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ANFIS Modeling and Experimental Study of Standalone Photovoltaic Battery Charging System

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Abstract: *Due to scarcity of fossil fuel and increasing demand of power supply, we are forced to utilize the renewable energy resources. Considering easy availability and vast potential, world has turned to solar photovoltaic energy to meet out its ever increasing energy demand. The mathematical modelling and simulation of the photovoltaic system is implemented in the MATLAB/Simulink environment and the same thing is tested and validated using Artificial Intelligent (AI) like ANFIS. This paper presents a scheme for transferring power from photovoltaic (PV) module to a battery using solar charge controller based on buck DC/DC converter. The converter is configured in open loop mode and the same thing is implemented in hardware. The results reveals that the implemented hardware results matches closely with the simulated software results. Due to high initial investment on PV systems and non linearity of PV cell output characteristics counteract its wide commercialization. The PV array has an optimum operating point to generate maximum power at some particular point called maximum power point (MPP). To track this maximum power point and to draw maximum power from PV arrays, MPPT controller is required in a stand-alone PV system. Due to the nonlinearity in the output characteristics of PV array, it is very much essential to track the MPPT of the PV array for varying maximum power point due to the insolation variation. In order to track the MPPT conventional controller like PI controller with Incremental conductance algorithm is proposed and simulated. The output of the controller, pulse generated from PWM can switch MOSFET to change the duty cycle of buck DC-DC converter. The result reveals that the maximum power point is tracked satisfactorily for varying insolation condition.*

Key words: *Photovoltaic, Pulse Width Modulation, Proportional Integral Controller.*

I. INTRODUCTION

Today photovoltaic (PV) systems are becoming more and more popular with increase of energy demand and there is also a great environmental pollution around the world due to fossils and oxides. Solar energy which is free and abundant in most parts of world has proven to be economical source of energy in many applications [1]. The energy that the earth receives from the sun is so enormous and so lasting that the total energy consumed annually by the entire world is supplied in as short a time as half an hour. The sun is a clean and renewable energy source, which produces neither green house effect gas nor toxic waste through its utilization. It can withstand severe weather conditions, including cloudy weather. The watt peak price is decreased since the

seventies, this leads to large scale promising areas. It does not have any moving parts and no materials consumed or emitted. Unfortunately, this system has two major disadvantages, which the low conversion efficiency of electric power generation (9 to 16%), especially under low irradiation conditions and the amount of electric power generated by solar array changes continuously with the weather conditions like irradiation and temperature. To overcome this problem, maximum power point tracking (MPPT) technique will be used.

In order to regulate the converter due to non linearity conventional controller like PI controller with Incremental conductance algorithm is proposed and simulated. The tracking algorithm integrated with a solar PV system has been simulated with buck DC-DC converter for the application of battery charging in stand - alone PV system. The proposed PV system with buck DC-DC converter is shown in Fig.1.

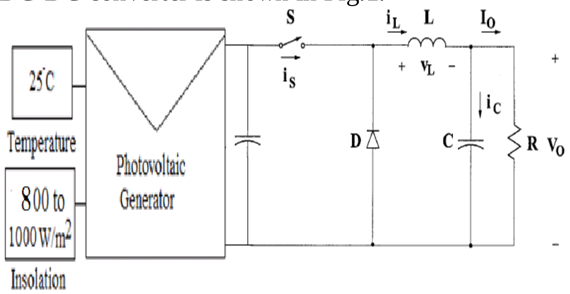


Fig.1. Photovoltaic module with DC-DC buck converter.

II. MATHEMATICAL MODELING OF PHOTOVOLTAIC CELL

The proposed MPPT is based on the behavior of the photovoltaic array by means of temperature and irradiation variation [2]. The mathematical model of PV array is implemented in the form of current source controlled by voltage, sensible to two impact parameters, that is, temperature (°C) and solar irradiation power (w/m^2).

An equivalent simplified electric circuit of a photovoltaic cell presented in Fig.2.

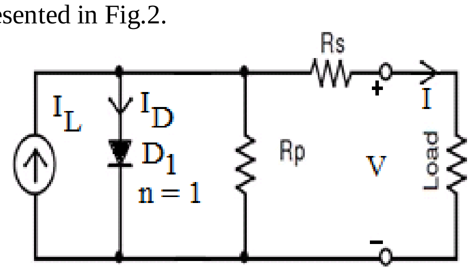


Fig.2. Equivalent circuit of photovoltaic cell.

