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# Deploying Whale Optimization Algorithm-based Controller, and Perturb and Observe Algorithm-based Controller for Maximum Power Point Tracking: A Comparative Study

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***Abstract:*** *The use of maximum power point tracking (MPPT) algorithms on photovoltaic (PV) system is very important. These algorithms offer a significant increase in system efficiency, reduction in terms of PV panels, and maintenance cost of running the plant than if it were a fossil-fuelled plant, above all, the role renewable energy systems have so far played in green engineering has helped a lot in reducing CO2 emissions. In this study, perturb and observe (P and O) algorithm, and whale optimization algorithm (WOA)-based MPPT controllers are tested on a 500 kW solar hybrid power system (SHPS) microgrid. The significance of the study is to ascertain the MPPT controller that would track the highest amount of power at the output of the PV array. Some parameters such as irradiance, current, voltage and power output of each controller were also investigated. After performing the 5 seconds simulation on MATLAB/Simulink, P and O algorithm MPPT controller tracked up to 466.2 kW, while WOA-based MPPT controller tracked the highest power of 530.4 kW at the output of the PV array.*

***Keywords:*** *Maximum power point tracking (MPPT), Perturb and Observe (P and O), Photovoltaic (PV), Whale optimization algorithm (WOA).*

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## I. Introduction

The dearth of fossil fuels; the emission of CO2 due to combustion process which causes depletion of the ozone layer and global warming;; the need for communities located far from grid to generate electrical power using the available renewable energy resources such as sun, wind, biomass et cetera; the growing demand for utilization of power across the globe has necessitated an alternative way of obtaining various renewable approaches to generation of electrical energy.

The need to harvest maximum amount of power from a solar hybrid renewable power system is paramount. The PV cell is one of the most cleanest sources among all renewables, it offers reduced cost in terms of running a renewable energy plant, possess no greenhouse effect, and is noiseless. Maximum power plant tracking is an important terminology while dealing with such systems, MPPT algorithms offer sufficient reduction in the overall cost of the PV array by reducing the number of PV panels required in order to achieve the desired output power.

Maximum power point tracking (MPPT) may include fuzzy logic method, incremental conductance (InC) method, and perturb and observe (P and O) method. This study presents a comparative analysis of P and O algorithm, and whale optimization algorithm (WOA) as applied to MPPT controllers. The P and O algorithm when applied to PV cells tries to obtain the maximum power point (MPP) under varying climatic conditions, the major drawback of the P and O algorithm is oscillation at MPP which leads to power loss. However, power loss due to oscillation at MPP could be eliminated by a meta-heuristic technique; the WOA-based MPPT controller eliminates oscillations at steady-state and tracks the maximum power required at the output of the PV panel/array.

## II. Literature Survey

A new swarm-based optimization algorithm inspired by the hunting behaviour of humpback whales was performed[1]. The proposed method, Whale Optimization Algorithm (WOA), included three operators to stimulate the search for prey, encircling prey, and bubble-net foraging behaviour of humpback whales. The WOA is found to be competitive with other state-of-the-art meta-heuristic methods and has proffered solutions to most engineering problems, among which is the solving of the optimal power flow problem. Implementation of perturb and observe (P and O) algorithm on PV module using embedded software was performed. The basic P and O algorithm was implemented using analogue blocks and it was simulated in PSIM software. DC/DC converter was inserted between the PV generator and the load. According to the authors, to operate a PV panel at the MPP, the DC/DC converter controlled by MPPT is inserted between the PV panel and the load. The current and voltage, voltage and power characteristics curves were analysed and results showed that P and O algorithm minimizes the oscillation in the output power[2]. WOA-based MPPT controller was used to track the maximum amount of output power from a PV array. The study experimented how to track the maximum power at variable climatic and partial shaded condition (PSC). The proposed technique was tested on various PV array configurations for different shading patterns. Comparison of GWO and PSO-MPPT algorithms with WOA-MPPT (the proposed technique) were simulated with results presented. The proposed technique proved to possess a superior fit in terms of accuracy and tracking speed[3]. Implementation of the Perturb and Observe (P and O)-based MPPT algorithm for photovoltaic system. The system consisted of PV panel, DC-DC boost converter controlled by an arduino microcontroller based unit and a resistive load. The P and O method was applied and the proposed technique showed how higher efficiency and lower cost could be modified to handle energy resources. The results proved that P and O MPPT-based controller increases output power of PV modules/array which equally increases the system efficiency[4]. A new efficient step-up boost converter with CLD cell for electric vehicle and new energy systems was proposed. The experimental and simulation results of the proposed converter were carried out in a laboratory with the aid of MATLAB/Simulink. 10 V was given as an input voltage and at the output, 100 V was achieved. The results suggest that the proposed converter could can obtain high voltage gain without operating at the maximum duty cycle, and the proposed system is more efficient than a conventional converter. A new efficient topology of a charge pump-capacitor (CPC) for RESs which is based on high voltage gain technique DC-DC boost converter (DCBC) was also studied. To test the efficacy of the introduced topology, a prototype was developed in a laboratory where the input was 10 V while 80 V output voltage was achieved at the load side. The experimental results proved that the voltage stress of MOSFET switches is very less in comparism with the conventional boost converter with the same parameters as the proposed converter[5,6]. WOA-based MPPT controller for the control of 3.5 MW SHPP of the Joseph Sarwuan Tarka University was proposed. Data obtained from the existing plant showed that an output of 1,800 kW was generated from the PV array. According to the authors, the main purpose of the research is to obtain an improved output from the PV array when a new MPPT controller is tested. When the proposed controller was employed, an output power of 2,800 kW from the PV array was realized. In order to test the efficacy of the proposed control technique, a conventional P and O MPPT controller was also tested on the same system which gave an output power of 2,300 kW proving the WOA-based MPPT controller's superiority over the existing system and the P and O control technique. However, the research was limited to modelling, simulation and optimization of the SHPP on MATLAB/Simulink platform[7].

