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Improvement of a MPPT Algorithm for PV Systems and Its Experimental Validation

A.J. Mahdi, W.H. Tang and Q.H. Wu
Department of Electrical Engineering and Electronics
The University of Liverpool, Liverpool, L69 3GJ, U.K.
E-mail: whtang@liv.ac.uk

Abstract. The amount of power generated from a photovoltaic (PV) system mainly depends on the following factors, such as temperatures and solar irradiances. According to the high cost and low efficiency of a PV system, it should be operated at the maximum power point (MPP) which changes with solar irradiances or load variations. This paper presents an improved maximum power point tracking (MPPT) algorithm of a PV system under real climatic conditions. The proposed MPPT is based on the perturbation and observation (P&O) strategy and the variable step method that control the load voltage to ensure optimal operating points of a PV system. The proposed MPPT algorithm has been implemented by a dSPACE DSP controller. The experimental results show that the PV power system, using the proposed MPPT algorithm, is able to accurately track maximum power points (with minimum steady-state power oscillations) under rapid irradiance variations.

Key Words

Photovoltaic generation system, maximum power point tracking, perturbation and observation algorithm, boost converter, real-time controller.

1. Introduction

The optimal operation of a PV system is important due to the low efficiency of solar panels. The output characteristic of a PV system is nonlinear and varies with ambient temperatures and solar irradiance levels. Therefore, a MPPT technique is required to obtain maximum power from a PV system.

A number of MPPT techniques have been developed for PV systems, and for all conventional MPPT techniques the main problem is how to obtain optimal operating points (voltage and current) automatically at maximum PV output power under variable atmospheric conditions. The majority of MPPT control strategies depend on characteristics of PV panels in real time, such as the duty cycle ratio control [1] and using a look-up table. MPPT techniques can be generally classified into four types: (i) the perturbation and observation (P&O) algorithm is based on making perturbation in PV operation points of a PV panel in order to force the direction of tracking toward an MPP; (ii) the hill-climbing algorithm which directly makes a perturbation in a duty cycle of a DC-DC power converter; (iii) the incremental conductance (INC) algorithm is implemented by periodically checking the slope of the P-V curve of a PV panel. If the slope becomes zero or equal to a defined small value, the perturbation is stopped and the PV panel is forced to work at this operating point [2]; and (iv) the constant voltage algorithm is based on keeping the ratio between the PV voltage at the maximum power (V_{mp}) and the open circuit voltage (V_{oc}) as a constant value [3], and also in this method the effect of solar irradiance variations is neglected.

The first three methods provide a satisfactory solution for tracking maximum power points of a PV system because of the simplicity in implementation and satisfactory accuracy without measuring solar irradiances and temperatures. Despite of those advantages, there are some drawbacks: firstly, these methods cause a power oscillation around an MPP in the steady-state and the amount of this oscillation depends on the perturbation step size which ensures a good matching between the tracking speed and the system dynamics; secondly, the direction of tracking may be wrong especially under rapid atmospheric condition variations.

Tina *et. al.* [4] developed a mathematical electrical-thermal model of a PV module depending on ambient temperature, wind speed, wind direction, relative humidity and electrical operating point (voltage and current values). Kaiser *et. al.* [5] proposed a new MPPT control method for solar electric vehicles based on an offline artificial neural network (ANN), trained using a back-propagation with a gradient descent momentum algorithm, which is used for the online generation of a reference voltage. The MPPT algorithm varies the duty cycle of a boost converter that ensures the output voltage of a PV panel follow a reference voltage at any solar irradiance and load conditions. The obtained simulation and experimental results showed that the proposed control system was highly efficient. Lee *et. al.* [6] developed a novel MPPT algorithm based on

