Fuzzy MPPT Control and Power Regulation for Standalone Photovoltaic Energy Conversion System

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Abstract: In this paper, a maximum power point tracking (MPPT), based on fuzzy logic control, algorithm is proposed to operate a standalone photovoltaic energy conversion with battery storage. The fuzzy algorithm minimizes the error between the actual power and the estimated maximum power. In order to ensure a smooth power transfer in the system, load voltage, power and battery charge-discharge are controlled using cascade control loops. Experimentation was conducted using Opal-RT real time simulator and a physical PV system. Experimental results were presented to validate the effectiveness of the proposed MPPT controller.

Keywords: PV System, Fuzzy Logic Control, Maximum Power Point Tracking, Battery Storage

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I. INTRODUCTION

The dependence on non-renewable fossil fuel energy causes many environmental problems like global warming and pollution. In order to minimize these effects, renewable energy supplies should be used instead of non-renewable sources. One of the most appropriate renewable energy sources is solar energy. PV solar panels convert the energy from the sun to electrical energy so that it can be used by loads and devises. To benefit from the solar energy for homes and other uses, PV panels are imbedded in models which are a part of the system that provides energy to different loads [1, 2]. Solar panels do not need much maintenance, produce no noise or pollutants, and have no moving parts. The issue with solar systems is the high installing cost and the variation of energy form the solar panel with environmental conditions. [3]. For these reasons and in order to attain the maximum efficiency from the solar panel, it is important to obtain the maximum available power at any operating condition. Also, the power distribution across the system has to be managed. Storage devices are used so that the energy is stored or supplied according to the availability of sufficient power and the load requirements.

In the presence of nonlinear and unpredictable systems, it is found that fuzzy logic controllers (FLC) perform better than traditional proportional-integral-derivative (PID) controllers [4] and has been used in different applications [5, 6]. Therefore, FLC can be used for maximum power operation of PV system due to its suitability to nonlinear operation and fast response in high varying conditions [7], [8].

The behaviour of PV solar systems is characterised by fast and frequent changes in the supplied power. This is due to the influence of variation in temperature, sun radiation and incident angle on the power produced by the PV panel [2]. Maximum power point tracking (MPPT) techniques are used to operate the panel at the maximum power point at any condition. The MPPT control system consists of an algorithm and a controller, and provides adequate voltage-current corresponding to the maximum power point [8]. Furthermore, the standalone PV system is controlled, by maintaining a constant load power regardless the variation in external conditions, through regulating the voltage load [4]. In the case of excess in power supply from the PV system, the extra power is stored in batteries. Also, the batteries would supply the system at times of non-sufficient power supply [9]. The charging-discharging of batteries is conducted through regulating the DC-link voltage to follow a constant value [10, 11].

In this paper, a control system for a standalone PV system with battery storage to feed a DC load is implemented. Mamdani fuzzy control method is used to obtain the maximum power. The fuzzy control algorithm is based on minimizing the error between the estimated maximum power, as a reference, and the actual power from the PV panel. PI controllers are used to control the load power and to regulate the battery charge and discharge [7, 8].

II. STAND-ALONE PV ENERGY CONVERSION SYSTEM

The standalone PV energy conversion system consists of a PV module, DC-DC converters, battery based energy storage and a DC load as shown in Figure 1.

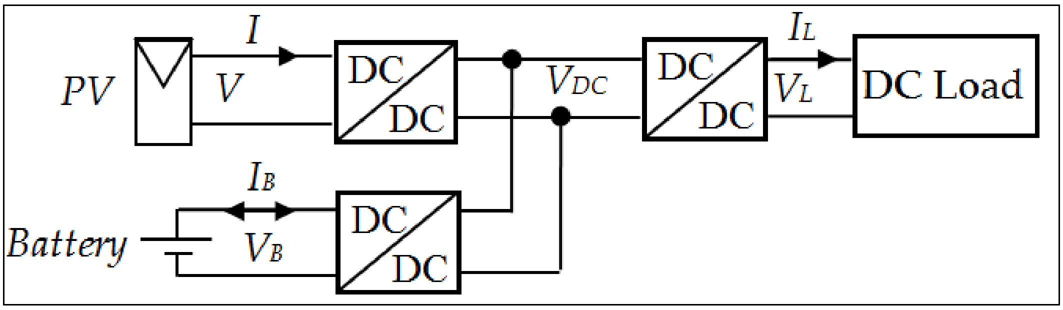


Figure 1. Standalone PV energy conversion with batter storage system

A. PV Panel Modeling

The current-voltage relationship a PV module, represented by the PV cell equivalent circuit shown in Figure 2, is given by the following expression

$$I = n_p I_{ph} - n_p I_{sat}\left(\exp\left(\left(\frac{q}{AKT}\right)\left(\frac{V}{n_s} + IR_s\right)\right) - 1\right) - \frac{V + R_s I}{R_{sh}} \qquad (1)$$

where, I is the module terminal current, I_{ph} is the photocurrent, I_{sat} is the diode saturation current, V is the module terminal voltage, q is the electron charge, A is the diode ideality factor, K is the Boltzmann constant, n_p number of cells in parallel, n_s is the number of cells in series, R_s and R_{sh} are the series and shunt resistances, respectively, and T is the surface temperature of the PV module.