## III. System Description and Methods

The experiment is tested on a 500 kW micro-grid system comprising 20 series and 84 parallel-connected PV cells, 140 batteries and a 6.6 kV network. The system's base source of power is the PV array, the array derives its source from sun light and directly converts it into electrical voltage using photovoltaic effect. Power is then utilized and simultaneously charges batteries. In a case of little or no solar irradiation and exhausted state of charge (SoC), priority is shifted to the public supply for onward charging of batteries and continuous power delivery. However, when there is no solar irradiation, batteries attaining their depth of discharge (DoD), and when there power outage from the public supply, there would be a system collapse. This is one major drawback of the proposed system. The Simulink model of the SHPS is shown in Fig. 1.

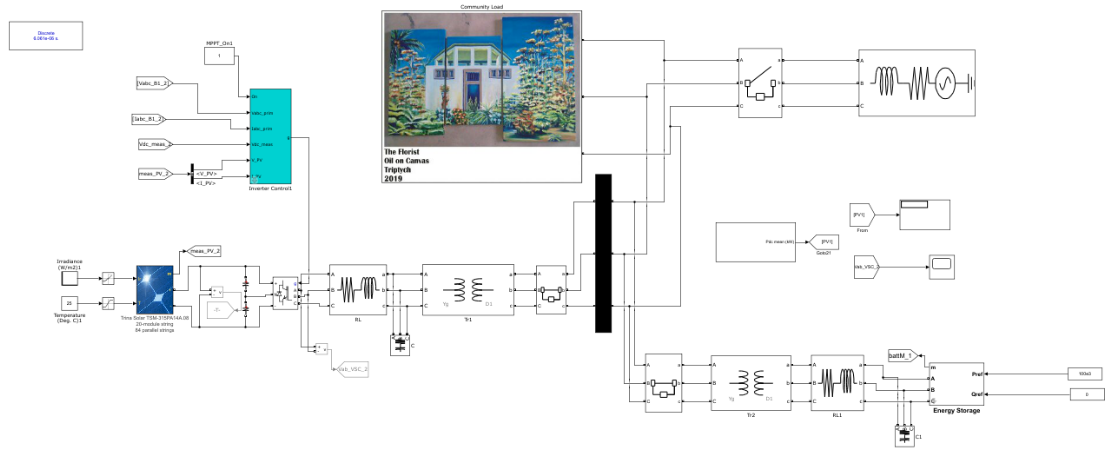

**Figure 1:** 500 kW Solar Hybrid Power System (SHPS) Model

### 3.1 PV Module

PV module/cells are essentially a very large area p-n junction diodes where such a diode is created by forming a junction between the n-type and p-type regions. Sunlight strikes a PV cell, the incident energy is converted directly into electrical energy. Transmitted light is absorbed within the semiconductor by using the energy to excite free electrons from low energy status to an unoccupied higher energy level. When a PV cell is illuminated, excess electron-hold pairs are generated by light throughout the material, hence the p-n junction is electrically shorted and current will flow[8]. The photovoltaic module is modelled in MATLAB/Simulink using the PV array block, which implements a PV array built of series and parallel connected PV modules. It allows modelling a variety of pre-set PV modules available from the national renewable energy laboratory (NREL) system advisor model as well as a user-defined PV module. The PV array block has two inputs that allow the supply of varying solar irradiance (input I_r (W/m^2)) and temperature (input T in degrees Celsius) data. The Simulink block of the photovoltaic module is shown in Fig. 2.


