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A Variable Step Size Perturb and Observe Algorithm for Photovoltaic Maximum Power Point Tracking

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Abstract**—Photovoltaic (PV) panels are devices that convert sun light into electrical energy and are considered to be one of the major ways of producing clean and inexhaustible renewable energy. However, these devices do not always naturally operate at maximum efficiency due to the nonlinearity of their output current-voltage characteristic which is affected by the panel temperature and irradiance. Hence, the addition of a high-performance maximum-power-point tracking, MPPT, power-converter interface is the key to keeping the PV system operating at the optimum power point which then gives maximum efficiency. Many MPPT power-converters and different types of control techniques have been considered in the past. This paper primarily considers the MPPT power-converter control method or algorithm. A so called perturb and observe (P&O) technique is considered in this work. This technique is widely used due to its low cost and ease of implementation. With conventional P&O algorithms using fixed iteration step-size, it is impossible to satisfy both performance requirements of fast dynamic response and good accuracy during the steady state at the same time. This is because, if the step-size is set to be big enough for a fast dynamic response, the oscillation around the maximum-power operating point will increase during the steady state leading to lost power generation, and if the step size is too small optimum generation is not quickly restored during changing operating conditions. To overcome these limitations a new adaptive P&O method with variable step size has been investigated which has been implemented using fuzzy logic control. The proposed method has been evaluated by simulation using MATLAB and compared with the conventional P&O under different insolation, or sun-light intensity, levels. The obtained results illustrate the effectiveness of the proposed technique and its ability for practical and efficient tracking of maximum power.**

Index Terms**—Fuzzy Logic Control, Maximum Power Point Tracking (MPPT), Photovoltaic (PV), Perturb and Observe algorithm (P&O), Variable step size.**

I. Introduction

Over the past two decades renewable energy sources have gained more attention in contributing to power production due to the increase of power demand in the world. Especially as there is much concern with the world's energy crises, oil shortage and environmental problems caused by conventional power generation sources such as fossil (i.e. oil, natural gas, coal) and nuclear fuels. Renewable energy sources such as wind energy, wave energy and solar energy may be the right solution for these problems. Solar energy is a very attractive renewable source amongst all the aforementioned renewable sources due to relative small system size, free and sustainable generation source or fuel, noise free operation due to the absence of moving parts, the possibility to put it close to the user, ease of installation and systems require relatively little regular maintenance. However the efficiency of solar panels is not very high. Their ability to transfer sunlight to electrical power is relatively inefficient, with conversion efficiency typically in the range 12 ~ 20%. The range of efficiency can drop further during varying solar irradiation, panel temperature and load conditions. Therefore, if the load is directly coupled to the PV array, the PV array must usually be oversized to supply the required power to the load. This leads to an over-sized expensive system. The overall system cost can be reduced and operation is possible at increased efficiency if the solar panel is constantly used to extract as much power as possible during the day-light hours by ensuring that the panel is always operating under optimal power delivery conditions, rather like impedance matching allows maximum power to be extracted from a voltage source with internal resistance. To accomplish this, maximum power point tracker (MPPT) systems are employed. A typical MPPT system consists of a switch-mode power-converter inserted between the PV source and the load, and the duty cycle of the converter is controlled by a control algorithm to enable tracking of the MPP [1]. A large amount of research work has been carried out by different researchers and designers to investigate power converter and control methods to track the MPP of a photovoltaic module [1-5]. In recent years, many techniques for automatically identifying and operating at the maximum power point have been published and implemented with different variations. In [6, 7] at least 19 distinct techniques are discussed, analyzed to determine their advantages and disadvantages, and summarized in a table as a helpful guide in choosing the appropriate MPPT method for specific PV system.

The maximum power point tracking techniques can be classified as incremental conductance (IncCond) [3], fractional short-circuit current [4], fractional open-circuit voltage [5], load current voltage maximization, ripple correlation control, hill climbing/perturb and observe (P&O) [2], neural network [8], fuzzy logic control and other MPPT methods [6, 9].

