Intelektual Journal of Energy Harvesting and Storage
Vol. 2, No. 1, 2024, pp. 40~47
ISSN: 2963-6272, DOI: 10.11591/ehs.v2i1.pp40-47

Photovoltaic battery storage system for maximum power point tracking using hybrid firefly and perturbation and observation algorithm

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Article Info

Article history:

Received May 29, 2023
Revised Apr 5, 2024
Accepted May 1, 2024

Keywords:

Firefly algorithm
MPPT
P&O method
Photovoltaic

ABSTRACT

This paper presents the novel maximum power point tracking (MPPT) approach for a small 50 W photovoltaic (PV) based battery storage system using the DC-DC converter. The method of modeling of PV module is discussed. The firefly (FFY) algorithm along with the perturbation and observation (P&O) algorithm are combined together to implement MPPT of the PV battery storage system. The operating principle is discussed in detail and steady-state analysis of the proposed system is implemented through simulation. The charging profile of the battery is also studied. Furthermore, a low-cost microcontroller-based experimental setup rated at 50 W battery storage systems was built to implement a hybrid FFY-P&O algorithm. The experimental results are in line with the simulation result. It showed the fast and excellent maximum power point operation due to rapid as compared to conventional P&O method.

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1. INTRODUCTION

Solar photovoltaic battery storage system becomes one of the most important applications of renewable energy. Considering economic issues, this scheme is of great concern for standalone PV systems. Renewable energy sources are showing remarkable growth in the last 20 years. Out of this PV energy has been shown rapid growth these days. The optimal harnessing of photon energy is challenging for researchers. The cost of PV generation is falling day by day which forced the consumer to pay more attention to PV generation. It is becoming more commercial in rural areas, hills, islands, and agricultural fields. The world energy demand has shown drastic growth and the conventional energy sources like oil, natural gas, and coal are exhausting in the coming days. Moreover, conventional energy sources also produce global warming to the earth. Hence the requirement of a clean, sustainable, and cost-effective source of energy is demanded whose solution is PV energy. Recently many researchers are working to control the performance of PV systems by operating them at maximum power [1], [2]. The only limitation is their operating characteristic which is highly non-linear. This forces researchers and scientists to develop different algorithms/techniques to extract maximum power by matching the load. Due to the dc output of the PV panel, the intermediate DC-DC controller is needed to control and govern the performance characteristics for stable optimal operation. A general boost converter is preferred for the implementation of maximum power point tracking (MPPT) algorithms [3]–[5]. The complete review of MPPT algorithms with respect to state of art, design specification, control strategy, the convergence of operation, stability issues, and comparison of various techniques based on suitability in various applications are discussed [6]–[8]. To make the planet free from pollution battery-fed electrical vehicles are preferred.

The control technique is essential for the optimal stable operation of the PV system. A sliding mode control of a PV system is best suited for water pumping applications [9], [10]. However, in a battery charging system, it becomes complex to implement efficient charging methods. The partial shading issues in the PV system are discussed for performance improvement [11]. The second limitation of a PV system is that it is available only during the daytime, hence storage system is essential. Battery storage is the cheapest and commercially used in small-scale as well as large-scale applications. The standards of the battery charging system are given in [12]–[14]. Sun *et al*. [15] has shown the flywheel energy storage system for fast charging electrical vehicle is proposed, but this system is costly and preferred for a large system. The control strategy of the DC-DC buck converter using feedforward control is essential for the stable and efficient operation of the PV system [16].

Maximum power point tracking (MPPT) has shown tremendous popularity for the PV system. A large number of publications are available in the literature which employ single-diode or double-diode models for the prediction of the maximum power point. Since DC-DC converters and diode model of PV system both show non-linear behavior, therefore it becomes very difficult for a controller to achieve MPPT operation under varying insolation conditions. Different charging methods and their efficient control are available in the literature [17], [18].