Figure 3 illustrates the current-voltage curve under different operating conditions.

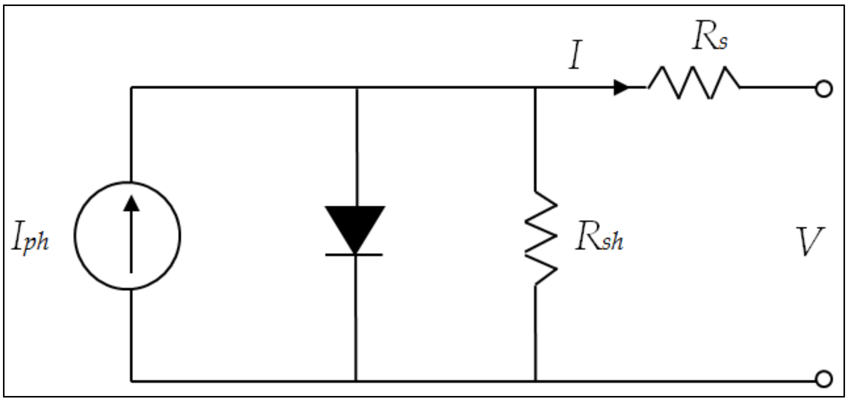


Figure 2. Equivalent circuit of a PV cell

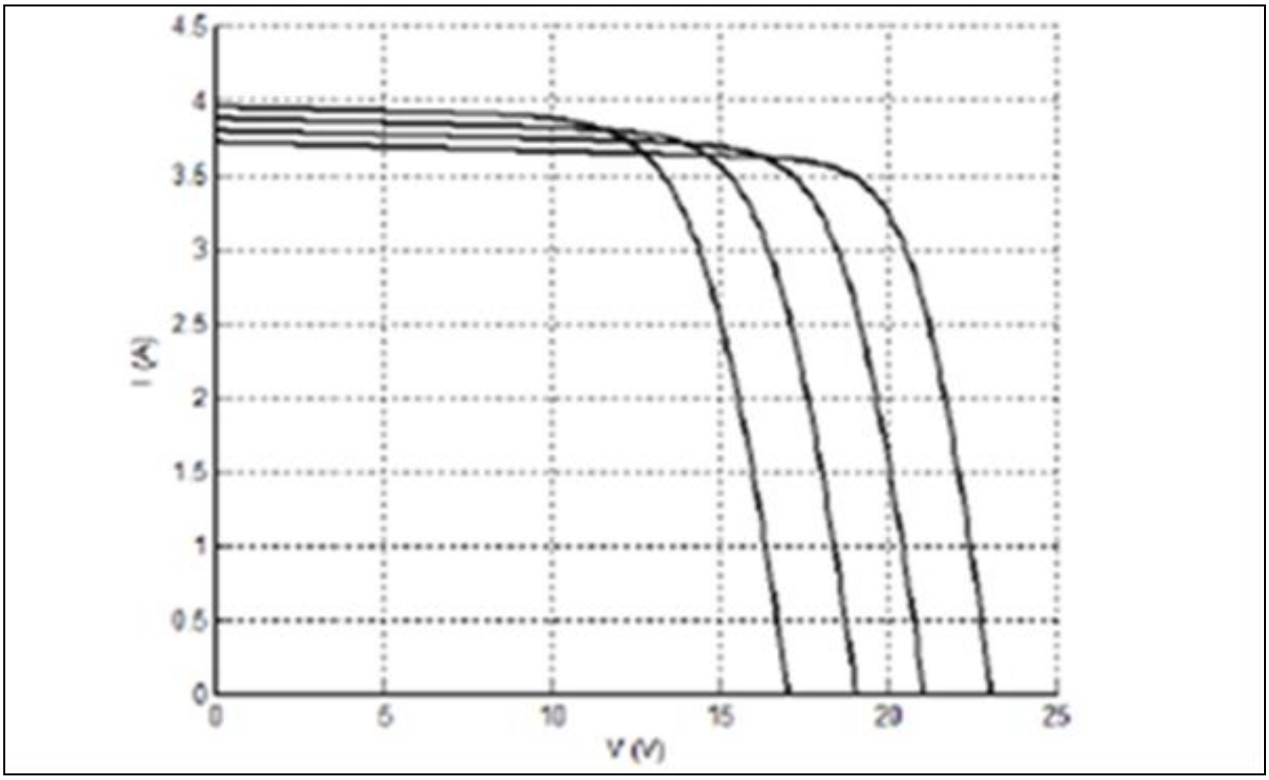


Figure 3. Current-voltage characteristics of a PV cell

B. MPPT Control System

The MPPT control system consists of a MMPT algorithm and a DC-DC boost converter. The duty cycle D, generated by the MPPT algorithm, is fed to the gate of the converter through pulse width modulation block. The MPPT control system is shown in Figure 4.