In practice, the P&O method is the most commonly used technique, owing to its low cost, ease of implementation and its relatively good tracking performance, when compared to the other techniques. Nevertheless the P&O method fails to track the MPP when the atmospheric conditions change rapidly. And oscillates around the MPP or near to it when the atmospheric conditions change slowly or constant. Consequently, part of available energy is wasted. Many authors have proposed different improvements of the basic P&O algorithm as in [10-15].

In this work, a P&O algorithm with variable step size is proposed for further improvement in the tracking speed and steady state accuracy, which may be implemented using a fuzzy logic controller.

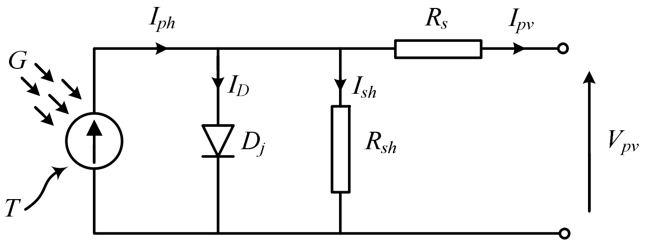


Fig.1.The electric equivalent circuit of a solar cell.

II. SOLAR ARRAY MODEL

The basic solar cell is usually represented by a p-n junction diode connected in parallel with a current source and modeled by equations (1) to (5) as in [16]. This conventional equivalent circuit as illustrated in figure (1). The current source in the circuit represents the photocurrent produced by the sunlight and the diode models the current-voltage characteristic of the cell. The current-voltage characteristic function can be gained by applying Kirchhoff's current law to the circuit. According to Kirchhoff's current law,

$$I_{PV} = I_{ph} - I_D \tag{1}$$

D_j represents the ideal p-n diode, I_D the diode internal diffusion current, R_{sh} and R_s are shunt and series resistance and I_{ph} expressed as the photocurrent or light generated current and it is proportional to the radiation and surface temperature. The output current and voltage of the solar cell is represented by I_{PV} and V_{PV} respectively. The diode internal diffusion current is defined by equation (2).

$$I_D = I_S \cdot \left[\exp\left(\frac{q \cdot V_{PV}}{A \cdot K \cdot T_C}\right) - 1\right] \tag{2}$$

q is the charge of electron ($=1.61*10^{-19}C$), A is the diode ideality factor, K is Boltzmann's constant of $1.38*10^{-23}$ J/K and T_C is the cell's operating temperature in Kelvin (K). The cell dark saturation current (I_S) varies with the temperature according to equation (3).

$$I_S = I_{RS} \cdot \left(\frac{T_C}{T_{Ref}}\right)^3 \cdot \exp\left[\frac{q \cdot E_{gap}}{A \cdot K}\left(\frac{1}{T_{Ref}} - \frac{1}{T_C}\right)\right] \tag{3}$$

T_{Ref} is the cell reference temperature in Kelvin (K), I_{RS} is the cell reverse saturation current in ampere (A) at reference temperature (T_{Ref}) and solar radiation (G). E_{gap} is the band-gap energy of the semiconductor used in the cell. The photocurrent (I_{ph}) mostly depends on the cell's operating temperature and solar intensity as in equation (4).

$$I_{Ph} = \left[I_{SC} + K_I \cdot \left(T_C - T_{Ref}\right)\right] \cdot \frac{G}{1000} \tag{4}$$

Where I_{SC} is the short-circuit current at reference temperature 25^o C and solar radiation of 1kW/m^2, K_I is the temperature coefficient of the cell's short circuit, and G is the solar insolation in kW/m^2 [16-18]. For the most practical applications the solar cells are connected in series and parallel to produce enough power voltage and current.

$$I_{PV} = I_{Ph} - I_S \cdot \left[\exp\left(\frac{q \cdot (V_{PV} + I_{PV} \cdot R_S)}{A \cdot K \cdot T_C}\right) - 1\right] \tag{5}$$

Equation (5) was used in Matlab/Simulink to set up the PV electrical characteristics of SANYO HIT180W module model as well as to simulate the I-V and P-V characteristics for different irradiation levels at fixed temperature of 25^{o}C. The test PV module used in this work is 96 SANYO HIT180 180W panels connected in 12×8 matrix. Table I shows the characteristic values and performance of the PV panel with respect to STC and are obtained from module datasheet. Figure 2 shows the variation of output I-V and P-V characteristics of the simulated PV module as function of irradiation. I-V and P-V from the simulated model correlates well with the characteristics provided by the module manufacture. Therefore the model can be used for testing MPPT algorithms.