This paper deals with the implementation of a PV battery storage system, capable of maximum power operation. Section 2 describes the modeling of PV panels using a double diode model. Section 3 establishes the control strategy using a hybrid firefly (FFY)-perturbation and observation (P&O)-MPTT algorithm for maximum power tracking and charging of the battery. Section 4 deals with the simulation of the proposed PV battery energy storage system for maximum power operation. Section 5 shows the experimentation of the proposed system. Section 6 explains the results obtained from simulation and experimentation under varying insolation conditions. Finally, the conclusion of the proposed work is explained in section 7.

2. MODELING OF PV PANEL

The PV panel is modeled as light generated current (IL) connected in parallel with two diodes, with a high-value resistance in parallel and low resistance in series as shown in Figure 1. In (1) shows the double exponential model of PV cell most suitable for polycrystalline silicon construction. The various unknown parameters used in the model are extracted using [5].

$$I_{pv} = \left(\frac{G}{1000}\right) * I_L - I_{01}\left(e^{\frac{V_{pv}+IR_{se}}{a_1}} - 1\right) - I_{02}\left(e^{\frac{V_{pv}+IR_{se}}{a_2}} - 1\right) - \frac{V_{pv}+I_{pv}R_{se}}{R_{sh}} \quad (1)$$

where:

$$a_1 = \frac{n_s \nu KT}{q} \;\&\; a_2 = \frac{n_s \nu KT}{q} \quad (2)$$

q is the electronic charge 1.6×10^{-19} C, G is the solar insolation in W/m2, ν is the photovoltaic single-cell ideality factor of the diode, IL is light generated current, K is Boltzmann's constant, n_s is the number of cells in series in a PV panel, T is the ambient temperature of PV panel in degree kelvin, I_{01} is reverse saturation current of diode due to diffusion and I_{02} is saturation current of diode due to recombination take place in space charge layer.

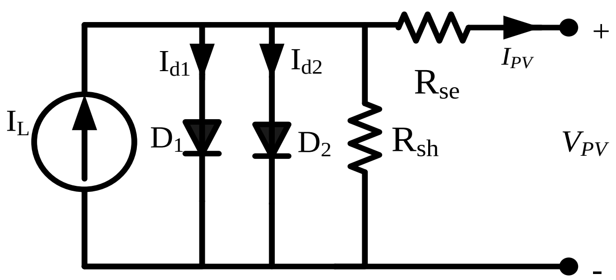


Figure. 1. Double diode model of PV panel

3. CONTROL STRATEGY OF PROPOSED PV BATTERY STORAGE SYSTEM
3.1. Perturbation and observation method

The nonlinear characteristics of PV module depict a one unique maximum power point (MPP) under varying temperature and insolation conditions. Therefore, MPPT algorithm is essential to locate MPP. In P&O method module voltage and current are sensed to calculate power. Power is continuously checked by creating perturbation in the voltage (ΔV) and the tracking algorithm is continuously followed till maximum power is tracked. The voltage is changed by perturbation in the duty ratio (ΔD) provided by DC-DC converter as shown in (3). The various steps to be followed in this method are shown in the flow chart in Figure 2.