The power produced by the PV module is expressed as

$$P_{PV} = V \times I \tag{2}$$

The input-output voltage relationship of the DC-DC boost converter is given by

$$\frac{V_{DC}}{V} = \frac{1}{1-D} \tag{3}$$

where, V is the PV panel voltage, V_{DC} is the DC-link voltage and D is the duty cycle.

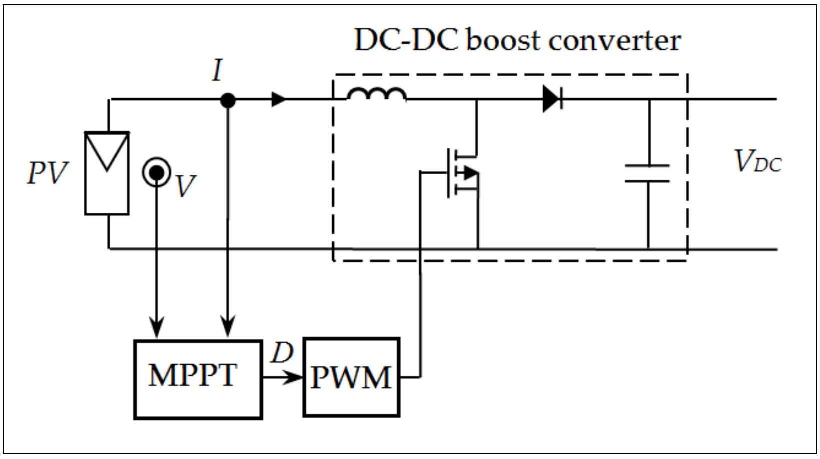


Figure 4. MPPT control of the PV system

C. *Energy Storage System*

The energy storage system consists of battery and a DC-DC buck-boost converter. The charge-discharge process. The charge and discharge operation for the battery is controlled by two loops as shown in Figure 5. The difference between desired load power (P_L) and the PV power (P_{PV}) is divided by the battery voltage (V_B) to produce the desired battery current, which is compared to the battery current and passed through a PI control to generate the PWM output of the DC-DC converter gate.

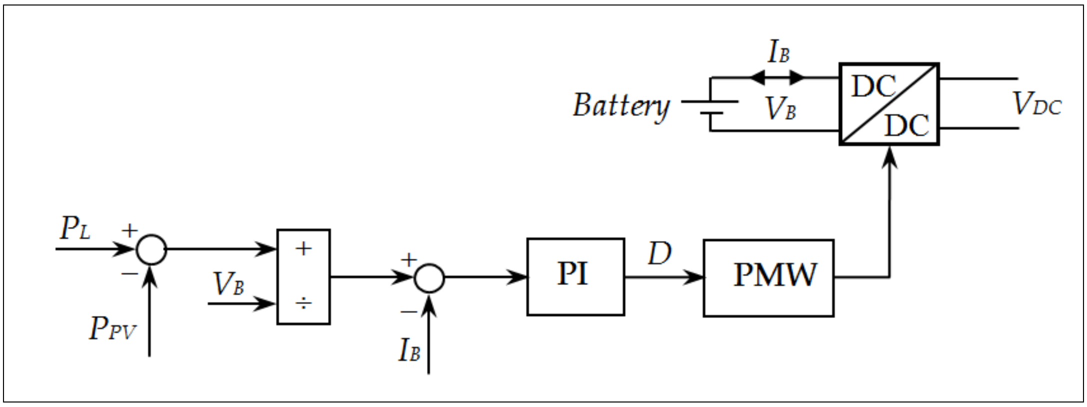


Figure 5. Battery storage control system

The input-output voltage relationship of the DC-DC buck-boost converter is given by

$$\frac{V_{DC}}{V_B} = \frac{D}{1-D} \tag{4}$$

The sign and the value of the desired battery current operate the battery in charge and discharge modes as follows:

- ***Battery charge mode***: In this mode, the power from the PV system is more than the load requirements ($P_{PV} > P_L$). The battery is charged which the difference between the two powers.
- ***Battery Discharge Mode***: The power from the PV system is less than the load requirements ($P_{PV} < P_L$). The battery will discharge the stored power to provide the load demand.
- ***No Action Mode***: In this mode, the load demand is equal or nearly equal to the supplied power and there will be no charge or discharge from the battery side.