The expressions obtained from fig.2. are given below.

The load current I_L is obtained is given in equation (1) as,

$$I = I_L - I_o\left[\exp\left(\frac{q(V+IR_s)}{\gamma k T_c}\right) - 1\right] \quad (1)$$

I_L is the photo electric current related to the given irradiation condition given by equation (2),

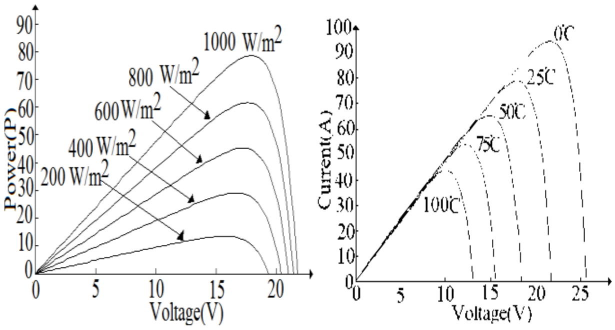
$$I_L = \left(\frac{G}{G_{REF}}\right)\left[I_{L,REF} + \mu_{ISC}\left(T_C - T_{C,REF}\right)\right] \quad (2)$$

The diode saturation current (I_o) is given by the equation (3),

$$I_o = I_{o,REF}\left(\frac{T_C}{T_{C,REF}}\right)^3 \exp\left[\left(\frac{qEg}{k\gamma}\right)\left(\frac{1}{T_{C,REF}} - \frac{1}{T_C}\right)\right] \quad (3)$$

where - I_D is the diode current; I_L- is the photoelectric current related to a given condition of irradiation and temperature; V is the output voltage [V]; I_o is the saturation diode current [A]; γ is the form factor which represents an index of the cell failing; R_s is the series resistance of the cell [Ω]; q is the electric charge ($1.602*10^{-19}$C); k is the Boltzmann's constant ($1.381*10^{-23}$K); T_c is the module temperature [K]. E_g is the energy gap of the material with which the cell is made (for the silicon it is 1.12 eV); G is the radiation [W/m^2]; G_{REF} is the irradiation under standard conditions [W/m^2] $I_{L,REF}$ is the photoelectric current under standard conditions [A]; $T_{C,REF}$ is the module temperature under standard conditions [K]; μ_{ISC} is the temperature coefficient of the short circuit current [A/K], given by the manufacturer according to CEI EN 60891 standard [3-4].

Figure 3 shows the simulated P-V characteristics for varying irradiation and temperature in MATLAB/SIMULINK environment. It can be observed from simulated results as shown in Fig. 3(a), the photo current is directly proportional to irradiation. It is noted from Fig. 3(b) that the terminal voltage increases with decreasing temperature.



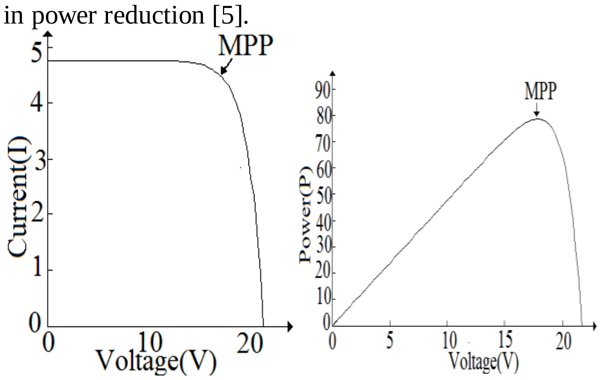
(a) *(b)*

Fig.3. Simulated waveforms showing the effect of (a) radiation and
(b) temperature on P-V characteristics.

The manufacturers data at standard conditions are given as P_{max} = 80W, I_{max} = 4.515 A and V_{max} = 21.6V. The simulation results obtained were: P_{max} = 78.51W, I_{max} = 4.35 A and V_{max} = 18.2 V. It is seen that the simulation model showed excellent correspondence to manufacturer's data and therefore this model was considered sufficient for the purpose of further study [4-8].

Simulated I-V, P-V characteristics for the maximum power point tracking (MPPT) is shown in figure.4.

At this Maximum Power Point (MPP), the solar array is matched to its load and when operated at this point the array will yield the maximum power output. From Fig. 4 (a) & (b), it is observed that the power output has an almost linear relationship with array voltage unit, hence the MPP is attained. Any further increase in voltage results in power reduction [5].