Table I

Electrical Characteristics of SANYO HIT180W	
Parameter	**Value**
Rated Power (Pmax)	180 W
Maximum Power Voltage (Vpm)	54.0 V
Maximum Power Current (Ipm)	3.33 A
Open Circuit Voltage (Voc)	66.4 V
Short Circuit Current (Isc)	3.65 A
Temperature Coefficient (Voc)	-0.173 V / °C
Temperature Coefficient (Isc)	1.10 mA / °C

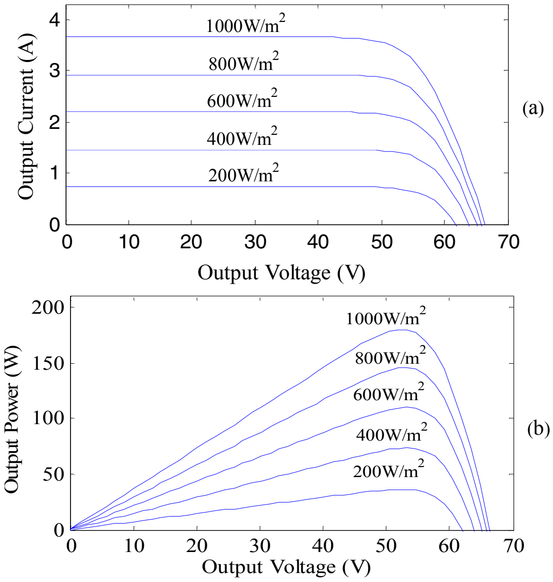


Fig.2. Effect of irradiance on (a) *I-V* curve and (b) *P-V* curve at constant temperature.

III. CONVENTIONAL PERTURB AND OBSERVE ALGORITHM (P&O)

The Perturb and Observe algorithm is considered to be the most commonly used MPPT algorithm of all the techniques because of its simple structure and ease of implementation. It is based on the concept that on the power-voltage curve dP/dV goes to zero at the top of the curve as illustrated in figure 2b [1, 2, 10, 19]. The P&O operates by periodically perturbing (incrementing or decrementing) the PV array terminal voltage or current and comparing the corresponding output power of PV array $P(n+1)$ with that at the previous perturbation $P(n)$. If the perturbation in terminal voltage leads to an increase in power ($dP/dV>0$), the perturbation should be kept in the same direction otherwise the perturbation is moved to the opposite direction. The perturbation cycle is repeated until the maximum power is reached at the $dP/dV=0$ point . The flowchart of P&O algorithm is shown in figure (3)

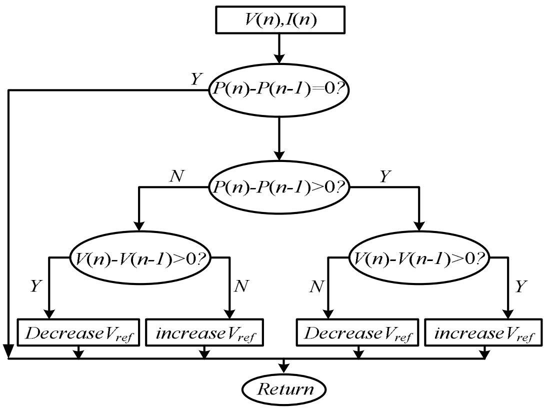


Fig.3.Flowchart of the P&O algorithm.