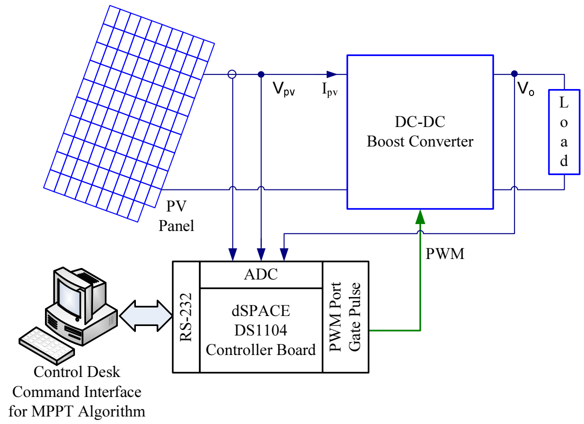

Fig. 1. Configuration of a PV power control system

a current controller by varying the reference current in each sampling time. The proposed control method was similar to the hill-climbing strategy, and by implementing this method the PV voltage follows the variable reference voltage and the power extracted from a PV panel was increased around 9%. Furthermore, the advantages of the MPPT method were a simple control design and a high efficiency.

This paper focuses on maximising PV system power outputs at all solar irradiance levels. In Section 2, the electrical models of a PV panel and a boost converter are presented and analysed. Section 3 describes the proposed MPPT algorithm and explains the variable perturbation step method. Section 4 discusses the experimental setup followed by experimental results. Finally, some conclusions are presented in Section 5.

2. PV Power System Configuration

Figure 1 illustrates a real-time implementation of a PV system using a fast dSPACE DSP controller. This system consists of two PV panels connected in series (the rated power of each panel is 162 W at a solar irradiance of 1000 W/m^2 and a temperature of 25°C), a boost converter to control the load voltage, a dSPACE controller to implement the proposed MPPT algorithm, sensors to measure the PV voltage, PV current and load voltage which are input signals to the MPPT controller, and a stand-alone resistive load.

A. PV Model and Characteristics

A solar cell is a basic building block of a PV system. Normally, a small solar cell (a few square inches size) generates about one watt. A group of solar cells are connected in series and parallel circuits to generate high power and this combination is a so-called PV module. A group of such modules can be electrically connected in series-parallel combinations to generate required currents and voltages as a PV array. In darkness, a solar cell becomes a p-n junction diode and it only generates a current. A simple electrical equivalent one-diode model, as illustrated in Fig. 2, expresses a solar cell, which is modelled as a photocurrent source I_{ph}, one diode, and a series resistance R_{S}, representing the PV cell resistance. Thus, equations to describe the relationship between the current and voltage of a PV cell are [7]:

Table I

PV MODEL PARAMETER DEFINITION

Symbols	Definition
I_{pv}	Photovoltaic current (A)
I_{ph}	Photo current (A)
I_{sat}	Saturation current (A)
I_{D}	Diode current (A)
q	Charge of an electron (1.602×10^{-19} C)
V_{pv}	Photovoltaic voltage (V)
R_{s}	Series resistance (Ω)
A	Idealist factor for a p-n junction (1 or 2)
K	Boltzman's factor (1.381×10^{-23} J/K)
T	Temperature of a solar array (°C)
λ	Solar irradiance (W/m^2)
I_{sc}	Short-circuit current (A)
K_I	short-circuit current temperature

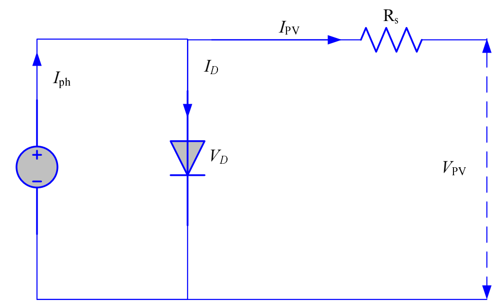

Fig. 2. The solar PV panel model

$$\begin{cases} I_{\text{pv}} = I_{\text{ph}} - I_{\text{sat}}[\frac{q(V_{\text{pv}}+I_{\text{pv}}R_s)}{(AkT-1)}] \\ , \\ I_{\text{ph}} = (\frac{\lambda}{1000})[I_{\text{sc}} + K_I(T-25)] \end{cases} \quad (1)$$

where the definitions of PV model parameters are listed in Table I. Figure 3 illustrates the $I-V$ and $P-V$ characteristics of the PV panels used in this research at a solar irradiance of 1000 W/m^2. If the PV panels are connected to a resistive load R, the operating point lies between the points A and S depending on the load resistance. As shown in Fig. 3, the load characteristic is a straight line with a slop as:

$$\frac{I}{V} = \frac{1}{R}. \quad (2)$$

If R is small, the operating point of the PV panels lies between the points of M and N. In this case, the PV panels behave as a constant current source and its value is approximately equal to the short circuit current. Whilst, if R is large, the operating point of the PV module lies between the points of P and S. In this case, the PV panels behave as a constant voltage source and its value is approximately equal to the open-circuit voltage. To achieve

