Improved Perturb And Observe Maximum Power Point Tracking Algorithm In Grid-Connected Photovoltaic Systems

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Abstract—Maximum power point tracking efficiency and dynamic performance of any maximum power point tracking algorithms play a vital role in grid-connected PV systems. This paper deals with an improved perturb and observe maximum power point tracking algorithm capable of enhancing the steady state and transient behavior. Selecting optimized perturbations parameters are achieved through analyzing the transient behavior of perturb and observe method. This algorithm is performed using an interface DC-DC boost converter. MATLAB/Simulink environment is used for simulating a 8.1 Kw grid-connected Photovoltaic systems and verified algorithm expected merits.

Keywords—grid-connected PV systems; Maximum power point tracking; perturb and observe.

I. INTRODUCTION

It goes without saying that renewable energy exploitations have become one of the most pressing concerns facing all electrical engineering. Quite recently, considerable attention has been paid to photovoltaic systems (PV). The conventional fossil fuels depletion and environmental pollution go hand-in-hand for extending PV technology. PV systems have been utilized in many applications such as satellite power supplier, electric vehicle and addressing the electrical power demands of impassable regions [1]-[4].

On the negative side, some detriments such as non-cost effectiveness and low conversion efficiency make PV usages be limited. Although there is low maintenance cost due to lack of mechanical equipments, the initial investment cost is absolutely high and considerable. In addition, variations occurring in the solar irradiance and the ambient temperature either from one place to another or from one time to another makes PV be somewhat unreliable. Accordingly, an interface converter capable of performing maximum power point tracking (MPPT) is necessarily required. In the last few years there has been a growing interest in introducing a DC-DC converter with the optimized MPPT algorithm [4]-[6].

The literature on MPPT issue shows a variety approaches presenting briefly here. Previously, great efforts have been devoted to the study of incremental conductance (Inc-Cond) algorithm [1]-[11]. Basically this algorithm performs MPPT by comparing incremental conductance (ΔI/ΔV) and instantaneous conductance (I/V) of PV arrays in order to harvest maximum power. Although the structure of this algorithm seems to be straightforward, for having a low oscillation around maximum power point the incremental size should be reduced leading to be time consuming method. Moreover, this method cannot work properly under the partial shading condition.

Another possible method reported by [12]-[14] is ripple correlation control (RCC). This algorithm finds maximum power point adjusting duty cycle of interface DC-DC converter. This technique has advantages including well-tracking at high solar irradiance, fast MPPT response and less expensive. However, at low solar irradiance there would be large oscillation in power extraction [12]-[14].

To the authors’ knowledge, new studies have been carried out some complex algorithms such as particle swarm optimization (PSO) [15]-[20], differential evolution (DE) [21], genetic algorithm (GA) [22] and artificial neural network (ANN) [18]. These newly introduced approaches harvest maximum power in a better manner at expense of cancelling the control simplicity. However, for more details the interested readers are referred to [23].

The other simple and effective previously-introduced methods are perturb and observe (P&O) and the hill climbing (H&C) techniques [24-27]. The tangible advantage of these methods is their implementation simplicity along with fewer electrical sensor requirements. However, a major drawback would be appeared in the transient of maximum power harvesting providing that the step changes width are not precisely selected. In all methods which in iterative techniques are required for performing the method processing, selecting these step changes properly has paramount of importance in transient response of MPPT. This paper presents a new approach of obtaining desired duty cycle step changes and time intervals for P&O algorithm. By using this new approach, the transient response in MPPT is improved.

The remainder of the paper is organized as follows. In the following section photovoltaic characteristics and its modeling will be discussed. While section III is devoted to
establish new approach of obtaining duty cycles step changes and time intervals, the photovoltaic system parameters as a case study are explained in section IV. The simulation and its results are entirely discussed in section V. Finally a conclusion of this work will be drawn.

II. PHOTOVOLTAIC CHARACTERISTICS AND MODELING

The PV generator consists of some PV modules connected in series and parallel. In this paper a detailed PV electrical model is resorting based on the Shockley diode equation. For considering the number of cells in the module, the same model for the solar cell is used [8]-[31]. It is clear that three key factors including solar radiation, ambient temperature and load condition determine output power value. It is also mentioned that many models which are extracted from physical equations, using curve fitting or artificial intelligence have been proposed. Discussing these models is completely beyond this study and the interested readers are invited to study [32].