(a) *(b)*

Fig.4. PV array simulated curves (a) I-V curve (25°C) and (b) P-V curve (1000w/m^2).

III. ANFIS MODELING

The main objective of this work is to investigate the suitability of artificial intelligent systems (neural network and fuzzy logic) for validating the proposed PV system under variable climatic condition. Neural network models are data based where as fuzzy logic models are based on expert knowledge; in a situation in which both data and knowledge of underlying system are available, a neuro fuzzy approach is able to exploit both sources.

a. *Stand – Alone Photovoltaic System*

Fig.5 shows the overall simple configuration of the stand alone Photovoltaic power supply system.

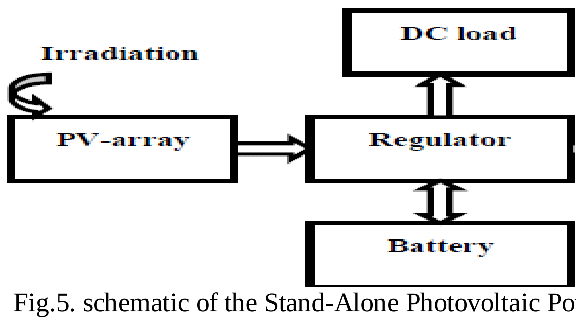


Fig.5. schematic of the Stand-Alone Photovoltaic Power supply system.

b. *ANFIS Modeling of photovoltaic system*

The Neuro-Fuzzy system used here is the adaptive network based fuzzy inference system (ANFIS). Fig.6 shows the developed ANFIS model. In order to obtain the modeled, predicted and optimized PVPS system due to its non linearity this is influenced by variable climatic conditions like solar irradiation and ambient temperature. Artificial Intelligent technique like ANFIS is proposed and simulated. The ANFIS was validated with several test data by minimizing mean square error.

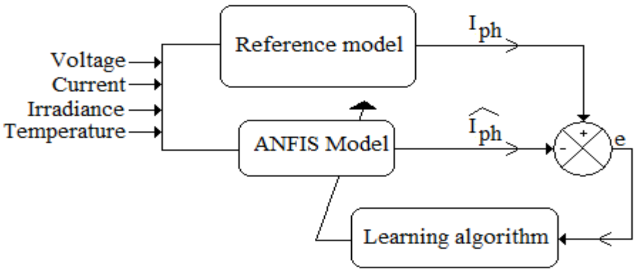


Fig.6. Developed ANFIS model.

Fig.7 shows the architecture of an ANFIS equivalent to a first-order sugeno fuzzy model with two inputs and two rules consisting of five different layers.

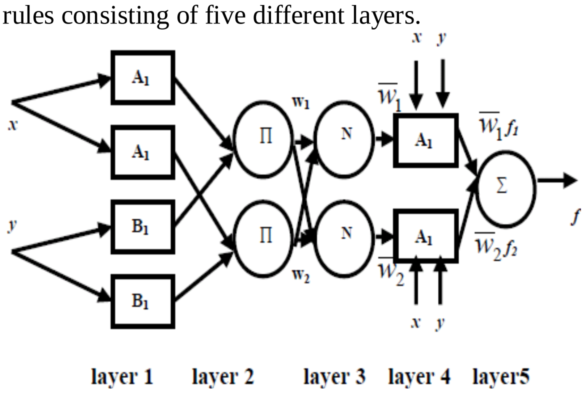


Fig.7. Architecture of an ANFIS equivalent to a first-order *sugeno* fuzzy model with two inputs and two rules.

The detailed description of the each layer is given as below:

Layer 1:

Generates the membership grades based upon premise signals using any appropriate parameterization membership function such as the generalized bell function given in equation (4):

$$O_{1,i} = \mu_{Ai}(x) = \frac{1}{1+\left|\frac{x-c_i}{a}\right|^{2bi}} \quad (4)$$

Layer 2:

Generates the firing strength of each rules using designated Π which is given by equation (5):

$$O_{2,i} = w_i = \mu_{Ai}(x)\mu_{Bi}(y) \ \ i=1,2 \quad (5)$$

Layer 3:

Generates the normalized firing strength which is given by equation (6)

$$O_{3,i} = \overline{w_i} = \frac{w_i}{w_1+w_2} \quad (6)$$

Layer 4:

Calculates the rule outputs based upon consequent parameters using the function (7):

$$O_{4,i} = \overline{w_i} f_i = \overline{w_i}(p_i x + q_i y + r_i) \quad (7)$$

Layer 5:

Gives the overall ANFIS output by equation (8).

$$O_{4,i} = \sum_i \overline{w_i}\, f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (8)$$

Where: A_i, B_i are the linguistic labels ("small", "large," etc.); $\{a_i, b_i, c_i\}$ is the premise parameter; w_i is the weight factor; $(p_i, q_i, r_i,)$ is the consequent parameter; O is the output function and Π is the firing strength of each rule.

