A SIMPLE IMPLEMENTATION OF PERTURB AND OBSERVE CONTROL METHOD FOR MPPT WITH SOFT SWITCHING CONVERTER INTERFACE

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Abstract

This paper presents a new approach based upon Perturb and Observe (P&O) to track Maximum Power Point (MPP) in Photovoltaic (PV) systems. This algorithm has a wide step length range which results in a very high response time to changing ambient condition. This method is analogue based and thus no DSP and/or A/D are employed in this system which greatly reduces the complexity and cost. To further increase the total efficiency, a soft switching converter as an interface circuit is applied. Semiconductor devices in underutilized converter entirely are fully soft switched. The proposed system is analyzed and the simulation results are presented. A 135W prototype system is implemented and the stated experimental results confirm the veracity of the theoretical analysis.

Keywords: Maximum Power Point Tracking, Perturb and Observe, Photovoltaic Panel, Zero Current Switching Converters

I. Introduction

Renewable energy resources typically solar energy plays a vital role in electric power generation which led it to become an essential supply due to paucity of conventional fuels and their nasty environmental impacts [I]. Despite all the PV cells’ advantages, the efficiency of energy conversion is currently low, and amount of electric power generated by solar arrays changes continuously with weather conditions [II]. Therefore in order to achieve maximum efficiency in operation, it necessitate to applying techniques to extract the maximum power from solar panels.
The PV power characteristic is nonlinear, which makes the extraction of maximum power a complex task, considering rapidly changing environmental conditions and partial shaded conditions. To attain maximum power, it essential to use an interface circuit that leads the PV system to operate at its Maximum Power Point (MPP), this will be tracked by different Maximum Power Point Tracking (MPPT) techniques. This circuit consists of a power section and a control section. Various methods are introduced to extract maximum possible power from the PV modules [III].

A prevalent MPPT technique is regulating PV voltage to a fixed reference voltage. This approach posits that each variation in the irradiation and temperature are insignificant. This control method can work well even when large load variations occur. Although the implementation of this method is simple, the method is not very precise, since it ignores the effects of temperature and irradiation. To improve this algorithm, the reference voltage can be set to a fixed fraction of the open-circuit voltage ($V_{oc}$) which is measured by momentarily interrupting the normal operation of the PV or using pilot cells that must be carefully chosen to closely represent the characteristics of the PV array [1V]. In [V] it is supposed that the voltage at the peak power is located around 70%–80% of $V_{oc}$. Since the nonlinear relationship between the voltage at MPP and open-circuit voltage is only estimation, the PV array practically never operates at the MPP. Therefore, this method is simple and low cost to implement.

As, the efficiency of the PV system contingent upon several climatic factors, the maximum power point varies with radiation and temperature. It is difficult to estimate the proper points at all radiation levels so many research papers have focused in overall efficiency improvement of the solar system, by adjusting the operating point of the DC–DC converter to capture maximum power. A DC–DC converter functions as interface between load and the PV module [VI].

Should source impedance be equal to the load impedance, maximum power will transfer from source to load by regulating the duty cycle of the DC/DC converter of PV. To track MPP, the converter has to operate with corresponding duty cycle. In the unstable atmospheric conditions the duty cycle of the DC/DC converter has to be controlled to elicit maximum power from PV module [IV].

Due to duty cycle regulation, load impedance seen from the source changes in order to provide maximum power from the PV source whereas maintaining the voltage–current relationship. Over a number of years, a train of MPPT techniques have been introduced, developed and implemented. These methods vary in aspects such as complexity, required number of sensors, cost, range of effectiveness, etc [VI].

The most common approach in the current literature is directly employing the DC/DC converter duty cycle or PV voltage as the control parameters forcing the $\frac{dP_{out}}{dD}$ or $\frac{dP_{out}}{dV}$ to zero, where $P_{out}$, $D$ and $V$ are PV array output power, duty cycle and PV array output voltage respectively.

Hill climbing and perturb and observe methods are widely employed in the MPPT controllers because of their simple structure and implementation [VI], [VII].

In P&O method, the reference voltage is perturbed in an arbitrary direction and the PV array output power change is detected by comparing the present and previous voltage levels, in order to calculate a new reference voltage. A PI controller is also required to match the PV array and reference voltage levels [VIII]. The maximum
power tracking system’s control flowchart is shown in Fig.1 which explains the circumstances of aforementioned algorithm [I].

In Hill Climbing method, the duty cycle of the power converter is perturbed in an arbitrary direction and depending upon the sign of the power change, the direction for further perturbation is determined. Hill climbing has simplified control structure with no feedback control loop that makes this technique a popular one [IX]. Fig.2 shows the control flowchart of Hill Climbing method [I].

