Performance evaluation of online open-circuit voltage estimation method for photovoltaic system

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Abstract

In this paper, an online method is presented for the estimation of open-circuit voltage (V_{oc}) of the photovoltaic (PV) system. This technique analytically calculates the V_{oc} by sensing the voltage, current, and temperature of the PV system without interrupting the power flow to load. The online technique is accurate, fast, and easy to implement. The accuracy and potency of the online technique are verified by both simulation and practical results of a 245 W PV panel. Moreover, for the fair analysis, the recently developed analytical technique, i.e., two temperature sensor method is compared with the online method. It is verified from the hardware results that the accuracy of the online technique is higher than the two temperature sensor method.

Keywords Photovoltaic systems · Open-circuit voltage · Boost converter

1 Introduction

The unpredictable oil prices, depletion of conventional energy sources and increasing energy demand has encouraged us to move towards renewable energy resources. Among all, solar energy is the eminent renewable energy source for power generation. The production cost per unit of PV panels is continuously decreasing. Currently, the total installed capacity of PV system is reported near 627 GW [1]. Although PV panel is environmental friendly, its power is a non-linear function and therefore to fetch maximum power or operate at maximum power point (MPP), an efficient maximum power point tracking (MPPT) algorithm is required. The conventional PV system consists of:

1. PV panel which produces the electric power
2. DC-DC converter which transfers the maximum power to the load
3. MPPT algorithm which captures the MPP
4. Electric load

Many researchers have designed different MPPT algorithms [2]. In almost every MPPT algorithm, the PV system is either operated at V_{mp} (voltage at MPP) or I_{mp} (current at MPP) where PV panel provides the maximum power. The MPP depends upon the temperature and irradiance. Among all MPPT algorithms, fractional open-circuit voltage (FOCV) algorithm is low cost and simple to implement. In FOCV, V_{mp} is obtained by multiplication of V_{oc} (open-circuit voltage) and constant voltage factor k_{oc} . The effectiveness of the FOCV algorithm depends upon the accuracy of V_{oc} value and the cost and complexity of the V_{oc} estimation method. To increase the tracking efficiency, the V_{oc} value must be accurate for different environmental conditions. In conventional method, V_{oc} is determined by periodically isolating the PV panel, however, this causes power loss [3, 4].

Another challenge in the design of FOCV algorithm is the selection of a sampling period. If sampling period is large, the probability of power loss becomes increased. This is because if irradiance/temperature changes before

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the two consecutive samplings, the PV panel will follow the unchanged reference point. Also, when sample and hold amplifier is used (to hold the sample value), and the sampling period is large, the hold capacitor will droop which changes the reference value [5]. This problem can be resolved by using an extended sample and hold amplifier circuit, which can be implemented by stacking two sample and hold circuits in a chain, however, the number of components and system cost increased. To overcome this problem, a look-up table method can be used. In this method, the previous knowledge of PV panel characteristics, and technical data are stored and compared with the panel output values to track the reference value [6]. For different environmental condition, the huge amount of data need to be stored which make the system complex and slow.

To cope with the aforesaid problems, a pilot cell can be used [7, 8], however, during the mismatch of irradiance between pilot cell and main PV panel, pilot cell gives the wrong value of V_{oc} [9]. In [10], a semi pilot cell is presented in which one cell of PV panel is used for V_{oc} measurement, but power loss (1.8%) occurs due to this single cell. In [11, 12], authors present the analytical solution of V_{oc} measurement which estimates the open-circuit voltage by using irradiation and temperature sensor. But the open-circuit voltage results are not promising during the temperature variation condition. In [13], authors determine the V_{oc} by measuring the short circuit current of PV panel. As short circuit current value is not changed too much during the temperature variation, therefore, this method only works for constant temperature condition. In [14], authors provide a low cost solution by using the two temperature sensors. One temperature sensor measures the ambient temperature T_a and second measure the cell temperature T_c of PV panel. This method accurately estimates the open-circuit voltage in variable irradiance condition. However, this method does not perform well in variable temperature condition. In [15], authors present the low-cost temperature gradient method for V_{oc} determination which works well during the temperature variation. But this method does not work during the variable irradiance condition.