D. ***Load Side Control***

The control of the load voltage and current according to the load requirements is done by two control loops. The outer loop is used to control the load voltage, and the inner loop to control the current as shown in Figure 6. The error for the outer loop is obtained by subtracting the actual load voltage (V_L) from the desired load voltage (V^*) and then the output is given to a PI controller. The output of the PI controller (I^*) is subtracted from the load current (I_L) to produce the error signal. The error is directed to the proportional controller, then to the signal generator to produce the output. The output of the signal generator determines the duty cycle of the DC-DC Buck-Boost converter to increase or decrease the load voltage to the control signal.

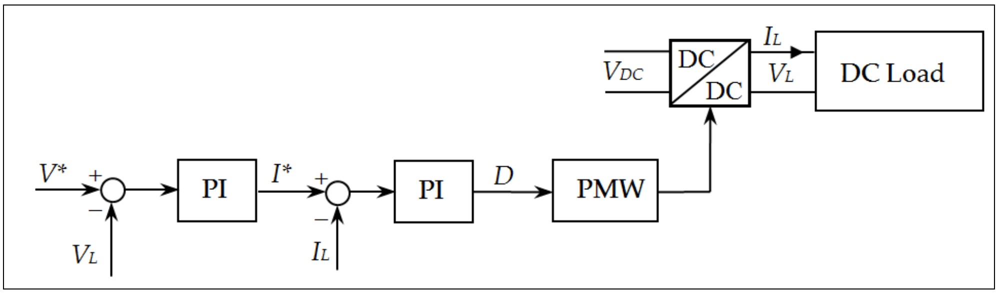


Figure 6. Load side control system

III. MPPT FUZZY LOGIC CONTROLLER

The MPPT function is realised by using a Fuzzy PI controller that has one input, which is the error (e) between the desired maximum power and the actual power. The estimated maximum power (P_m) is based on the open-circuit voltage (V_{OC}) and the short-circuit current (I_{SC}) such as

$$e = P_m - P_{PV} \tag{5}$$

$$P_m = V_{OC} \times I_{SC} \tag{6}$$

The values of short circuit current and open circuit voltage are found from the specifications of the PV panel.

The structure of the MPPT fuzzy logic controller is illustrated in Figure 7.

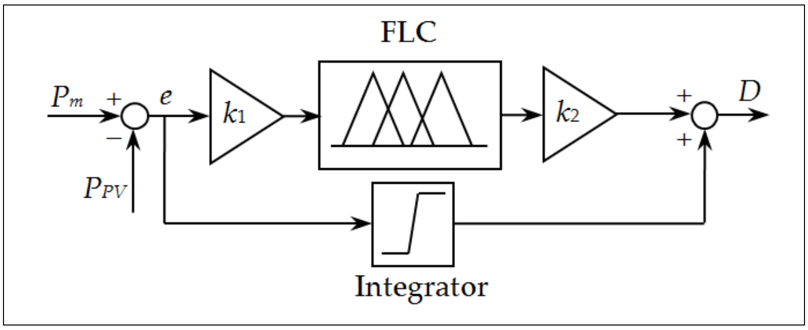


Figure 7. MPPT fuzzy logic controller

The FLC uses triangular type membership functions for both the error and the output that have three values as shown in Figure 8. The integral function is fed directly from the error to be added to the fuzzy control output (s). The gains (k_1 and k_2) are used to scale the range of real variables to the FLC. Usually when using Fuzzy controllers, the values are scaled to a range of 0 to 1 by division by a gain. The range of the fuzzy membership function is called the Universe of Discourse [12]. The range of values for the error (e) is chosen from monitoring the values of the same operation when the conventional PI controller was used and estimating similar values.

Three membership functions for both the error (e) and the output signal were used: small (S), medium (M) and Big (B). The shape and value of membership functions are illustrated in Figure 8.

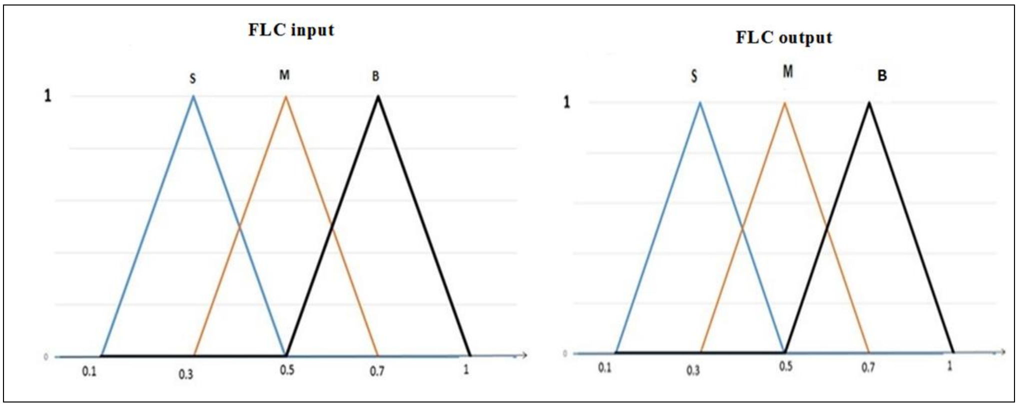


Figure 8. Fuzzy membership functions

Mamdani fuzzy rules were used in the development of the MPPT FLC. In its operation, the value of the voltage is needed to be brought to a point which achieves the desired maximum power. This means that the signal should follow the error between the actual and the reference power. The rules were derived depending on the following reasoning:

- When the error is small, it means that the actual value of power is close to the desired value and only a small signal is needed to accomplish that.

