Global MPP Tracking for Photovoltaic Panel under Shading Conditions using Robust Numerical Algorithm

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Abstract. This paper presents a new numerical approach for the modelling of the PV panels under partial shading conditions. It also solves the major drawback of the PV systems, which is the tracking of maximum power point under partial shading conditions where the P-V characteristic has a more complex structure with many local maximums on the graph. This paper aims to resolve this phenomenon using Newton method in order to find the global maximum power point.

1. Introduction

The use of renewable sources to produce energy is a promising option for energy supply that meets the world's growing demand [1], with benefits such as abundance, the absence of pollution and the availability on several places of the terrestrial globe. Solar energy [2, 3] is a good choice for electric power generation using as a technology the photovoltaic (PV) panels. However, the efficiency of the chain of conversion of this energy is relatively low [4, 5], due to the effect of the shadows on the performance of the photovoltaic panels. This shadow can be created by clouds, neighbouring buildings, trees or sometimes even dust. Where the panels depend heavily on the environmental conditions such as the ambient temperature and the solar radiation [5, 6], these two are mainly affected by the shading. Causing not only a loss in the produced power, but also generate multiple summits in the power-voltage (P-V) and current-voltage (I-V) characteristics of the PV array.

To extract the maximum power produced by a photovoltaic array, there have been proposed in the literature many classical conventional methods (Perturb & Observe, Incremental conductance) [7-12]. Many studies have proved that these methods are known to be very effective for tracking the maximum power point (MPP) which changes according to the solar radiation. Nevertheless, these classical methods rely on the fact that the PV array is exposed to a uniform solar radiation, where the P-V characteristic has only one maximum power point. Whereas if there is a non-uniform radiation applied to the PV array, the P-V characteristic will have a more complex curve resulting in many local maxima. This leads to the failure of those methods on tracking the global maximum power point [13-15]. Many researches have been conducted in order to improve the performance of these methods.
under partial shading conditions [15-20], either by adding a modification to the algorithms or by applying a variable step to the classical methods. In spite of this, the application of these new approaches in the real time remains difficult due to the fact that these methods have limitations on tracking the maximum power point under rapidly changing atmospheric conditions, especially if non-uniform.

In order to bridge over this inconvenience and to achieve a better maximum power point tracking, this paper presents a new, rapid and simple method for detecting the global power point under non-uniform illumination based on a numerical model analysis of the PV array with Newton method.

2. Modelling of the photovoltaic panel behaviour

2.1. The equivalent equation of the PV cell

The PV cell converts the sunlight radiation to electricity. In the literature the photovoltaic cell can be represented by the equivalent circuit shown in figure 1. This circuit consists of a diode which represents the PN junction of the cell, and a constant current source whose current amplitude depends on the intensity of the radiation. There is also the material resistivity which is represented by \( R_p \), parallel resistance, characterizing the leakage current at the surface of the cell due to the impurities near the PN junction. The serial resistance \( R_s \).

![Figure 1. Equivalent circuit of a photovoltaic cell](image)

The mathematical model of the PV cell can be obtained by applying the Kirchhoff’s circuit laws to the circuit above resulting into

\[
I = I_{ph} - I_D - \frac{V + IR_s}{R_p}
\]

with

\[
I_D = I_s \left[ \exp \left( \frac{V + IR_s}{V_{th}} \right) - 1 \right]
\]

and

\[
V_{th} = \frac{nKT}{q}
\]

where \( I_{ph} \) is the photocurrent, \( I_D \) is the current through the diode, \( I_s \) is the saturation current of the diode, \( q \) stands for the electronic charge, \( k \) is Boltzmann constant, \( n \) is the junction ideality factor, \( T \) is the junction temperature , \( I \) is the current supplied by the cell and \( V \) is the output voltage of the cell.

From (1) to (3) results that the current is
\[ I = I_{ph} - I_{s} \left[ \exp \left( \frac{V + IR}{V_{th}} \right) - 1 \right] \frac{V}{R_p} \]. \quad (4)

Resistance \( R_p \) is generally neglected and the photocurrent is approximately equal to the short circuit current \( I_{sc} = I_{ph} \). Also, when there is an open circuit

\[ V_{oc} = V_{th} \ln \left( \frac{I_{sc}}{I_{s}} \right) \]. \quad (5)

and the saturation current can be expressed as

\[ I_{s} = I_{sc} \exp \left( \frac{V_{oc}}{V_{th}} \right) \]. \quad (6)

So, equation (4) for the supplied current becomes

\[ I = I_{sc} \left[ 1 - \exp \left( \frac{V - V_{oc} + IR}{V_{th}} \right) \right] \]. \quad (7)

2.2. Modeling of photovoltaic panel

To obtain a more accurate modelling of PV cell, the impact of the solar radiation and the ambient temperature should also be considered [5, 6]. Normally, the cell parameters are provided by the manufacturers under standard test conditions (STC), which are 25 °C and 1000 W/m². For this, the different components of the equation (7) are written as a function of the available radiation \( G \) and present temperature \( T \) according to following equations

\[ I_{sc} = I_{sc,0} \frac{G}{G_0} \left[ 1 + k_0 (T - T_0) \right] \]. \quad (8)

\[ V_{oc} = V_{oc,0} + C_1 (T + C_2 G - T_0) \]. \quad (9)

where \( G_0 \) and \( T_0 \) are the standard test conditions of irradiance and temperature and \( I_{sc,0} \) and \( V_{oc,0} \) are the measured current and voltage under these conditions. The coefficients \( k_0 \) and \( C_3 \) are the temperature coefficient of the photocurrent and voltage respectively, and \( C_2 \) is the radiation coefficient of the open circuit voltage \( V_{oc} \). By establishing these two equations, it is assured that the variation of the radiation and the ambient temperature is taking into consideration.