To overcome the above-mentioned problems, we had developed an online technique in our previously published research article [16]. This method calculates the V_{oc} without isolating the PV panel. The single diode model of PV panel is used for V_{oc} estimation (explained in Sect. 3). In this paper, the performance of the online method is evaluated comprehensively. The online method is tested by using 245 W (Yingli YL245C-30b) PV panel for variable environmental conditions. The specifications of a single PV panel are shown in Table 1.

The paper is structured as follows: Sect. 2 elaborates the different analytical methods for V_{oc} measurement.

Table 1 Data Sheet of PV panel Yingli YL245C-30B

Parameters	Description	Values
P_{mp}	Maximum power point	245.328
V_{oc}	Open circuit voltage	38.1 V
I_{sc}	Short circuit current	8.59 A
N_s	Number of series connected cells	60
V_{mp}	Voltage at maximum power point	30.4 V
I_{mp}	Current at maximum power point	8.07 A
k_v	Temperature coefficient of V_{oc}	− 0.32 (%/°C)
k_i	Temperature coefficient of I_{sc}	0.044 (%/°C)

Section 3 presents the online method for V_{oc} calculation. Section 4 describes the different methods to estimate the operating temperature of PV panel. In Sect. 5, hardware setup is presented. In Sect. 6, calibration of the current, voltage, and temperature sensors are discussed. In Sect. 7, results of the online method are analyzed and compared with the pilot PV panel V_{oc} value, and two temperature sensors method. In Sect. 8, the comparative analysis of the online and two temperature sensors method are presented. Finally, conclusion of the paper is provided in Sect. 9.

2 Analytical methods for V_{oc} estimation

The explanation of different analytical methods for V_{oc} determination is provided below.

2.1 Irradiation and temperature sensor method

In [11], authors proposed the analytical solution for the estimation of V_{oc} . By using an irradiance and temperature sensor, the photo-generated current I_{ph} is calculated as follows:

$$I_{ph} = [I_{ph,STC} + k_i(T_c - 298)] \times \frac{G}{1000} \quad (1)$$

where, $I_{ph,STC}$ is the photo-generated current at standard testing condition, k_i is the temperature coefficient of I_{sc} , T_c is the cell temperature in kelvin, and G is the irradiance. After I_{ph} measurement, author calculates the V_{oc} by the following equation:

$$V_{oc} = N_s V_t \left[\ln \left(\frac{I_{ph} + I_s}{I_s} \right) \right] \quad (2)$$

where N_s is the number of series-connected cells, V_t is the thermal voltage, and I_s is the diode reverse saturation current.

2.2 Short circuit current method

In [13], V_{oc} is calculated through short circuit current measurement. The I_{sc} can be determined by offline technique or by an irradiation sensor. The V_{oc} is calculated by the following equation:

$$V_{oc} = \frac{N_s}{\lambda} \left[\ln \left(\frac{I_{sc} + I_s}{I_s} \right) \right] \quad (3)$$

where λ is a constant coefficient that depends on the cell material.

2.3 Two temperature sensors method

In [14], an efficient low cost two temperature sensors method is presented. In first step, irradiance is calculated by measuring cell temperature and ambient temperature using the following equation:

$$G = \frac{(T_c - T_a) \times 800}{(NOCT - 20)} \quad (4)$$

where $NOCT$ is the normal operating cell temperature. In second step, the V_{oc} is calculated using Eqs. (1) and (2).

2.4 Temperature gradient method

In [15], authors present the low-cost temperature gradient method. The V_{oc} is calculated by the following equation:

$$V_{oc} = V_{oc,STC} + (T - 298) \frac{dV_{oc}}{dt} \quad (5)$$

where $V_{oc,STC}$ is the open-circuit voltage at standard testing condition and dV_{oc}/dt is the temperature gradient.

3 Online method for V_{oc} estimation

The PV panel is a current source which generates current when solar light falls on it. There are different models of PV panel, but the single diode model is the most prominent. The equivalent single diode model of PV panel is depicted in Fig. 1 [17]. The single diode model consists of:

1. Current source I_{ph} whose value depends upon irradiance and temperature
2. D , diode
3. R_p , parasitic or shunt resistance
4. R_s , series resistance