The advantages of this technique as mentioned before are simplicity; ease of implementation and it does not require a prior knowledge of the PV generator. However, the P&O will not stop perturbing when the MPP is reached and will oscillate around it resulting in power loss. The P&O algorithm can be implemented using two different approaches. Either using direct duty-ratio control where the power is measured every PWM cycle [2, 20], or reference voltage control, where a reference voltage is used as a perturbation parameter and a PI controller is needed to adjust the duty ratio [10, 15, 21]

IV. MODIFIED VARIABLE STEP-SIZE PERTURB AND OBSERVE ALGORITHM (MP&O)

Generally the P&O MPPT algorithm is run with a fixed step-size. If this step-size is set to be large the algorithm will have a faster response to dynamics to track the MPP. However, the algorithm with a large step-size results in excessive steady state oscillation, which reduces power efficiency. This performance situation is reversed when the P&O MPPT is running with a small step-size. Therefore, P&O MPPT with fixed step-size does not allow a good tradeoff between steady-state oscillation and dynamic response to changing operating conditions. Therefore, in this work a modified P&O MPPT algorithm with variable step-size is proposed, which may be implemented using fuzzy logic control as shown in figure (4).

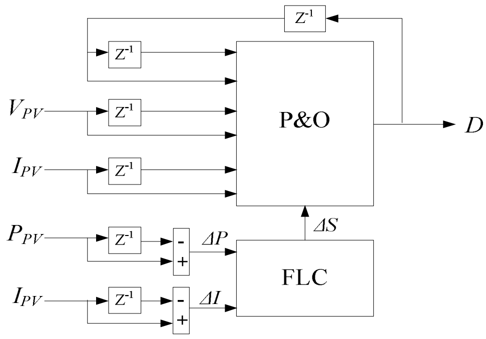


Fig.4.Block diagram of the proposed P&O algorithm with variable step-size.

A. *Fuzzy logic control (FLC)*

A fuzzy logic controller (FLC) is used to vary the step-size. The proposed fuzzy logic controller is based on prior expert knowledge of the system. The main elements of the FLC systems are shown in figure 5. It consists of four sections, Fuzzification, Inference engine, Defuzzification and Rule-Base. The input variables of the FLC are (ΔP_{PV}) and (ΔI_{PV}) the change in PV power and the change of PV current, respectively, whereas the output of the FLC is the variable step-size (ΔS) of the P&O algorithm

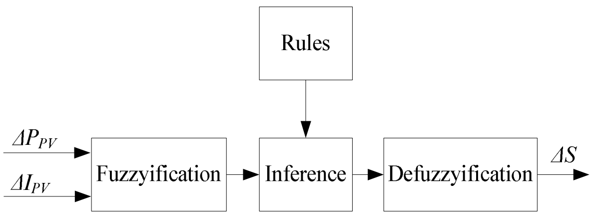


Fig.5.General diagram of fuzzy logic controller.

Where the input variables (ΔP_{PV}) and (ΔI_{PV}) can be calculated by equations (6) to (8).

$$P_{PV}(k) = V_{PV}(k) * I_{PV}(k) \quad (6)$$

$$\Delta P_{PV}(k) = P_{PV}(k) - P_{PV}(k-1) \quad (7)$$

$$\Delta I_{PV}(k) = I_{PV}(k) - I_{PV}(k-1) \quad (8)$$

Quantities $P_{PV}(k)$ and $I_{PV}(k)$ are the PV array power and current, respectively, and $V_{PV}(k)$ is the PV array voltage. The membership function of the input and the output variables are shown below in figures 6-8. All the membership functions are expressed by triangular functions. They consist of five fuzzy subsets which are denoted by NB (negative big), NS (negative small), ZZ (zero), PS (positive small) and PB (positive big).

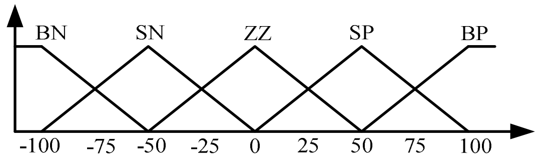


Fig.6. Membership functions of the 1st input variable (ΔP_{PV}).

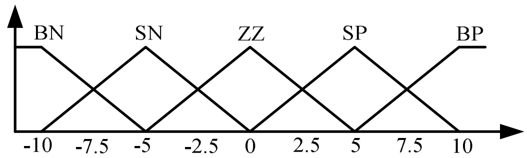


Fig.7. Membership functions of the 2nd input variable (ΔI_{PV}).