Fig.8 shows the simulated result of a photovoltaic power supply system using an adaptive Neuro-Fuzzy Inference System (ANFIS) under standard test condition of irradiation 1000w/m^2 and temperature of 25 °C.

The result reveals that the correlation coefficient between measure values and those estimated by the ANFIS gave good prediction accuracy. The satisfactory performance of ANFIS proves that it can be used for the prediction of the optimal configuration of the PV system.

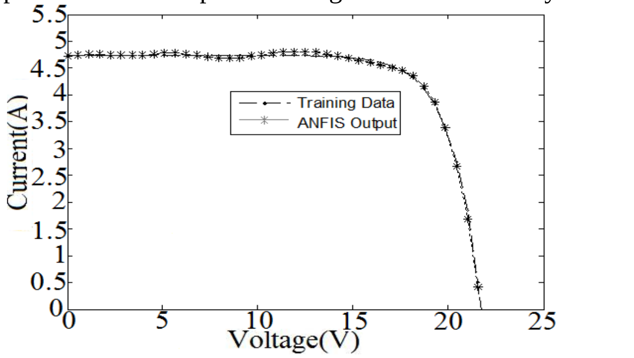


Fig.8. ANFIS modelling of the photovoltaic system for irradiation of 1000w/m^2 and temperature 25 °C.

IV. DESIGNING OF BUCK CONVERTER

a. Circuit diagram of buck converter.

Fig.9 shows the schematic diagram of buck converter with varying irradiation, which consists of DC supply voltage V_s, as PV generator controlled switch S, diode D, buck inductor L, filter capacitor C and load resistance R. The current and voltage waveforms of the converter in CCM are presented in fig.10.

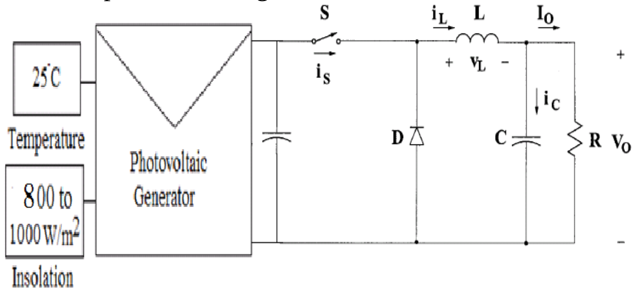


Fig.8. Circuit diagram of buck converter with PV module.

It can be seen from the circuit that when the switch S is commanded to the on state, the Diode D is reverse biased. When the switch S is off, the diode conducts to support an uninterrupted current in the inductor through the output RC circuit using faradays law for the buck inductor as given in (9)

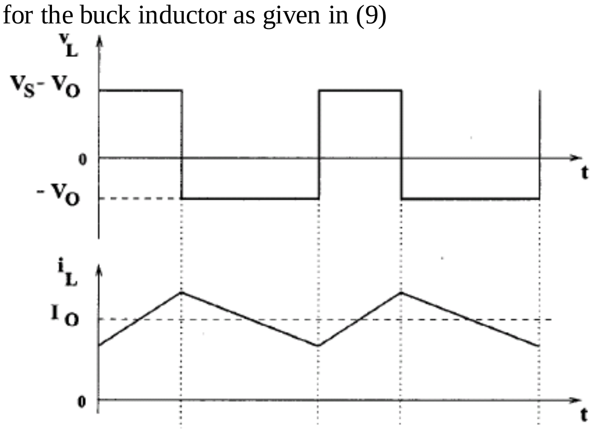


Fig.10. Theoretical voltage and current waveforms of buck converter.

$$(V_s - V_o)DT = (-V_o)(1-D)T \quad (9)$$

The DC voltage transfer function turns out to be,

$$M_v = \frac{V_o}{V_s} = D \quad (10)$$

The buck converter operates in the CCM for L>Lb. The calculated value of inductance L=20µH. To limit the ripples in the output side, larger filter capacitor is required. The filter capacitor must provide the output dc current to the load when diode D is off. The minimum value of filter capacitance calculated that results in the voltage ripple V_r is given by C_{min} =472.5uF.