- When the error is zero, it means that the actual power is the same as the desired power.

- When the error is positive, it means that there is a big difference between the actual power and the desired power, which puts the choice of a (B) signal.

The rules are presented as follows

If e is Small then s is Small (7.a)

If e is Medium then s is Medium (7.b)

If e is Big then s is Big (7.c)

IV. EXPERIMENTAL RESULTS

The experimental setup, shown in Figure 9, includes a PV module, three DC-DC converters, and a resistive load. The schematic of the PV system with battery storage is detailed in Figure 10. The system is operated using the Opal-RT real time system, a powerful tool suitable for hardware-in-the-loop (HIL) applications, which includes the real-time digital simulator (OP5600), to execute the control algorithms, and the data acquisition board (OP8660) to measure voltage and current at different locations in the PV energy system.

Specifications of the PV module and the battery, used in this experiment, are given in Tables 1 and 2, respectively.

The usual difference between the estimated and the actual power ranges between 0 and 5 volts. Therefore, the input and output of the fuzzy controller were scaled by the gains k_1= 0.2 and k_2=5, respectively. The parameters of the PI controllers were chosen by trial and error. The irradiation was varied by turning ON-OFF different industrial lamps.

The PV system was tested under variable irradiance and voltage-current-power responses were measured at the PV module, battery and load sides to verify the performance of the proposed control system. Experimental results are depicted in Figures 11−12.

In this work both maximum power tracking and power control for the PV energy system with the battery storage were implemented. The MPPT controller was used to achieve the maximum power through the fuzzy logic control strategy. It can be observed that the MPPT control system was able to boost the voltage output at the DC-DC converter of the PV system as shown in Figures 11 (a) and (b). Also the maximum power was obtained despite the changes in the PV current, Figure 12 (a), due to the variable irradiance as shown in Figure 13 (PV power). The MPPT based FLC provides fast response and tracking of the maximum power.

Table 1. Specifications of the PV module CS6P under STC[1].

Quantity	*Unit*	*Value*
Maximum Power	W	260
Open Circuit Voltage	V	37.8
Short Circuit Current	A	8.99
Maximum Power Point Voltage	V	30.7
Maximum Power Point Current	A	8.48

[1] STC: irradiance=1000W/m^2; Module temperature 25^{o}C, AM=1.5.

Table 2. Specifications of the lead acid battery (VRLA).

Quantity	***Unit***	***Value***
Voltage	V	48
Capacity	Ah	10
Short Circuit Current	A	8.99
Maximum Charge Current	A	4
Maximum Discharge Current	A	7