**Figure 2:** Simulink block of a Solar Photovoltaic Module

The positive (+) and negative (-) terminals represent the connection point through which the DC link is connected. The port marked "m" represents the output terminal of the block. Figure 3 is the PV parameter dialogue box. Settings for the PV module can be achieved through its block parameters dialogue box, it enables the configuration of the PV module/array in MATLAB/Simulink is shown in Fig. 3.

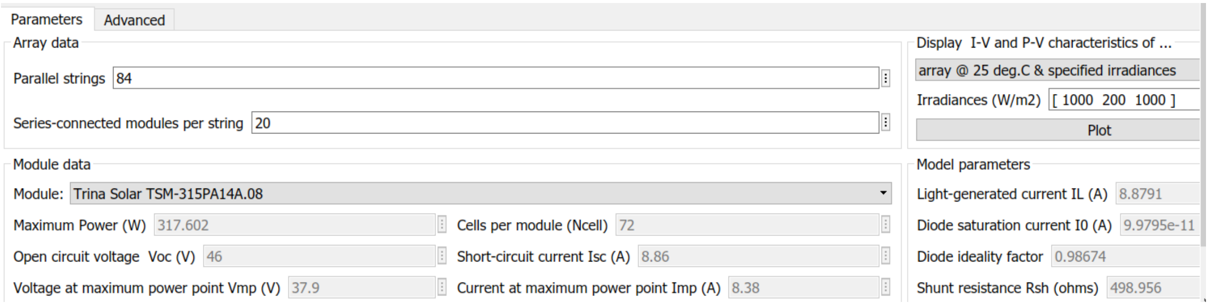


**Figure 3:** Parameters dialogue box of the PV Array/module

**Table 1:** PV Module Parameters

| Manufacturer: Trina Solar TSM | |
|---|---|
| Maximum power (W) | 317.602 |
| Cells per module (Ncell) | 72 |
| Open circuit voltage Voc(V) | 46 |
| Short circuit current Isc (A) | 8.86 |
| Voltage at maximum power point Vmp(V) | 37.9 |
| Current at maximum power point Imp(A) | 8.38 |
| Temperature coeff. of Voc (%/°C) | -0.03 |
| Temperature coeff. of Isc (%/°C) | 0.05 |

| | |
|---|---|
| Light-generated current I (A) | 8.8791 |
| Diode saturation current IO (A) | 9.9795e-11 |
| Diode ideality factor | 0.98674 |
| Shunt resistance Rsh (Ohms) | 498.956 |
| Series resistance Rs (Ohms) | 0.30916 |

Table 1 contains the parameters of the PV module. A solar PV module/cell is made of semi-conductor material which converts sunlight into electricity by means of photovoltaic effect[10]. However, performance of the PV model is highly influenced by the weather conditions, particularly, the impact of temperature[9]. Hence, five parameters α, β, γ, Rs and a are acquainted for the non-linear impacts of the fault condition. The expression for the maximum output power generated by the PV module Ppv is given in Equation (1) as:

$$P_{pv}(t) = N_s N_p * \frac{\left[\frac{V_{oc}}{V_t} - \ln\frac{V_{oc}}{V_t} + 0.72\right]}{1 + \frac{V_{oc}}{V_t}} * \left(1 - \frac{R_s I_{sc}}{V_{oc}}\right) * I_{sco}\left(\frac{G}{G_o}\right)^{\alpha} * \frac{V_{oco}}{1 + \beta \ln\frac{G_o}{G}} * \left(\frac{T_o}{T}\right)^{\gamma} \quad (1)$$

where:

$$V_t = \frac{aKT}{q} \quad (2)$$

Equation (3) represents the thermal voltage
a is the ideality factor,
K is the Boltzmann constant,
T is the temperature of the PV module, and G is irradiance
q is the charge of the electron.
$N_s$ and $N_p$ are the series and parallel PV modules, respectively.
$R_s$ is the series resonant,
α represents the photocurrent factor,
β is the PV dimensionless coefficient, and
γ represents the non-linear factor.
In addition, $V_{oc}$ and $I_{sc}$ are the open-circuit voltage and short-circuit current of the PV module, respectively.