$$V(n+1) = V(n+1) \pm \Delta V$$
$$D(n+1) = D(n+1) \pm \Delta D \tag{3}$$

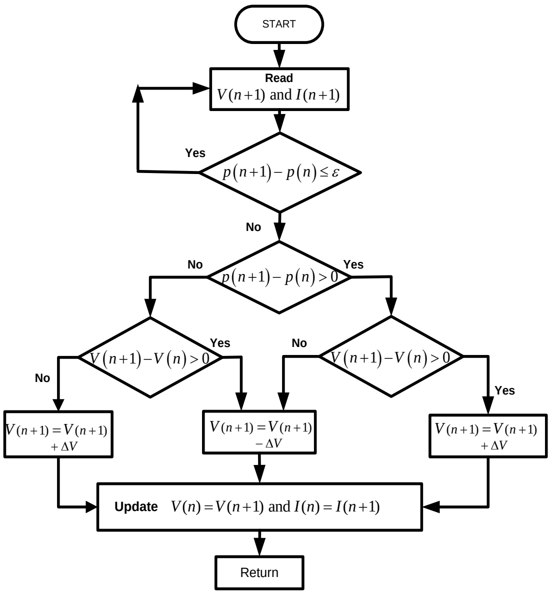


Figure 2. Flow chart showing P&O method

3.2. Firefly (FFY) algorithm

It is an algorithm for tracking the maximum power point for optimization. In this algorithm, fireflies are attracted by other fireflies (opposite sex) by using flashing behavior. The fireflies are considered unisex in nature while deriving a mathematical model of the firefly algorithm. Fireflies are mutually independent and can attract any fireflies. The brighter fireflies are more attractive and attract the less bright fireflies, which can be moved towards brighter fireflies. The variation in attractiveness of fireflies with distance R is given by (4).

$$\beta = \beta_0 e^{-\gamma R^2} \tag{4}$$

β_0 is attractiveness at distance R=0, γ is the light absorption coefficient.

Consider two fireflies Xi and Xj, separated by distance Rij. When less bright firefly Xi, is attracted to another brighter firefly Xj, then movement generated due to attraction is given by (5).

$$X_i^{n+1} = X_i^n + \beta_0 e^{-\gamma R_{ij}^2}\left(X_j^n - X_i^n\right) \tag{5}$$

In (5), the firefly algorithm is developed and a series of steps are followed for the execution of FFY algorithm as shown in the flow chart in Figure 3. The objective function which is to be minimized is the integral time absolute error signal of power between two intervals.

$$F(x) = \int |e(t)|\, dt \tag{6}$$

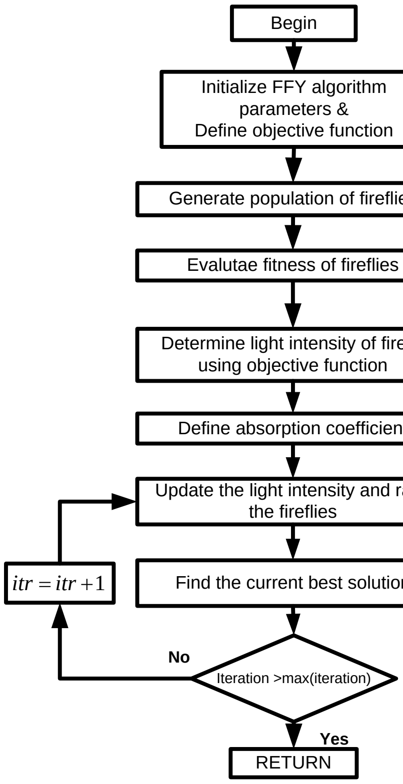


Figure 3. Flow chart for firefly algorithm

Figure 4 shows the proposed block diagram of battery energy storage system using DC-DC buck converter connected with a combined hybrid FFY-P&O-MPPT algorithm for maximum power operation. In this system, the duty ratio for switching pulse is controlled using an intermediate buck converter for maximum power operation. Figure 5 shows the flow chart of different steps involved in the generation of the reference voltage for maximum power tracking. This shows initially FFY algorithm is executed till the convergence of objective function is achieved. Afterward P&O algorithm tracks the peak operating point. In each iteration, the reference voltage is varied by suitably varying the duty ratio of gate pulses given by (3). The generated reference voltage is fed to the proportional integral derivative (PID) controller which is compared with a 50 kHz triangular signal for the generation of pulse width modulation (PWM) pulses for the buck converter switch. The PID controller is continuously regulating the reference voltage that corresponds to maximum power at different insolation conditions. The design specifications of the system are shown in Table 2, which are employed for simulation. The maximum power is always tracked and fed to load considering stability issues.