The PV model is an assembly of many PV cells which can be connected into series or parallel or mixed configurations and are accompanied in many cases by a bypass diode, as can be in figure 2.
Figure 2. Photovoltaic panel

Figure 2 represents the configuration of a photovoltaic panel where $N_p$ and $N_s$ are the number of cells connected in parallel and series configuration. The PV panel current is then given by:

$$I_{pv} = N_p I_{sc} \left[ 1 - \exp \left( \frac{V_{oc} - N_s V_{oc} + I_{pv} N \frac{R_s}{N_p}}{V_{oc, pv}} \right) \right].$$

(10)

This equation is an implicit function which depends on the overall short circuit current and on the open circuit voltage of the panel along with the equivalent series resistance. For the modelling of the PV panel shown in figure 3, MATLAB Simulink has been used, through a combination between Simscape and Simulink libraries. MATLAB Simulink allowed the simulation of the behaviour of the panel and characterize its nonlinear $P/V$ and $I/V$ curves to better understand the effect of radiation and temperature on the output current and voltage.

Figure 3. MATLAB interface model for a PV panel

2.3. The effect of the shading on the photovoltaic panel

When a cell is shaded, it behaves as an overload, dissipating the electrical energy by Joule effect. This leads to temperature increases and generates the so-called hot spots, thus helping to create an open
circuit in the whole of the photovoltaic module system. Therefore, the detection of the maximum power of the photovoltaic panel under shaded conditions in real time is vital.

![Shaded photovoltaic cells](image)

**Figure 4.** PV panel structure with different illuminations

In order to overcome this inconvenience and to achieve a better maximum power point tracking (MPPT) process, this paper presents a new, fast and simple method for MPPT under non-uniform illumination based on a numerical model analysis of the PV array using Newton method.

3. **Newton method for shaded photovoltaic panel**

3.1. **Newton numerical approach**

In numerical analysis, the Newton method, in its simplest application, is the most well-known and efficient algorithm to find the precise numerical approximation to the roots of a real valued function

\[ f(x) = 0. \] (11)

The method calculates the tangent at the point \( x_0 \) (the function derivative) which is the initial value chosen near the solution. The next value to use is the intersection between the tangent and the x-axis. It is an iterative process which will stop when the convergence criteria are achieved. The Newton method can be used in the case of continuous and differential functions in a certain interval \([a, b]\). The differentiability condition assures the presence of a linear tangent for the function. The continuity condition assures that there are no jumps in the function. The graph slope is obtained by

\[ f'(x_n) = \frac{\Delta y}{\Delta x} = \frac{f(x_n)}{x_n - x_{n+1}} \] (12)

are if the terms are reorganized, equation (12) reduces to

\[ x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \] (13)

The Newton method can also be used to find local minimums and maximums. When a minimum or a maximum is achieved, the solution \( x^* \) is the stationary point of the \( f(x) \) function (\( x^* \) is the solution to \( f'(x) \)). Newton method steps can be resumed as follows:

- Chose an initial approximation \( x_0 \);
- Calculate the value of the function at this point \( f(x_0) \);
- Calculate the function derivative \( f'(x) \) and evaluate its value at \( f'(x_0) \);

\[ f'(x) = \]
• The approximation \( x_i \) is obtained with \( x_i = x_0 - \frac{f(x_0)}{f'(x_0)} \);

• Repeat the process till finding the solution \( x^* \) using \( |x_{n+1} - x_n| < \epsilon \) as a stopping criteria.

3.2. Application of the Newton method to the MPPT

As a first step the Newton iterative method has been applied for uniform illumination where there is the presence of only one maximum power point, so if the PV array is operating with a a voltage lower than the maximum \( V_m \), then \( \frac{dP}{dV} \neq 0 \) since \( \frac{dP}{dV} = 0 \) only occurs at the maximum power point. This paper seeks to find the solution of \( \frac{dP}{dV} = 0 \) by the Newton iterative method in order to detect the global maximum power point rapidly with high precision.