### 3.2 Battery Stack

The battery stack is used to store the energy when the generated power is greater than the load demand. The battery power will be extracted when the generation cannot satisfy the load requirements. Depending on the charging and discharging state, the current may be positive or negative. Losses may occur in both states, and hence, the state of charge (SoC) of the battery is expressed in Equation (3) [9]

$$SoC(t+1) = SoC(t) * \left(1 - \frac{\delta * \Delta t}{24}\right) + \frac{I_b(t) * \Delta t * \eta_b}{C_b} \quad (3)$$

where, $\delta$ represents the self-discharge rate,
$I_b(t)$ is the current rate of the battery at time t,
$C_b$ is the available capacity of the battery, and
$\eta_b$ is the efficiency of the battery.
The out- put power of the battery for the HRES is given in Equation (4) as:

$$P_b(t) = P_{pv}(t) + P_w(t) - \frac{P_{acload}(t)}{\eta_{inv}} - P_{dcload} \quad (4)$$

where:
$\eta_{inv}$ is the inverter efficiency,
$P_{acload}$ and $P_{dcload}$ are the AC and DC loads repectively.
The limit of SoC of the battery stack is expressed in Equation (5):

$$SoC_{min} \le SoC(t) \le SoC_{max} \quad (5)$$

## 3.3 Maximum Power Point Tracking (MPPT) Controller

Renewable energy systems are needed in order to meet the increasing demand of the global energy consumption, and power electronic converters are an important module in such systems[6]. The MPPT controller is modelled based on the P and O/WOA. This MPPT system automatically varies the VDC reference signal of the inverter VDC regulator in order to obtain a DC voltage which will extract maximum power from the PV array.

In modelling the WOA-based MPPT controller, a MATLAB function block is used. The Simulink block and system are shown Figure… when it is switched to $S_1$, the system is operating on WOA-based technique, similarly, at switch $S_2$ the system is on P and O control technique. In modelling the WOA-based MPPT controller, a MATLAB function block is used.

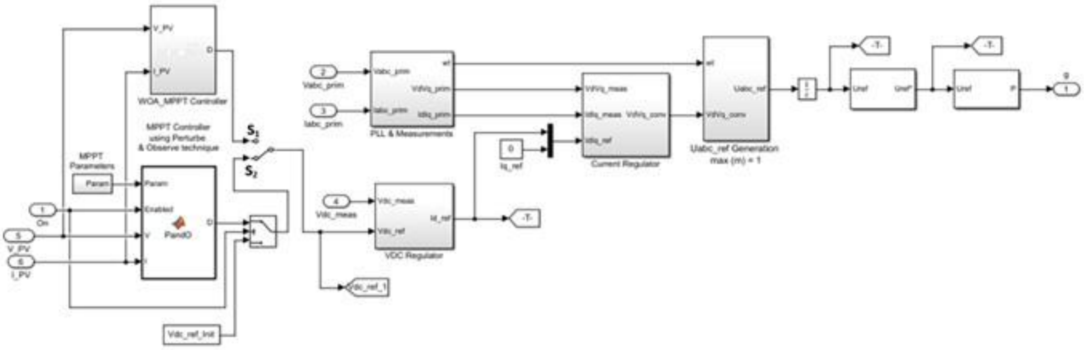

**Figure 4:** MPPT Controller on WOA and P and O Technique.

## 3.4 Perturb and Observe Algorithm

The P and O method for MPPT is proposed for this research, because of its simplicity; it possesses fewer measured parameters and can track maximum power point under varying irradiation and temperature quite accurately[2,4]. It can be seen in Fig. 5 that, on right hand side of the P-V characteristics curve, as voltage decreases, power increases, while on left hand side of the characteristics curve, voltage increases as power increases. This is the main idea used in the p and o algorithm to track the maximum amount of power under all conditions.

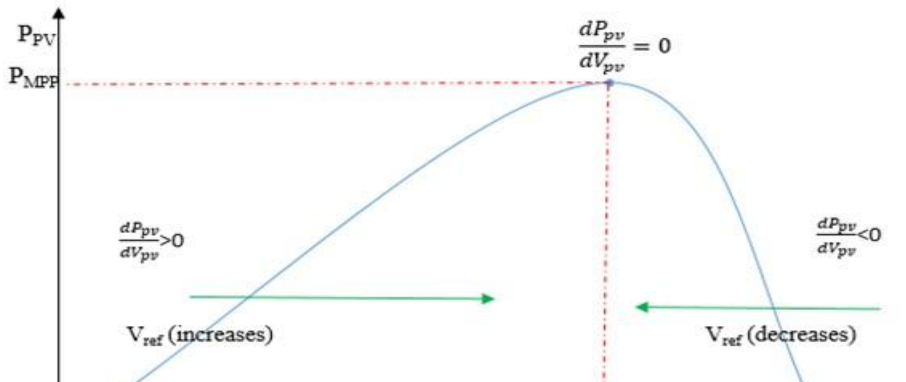


**Figure 5:** P-V Characteristics of PV panel[2].

## 3.5 Flowchart of the P and O Algorithm

As seen in Figure 6, the P and O method is operated on the basis of periodical perturbations.