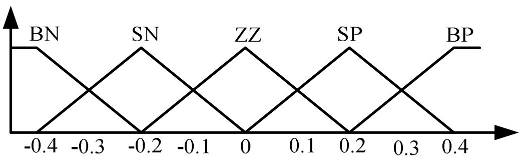


Fig.8. Membership functions of the output variable (ΔS).

The fuzzy inference rules of the FLC consist of 25 rules as illustrated in table II, which determine the output of the controller. The fuzzy logic rules are expressed in terms of IF-THEN and are written as:

IF $\Delta P_{PV}(k)$ is NB and $\Delta I_{PV}(k)$ is NB THEN ΔS is NB.

The defuzzification stage is required to calculate the crisp output value. Hence the output of the FLC defuzzified using centre of gravity (COG) method to calculate ΔS [22].

TABLE II
FUZZY RULES BASE TABLE I

ΔI_{PV}	ΔP_{PV}				
	NB	NS	ZZ	PS	PB
NB	NB	NS	NS	ZZ	ZZ
NS	NS	ZZ	ZZ	ZZ	PS
ZZ	ZZ	ZZ	ZZ	PS	PS
PS	ZZ	PS	PS	PS	PB
PB	PS	PS	PB	PB	PB

V. SIMULATION RESULTS

A block diagram of the proposed system is illustrated in figure (9). A DC/DC buck converter is used to interface PV output to the resistive load to track the maximum power of the PV array. To perform the tracking of maximum power, a modified perturbation and observation algorithm has been implemented. The system has been modeled and operation simulated in MATLAB/Simulink.

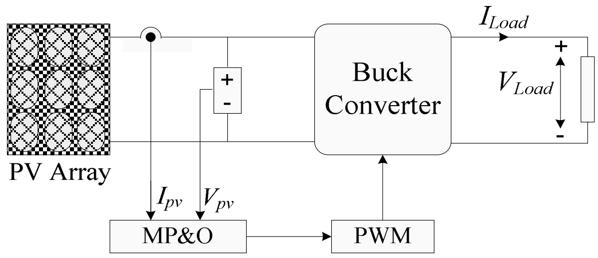


Fig.9. Photovoltaic module output current using P&O algorithm.

The buck converter is conducted in MATLAB and simulated using SimPowerSystems blocks. The converter consists of an IGBT switch and freewheeling diode. Additionally, input and output filters are included. The input capacitance C_{in} of the buck converter is 172μF, output capacitance C_{out} is 40μF and its inductance L is 444μH. The simulations allow verification of the feasibility and the performance of the proposed modified variable step-size P&O algorithm. Additionally, a comparison is carried out between the performance of the modified P&O algorithm and the conventional P&O algorithm by simulating both MPPT methods under exactly the same conditions. The main focus is on how fast the MPP is being tracked during the dynamic state and the level of power ripple caused by oscillations around the MPP under steady state conditions.

In reality, the output power of a photovoltaic cell is mainly influenced by ambient temperature and solar irradiation. Though the change in ambient temperature has a slow influence on the PV cell and it is not directly related to the dynamic response. Therefore the cell working temperature is fixed at the value of 25°C in all simulations. In practice, clouds sometimes move very quickly leading to a sudden change in the PV panel output power, consequently, the algorithm has to be tested under different irradiation levels to verify the speed of tracking. The PV panel is configured to produce 180W with an open-circuit voltage of 66.4V at 1000 W/m^2 solar irradiance. The irradiation was abruptly decreased from 1000 W/m^2 to 400 W/m^2 at 0.3s and increased back to 800 W/m^2 at 0.6s.

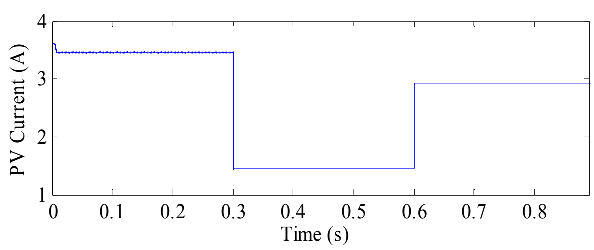


Fig.10. Photovoltaic module output current using P&O algorithm.