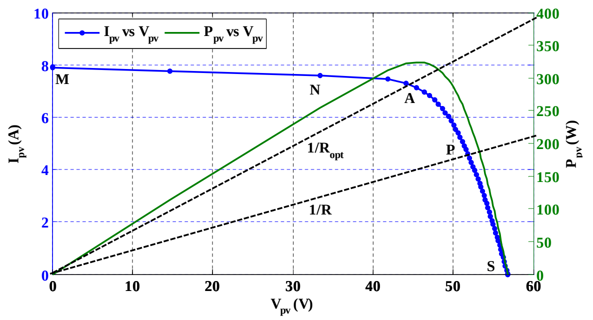

Fig. 3. The PV panel characteristics at a solar irradiance of 1000 W/m^2

the optimum operating point A ($V_{\text{mpp}}, I_{\text{mpp}}$), it is required to set the load R equal to the optimal resistive load R_{opt}, and as a results the power dissipated in the resistive load is maximum:

$$P_{\max} = I_{\text{mpp}} V_{\text{mpp}}. \tag{3}$$

B. Boost Converter Analysis

A step-up converter is used in this research to connect a PV panel with a load in order to adjust the operating voltage and current of the PV panel at optimal values. A simplified diagram of a boost converter is illustrated in Fig. 4. The boost converter contains an IGBT and a diode which are represented as a dual ideal switch U in order to simplify the circuit analysis. If U is a state of 0, the diode is on and the IGBT is off and vice versa if U is a state of 1. The boost converter contains also passive components: an inductor L, an capacitor C and a resistance R. The operation principle of the boost converter can be demonstrated for each switching period under the continuous conduction mode (CCM) into two modes [8]: the first mode is an ON mode in the duration the period $0 \leq t \leq t_{\text{on}}$ and its state equations can be represented as follows:

$$\begin{cases} L\frac{di_L}{dt} = V_{\text{pv}} \\ C\frac{dv_{\text{o}}}{dt} + \frac{v_{\text{o}}}{R} = 0 \end{cases}, \tag{4}$$

where t_{on} is the ON mode time and i_L the continues inductor current. The second mode is an OFF mode in the duration $t_{\text{on}} \leq t \leq T_s$, and its state equations can be represented as the following:

$$\begin{cases} L\frac{di_L}{dt} + v_{\text{o}} = V_{\text{pv}} \\ i_L - C\frac{dv_{\text{o}}}{dt} - \frac{v_{\text{o}}}{R} = 0 \end{cases}, \tag{5}$$

where T_s is the switching period. The design of a boost converter for a PV system is a complex task which involves many factors. In general, the input and output voltages of the boost converter are varied with the the solar irradiances and load variations. The output voltage is also varied which follows the reference voltage generated from an

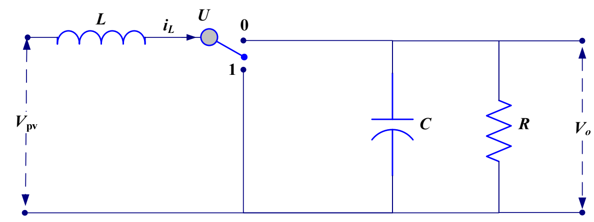

Fig. 4. Boost converter circuit diagram

Table II

SPECIFICATIONS OF THE BOOST CONVERTER

Parameter	Symbol	Value	Unit
Switching frequency	f_{sw}	20.0	kHz
Minimum input voltage	$V_{\text{pv(min)}}$	45.6	V
Maximum input voltage	$V_{\text{pv(max)}}$	56.8	V
Maximum output voltage	$V_{o(\max)}$	230	V
Rated load current	I_o	0.97	A
Maximum voltage ripple	$V_{\text{ripple(max)}}$	0.20	V