Fig. 1 Equivalent circuit of PV panel

Applying KCL to node a, we can write:

$$I_{ph} = I_{pv} + I_d + I_p \quad (6)$$

where, I_{ph} is the photo-generated current of PV panel, I_d is the diode current, I_p is the parasitic resistance's current or the shunt current, and I_{pv} represents the output current of the PV panel. In Fig. 1, V_{pv} represents the output voltage when PV panel is connected to load, and V_{oc} denotes the open-circuit voltage of PV panel. The parasitic resistance current I_p is determined by the following equation:

$$I_p = \frac{V_d}{R_p} \quad (7)$$

where V_d represents the voltage drop across the diode and is calculated by the following equation:

$$V_d = V_{pv} + I_{pv} R_s \quad (8)$$

Diode current I_d is determined from the Shockley diode equation [18]:

$$I_d = I_s \exp \left(\frac{V_d}{N_s V_t} - 1 \right) \quad (9)$$

where I_s is the diode reverse saturation current, V_t represents the thermal voltage whose value equal to $\frac{n k_b T}{q}$. k_b is the Boltzman constant, T represents the PV panel cell's temperature in kelvin, q is the charge on electron, n represents the ideality factor, and N_s is the total series-connected cells of PV panel. The diode reverse saturation current is determined by the following expression [19]:

$$I_s = I_{s,STC} \left(\frac{T}{298} \right)^3 \exp \left(\frac{q E_g}{N_s k_b V_t} \right) \left(\frac{1}{298} - \frac{1}{T} \right) \quad (10)$$

where, $I_{s,STC}$ is the reverse saturation current at standard testing condition, and E_g represents the band gap energy of silicon in electron volt whose value equal to $1.12[1 - 0.0002677(T - 298)]$ [16]. The Eq. (10) depicts that I_s depends upon temperature. At open circuit condition of PV panel, I_{pv} becomes zero. Furthermore, neglecting I_p at open circuit, Eq. (6) can be modified as:

$$I_{ph} = I_d \quad (11)$$

As the diode voltage V_d equal to the open circuit voltage at open circuit condition, therefore, Eq. (9) can be rewritten as:

$$I_d = I_s \exp \left(\frac{V_{oc}}{N_s V_t} - 1 \right) \quad (12)$$

Equating Eqs. (11) and (12), the following equation is produced:

$$I_{ph} = I_s \exp \left(\frac{V_{oc}}{N_s V_t} - 1 \right) \quad (13)$$

The open circuit voltage is derived by solving the Eq. (13):

$$V_{oc} = N_s V_t \left[\ln \left(\frac{I_{ph} + I_s}{I_s} \right) \right] \quad (14)$$

The calculated V_{oc} works well in variable irradiance but can not accurately estimate the V_{oc} under variable temperature condition. Let the temperature remains constant, then Eq. (14) can be rewritten as:

$$V_{oc,ir} = N_s V_{t,STC} \left[\ln \left(\frac{I_{ph} + I_{s,STC}}{I_{s,STC}} \right) \right] \quad (15)$$

where, $V_{t,STC}$ is the thermal voltage at STC. As I_{ph} depends upon irradiance, therefore, the Eq. (15) only works for variable irradiance condition. The open circuit voltage V_{oc} variation due to temperature is determined by the following equation:

$$V_{oc,t} = k_v (T - 298) V_{oc,STC} \quad (16)$$

where, k_v represents the temperature coefficient of V_d and $V_{oc,STC}$ represents the open circuit voltage at standard testing condition. Finally, the open-circuit voltage V_{oc} is calculated by adding Eqs. (15) and (16).

$$V_{oc} = N_s V_{t,STC} \left[\ln \left(\frac{I_{ph} + I_{s,STC}}{I_{s,STC}} \right) \right] + k_v (T - 298) V_{oc,STC} \quad (17)$$

The online method for V_{oc} estimation is elaborated in Fig. 2. The I_{pv} , V_{pv} , and T values are measured using current, voltage and temperature sensors, respectively. The I_s and V_d is calculated by using Eqs. (8) and (10). The I_p and I_d is determined from Eqs. (7) and (9), respectively. The addition of I_{ph} , I_{pv} , and I_d gives the I_p value. Finally, the value of V_{oc} is estimated by using Eq. (17).