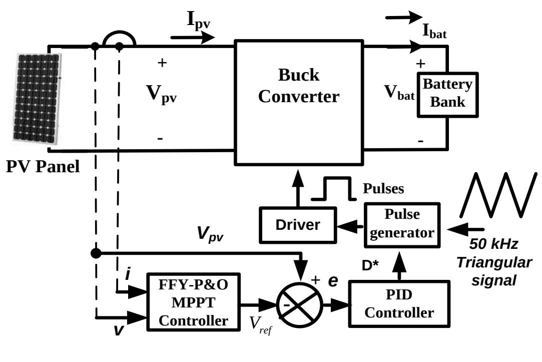


Figure 4. Block diagram of proposed MPPT operation of a battery storage system

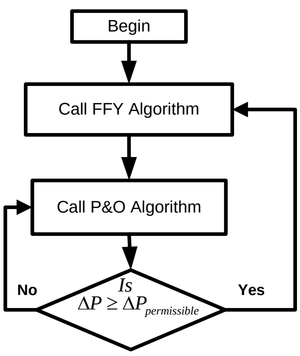


Figure 5. Flow chart of proposed FFY-MPPT algorithm

Here PID controller is used to generating the duty ratio D_n at the nth interval is given as (7).

$$D_n = D_{n-1} + K_p\left(V_{e,n}\right) + K_d \frac{d(V_{e,n})}{dx} + K_I \int V_{e,n} dt \qquad (7)$$

K_P is a proportional constant, K_d is a derivative constant and K_I is an integral constant and $V_{e,n}$ is the error voltage given by (8).

$$V_{e,n} = V_{ref} - V_{pv} \qquad (8)$$

4. PV SYSTEM SIMULATION

Using MATLAB/Simulink software, this proposed battery charging PV system is simulated. Figure 6 shows the schematic diagram of simulation system for a proposed PV system. It consists of four subsystems, namely PV panel, DC-DC buck converter, FFY-P&O-MPPT controller, and PID controller. The PV panel specifications are shown in Table 1. The design specifications of the proposed system employed for simulation are shown in Table 2.

Table 1. PV panel specifications

S. No.	Symbol	Typical electrical characteristics	Panel
1	P_{max}	Maximum power	50 W
2	V_{mp}	Voltage at maximum power	17.3 V
3	I_{mp}	Current at maximum power	2.89 A
4	I_{sc}	Short circuit current	3.17 A
5	V_{oc}	Open circuit voltage	21.8 V
6	N_s	Number of cells in series	36
7	α_i	Temperature coefficient of current	0.065±0.015

Table 2. Design specifications of the proposed system

S. No.	Symbol	Parameters	Values
1	V_i	Input voltage	15-18 V
2	V_o	Battery voltage	12-13 V
3	f_S	Switching frequency	50 kHz
4	L	Main buck inductor	1 m H
5	C_o	Output capacitor	100 µ F
6	C_i	Input capacitor	1000 µ F
7	P	Power	50 W
8	SMF	Battery capacity	7.5 Ah, 12 V

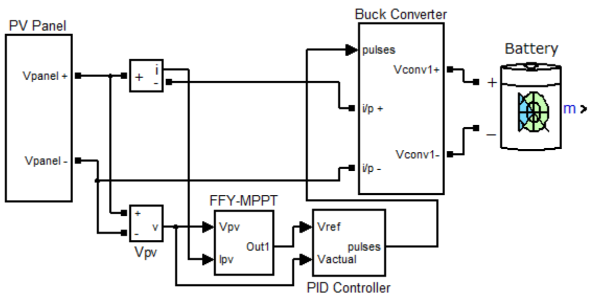


Figure 6. Simulation model of proposed battery charging PV system

5. EXPERIMENTATION

Figure 7 shows the experimental prototype of the proposed battery storage PV system. It consists of the buck converter, a driver circuit, control circuit, and battery. A small 50 W PV panel is used for experimentation. The buck converter is fabricated using power MOSFET IRF540N with fast switching behaviour and low reverses recovery charge carriers for high frequency switching at 50 kHz. The diode D used is BYV32E. The inductor used on the buck converter is 1 mH which is constructed in the laboratory using a toroidal ferrite core. The current sensor used is LEM (LTS 15-NP) Hall effect current transducer. The microcontroller used is ATmega328P in the Arduino microcontroller board.