Table III

PARAMETERS OF THE BOOST CONVERTER

Parameter	Symbol	Value	Unit
Minimum duty cycle	$D_{\min}$	0	%
Maximum duty cycle	$D_{\max}$	80	%
Minimum inductance	$L_{\min}$	545	μH
Peak inductor current	$I_{L(\text{pk})}$	7.855	A
Minimum capacitance	$C_{\min}$	485	μF

MPPT controller. Thus the selection of boost converter components (the input inductor and the output capacitor) is a compromise between dynamic responses and the MPPT algorithm trigger time. The maximum value of the state variables should be calculated to estimate the value of the boost converter [8]. The specifications of the boost converter are summarised in Table II and the calculated parameters of the boost converter are listed in Table III The s-domain transfer function of the boost converter G_{vd} is calculated using a small-signal model as follows:

$$G_{\text{vd}} = \frac{(1-D)V_{\text{o}} - LI_L s}{LCs^2 + \frac{L}{R}s + (1-D)^2}, \tag{6}$$

where V_{o} is the steady-state output voltage which can be calculated by supposing the steady-state PV voltage equals to its value at the maximum power point, R the resistive load, L the boost inductor, and C the output capacitor. The steady-state control variable D is chosen at a median value 0.5. The open-loop transfer function G_{vd} is then numerically represented as below:

$$G_{\text{vd}} = \frac{-1.8e004s + 9e008}{s^2 + 100s + 5e006}. \tag{7}$$

Figure 5-a shows the open-loop step response and Figure 5-b shows the closed-loop step response of the boost converter. It is clear that the system settling time (which is the time required for the transient's damped oscillation to reach a steady-state) is approximately 0.084s. It is important to note that the PI controller is optimally tuned for the purpose of stabilising the closed-loop of the control

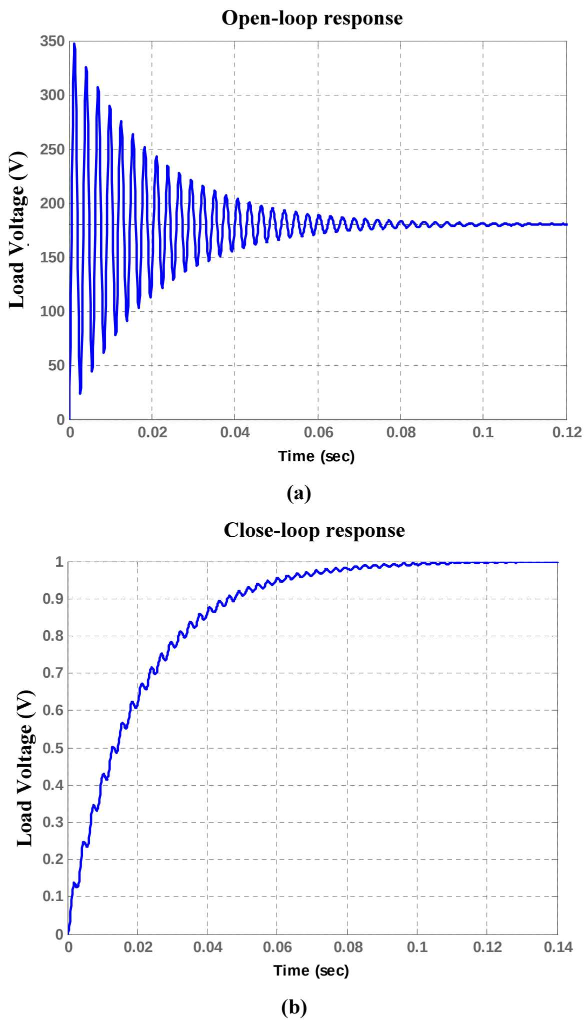

Fig. 5. Step responses of the boost converter

system over the full range of solar irradiance levels. The boost converter transfer function G_{vd} is utilised to design a PI controller using SISO tools which are available in the control tool box in MATLAB. The optimal values of PI parameters are obtained by using singular frequency based tuning as $K_p = 0.00021865$ and $K_i = 0.27677$.