Thus the buck converter is designed in the open loop for the supply voltage of 21.7V DC, which is generated by the Photovoltaic panel for 1000w/m^2 and 25°C. Fig.11 shows the simulated voltage and current waveforms of buck converter. It is seen that these waveforms are agreed closely with theoretical waveforms as shown in fig.10 [9-11].

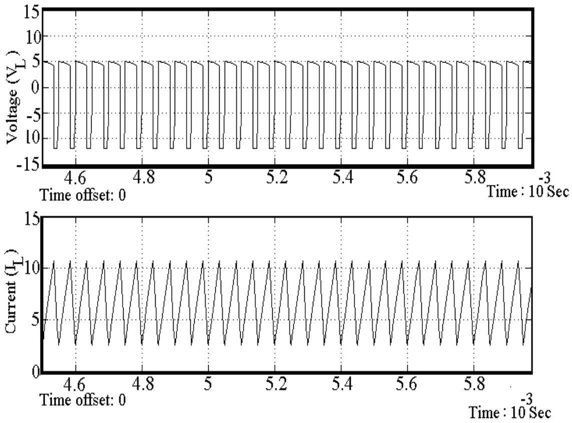


Fig.11. Simulated waveforms showing the voltage and current of buck converter.

V. CLOSED LOOP SIMULATION OF BUCK CONVERTER WITH INCREMENTAL CONDUCTANCE MPPT ALGORITHM

The block diagram of closed loop simulation with MPPT algorithm is shown in fig.12. To regulate the output voltage V_o, the switching frequency of the PWM pulses are varied depends on error.

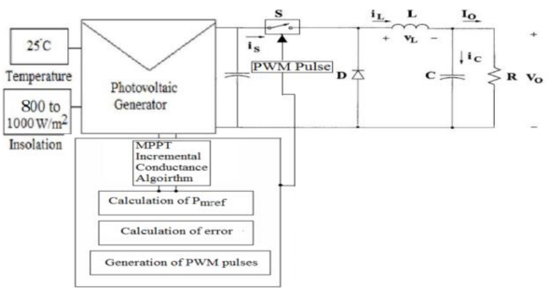


Fig.12. Block diagram of the proposed Incremental Conductance based MPPT scheme.

a. MPPT with incremental conductance algorithm

To track and extract maximum power from the PV arrays for a varying insolation level and at a given cell temperature, a conventional controller like proportional integral controller is proposed with incremental conductance algorithm as tracking method [11-16]. The Flow chart of the proposed Incremental Conductance algorithm is shown in Fig.13. This algorithm has the advantage of fast response to the rapidly varying illumination condition. The conventional PI controller parameters are obtained by Z-N open loop method [9] as proportional gain K_c= 1e-5 and integral gain K_i = 0.01.

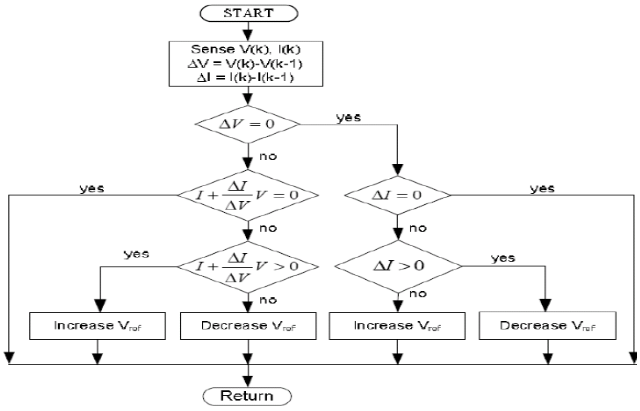


Fig.13. Flow chart of the proposed Incremental Conductance algorithm.