Accordingly, here a model based on the single diode assumption is considered. This model is illustrated in Fig. 1. The required parameters can be found from the PV module datasheet. In this model, the solar cell or PV module can be considered as an equivalent circuit of a diode and a dependent current source connected in parallel. This dependent current source and diode represent the photo current of sunlight hitting to the solar panel and the P-N transition area of the solar cell respectively. In addition, the resistors represent the losses owing to the body of the semiconductor and the contacts.

Using Kirchhoff current law, it is obtained that

\[ I_{pv} = I_{light} - I_{d} - I_{sh} \]  

(1)

Where all the above parameters are represented in Fig. 1. Therefore the output current \( I_{pv} \) can be evaluated by Equation (2). Regarding this equation, the last term can be neglected providing that the shunt resistance \( R_{sh} \) is completely high.

\[ I_{pv} = I_{light} - I_{d} (e^{\frac{V_{dc}}{A R_{s}}} - 1) - \frac{V + I_{pv} R_{s}}{R_{sh}} \]  

(2)

Evaluating the parameters \( R_{s}, R_{sh}, A, I_{0} \) is somewhat involved and beyond this study. However, these parameters can be calculated by using PV datasheet and some formulae [33]. The light-generated current \( I_{light} \) is nearly equal to the short circuit current \( I_{sc} \). This current varies directly proportional to the solar radiation and cell temperature. Fig. 2 demonstrates that to what extent the solar radiation and cell temperature can affect the PV generator characteristics. Regarding this figure, temperature increasing makes output power be reduced in both considered solar radiations.

![Fig. 2. PV generator characteristics for solar radiation 1000 W/m² and 300 W/m², temperature 20°C and 40°C: (a) current vs. voltage and (b) power vs. voltage.](image)

III. IMPROVED P&O MAXIMUM POWER POINT TRACKING

Significant researches have been reported using this algorithm. However, to the authors' knowledge, analyzing the transient behavior of the system using this method has rarely been discussed. In addition, none of the related researchers have worked on finding the duty ratio perturbation value \( \delta d_{p} \) and the minimum time interval between these perturbations \( \delta T_{p} \). This section presents some useful guidelines making P&O maximum power point tracking efficiency and dynamic response be improved.

A. Transient Analysis

A small signal analysis has been employed for explaining the effects of perturbation \( \delta d_{p} \) and the time interval \( \delta T_{p} \) in the P&O MPPT algorithm. A simplified equivalent circuit for the grid-connected PV system is depicted in Fig. 3, where the PV generator is linked to a grid-inverter via a dc/dc boost converter. It is noted that the equivalent series resistances of the inductor (L), the capacitor (C in) and the other parasitic components have been neglected. Moreover, the equivalent shunt resistance \( R_{sh} \) of the solar array is ignored. The inverter DC link voltage is considered as a voltage source \( e \).
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Fig. 3. Simplified equivalent circuit for the grid-connected PV system.

The inputs of the system are the solar radiation (S), the cell temperature \( T_c \), the inverter equivalent voltage (e), and the dc/dc converter duty ratio (d). The outputs are the PV generator output voltage \( V_{pv} \) and output current \( I_{pv} \). The temperature dynamic effect can often be ignored due to small thermal inertia and small perturbations in power \([31]\). By analyzing the system, the following circuit equations can be obtained:

\[
i_{L} = \frac{1}{L} (V_{pv} - e(1 - d))
\]  

\[
V_{pv} = \frac{1}{C_{in}} (I_{pv} - i_{L})
\]  

Regarding Equation (2) and above equations we attain that:

\[
\frac{\partial I_{pv}}{\partial V_{pv}} = K_{pv} = \frac{-I_{o}}{A e^{-(V_{pv0} + R_{S} I_{pv})/A} + I_{pv} R_{S}}
\]  

\[
\frac{\partial I_{pv}}{\partial S} = K_{S} = \frac{1}{S_{T}} (I_{sc} + \mu_{sc} (T_{C} - T_{C}^0))
\]  

Using common small signal analysis, the state space representation of the system can be provided in the form of Equations (7) and (8). Prefix \( \delta \) demonstrates small signals (increment) from ac signals. Symbol \( (0) \) in the subscript corresponds to the zero initial condition at \( t=0 \). \[ \dot{x} = Ax + Bu \]

\[ y = Cx + Eu \]

And in the expanded form:

\[
\left[ \begin{array}{c} \delta I_{L} \\ \delta V_{pv} \end{array} \right] = \left[ \begin{array}{cc} -\frac{R_{S}}{L} & \frac{1}{L} \\ \frac{1}{C_{in}} & -\frac{K_{pv}}{C_{in}} \end{array} \right] \left[ \begin{array}{c} \delta I_{L} \\ \delta V_{pv} \end{array} \right] + \left[ \begin{array}{c} \frac{E_{p}}{L} \\ \frac{K_{S}}{C_{in}} \end{array} \right] \delta d + \left[ \begin{array}{c} 0 \\ \frac{K_{S}}{C_{in}} \end{array} \right] \delta s
\]  