![Image](image_url)

**Figure 5.** Mathematical relations of Output Power and Output Voltage

According to what has been described, the Newton method is useful in finding the roots of any non-linear function. As can be seen from figure 8, the roots of the derivative of the power curve correspond to the point of MPP, which can be obtained through Newton’s method. For this reason, the function of the power derivative is taken as the objective function for the Newton method, where the power curve has been approximated by the quadratic form

\[
q(V) = P(V_k) + (V - V_k) P'(V_k) + \frac{(V - V_k)^2}{2} P''(V_k)
\]  

(14)

To maximize this expression, its derivative is taken to be zero

\[
q'(V) = 0 = P'(V_k) + (V - V_k) P''(V_k)
\]

(15)

resulting into

\[
V_{k+1} = V_k - \frac{P'(V_k)}{P''(V_k)}
\]

(16)

with

\[
P'(V_k) = \frac{P(V_k) - P(V_{k-1})}{V_k - V_{k-1}} \quad \text{and} \quad P''(V_k) = \frac{P'(V_k) - P'(V_{k-1})}{V_k - V_{k-1}}.
\]

(17)
3.3. Simulation and results

A 100W PV array was chosen for modelling in MATLAB. The electrical characteristics specifications of the used panel are shown in Table 1.

| Parameter             | Variable | Value |
|-----------------------|----------|-------|
| Maximum power         | $P_m$    | 100 W |
| Voltage at Pmax       | $V_m$    | 17.6 V|
| Current at Pmax       | $I_m$    | 5.71 A|
| Short circuit current | $I_{sc}$ | 6.4 A |
| Open circuit voltage  | $V_{oc}$ | 21 V  |

3.3.1. Uniform illuminations

The MATLAB model simulation results are represented in the figure 3, through the P-V and I-V characteristics obtained with uniform illumination and temperature on the overall panel corresponding to the Standard Test Conditions ($T = 25°C, G = 1000W/m^2$).

Figure 6 shows the characteristics of the PV panel obtained by the MATLAB modelling, where the blue curve represents the I-V characteristic and the violet represents the P-V characteristic. Table 2 shows the values of the voltage and the output power of the MPP obtained by the Newton method.

| Newton method results (uniform illuminations) |
|-----------------------------------------------|
| Voltage at MPP (Newton)                       | 16.354 V |
| Power at MPP (Newton)                         | 99.765 W |
Observation of the curves on figure 6 and table 2, it was found that the P-V and I-V characteristics of the simulation were closely matched with the characteristics found by the manufacturer under the same conditions. And as can be seen, the P-V characteristic presents a peak where the maximum power is. The detection of this output power was obtained by applying the Newton method which showed that the maximum power is 99.765 W as presented in table 2. Therefore, the use of Newton’s method has been verified and validated for finding the maximum point under uniform illumination and temperature.

3.4. Non-Uniform illuminations

Before applying the Newton method to non-uniform illumination condition, a mathematical model was required to establish the equation of the PV system under partial shadowing conditions. A wide study has been undertaken to set up a mathematical model of the PV panel under partial shading conditions, which helped test the behaviour of a PV array under non-uniform illuminations. The same parameters shown in table 1 were applied to the mathematical model and the global current calculated is obtained by the sum of all the output currents with a variation of the irradiance that has been made in order to achieve the impact of the shading on the photovoltaic panel.

Using a PV array of dimensions $1 \times 36$, receiving four different levels of radiation which are: 500 W/m$^2$, 1000 W/m$^2$, 100 W/m$^2$ and 1300 W/m$^2$. The same process of the Newton method has been applied in this case where at first the four peaks of the P-V characteristics have been detected, thus the global maximum power point has been found.

Figure 7 shows the MATLAB simulated characteristics of the previously described PV array receiving four different levels of illumination. As can be seen, the overall PV characteristic presents multiple peaks which are not well-handled by the conventional MPPT methods.

| Voltage at MPP | 31.9 V |
|---------------|--------|
| Power at MPP  | 191.6681 W |

Table 3. Voltage and power at MPP of a PV panel under different illuminations obtained by Newton’s method.
As can be seen in figure 7 and table 3 the overall P-V characteristic has a very complex curve with a maximum power point at 192.9 W and 31.25 V, accompanied by three more local maximum powers. In this case, the downside of the conventional methods [13, 14] is evident since they will only follow the first local maximum power point. Table 3 shows the maximum power point coordinates obtained by Newton method indicating that the maximum power point is 191.67 W at a voltage of 31.9 V, which correspond to the global MPP coordinates given by the figure 7. This proves the accuracy and the precise convergence of the iterative Newton process. Thus, under partial shading conditions, finding the global power point for a PV array can be accomplished by applying the Newton iterative method.

4. Conclusion

This paper firstly presented the modelling of a PV panel under the MATLAB interface based on a numerical approach using the equations that describe the behaviour of the PV panel. Also, it brings out the major phenomena facing this technology which is the partial shading, where the conventional popular MPPT methods, namely the Perturb and Observe and Incremental conductance methods, cannot perform MPPT under these conditions due to multiple local maximums that are exhibited on the P-V characteristic. Although some researchers have worked on improving these methods for MPPT under partial shading conditions, they still have some drawbacks. In order to overcome this inconvenience, this paper, focus mainly on developing an easy and fast numerical approach to track the maximum power point under partial shading conditions using the Newton method to solve the equation of the PV system under these conditions, where a MATLAB based PV model is presented with the aim to detect the global maximum power point under partial shading conditions. According to the results, it has been shown that this method has good performance with small errors under non-uniform illumination and with fast convergence.

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