Fig. 2 Online method for V_{oc} Calculation

4 Estimation of operating temperature of PV panel

The operating temperature of PV panel depends upon many factors such as environmental temperature, irradiation, wind speed, wind direction, tilt angle, and mounting conditions of PV panel [20]. Many researchers proposed different techniques to determine the PV panel's operating temperature. In [21], authors predict the operating temperature of PV module by using Normal operating cell temperature (NOCT) model. The NOCT, defined by IEC61215 standard, is that temperature of PV panel when wind speed equal to 1 m/s, ambient temperature (T_a) is 20 °C, and irradiance (G) equal to 800 W/m². As per NOCT model, cell temperature is determined by the following equation:

$$T_c = T_a + \frac{G}{800} (NOCT - 20) \quad (18)$$

As this expression does not incorporate the wind speed, wind direction, and tilt angle of PV panel, therefore, this model is not valid for all the environmental conditions. In [22], authors present an infrared imaging technique but due to infrared camera, this is an expensive method. The above-mentioned issues can be addressed by using the temperature sensor [20]. In this work, digital waterproof DS18B20 temperature sensor is used to estimate the temperature of PV panel due to its low cost and accurate results.

5 Implementation of the online method

The hardware implementation of the online algorithm is depicted in Fig. 3. The PV panel is interfaced with load through a boost converter. Three sensors such as voltage, current, and temperature sensors are used for V_{oc} determination. The voltage sensor consists of a potential divider forming between two R_1 and R_2 as shown in Fig. 3. In this scheme, the ACS712 20 amp sensor and DS18B20 sensor are used to measure the PV panel's output current

Fig. 3 Hardware implementation of the online method

and operating temperature, respectively. All the sensors are interfaced with micro-controller Arduino UNO which gives the V_{oc} value. The serial value of V_{oc} is converted into 12-bits value and 12-bits DAC MCP4725 gives the analog value of V_{oc} in terms of voltage. As maximum output voltage of DAC is 5V, therefore, the 38 V V_{oc} is scaled with 5 V DAC output. The output voltage of DAC is displayed in the digital oscilloscope. The online method is tested at 50 % duty cycle. The boost converter designed for hardware has the following parameters:

- $C_{in} = 4700 \mu\text{F}$
- $L = 460 \mu\text{H}$
- $C_{out} = 2000 \mu\text{F}$
- Load = 20 Ω
- $R_1 = 1 \text{ M}\Omega$
- $R_2 = 100 \text{ K}\Omega$
- Switching frequency (f_s) = 25 kHz

6 Calibration of sensors

The accuracy of V_{oc} value can be affected due to error in measured values of current, voltage, and temperature. Therefore, it is required that all the sensors should be calibrated before utilizing for the V_{oc} estimation. In this work, the calibration of the designed voltage sensor and ACS712 current sensor is performed using the standard digital multimeter (DMM). On the other side, the DS18B20 temperature sensor is calibrated using the digital thermometer. Please note that every sensor always gives some minor oscillations in the sensed values. In this work, these oscillations are reduced by taking the average values of different samples.

7 Results

In this section, the effectiveness of the online method is checked by analyzing the error of V_{oc} value. The error in V_{oc} value is determined as follows:

$$\text{Error}(\%) = \left| \frac{\text{Calculated Value} - \text{Ideal Value}}{\text{Ideal Value}} \right| \times 100 \quad (19)$$

7.1 Simulation results

The irradiance and temperature variation pattern are presented in Fig. 4. Initially, the irradiance intensity is 300 W/m² while temperature value is 10°C. After 0.2 s, irradiance is incremented 100 W/m² with a delay of 0.2 s. The irradiance value reaches 1000 W/m² at 1.4 s. In addition, the temperature value is incremented 5 °C with a delay of 0.2 s after 1.3 s. The temperature reaches 50°C at 1.7 s. Figure 5 shows the comparison of estimated V_{oc} value using the online method with the ideal value. It is observed from Fig. 5 and Table 2 that online method performs well for different conditions. Using Eq. (19), the overall average calculated error for the online method is 0.087 %.