The first stage of P and O algorithm is to measure the initial PV voltage and current for the measurement of the initial power of PV system. If the difference of measured power is compared with previous power and the resultant is positive, the next perturbation increases in the same direction. In the case of a negative, the next perturbation is a decrease or reversal in the direction. The perturbation size in voltage ($\Delta V$) or duty cycle ($\Delta D$) is very small. The entire process is repeated periodically till the maximum power is observed from solar PV system[10]. However, the main drawback of this algorithm is the presence of oscillations around MPP.

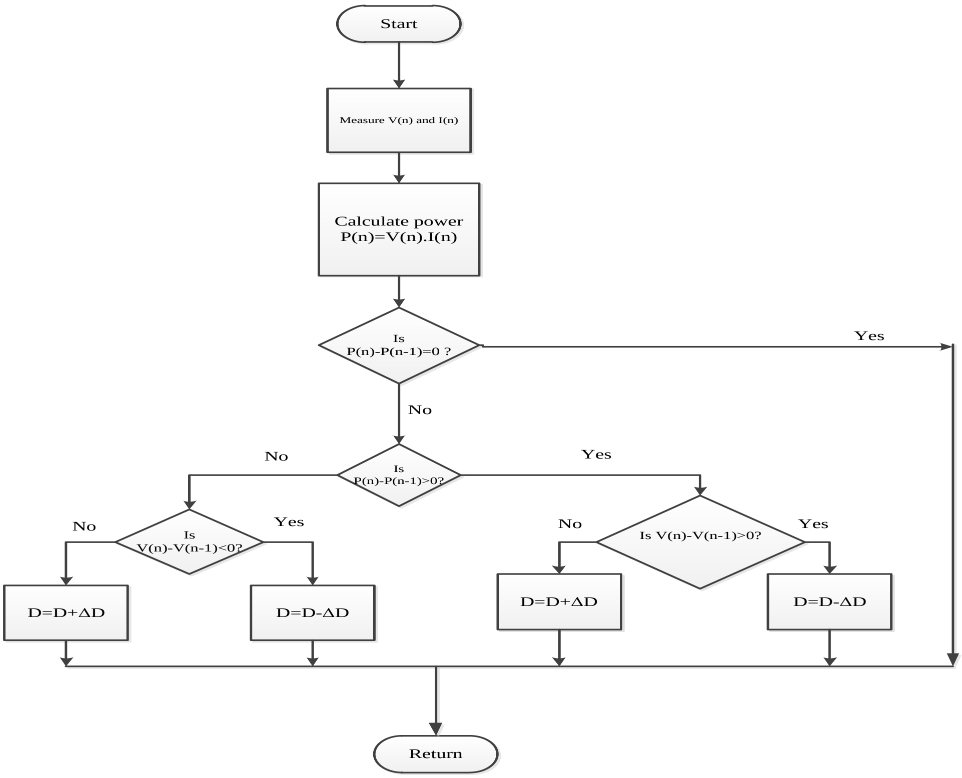


**Figure 6:** P and O algorithm flowchart

## 3.6 Whale Optimization Algorithm

WOA is inspired from bubble-net hunting strategy of humpback whales[1]. The humpback whales dive deeply, create bubbles in a spiral shape around the prey, and swim to the surface during the manoeuvre. They usually attack the small fishes close to the surface[11]. The humpback whale is the biggest of all whales and it has special hunting mechanism of spiral bubble-net feeding. These whales hunt the school of fish or krill on the surface by creating distinctive bubbles in circular path.

Humpback whales encircle the prey during the hunt and the encircling behaviour can be mathematically modelled as[1],

$$\vec{D} = |\vec{C}.\vec{X^*}(t) - \vec{X}(t)| \quad (6)$$

$$\vec{X}(t+1) = \vec{X^*}(t) - \vec{A}.\vec{D} \quad (7)$$

where:

$\vec{X^*}(t)$ is the whale's best position vector, which is updated in each iteration if there is a better solution [1],

$t$ represents the current iteration,

$\vec{X}(t)$ is the prey position vector,

$\vec{A}, \vec{D}$ and $\vec{C}$ are coefficient vectors, which can be calculated as follows:

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \quad (8)$$

$$\vec{C} = 2.\vec{r} \quad (9)$$

where:

$\vec{a}$ is linearly decreased from 2 to 0 over the course of iterations (in both exploration and exploitation phases) and $\vec{r}$ is a random vector in [0,1].