![Flow chart of HC MPPT technique according to [I]](image1)

![Flow chart of P&O MPPT technique according to [I]](image2)
Due to the selection of step value of switching duty cycle (or PV array voltage) there is a tradeoff between dynamic response and steady state performance of Hill Climbing or P&O methods. Through analysis, it is desired to make step sizes large enough during transient stage and small at steady state condition. The speed of achieving MPP depends upon the size of the increment. A small step size will lengthen the time required to reach the MPP, however it will track the closest of the ideal MPP. A larger step size will rapidly track the MPP but will oscillate about the maximum power point [X]. In a changing step size method, the step size can be evaluated from the slope of the power/duty cycle or power/voltage [VIII]. The drawback of implementing variable step size algorithms, is the circuit complexity and consequently higher system cost.

In the algorithm presented in this paper, step length can be changed as much as it needs, thus the response of the algorithm to changing the ambient condition is improved. To further efficiency improvement, a soft switching converter is implemented as the power interface.

In this document, an easy implementation of perturb and observe control method for tracking the maximum power for PV panels is proposed. A soft switching converter is also considered as interface between PV output and battery to track MPP. This paper is organized as follows: Section II provides the principles of a photovoltaic system and the characteristic model of PV is addressed. Section III, the purposed system is described. It is shown how harmonics and sub-harmonics of Bang-Bang control are reduced. Section IV, a ZCT Buck DC/DC converter is employed to improve efficiency. Section V, theoretical and experimental results are presented. Section VI includes the conclusion.

II. Theory

PV Module Characteristic

A solar cell acts as a p-n junction and explicates its electrical response according to cell’s nonlinear characteristics. Fig.3. shows the simplest equivalent circuit of a solar cell where a current source parallel with a diode. In dark, with no light, solar cell works like a diode in the reverse mode. The more intensity of light increases, the more current is generated by the solar cell. The output current is proportional to the solar radiation falling on the cell. Besides, the falling light on solar cell generates diode current also. The properties of the diode determine the I-V characteristics of the cell. In addition, a series resistance, $R_s$, is added to represent the resistance inside each cell, while shunt resistance, $R_p$, is added to represent the saturation current of the diode. However, as a fair approximation, $I_{ph}$ can be neglected because $R_p$ is assumed as a very large resistor [XI].
The solar cell has a nonlinear relationship between its output voltage and current. This nonlinear behavior can change due to the variations of irradiation and temperature as following:

\[
I = I_{ph} - I_s \left( e^{\frac{e(V+RI)}{kT}} - 1 \right) - \frac{(V + RI)}{R_s}
\]  

(1)

Where: \(I\) - output current of solar cell, \(I_{ph}\) - the current through the p-n junction, \(I_s\) - reverse saturation current of the cell, \(q\) - the electron charge, \(V\) - the output voltage of solar cell, \(R_s\) - the series resistance (ideally zero), \(K\) - the Boltzmann’s constant, \(T\) - the absolute operating temperature, and \(R_p\) - the shunt resistance, which is ideally infinity; Hence, last term in (1) is generally ignored [XIII].

![Equivalent circuit of solar cell according to [13]](image)

**Purposed System**

The proposed control block diagram and the PV system block diagram are shown in Figs. 4-5. Fig.6 shows flow chart of the mentioned algorithm.

In each iteration, the DC/DC converter input voltage and current are measured and the input power is calculated. The input power is compared to its previously calculated iteration value and according to the result of the comparison; the switch is either turned on or off. The switch situation remains unchanged until the power or voltage variation becomes complement.

Bang-bang control used in this paper has high convergence speed but causes many harmonics and sub harmonics in a low frequency. To reduce these harmonics and sub harmonics, switching frequency is limited. Thus, instead of using instantaneous voltage and current, the integrated values of these signals are applied. This integration is taken by a resettable integrator. If the time of integration is small enough, the voltage and current will be constant in the integration interval. So, the computed values are supposed to be the coefficients of instantaneous voltage and current. By using this method, the effect of noise in voltage and current signals is reduced.

\(T_s\), is the period of clock oscillator which triggers sample and hold ICs and resettable integrator. Thus, RC of the integrator shown in Fig.4, should be much less than \(T_s\) so that the integrator output reaches the final value in a half period (5RC=T/2).
Fig. 4. Proposed simple implementation of P&O algorithm

Fig. 5. Proposed PV system
To track the MPP a ZCT Buck DC-DC converter [XIV] used as an interface between the PV output and the battery as shown in Fig. 7. The output inductor is wound on a ferrite-core with air-gap to prevent core saturation that may result from a large DC current component value. The inductor is calculated as follows:

\[ L_{\text{out}} \geq \frac{mV_T}{\Delta I_{\text{out}}} \]  \hspace{1cm} (2)

\[ C_{\text{out}} \geq \frac{nI_T}{\Delta V_{\text{out}}} \]  \hspace{1cm} (3)

where \( f_s = 1/T_s \) - the switching frequency, \( V_{\text{out}} \) - the battery voltage, \( \Delta V_{\text{out}} \) - the output current peak to peak ripple, \( I_{\text{in}} \) - the PV current, \( \Delta V_{\text{in}} \) - the PV voltage peak to peak ripple, \( n \) and \( m \) - the maximum number of periods which switch may be on or off, respectively.