(9)

(10)

From (9) and (10), the time domain response of \( \delta V_{pv} \) with respect to duty cycle variations \( \delta d \) can be easily evaluated providing that other inputs' variation have been ignored. Therefore:

\[
\delta V_{pv}(t) = -E_{p}(1 - e^{-\zeta t/\sqrt{1-\zeta^2}} \sin(\omega_d t + \theta)) \delta d
\]  

Where

\[
\zeta = \frac{K_{pv}}{2 \sqrt{C_{in} L}}
\]

\[
\omega_d = \omega_a \sqrt{1 - \zeta^2}
\]

(12)

The time domain equation for the produced perturbation in power will be obtained:

\[
\delta P_{pv}(t) = K_{pv} \delta V_{pv}^2(t)
\]

\[
\delta P_{pv}(t) = K_{pv} E_{p}^2 \left(1 - \frac{e^{2 \omega_d t}}{1 + \omega_d^2} \sin^2(\omega_d t + \theta) - \frac{e^{2 \omega_d t}}{1 + \omega_d^2} \sin^2(\omega_d t + \theta) \right) \delta d^2
\]  

B. Design Of Perturbation Parameters

The minimum time interval \( (\delta T_p) \) required between every perturbation in the duty cycle can be extracted from Equation (12). \( \delta T_p \) can be considered equivalent to the settling time \( (T_{sttl}) \) for the power transient signal. The reason is that the signal would reach to its the steady state within this time. \( \delta T_p \), is provided in Equation (13) illustrating the capacitor effects on the dynamic behavior of the system.

\[
\delta T_p \approx T_{sttl} = \frac{4}{\xi \omega a} \approx \frac{8 \xi a}{K_{pv}}
\]  

(13)

Considering that the perturbation in power will be unity, from Equation (12) the minimum perturbation value in the duty cycle can be calculated. Additionally, \( K_{pv} \) is calculated with respect to the maximum power point.

\[
\delta d_p = \frac{1}{\sqrt{(-K_{pv} R_{p})}}
\]  

(14)

The \( V_{pv} - I_{pv} \) curve shape has the major effect on the system’s dynamic (Fig. 4). The \( V_{pv} - I_{pv} \) curve shape effect comes from the fact that: \( R_{pv} = 1/K_{pv} \). It means that as the voltage increases, the absolute value of \( (R_{pv}) \) decreases and this causes the system to be more damped (see Equation (11)).

Fig. 4. \( I_{pv} - V_{pv} \) curve at \( T_{c} =20^oC, S=1000 \, W/ m^2 \)

Accordingly, for obtaining the optimum \( \delta d_p \) and \( \delta T_p \) the worst case in the \( V_{pv} - I_{pv} \) curve should be considered. This mentioned case would be occurred when the voltage value is lower than maximum power point. In this region \( K_{pv} \) has its lowest value and the response would be oscillatory leading to higher settling time. Therefore, if \( \delta T_p \) is considered lower than \( T_{sttl} \), MPPT efficiency would be decreased.

IV. ANALYZED PV SYSTEMS CHARACTERISTICS

In this paper, a 8.1kW PV system is simulated with the datasheet parameters listed in Table. 1(under the reference solar radiation (1000 W/m²) and cell temperature (25°C)
Condition). The DC-DC boost converter parameters are considered as an inductance value $L=3 \text{ mH}$, and a capacitance value $C_\text{p}=100 \mu\text{F}$. Procedure of obtaining converter is beyond this study and interested readers are referred to [15]. It should be mentioned that inverter equivalent source value is $800\text{V} (\frac{3}{2}\text{V}_\text{L-LPeak})$. It is also mentioned that grid has line-line voltage of $380\text{V}$ and frequency of $50\text{Hz}$.

Here Improved P&O algorithm has been used for MPPT harvesting. This algorithm as a flowchart is illustrated in Fig. 5. A schematic circuit diagram of the $8.1\text{kW}$ PV generating system was shown in Fig.3, which has been simulated using the Matlab/Simulink. To demonstrate the proposed design results, the P&O algorithm as shown in Fig. 5 has been developed to control the system.