Where, $\vec{a}$ is linearly decreased from 2 to 0 over the course of iterations (in both exploration and exploitation phases) and r $^{\rightarrow}$ is a random vector in [0,1].

### 3.6.1 Application of WOA for MPPT

In this work, WOA is implemented as a direct control MPPT technique i.e., duty cycle control by taking the population of whales as duty ratios to reduce steady-state oscillations. Direct control MPPT decreases

power loss and therefore improves the efficiency of the system. For each population of whales, i.e., duty ratios, the corresponding voltage and current are sensed by the controller and output power is computed[4, 12]. The main objective of optimal control is to determine control signals that will cause a process (plant) to satisfy some physical constraints and at the same time optimise (maximise or minimise) a chosen performance criterion (performance index or cost function)[13].
Here, MPPT is formulated as objective function and it is represented as follows:

$$maximize\, P(d) > 0 \qquad (10)$$

maximize P(d) subject to Equation (11),

$$d_{min} \leq d \leq d_{max} \qquad (11)$$

where $P$ is PV output power, $d$ is duty ratio, $d_{min}$ is the minimum and $d_{max}$ is the maximum limits of duty ratio i.e., 0.1 and 0.9, respectively. For MPPT, Equation (7) can be remodelled as

$$d_i(k+1) = d_i(k) - A.D \qquad (12)$$

The objective function of WOA MPPT is formulated as

$$P(d_i^k) > P(d_i^{k-1}) \qquad (13)$$

where *i* is the population of whales.
PV power is dependent on climatic conditions, for a change in solar irradiation of PV modules, the power output of PV array changes correspondingly and proposed MPPT algorithm is reinitialized by sensing the change in PV output power using Equation (14).

$$\frac{P^k - P^{k-1}}{P^k} \geq 0.1 \qquad (14)$$

### 3.6.2 Flowchart of WOA-MPPT algorithm

The flow chart of the WOA is depicted in Fig. 7, firstly, the voltage and current are measured and their values are used to calculate power, which is compared with the previous one and accordingly increases or decreases the voltage to locate the MPP by altering the duty cycle of the converter. The DC/DC converter is characterized by its duty cycle (d) that gives the ratio between the input and the output voltage when the conduction is continuous.

$$Duty\ cycle\ (d) = 1 - \left(\frac{input\ voltage}{output\ voltage}\right) \qquad (15)$$