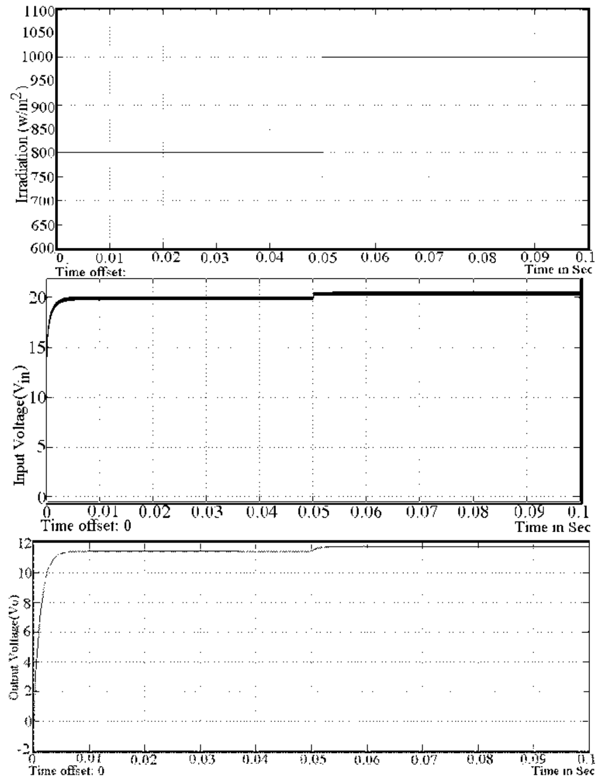


Fig.14. Simulation results depicting the change of insolation from 800 to 1000w/m2, input voltage (V_{in}) and output voltage (V_o).

The simulated closed loop output for the insolation variation from 800 w/m^2 to 1000 w/m^2 with input voltage (V_{in}) and output voltage (V_o) are shown in Fig.14.

VI. OPEN LOOP EXPERIMENTAL SET UP

The electrical characteristics of the proposed panel are given in table I.

TABLE I
STANDARD TEST CONDITION DATA

ELECTRICAL CHARACTERISTICS	
Cell	Poly-crystalline silicon

No of cells and connections	36 in series
Open circuit Voltage (V_{oc})	21.75 V
Short – circuit current (I_{sc})	4.85A
Maximum Power Voltage at P_{max} ,(V_{pm})	18.25 V
Maximum Power Current (I_{pm})	4.315 A
Maximum Power (P_{max})	78.24 W (+10%/-5%)
Module Efficiency (ηm)	13%
Series Fuse Rating	10 A
Type of output terminal	Junction Box
Temperature coefficient of I_{sc}	0.65e-3±0.015%/°C
Temperature coefficient of V_{oc}	-160±20mV%/°C
Temperature coefficient of Power	-0.5±0.05%/°C

a. Battery

The lead-acid battery of 13.3V (±1) with 7.5Ah is used for the solar photovoltaic charging application.

Fig.15. shows the input voltage to the buck converter from photovoltaic panel.

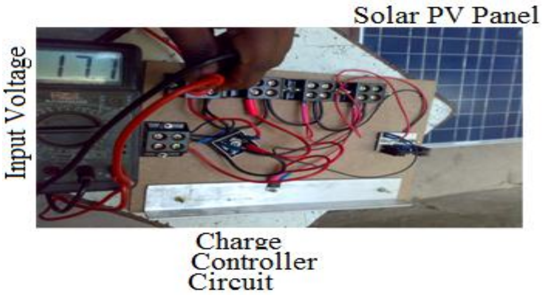


Fig.15. Photocopy of the Experimental setup showing input voltage (V_{in}) of 17.1 V from the photovoltaic panel under 1000w/m^2 irradiation.

Fig.16. output voltage (V_o) from the charge controller which charges the battery without MPPT algorithm.

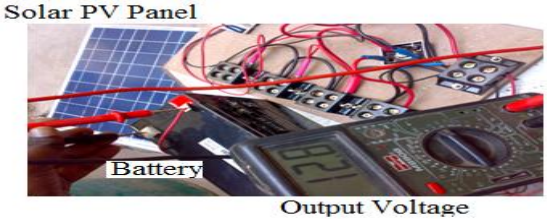


Fig.16. Photocopy of the Experimental setup showing output voltage (V_o) of 12.8 V from the charge controller which charges the battery under 1000w/m^2 irradiation.

VII. SCOPE FOR FUTURE WORK

The scope for future work is the hardware implementation of the above said stand alone process with MPPT algorithm in closed loop using PIC16F87X microcontroller for varying illumination.

VIII. CONCLUSION

Conventional PI Controller method for MPPT of Photovoltaic array is presented in this paper on the basis of Incremental Conductance algorithm. The simulation results show that the Incremental Conductance algorithm has the merits such as simplicity fast response, low over-tuning, high control, precision and easy implementation. The hardware results are in line with simulated results.

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