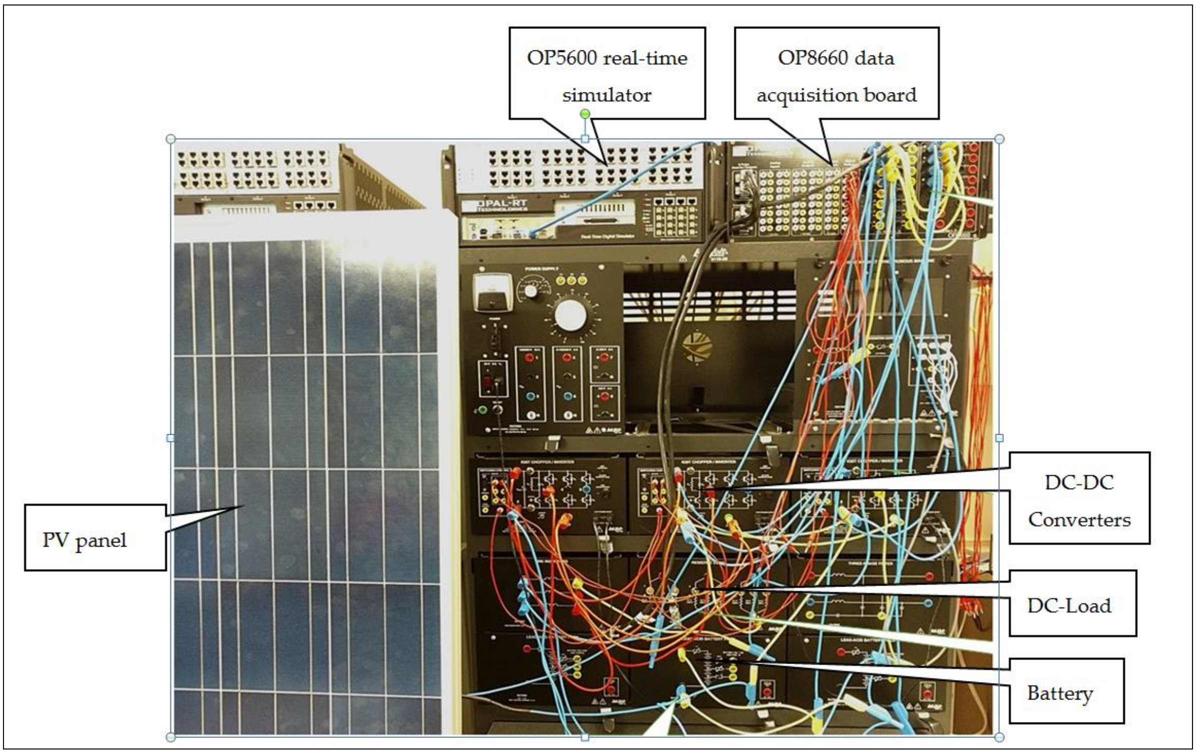


Figure 9. PV system experimental setup

The load voltage was controlled by PI controllers using two loops. The load side control system maintains a constant voltage, as shown in Figure 11 (d) and provides a constant power, as shown in Figure 13 (load power) despite the changes in the PV power supply due to the battery control system. This control system managed to stabilize the load current under different conditions as shown in Figure 12 (c), which helped in supplying a constant and stable power to the load.

The charge and discharge operation of the battery and the battery power control was done by PI controllers. The outer loop of the power control stabilizes the DC voltage. The use of power difference and two control loops, for the voltage and the current, gives more robustness to the charge and discharge operation, which was controlled in various conditions. From Figure 11 (b), it can be observed that the voltage at the DC-link is kept stable despite the varying input voltage. The power flow at the battery side is controlled by the current inner controller. From Figures 12 (b), it can be observed that the battery current changes with changing the input power, due to the discharge operation then stabilizes. When the power was not sufficient for the load, the battery discharged through the negative current. Figure 13 (battery power) illustrates that the battery power curve follows the PV voltage and power change.