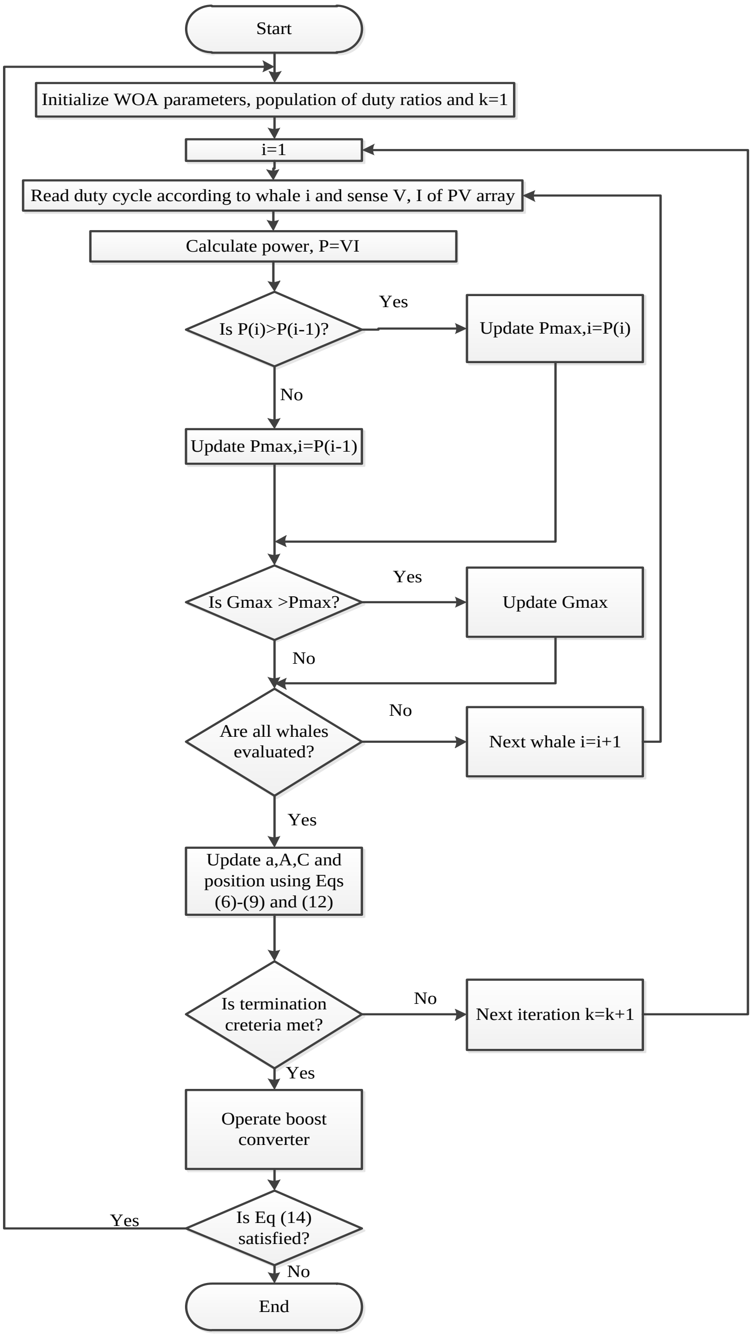


**Figure 7:** WOA-MPPT algorithm flowchart

## IV. Results and Discussion

Figs. 8a-c are obtained using the dialogue box in Fig. 3. Configurations of the PV module/array with respect to temperature and irradiance is achieved via the dialogue box. Figs. 9a and b demonstrate the P and O, and the WOA-based MPPT control methods with respect to solar irradiation, voltage and power of the PV array over a simulation period of 5 seconds. Figs. 10a and 10b represents the comparism of P and O, and WOA-based MPPT control technique with respect to current, voltage and output power of the PV array respectively.