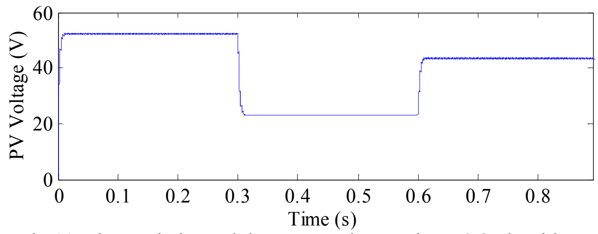


Fig.11. Photovoltaic module output voltage using P&O algorithm.

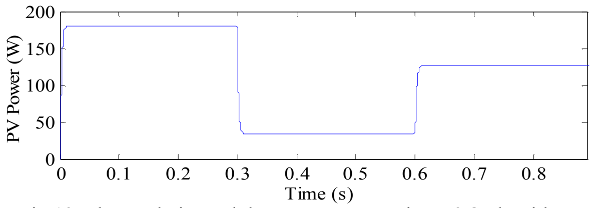


Fig.12. Photovoltaic module output power using P&O algorithm.

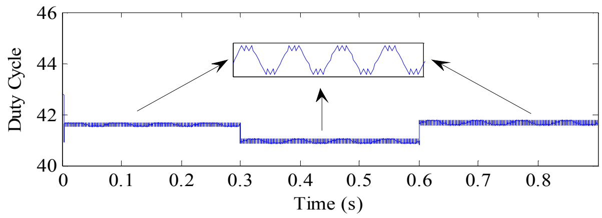


Fig.13. Duty ratio waveform of P&O algorithm.

The simulation results illustrated in figures 10-13 represent the performance of the maximum power point tracking using (P&O) control with fixed a step-size of 0.01. Figures 14-17 show the simulation results performance and effectiveness of the modified maximum power point tracking method (MP&O). The simulation waveform for both algorithms can be described as following. The duty ratio D adjusted quickly by MPPT until a stable maximized output power is reached. When the irradiation abruptly changes from 1000 W/m^2 to 400 W/m^2 and then increases again to 800 W/m^2 at 0.3s and 0.6s, the operating power points deviate from the optimal power point. The MPPT tracks again at that time to force the system to work at the new maximum operating point.

Figure 13 shows the duty cycle response of P&O algorithm to

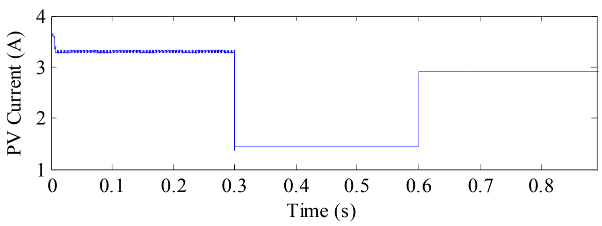


Fig.14. Photovoltaic module output current using MP&O algorithm.

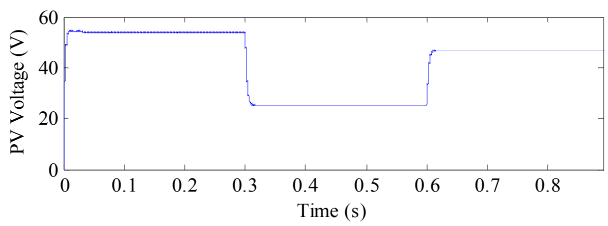


Fig.15. Photovoltaic module output voltage using MP&O algorithm.

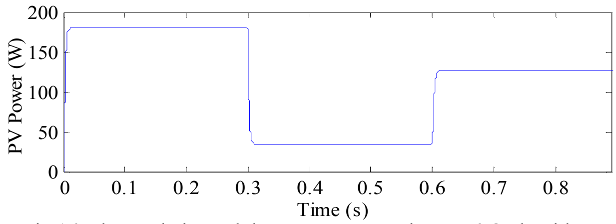


Fig.16. Photovoltaic module output power using MP&O algorithm.