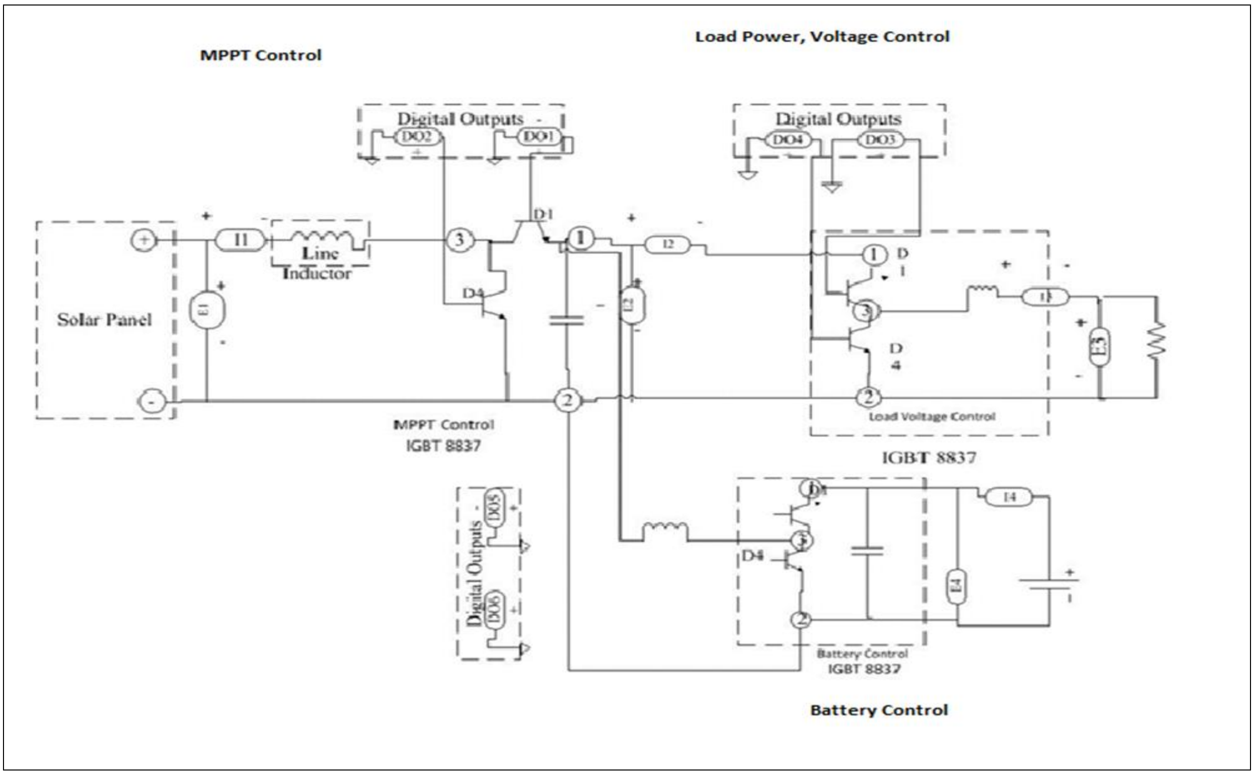
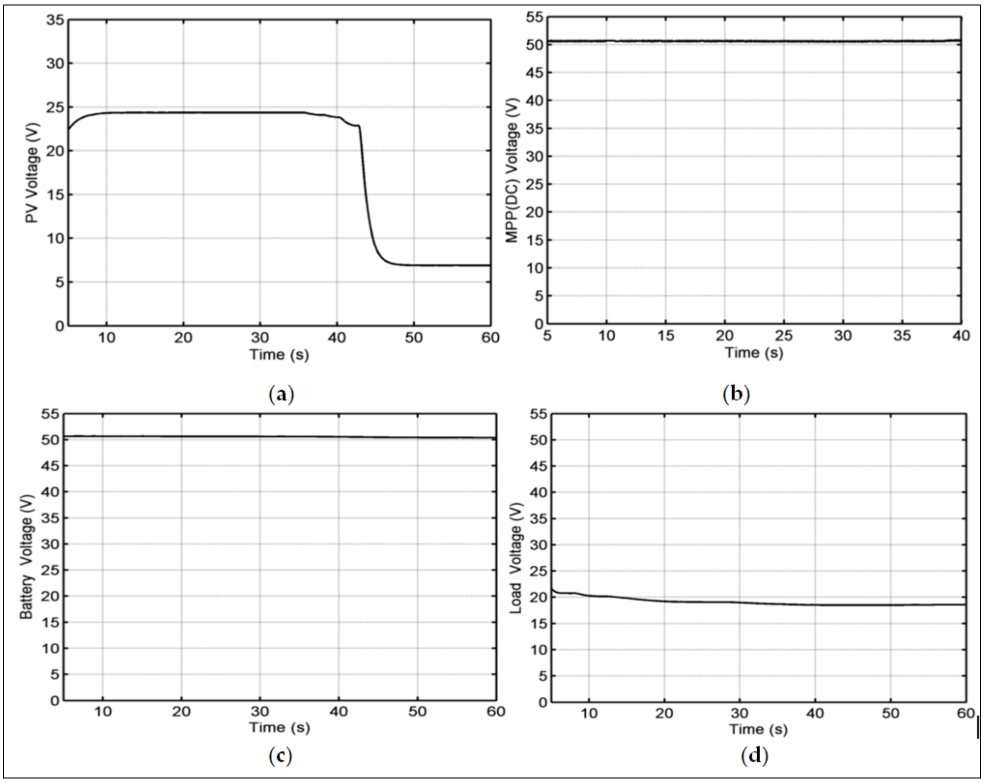


Figure 10. Schematic of the standalone PV system with battery storage



(a)

(b)

(c)

(d)

Figure 11. Voltage response in the PV energy system. (a) PV module voltage; (b) DC-link voltage; (c) Battery voltage; (d) Load voltage.

The experimental results and the observations demonstrate the good capabilities of the proposed control system to extract maximum power from the PV panel and the smooth power transfer between the PV panel, the battery and the load.