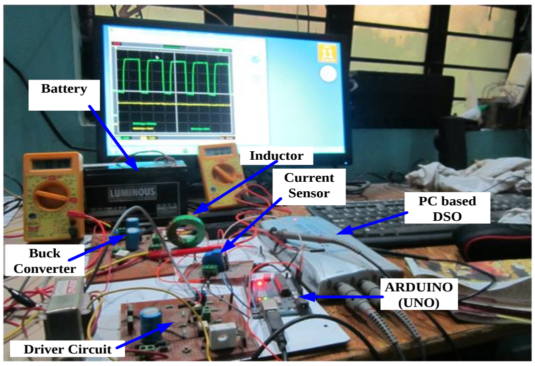


Figure 7. Photograph of proposed battery storage system

6. RESULTS AND DISCUSSION

Figure 8 shows the I-V characteristics and P-V curves of PV panel obtained from simulation when the load is varied from open circuit condition to short circuit condition and insolation is varied from 20% to 100%. Figure 9 shows the simulation results of the charging profile of the VRL battery. It shows up to 80 % of the SOC battery is charging under constant current mode and then constant voltage mode. The MPPT-FFY-P&O algorithm continuously generates the reference voltage corresponding to maximum power. The result shows maximum power of the PV panel can be obtained by continuously tuning the duty ratio D. The PID controller is continuously comparing the reference voltage with the actual voltage and generating duty for maximum power operation. The convergence of FFY algorithm applied to the fitness function with the number of iterations is shown in Figure 10. Figure 11 (a) PV panel and (b) battery, shows the output power of the PV and buck converter is always maximum irrespective of changes in insolation.

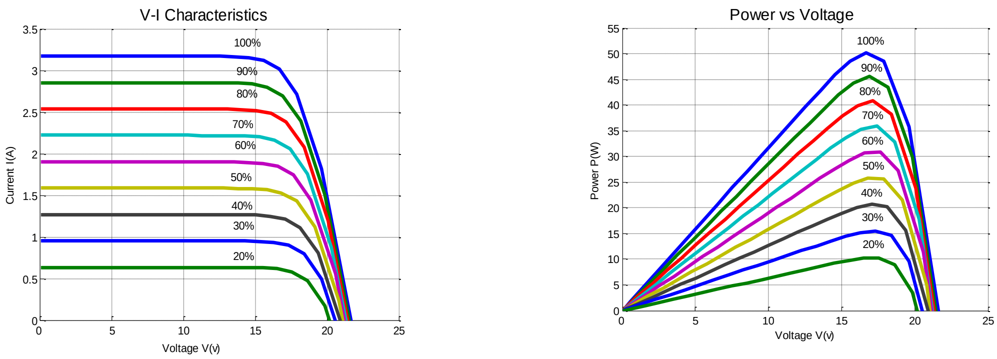


Figure 8. Simulation results showing I-V characteristics and P-V characteristics of a PV panel for changing v insolation level from 20 % to 100 % at 25 ºC