3. Proposed MPPT Algorithm

As explained previously, an MPPT controller is important for a PV system in order to increase the PV system efficiency. The principle of the proposed MPPT algorithm is to calculate the optimal reference output voltage that ensures the PV system is operated at its MPP. The implementation steps of the MPPT controller can be summarised as follows:

Step 1: An initial reference voltage is assumed to be equal to the double of the PV open circuit voltage.

Step 2: The PV voltage, the PV current and the load voltage are measured and applied to the MPPT controller as input signals.

Step 3: The PV power is calculated at the sample time k as below:

$$P_{\mathrm{pv}}(k) = I_{\mathrm{pv(av)}}(k)V_{\mathrm{pv}}(k). \tag{8}$$

Step 4: The PV current and PV power samples are delayed by a switching period.

Step 5: The PV current and PV power errors are calculated as follows:

$$\begin{cases} \Delta I = I_{\mathrm{pv}}(k) - I_{\mathrm{pv}}(k-1) \\ \Delta P = P_{\mathrm{pv}}(k) - P_{\mathrm{pv}}(k-1) \end{cases}. \tag{9}$$

Step 6: The reference voltage $V_{\mathrm{ref}}(k)$ is calculated as below:

$$V_{\mathrm{ref}}(k) = V_{\mathrm{o}}(k) + \Delta V_{\mathrm{ref}}, \tag{10}$$

where ΔV_{ref} the perturbation voltage is given by

$$\Delta V_{\mathrm{ref}} = sign(\Delta P \Delta I)V_{\mathrm{step}}. \tag{11}$$

where V_{step} is the perturbation step.

Step 7: The load voltage error is calculated as below:

$$\Delta V_{\mathrm{o}}(k) = V_{\mathrm{ref}}(k) - V_{\mathrm{o}}(k). \tag{12}$$

The load voltage error is then controlled by a PI controller to generate a required duty cycle d and a 20 kHz fixed-frequency PWM is applied to the driver of the IGBT.

Step 8: The previous steps are repeated until reaching the PV optimal operating points.

It is worth noting that the fixed V_{step} in the P&O algorithm is changed in this work to a variable V_{step} in order to improve the MPPT efficiency. V_{step} is varied according to the PV power slope as follows: (i) V_{step} is increased if the power slope is high; (ii) V_{step} is decreased if power slope remains constant. It is concluded that the variable perturbation step method can decrease the oscillation in the PV operating points [9]. It is important to calculate the trigger frequency of the MPPT algorithm accurately in order to allow the PV system to reach a steady state under variations of reference voltages. The trigger frequency is set to be equal to the exponential damping frequency σ_d, i.e., the magnitude of the real part of the system poles, which is given by

$$t_s = \frac{4}{\zeta \omega_n} = \frac{4}{\sigma_d}, \tag{13}$$

where t_s is the settling time of the system, ζ the damping ratio, and ω_n the natural frequency. In this research, the MPPT algorithm is triggered at a frequency of 7 Hz. This means that the MPPT program runs 7 times per second.

4. Experimental Setup and Results

A. Experimental Setup

The proposed MPPT algorithm is implemented using a digital controller based on a dSPACE DSP unit. The dSPACE is a powerful tool to modify the MPPT controller parameters real time and to monitor real processes while an experiment is operated. The system components are:

Table IV

PV Panel Specifications

Description	Symbol	Value	Unit
Open circuit voltage	V_{oc}	28.4	V
Rated voltage at MPP	V_{mpp}	22.8	V
Short circuit current	I_{sh}	7.92	A
Rated current at MPP	I_{mpp}	7.11	A
solar irradiance	Sun	1000	W/m^2
Temperature	T	25	^{0}C

