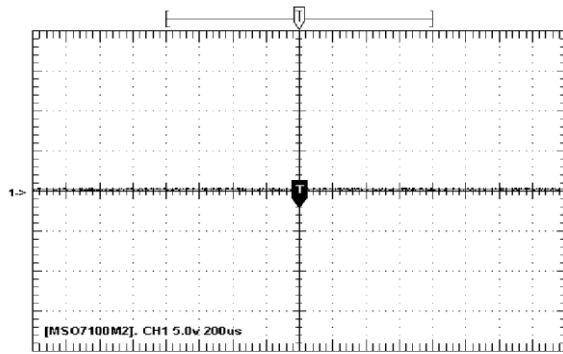*when battery voltage equals 29 V*

Figure 25 Waveform for charging current when battery voltage equals 29 V

6. Conclusion

This paper discusses in details the design and implementation of PWM fuzzy logic charge controller for PV system. This charge controller designed to operate near the maximum power point of the PV modules. The proposed charge controller prevents the overcharging and excess discharging for lead acid batteries in PV system. Also, a control strategy based on fuzzy control theory has been proposed to control the charging current in an effective way which make use of the full capacity of the battery and prolong its lifetime. Moreover, microcontroller system improves the reliability and decrease the cost of the designed system because all functions are performed by programming instead of designing different electronics circuits. Finally, the results obtained under different conditions are discussed and presented in this paper. The results prove that the validation and real time feasibility of the proposed charge controller.

7. References

[1] W. Thounaojam, V. Ebenezer, A. Balekundri, "Design and Development of Microcontroller Based Solar Charge Controller," International Journal of Emerging Technology and Advanced Engineering, Vol. 4, Iss. 5, May 2014.

[2] M. Shoaib, V. Nagaraj, "Novel Battery Charging Control System for Batteries Using On/Off and Pwm Controllers for Stand Alone Power Systems," IOSR Journal of Electrical and Electronics Engineering, Vol. 6, Iss. 3, PP 44-52, June 2013.

[3] M. Pammar, S. Chavan, "Design and Development Of Advanced Microcontroller Based Solar Battery Charge and Solar Tracking System," International Journal of Research in Engineering and Technology, vol. 03, May 2014, Available: http://www.ijret.org.

[4] M. O. Hamdan, A. N. Hejase, H. M. Noura, A. A. Fardoun, "ICREGA'14 - Renewable Energy: Generation and Applications", Springer International Publishing, 1st edition, 2014.

[5] I.Fajri, R. Nazir, "Fuzzy logic-based voltage controlling mini solar electric power plant as an electrical energy reserve for notebook," International Conference on Sustainable Energy Engineering and Application, 2014.

[6] S.H. Chen, A. J. Jakeman, John P. Norton, "Artificial Intelligence techniques: An introduction to their use for modelling environmental systems," Mathematics and Computers in Simulation, ELSEVIER, pp. 379–400, 2008

[7] L.Rutkowski, "Computational Intelligence: Methods and Techniques, "IEEE Computational Intelligence Magazine, 2011.

[8] C.R. Sánchez Reinoso, M. Cutrera, M. Battioni, D.H. Milone, R.H. Buitrago, "Photovoltaic generation model as a function of weather variables using artificial intelligence techniques, "International Journal of Hydrogen Energy, Vol. 37, pp. 14781–14785, 2012.

[9] R. Saiju, S. Heier, "Performance analysis of lead acid battery model for hybrid power system," IEEE Transmission and Distribution Conference, pp. 1-6, April 2008.

[10] H. M. Bahaidarah, B. Tanweer, P. Gandhidasan, and S. Rehman "A Combined Optical, Thermal and

Electrical Performance Study of a V-Trough PV System—Experimental and Analytical Investigations," Energies, pp. 2803-2827, 2015.

[11] U. Schwarzer, D. Doncker, "Design and implementation of a driver board for a high power and high frequency IGBT inverter," IEEE Int. Conf. on Power Electronics, Vol. 4, pp. 1907 – 1912, 2002

[12] M. Islam, S. Mekhilef, "High efficiency transformerless MOSFET inverter for grid-tied photovoltaic system," IEEE Int. Conf. on APEC, 2014

[13] R. Chokhawala, S. Sobhani, "Switching Voltage Transient Protection Schemes for High-current IGBT Modules," IEEE Trans. Industry applications, vol. 31, no. 2, pp. 256-263, 2011

[14] F. W. Combrink, Hd. T. Mouton, J. H. R. Enslin, H. Akagi, "Design optimization of an active resonant snubber for high power IGBT converters," IEEE Trans. on Power Electronics, Vol. 21, Iss. 1, pp. 114-123, Jan. 2006

[15] H. Du. T. Mouton, F. W. Combrink, J. H. R. Enslin, H. Akagi, "Design optimisation of a resonant turn-off snubber for high-power converters," IEE Proceedings on Electric Power Applications, Vol. 148, Iss. 3, pp. 229 - 236, May 2001

[16] Dubilier, C. "Application Guide Snubber Capacitors," Cornell Dubilier Electronics Inc., New Bedford, MA 02744. Available: http://www.cde.com.

[17] P. Lynn, "Electricity from Sunlight: An Introduction to Photovoltaic," John Willy, 1st Edition, 2010.

[18] Y. Zhang, S. Hou, S. Minami, A. Kozawa, "A high current pulse activator for the prolongation of Lead-acid batteries" IEEE Conference on Vehicle Power and Propulsion, pp. 1-4, Sept. 2008.

[19] D. Benchetrite, C. GENEC, F. Mattera, M. Perrin, J. L. Martin, O. Bach, M. Le-Gall, P. Malbranche,"Optimization of charge parameters for lead acid batteries used in photovoltaic systems," IEEE Conference on Photovoltaic Energy Conversion, Vol.3, May 2003

[20] N. Meena, V. Baharwani, D. Sharma, A. Sharma, B. Choudhary, P. Parmar, R. B. Stephen, "Charging and discharging characteristics of Lead acid and Li-ion batteries," Power and Energy Systems Conference, pp. 1-3, March 2014.

[21] S. Taniguchi, K. Adachi, Y. Tanaka, "A method for identifying the full charging point and the degree of deterioration of lead-acid batteries, "IEEE Telecommunications Energy Conference, pp. 609-614, Sep 2000.

[22] MickroC Pro for PIC (Version 1.65)[Computer Software]. (2002-2009). Available from Labcenter Electronics: http://www.labcenter.com/index.cfm.

[23] PROTEUS DESIGN SUITE (Version 7.7 SP2) [Computer Software]. (1989-2009). Available from mikroElektronika Company: http://www.microe.com.