Fig. 4 Variable irradiance and variable temperature testing Condition

Fig. 5 V_{oc} value comparison of the online method with ideal V_{oc}

Table 2 V_{oc} value comparison of the online method with ideal V_{oc}

Sampling time instant (s)	Ideal value	Online method	% Error
0–0.1	38.25	38.2	0.13
0.1–0.2	38.25	38.2	0.13
0.2–0.3	38.66	38.64	0.05
0.3–0.4	38.013	38.013	0
0.4–0.5	38.34	38.34	0
0.5–0.6	37.7	37.72	0.05
0.6–0.7	37.97	37.99	0.052
0.7–0.8	37.33	37.368	0.1
0.8–0.9	37.56	37.6	0.1
0.9–1	36.93	36.97	0.1
1–1.1	37.13	37.17	0.1
1.1–1.2	36.5	36.55	0.136
1.2–1.3	36.7	36.72	0.054
1.3–1.4	36.044	36.1	0.155
1.4–1.5	36.21	36.25	0.11
1.5–1.6	35.6	35.625	0.07
1.6–1.7	35.6	35.625	0.07
1.7–1.8	34.95	34.99	0.11
1.8–1.9	34.95	34.99	0.11
1.9–2	34.95	24.99	0.11

7.2 Hardware results

The online method is tested at 50 % duty cycle. The current variation is shown in Fig. 6. The measurements are started at 8:00 AM (Pakistan Standard Time) and ended at 5:00 PM. The total duration of testing is 9 hours. As current is directly related to irradiance, therefore, irradiance will vary with respect to the current. The

Fig. 6 PV panel current variation **Fig. 7** PV panel temperature variation **Fig. 8** V_{oc} measurement using online method, two temperature sensor method and pilot PV panel **Fig. 9** DSO graph of Pilot PV panel V_{oc} and DAC output Voltage

ambient temperature, cell temperature of PV panel using DS18B20 temperature sensor, and NOCT method is depicted in Fig. 7. From Fig. 7, it is clear that NOCT method and DS18B20 temperature sensor give almost the same temperature. The values of open-circuit voltage using online method, two temperature sensor method, and pilot PV panel are shown in Fig. 8. The open-circuit voltage majorly depends upon temperature and its value decrease with a rise in temperature. Therefore, the open-circuit voltage value must follow the temperature variation (Shown in Fig. 7). The average calculated error of the online and two temperature sensor method for the complete duration is 2.65 % and 14.85 %, respectively. The calculated values of V_{oc} can not be directly displayed on a digital oscilloscope. The serial values of V_{oc} is converted into 12-bits and then send to DAC MCP4725 which gives the desired output voltage. As DAC maximum output voltage is 5 V, therefore, its values is scaled up to 38 V by multiplying with 7.6 V in the digital oscilloscope. In Fig. 9, Ch. 1 and Ch. 2 represents the DAC output voltage and scaling factor 7.6 V (battery voltage with the help of potentiometer), respectively. The desired output is

Fig. 10 Experimental setup

obtained by multiplying Ch.1 and Ch.2. Ch. 3 represents the pilot PV panel voltage. Finally, Fig. 10 depicts the experimental setup.

8 Comparative analysis of the online technique and two temperature sensors method

The comparison between online and two temperature sensors method is shown in Table 3. In the online method, three sensors are required for V_{oc} estimation as well as MPP tracking. Conversely, in the two temperature sensors method two temperature sensors are needed for V_{oc} estimation while current and voltage sensors are utilized for MPP tracking. The algorithm complexity of the online method and the two temperature sensors method are equal. Note that, two temperature sensor method can

Table 3 Comparison of the online method with two temperature sensor method

	Online method	Two temperature sensors method [14]
Temperature sensor	1	2
Irradiation sensor	0	0
Voltage sensor	1	1
Current sensor	1	1
Algorithm complexity	Medium	Medium
V_{oc} measurement	Accurate	Not accurate for variable temperature

not determine the accurate value of V_{oc} for the variable temperature condition (verified in the hardware section). Hence, it is concluded that the online technique outperforms the two temperature sensors method.

9 Conclusion

This paper presents a simple and low-cost online technique to estimate the V_{oc} value of PV system. The online method efficiently estimates the V_{oc} without isolating the PV panel. It is verified from the simulation results that the online method has an average error of 0.087% under variable irradiance and temperature condition. On the other side, an experimental test has also been performed (for 9 hours) to evaluate the accuracy of the online method. The online method is tested at 50 % duty cycle and the estimated V_{oc} is compared with the two temperature sensors method. The average calculated error of the online and two temperature sensor methods are 2.65 % and 14.85 %, respectively. Thus, it is verified from the practical results that the accuracy of the online method is significantly higher than the two temperature sensor method. On the other side, note that the presented online V_{oc} technique is designed for the uniform irradiance condition. In future work, we will extend this method for the partial shading case (PSC).

Compliance with ethical standards

Conflict of interest The author declare that he has no conflict of interest.

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