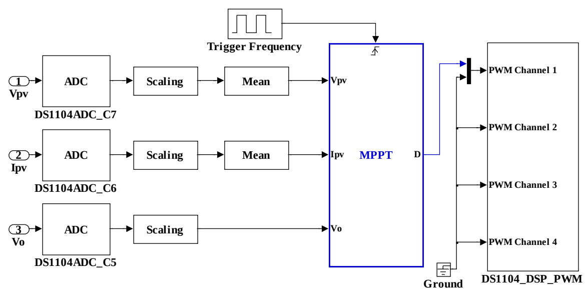

Fig. 6. Simulink model of the MPPT algorithm for dSPACE implementation

two PV panels as power source (its specifications are listed in Table IV), a boost converter as a power process unit, a resistive load, and a dSPACE DSP controller board which is interfaced with a PC. The MPPT algorithm is modelled in Simulink for dSPACE implementation as shown in Fig. 6. The output signals of the voltage and current transducers are sampled in dSPACE DSP via DS1104-ADC blocks. Low pass filters are used in measuring units to eliminate the unwanted high-frequency noise. The PWM pulses from the dSPACE DSP is sampled via a DS1104-DSP-PWM block to generate standard 20 kHz fixed-frequency PWM pulses.

B. Experimental Results

The proposed algorithm is tested under two different weather conditions, i.e. sunny and cloudy sky cases. The purposes of tests are to investigate the dynamic characteristics of a PV system and to calculate the amount of power increase using the proposed MPPT controller.

In the first test, the MPPT controller is tested under a sunny case for a short time as 1 s. This test aims to investigate the dynamic response of the PV system and to calculate the amount of the oscillation in PV operating points. It can be observed from Fig. 7 and Fig. 8 that the maximum voltage oscillation is 0.83 V and the maximum power oscillation is 8.9 W, respectively. The experimental PV characteristics for both with and without a MPPT controller are simultaneously obtained as shown in Fig. 9. It shows that the PV output power is increased as much as 859% of that without using the MPPT controller.

In the second test, the PV system is operated in a cloudy weather and the irradiance level changes rapidly because of passing clouds. The purpose of this test is firstly

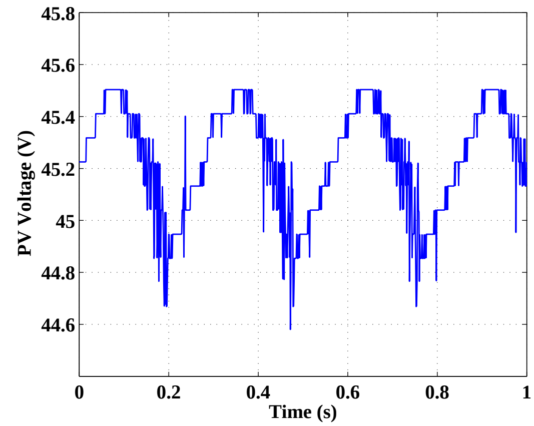

Fig. 7. Experimental PV voltage

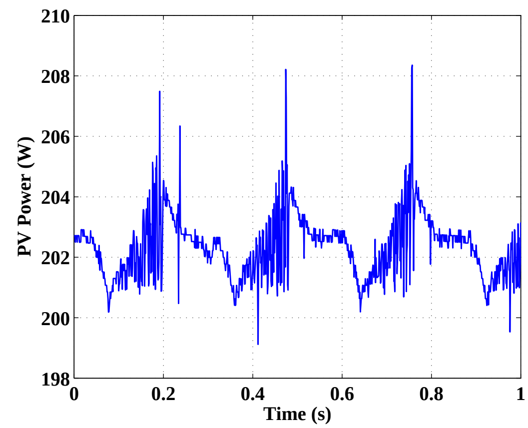

Fig. 8. Experimental PV power

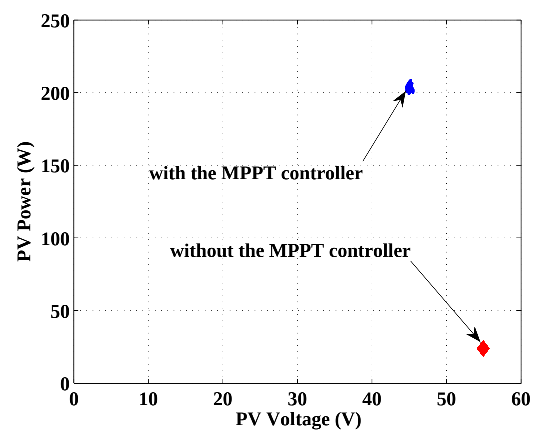

Fig. 9. Comparison of the experimental results obtained with and without using MPPT controller

to compare between the experimental and theoretical optimal voltages and secondly to investigate the dynamic performance of the PV system under sudden irradiance changes. It can be seen from Fig. 10 that the PV MPP is achieved when the PV voltage is 43.65 V (see Fig.