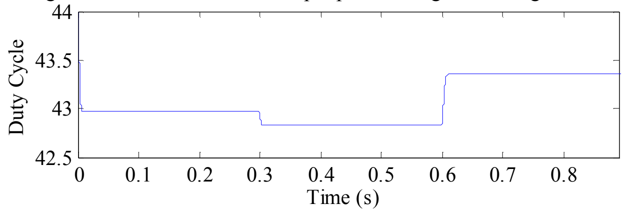


Fig.17. Duty ratio waveform of MP&O algorithm.

the change of irradiation levels. As the irradiation changes the duty cycle changes as well to track the new MPP. However during the steady state the duty cycle keeps swinging around the MPP instead of settling, which leads to some power loss. In contrast, if the perturbation step size is smaller the system will be more stable but slows down the response. However, According to the simulation results the proposed method shows better performance over conventional P&O technique. Figure 17 shows duty cycle waveform of the proposed method. This figure illustrates that, the algorithm stops oscillating in the steady-state as the maximum power point is reached. In addition, the proposed method shows faster dynamic performance than that of fixed step-size as illustrated in figures 18.

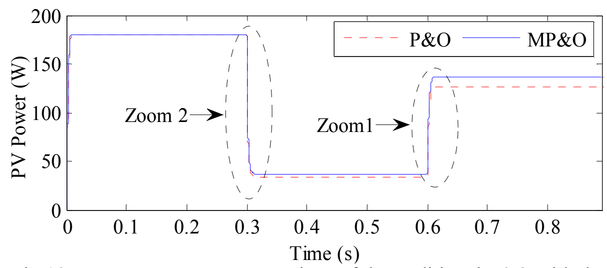
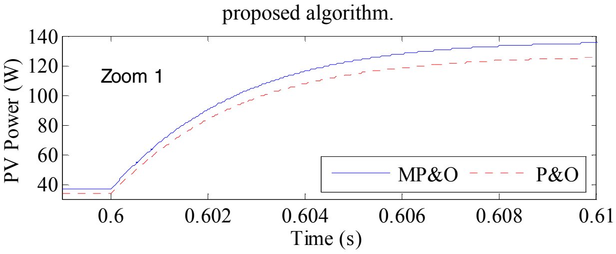
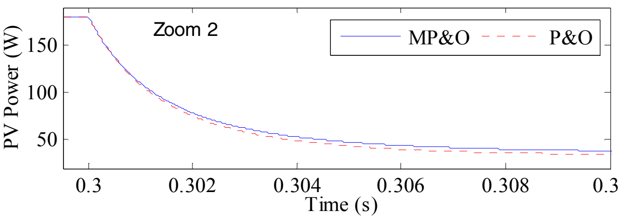


Fig.18. PV output power: comparison of the traditional P&O with the proposed algorithm.



Zoomed image of figure (18)



Zoomed image of figure (18)

VI. Conclusion

The output current-voltage characteristics of solar arrays are nonlinear, and the operating conditions of the optimum PV power gained from the PV array is affected by solar irradiation, cell temperature and loading conditions. Therefore, a maximum power point tracking control is needed to continually match the PV internal resistance with the loading effect, hence ensuring that maximum power is transferred to the load.

In this work, the photovoltaic panel has been modelled using a moderate complexity equivalent circuit, and the result compared with manufacture's datasheet characteristics. The simulated results match the characteristics given by the datasheet under different irradiation and cell temperature conditions. The effect of cell temperature and irradiation on the PV panel output characteristics have been investigated with varying load conditions. An adaptive P&O MPPT has been proposed and evaluated using fuzzy logic control to give variable step-size convergence to improve the efficiency of the PV system. To set up the complete PV system simulation model a Buck DC-DC converter was included with a PWM controller. The performance of modified P&O algorithm is evaluated and compared with traditional P&O algorithm using MATLAB simulation. The simulation results clearly show that, the modified P&O has the ability to improve both the steady state and dynamic performance of the photovoltaic power generator system.

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