Fig. 7. The ZCT buck converter according to [XIV]
Since increasing the oscillator clock frequency causes less ripple in the input signals (voltage and current of PV) and output signal (output current), the input capacitor and output inductor values would decrease. So, the frequency should be increased as much as the switches speed allows. The minimum value of oscillator clock frequency is limited by the input capacitor then to limit the input voltage ripple, the input capacitor and the oscillator clock frequency are determined.

In power interface converter, $L_{a1}$ provides zero current switching for the main switch at turn on. When the main switch is on, $C_{a}$ is charged through $L_{a2}$ in a resonance mode and just before turning the main switch off, the auxiliary switch is turned on and $C_{a}$ provides the output current. Then, the main switch current is reduced to zero and can be turned off under ZCS condition. In this mode, $L_{a1}$ current is equal to the output current and the auxiliary capacitor discharges until its voltage becomes zero. So, the main diode starts to conduct under zero voltage switching (ZVS) condition and the auxiliary switch can turn off under ZCS condition. When the main switch is turned on, two processes begin simultaneously $L_{a1}$ current begins to decrease linearly, and $L_{a2}$ current starts to increase in a resonance with $C_{a}$. So, the main switch turns on under ZCS condition. Thus, in this converter all semiconductor elements are soft switched [XIV].

To design the auxiliary circuit of the ZCS buck converter, the auxiliary inductor $L_{a1}$ should be chosen at first. The inductance of $L_{a1}$ depends on the main switch and main diode speed. Also, the peak of resonant current between $C_{a}$ and $L_{a1}$ should be greater than the output current to achieve ZCS condition for the main switch, therefore:

\[
\frac{V}{Z_i} \geq I_c \tag{4}
\]

\[
Z_i = \sqrt{\frac{L''}{C_c}} \tag{5}
\]

\[
T_i \geq \pi \sqrt{\frac{L_{a1}C_c}{}} \tag{6}
\]

For designing $L_{a2}$, there is a trade-off between main switch peak current and the clock period so 20% over design is required for $C_a$ [XIV].

III. Results

A 135W prototype of the proposed system is implemented using the controller in bang-bang mode. The buck interface converter is connected to batteries. The utilized PV array consists of 3 SGSC modules, giving 135W maximum power and a 16.3V open-circuit voltage at irradiation of 1kW/m and 25°C.

The ZCT buck converter is inclusive of the main switch S (IRFP150), the main diode D (BYW99), the auxiliary switch $S_a$ (IRFP150), and the auxiliary diode $D_a$ (BYW99). The auxiliary inductors $L_{a1}$ and $L_{a2}$ and the auxiliary capacitor $C_a$ are
calculated as 20μH, 2μH and 1μF respectively. The calculated input capacitor and the output inductor values are 800μF and 200μH respectively.

Fig. 8 shows the efficiency of a common Buck converter and the ZCT Buck converter used in this paper. The efficiency is increased by about 3 percent in a wide output power range near the nominal condition.

![Efficiency comparison of Buck (dash line) and ZCT Buck converter (line)](image)

Fig. 8. Efficiency comparison of Buck (dash line) and ZCT Buck converter (line)

In the fig 9. shows the PV system’s efficiency at various irradiation levels. It can be observed that the presented system tracks the PV maximum power point at most power conditions.

![System efficiency at various irradiation levels](image)

Fig. 9. System efficiency at various irradiation levels

Fig.10. shows the PV system waveforms at irradiation of 1kW/m and 25°C. The system convergence speed can be seen in Fig.11 as well. This figure shows the system output current from start up at nominal condition. The system output current rise time is about 1ms which is significantly smaller than the other P&O algorithms.
Fig. 10. PV system waveforms, the control signals for the main switch (top waveform), PV current (middle waveform), PV voltage (bottom), (vertical scale is 5V/div or 7 A/div, and the time scale is 50 μs/div)

Fig. 11. Output current waveform of ZVT buck converter (vertical scale is 8.5A/div, and time scale is 500μs/div)

In the Fig.12 and Fig.13 show soft switching of the converter main and auxiliary switches at turn on and turn off.

Fig. 12. ZCS converter main switch waveforms, voltage (top waveform), trigger signal (middle waveform) and current (bottom waveform), (vertical scale is 10V/div or 30A/div, and the time scale is 20μs/div)
Fig. 13. ZCS converter auxiliary switch waveforms, voltage (top waveform), current (middle waveform) and trigger signal (bottom waveform), (vertical scale is 10V/div or 11A/div, and the time scale is 5μs/div)

IV. Conclusions

In this paper a new method based on perturb and observe algorithm is presented to achieve MPP of photovoltaic arrays. This system greatly reduces the complexity and cost because no DSP and/or A/D are required. The soft switching converter introduced as an interface circuit, has further increased the total system efficiency. Whole semiconductor devices in this converter are fully soft switched. The proposed system is analyzed and a 135W prototype system is implemented and the experimental results justify the theoretical analysis.

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