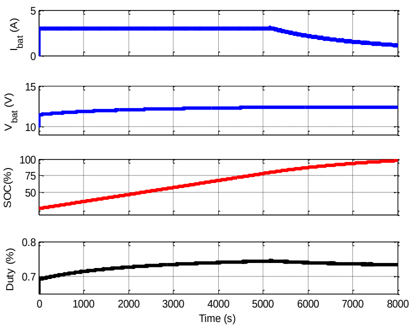


Figure 9. Battery charging profile of 7.5 Ah VRL battery

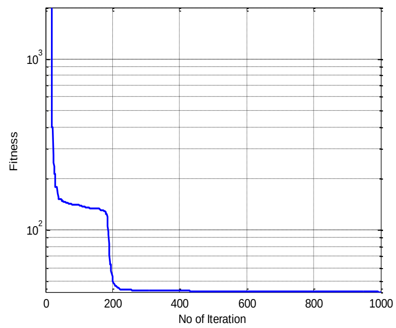
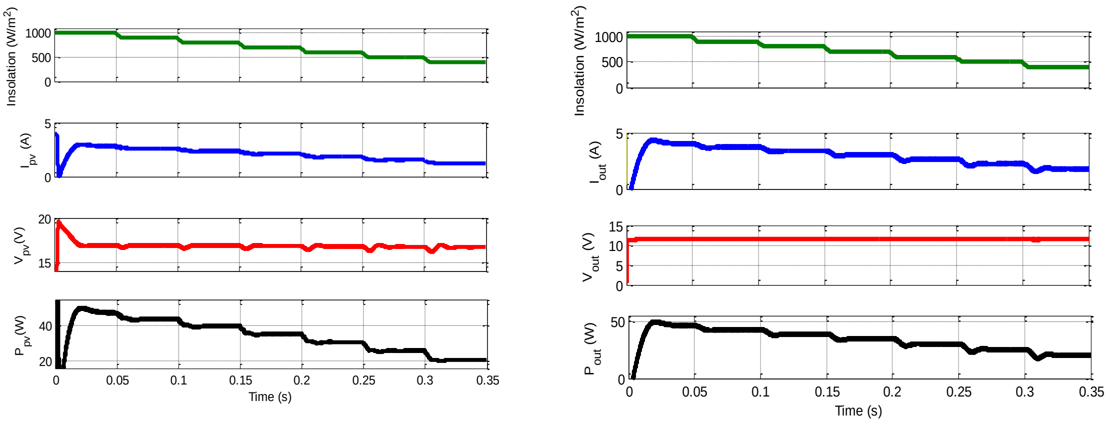


Figure 10. Response showing the convergence of fitness function using FFY algorithm



(a) (b)

Figure 11. Simulation results of proposed PV system and battery load for maximum power point operation for variation in insolation at 25 °C (a) PV panel and (b) battery

A small 50 W laboratory PV system is also built and experiments were conducted on the real system. The PV panel's current and voltage are continuously sensed and fed to FFY-P&O-MPPT controller which generates a reference voltage for maximum power point tracking. This reference voltage and panel voltage are compared and the error signal is generated is the input of the PID controller to generate the duty ratio of the converter. The output of the PID controller is then compared with a 50 kHz sawtooth carrier signal to generate PWM pulses for maximum power point operation. PWM signal is fed to gate drive circuit to generate pulses for switching of the converter. The control algorithm and PID controller tune the duty ratio for stable operation under steady-state conditions of a proposed PV system. Table 3 shows the experimental results of Power, current, and voltages of PV panel and output of DC-DC converter which validate the simulation result obtained for maximum power point operation for varying insolation conditions.

Table 3. Experimental results showing power, current, and voltages of PV panel and battery at different insolation levels with constant temperature conditions

S. No	Insolation	PV-panel			Battery			Efficiency (%)
		V_{PV} (V)	I_{PV} (A)	P_{PV} (W)	V_o (V)	I_O (A)	P_O(W)	
1	1000	16.86	2.846	47.9835	11.49	3.97	45.6153	95.0644
2	900	16.94	2.614	44.2811	11.47	3.67	42.0949	95.0627
3	800	16.83	2.381	40.0722	11.46	3.418	39.170	97.7491
4	700	16.86	2.125	35.8275	11.45	3.062	35.0599	97.8575
5	600	16.77	1.832	30.7226	11.43	2.674	30.2895	98.5901
6	500	16.78	1.548	25.9754	11.42	2.257	25.5808	98.4807
7	400	16.7	1.247	20.8249	11.4	1.814	20.406	97.9884

7. CONCLUSION

In this paper, a small PV-based battery storage system is investigated for maximum power operation. The modeling of the PV panel, buck converter, and battery are presented and has been easily implemented on MATLAB simulation software. The buck converter components inductor and capacitor are selected within a prescribed ripple limit for stable operation. The feedforward controller is developed using FFY and P&O algorithms to generate reference voltage feed to the PID controller to generate maximum power for the battery charging application. The PID controller is properly tuned considering stability issues. It was shown that the proposed system has satisfactory performance under varying atmospheric conditions. The control mechanism used is very simple and easily implemented using a low-cost microcontroller. The microcontroller is programmed for the implementation of the FFY-MPPT algorithm and PID controller. The proposed battery charging scheme along with the FFY-MPPT algorithm is also verified through experimental results. Moreover, this proposed scheme can be used for a large photovoltaic system employing the bidirectional converter considering the shading phenomenon for efficient utilization of the battery energy storage system as per requirement.

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