![Fig. 5. Perturb and observe algorithm](image)

Table 1. Solar module parameters

<table>
<thead>
<tr>
<th>Module characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>150 Watt</td>
</tr>
<tr>
<td>Voltage at Maximum Power</td>
<td>29.88 Volt</td>
</tr>
<tr>
<td>Current at Maximum Power</td>
<td>5.025 Ampere</td>
</tr>
<tr>
<td>Short Circuit Current</td>
<td>5.43 Ampere</td>
</tr>
<tr>
<td>Open Circuit Voltage</td>
<td>34.78 Volt</td>
</tr>
<tr>
<td>Temperature coefficient of $I_{sc}$</td>
<td>0.024%/°C</td>
</tr>
<tr>
<td>Temperature coefficient of $V_{sc}$</td>
<td>-356 mV/°C</td>
</tr>
<tr>
<td>Number of Modules</td>
<td>54</td>
</tr>
</tbody>
</table>

![Table 1. Solar module parameters](image)

Optimized $\delta d_p$ and $\delta T_p$ is calculated based on the aforementioned parameters using equations (13) and (14). To indicate the importance of $\delta T_p$ determination, Fig. 6 illustrates the power response settling time in both worst case (Fig. 6a) and MPPT case (Fig. 6b). Regarding this figure, optimized $\delta T_p$ is around 0.06 seconds.

![Fig. 6. Output power response due to $\delta d_p$ step variation, a) Worst case, b) Near MPPT](image)

V. SIMULATION RESULTS

Considering that this PV system is connected to the grid through a three-level inverter with switching frequency of 33 times the grid fundamental frequency. MPPT is achieved using a DC-DC boost converter with 5 KHz switching frequency. This improved MPPT algorithm is applied. In addition, this three-level inverter has been driven so that the active and reactive power injected to the grid is controlled. The overall schematic of this PV system is shown in Fig. 7.

A solar radiation step change was applied to the system from $400 \text{W/m}^2$ to $800 \text{W/m}^2$ and back again to its initial value. The MPPT controller was implemented with different perturbation parameters which are presented in Table 2. These perturbations are selected to demonstrate that how can MPPT efficiency can be improved using optimized parameters.

![Table 2. Perturbation parameters](image)

<table>
<thead>
<tr>
<th>Modes</th>
<th>$\delta d_p$</th>
<th>$\delta T_p$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smaller $\delta T_p$</td>
<td>0.002</td>
<td>0.04</td>
</tr>
<tr>
<td>Smaller $\delta d_p$</td>
<td>0.0005</td>
<td>0.06</td>
</tr>
<tr>
<td>Optimized $\delta T_p$ and $\delta d_p$</td>
<td>0.002</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The output power response to all operation modes listed in Table 2 is shown in Fig. 8. As it is expected the highest MPPT efficiency is occurred when the optimized perturbation parameters are selected. According to this figure, MPPT efficiency is about $97.54\%$ in solar radiation of $800 \text{W/m}^2$ and $97.25\%$ in solar radiation of $400 \text{W/m}^2$. One can find that for the other perturbation parameters values the MPPT efficiency is absolutely lower than for optimized parameters. Furthermore, the settling time for tracking the maximum power is meaningfully decreased by selecting optimized parameters. For a quantitative comparison, Table 3 is provided which in the MPPT efficiency and the settling time in all operation modes are listed.
Fig. 7. The overall schematic of this 8.1Kw grid-connected PV system

Table 3. Simulation Results including MPPT efficiency and settling time

<table>
<thead>
<tr>
<th>Modes</th>
<th>MPPT Efficiency (%)</th>
<th>Settling Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S=800 kW/m²</td>
<td>S=400 kW/m²</td>
<td></td>
</tr>
<tr>
<td>Smaller δT_p</td>
<td>93.85</td>
<td>0.32</td>
</tr>
<tr>
<td>Smaller δd_p</td>
<td>92.21</td>
<td>0.3</td>
</tr>
<tr>
<td>Optimized δT_p and δd_p</td>
<td>97.54</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Fig. 8. The output power response

VI. CONCLUSION

An improved perturbation and observed MPPT algorithm is presented. Optimized perturbation parameters can be obtained through discussing the transient response of a PV System connecting via a DC-DC boost converter. Not only does the newly presented algorithm satisfy power harvesting, but also in comparison with other non-optimized parameter it demonstrates a better dynamic and steady state performance. From the research that has been undertaken, it can be concluded that by selecting optimized perturbation parameters for a considered 8.1 Kw grid-connected PV system, at least there is a 3.69% increase in MPPT efficiency. In addition the power harvesting settling time is completely shortened.

A better dynamic and steady state performance makes this improved algorithm a good choice as a simple implemented MPPT algorithm in renewable energy.

REFERENCES

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