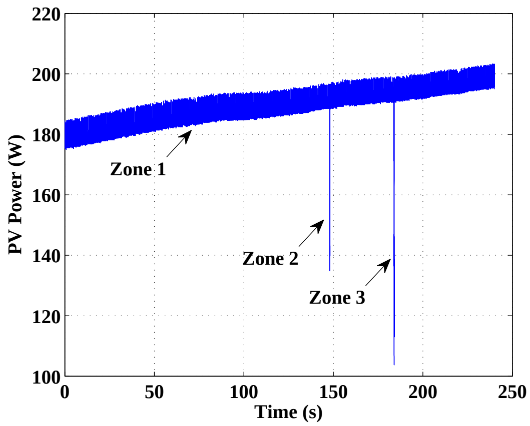

Fig. 10. Experimental maximum PV power

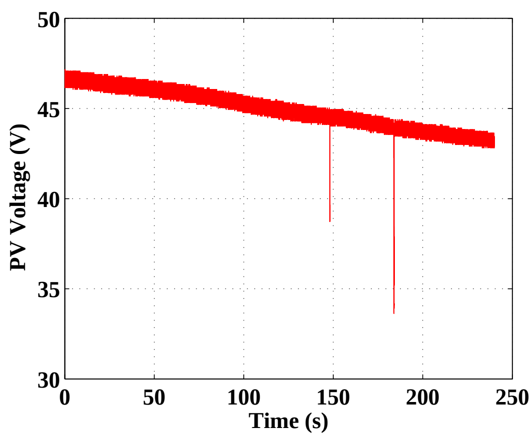

Fig. 11. Experimental maximum PV voltage

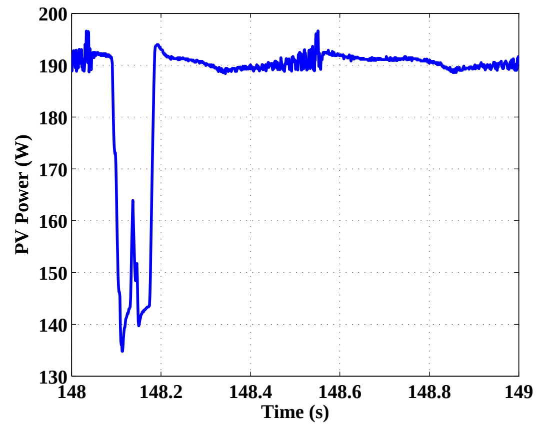

Fig. 12. Experimental maximum PV power of zone 2

Table V
EXPERIMENTAL RESULTS OF TEST 2

Time (s)	Weather State	PV Voltage (V)	PV Power (W)
0.000	Sunny	46.15	175.8
148.2	Cloudy	38.73	134.8
148.5	Sunny	44.04	188.9
184.0	Cloudy	33.63	104.4
184.1	Sunny	43.56	191.2
240.0	Sunny	42.83	195.7

11), which is close to the theoretical optimal voltage 45.6 V. Figure 12 displays the decreasing in the PV power through passing clouds. The experimental results of this test is summarised in Table V.

5. Conclusion

The main aim of this research is to develop an MPPT controller for a PV system to obtain maximum power with weather fluctuations. Mathematical models of a PV panel and a DC-DC boost converter are introduced. The system transfer function is used to optimally select the parameters of the DC-DC boost converter. A P&O strategy with the variable step method has been adopted for implementing the MPPT algorithm. The proposed MPPT algorithm has been implemented in a dSPACE controller to validate the performance of the PV power system. The experimental results show that the proposed MPPT algorithm is accurate which has a fast dynamic response under rapid solar irradiance variations.

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