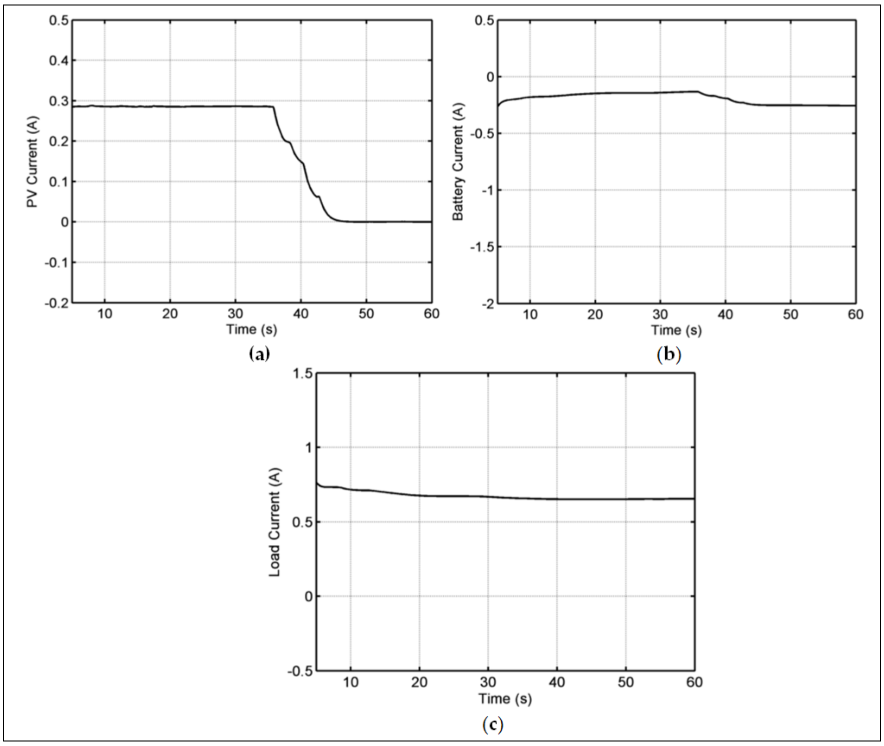


Figure 12. Current response in the PV energy system. (a) PV module current; (b) Battery current; (c) Load current.

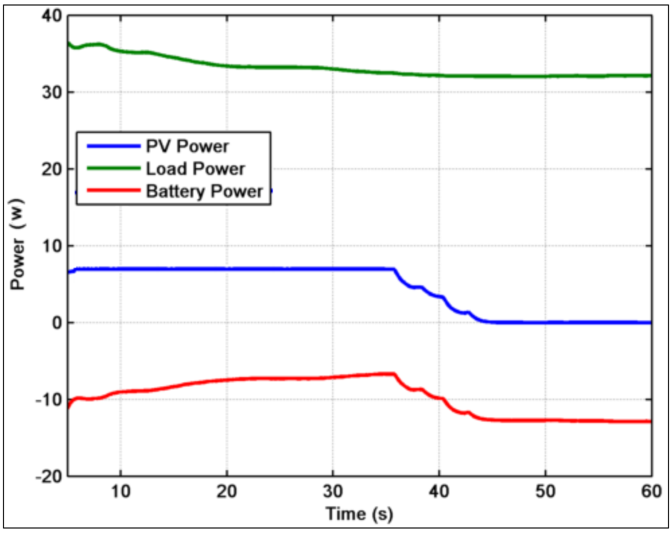


Figure 13. Power at different locations in the PV energy system

V. CONCLUSION

In this paper, a fuzzy MPPT controller and a control system has been developed to operate a standalone PV system with battery storage. The MPPT algorithm is based on a power error input to be minimized in order to maximize the power extraction. Smooth power transfer between the PV panel, the battery and the load has been successfully achieved using the developed control system as demonstrated through the experimental results.

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Conflict of Interest: The authors declare that they have no conflict of interest.

Ethical Statement: The authors declare that they have followed ethical responsibilities.

REFERENCES

[1] G. Cook, L. Billman and R. Adcock (1995). Photovoltaic Fundamentals, 3nd ed.; National Renewable Energy Laboratory, Washington DC, USA.

[2] N. Femia, D. Granzow, G. Petrone and G. Spagnuolo (2009). Optimized one-cycle control in photovoltaic grid connected application, IEEE Trans. Aerospace, vol. 42, no. 3, pp. 954–972.

[3] D.K. Chaturvedi (2010) Modelling and simulation of fuzzy systems using Matlab and Simulink, Tailor and Francis Group, New York, 2010.

[4] D. Hohm and M.E Ropp (2003). Comparative study of maximum power point tracking algorithms. Progress is Photovoltaics: Research and Application, vol. 11, pp. 47–62.

[5] T. Chopra (2015). Performance improvement in fault diagnosis using fuzzy logic type-2 classifier. International Journal of Advanced Engineering Research and Applications, vol. 1, no. 4, pp. 163–169.

[6] M. Talwar (2016). Fuzzy Logic Based CSTR Control. International Journal of Advanced Engineering Research and Applications, vol. 1, no. 11, pp. 446–453.

[7] E. Liu, J.Bebic, B. Kroposki and J. deBedout (2008). Distribution system voltage performance analysis for high-penetration photovoltaics. Proc. IEEE Energy 2030 Conference, GA, Atlanta, pp. 17–18.

[8] A.M. Eltamaly and H.M. Farh (2013). Maximum power extraction from wind energy system based on fuzzy logic. Electric Power Systems Research, 97, pp. 144–150.

[9] X. Sun, W. Wu, X. Li and Q. Zhao (2002). A research on photovoltaic energy controlling system with maximum power point tracking. Proc. IEEE Power Conversion Conference, Osaka, Japan.

[10] Y. Riffonneau, S. Bacha, F. Barruel and S. Ploix (2011). Optimal power flow management for grid connected PV systems with batteries. IEEE Trans. Sustainable Energy, vol. 3, no. 2, pp. 309–319.

[11] R.J. Wai,; W.H. Wang and C.Y. Lin (2008). High performance stand-alone photovoltaic generating system, IEEE Trans. Industrial Electronics, vol. 55, pp. 240–250.

[12] F. Grzegorz (2010). Modelling and simulation of fuzzy systems using Matlab and Simulink; Politechniki Krakowskiej, Kraków, Poland.