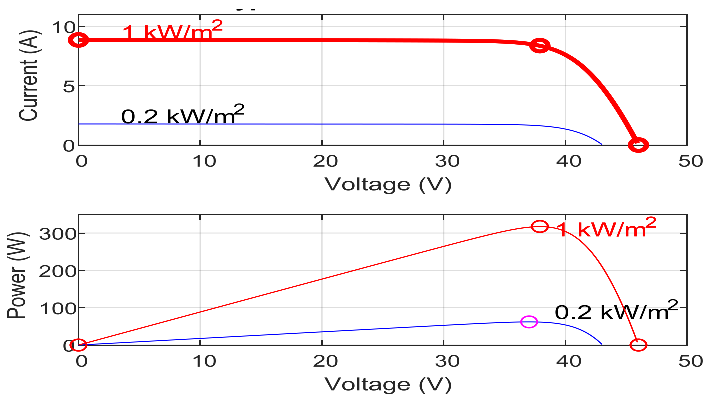


**Figure 8a:** Module at varying irradiance

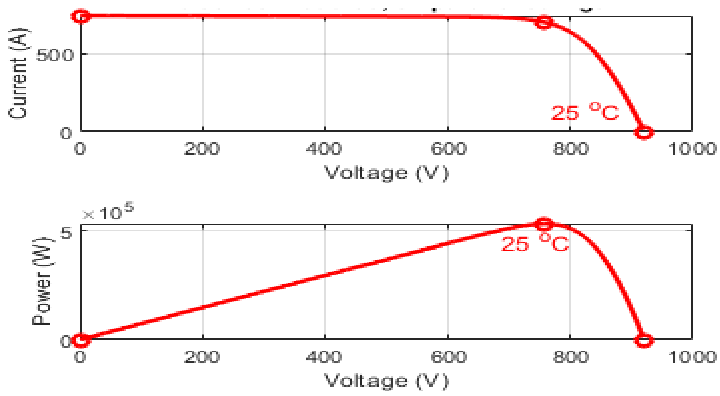


**Figure 8b:** Array at varying specified irradiance and temperature

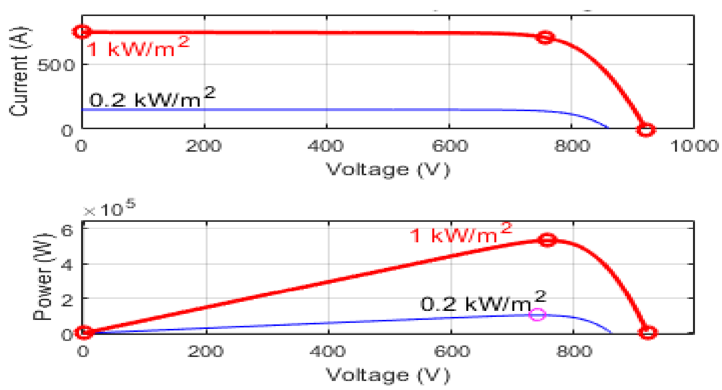


**Figure 8c:** Array at varying irradiance and specified temperature

As seen in Fig. 8a, a single module can attain at MPP a current of 8.86 A and a voltage of 46 V at 1,000 W/m$^2$ irradiance and at a low irradiance of 200 W/m$^2$, a current of 1.776 A and a voltage of 42.83 V is gotten. A single module can at MPP track power up to 317.6 W and voltage of 37.9 V at an irradiance of 1,000 W/m$^2$, while at 200 W/m$^2$ irradiance, a power of 62.03 W and voltage of 37.02 V is tracked. Fig. 8b shows the behaviour of the PV array at a specified temperature and irradiance. The operation of the PV system is largely dependent on climatic conditions. At a temperature of 25$^o$C and irradiance of 1,000 W/m$^2$, the array can extract up to 533.6 kW and 758 V at MPP, this is in conformity with Fig. 4 where the behaviour of the PV system is illustrated. Similarly, at varying irradiance and specified temperature of 25$^o$C, figure 8c shows the intrinsic variability characteristic of the PV array at 1,000 W/m$^2$ and 200 W/m$^2$ irradiance. At 1,000 W/m$^2$, a power of 533.6 kW and voltage of 758 V is attained, while at a low irradiation of 200 W/m$^2$, a power of 104.2 kW and voltage of 740.4 V is possible. Low irradiance could be typically attributed to rainy days, evenings or dull times. With the presence of MPPT methods in a solar hybrid power system (SHPS), when the maximum power is tracked and the DC component of power is stored via batteries, power could be utilized during the day/good days and during periods of little or no solar irradiation, the batteries could take priority of load delivery, this is one of the greatest advantages of SHPSs as emissions due to use of fossil-fuelled generators and low cost of maintenance is also possible.

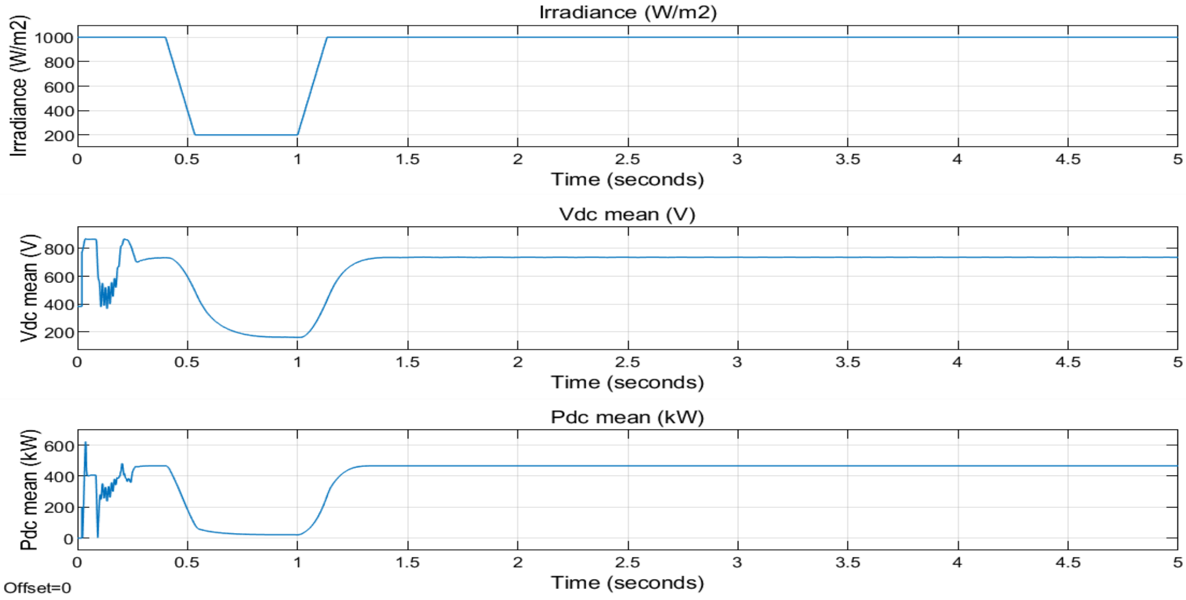


**Figure 9a:** Irradiance, Voltage and Power of the SHPS under P and O method

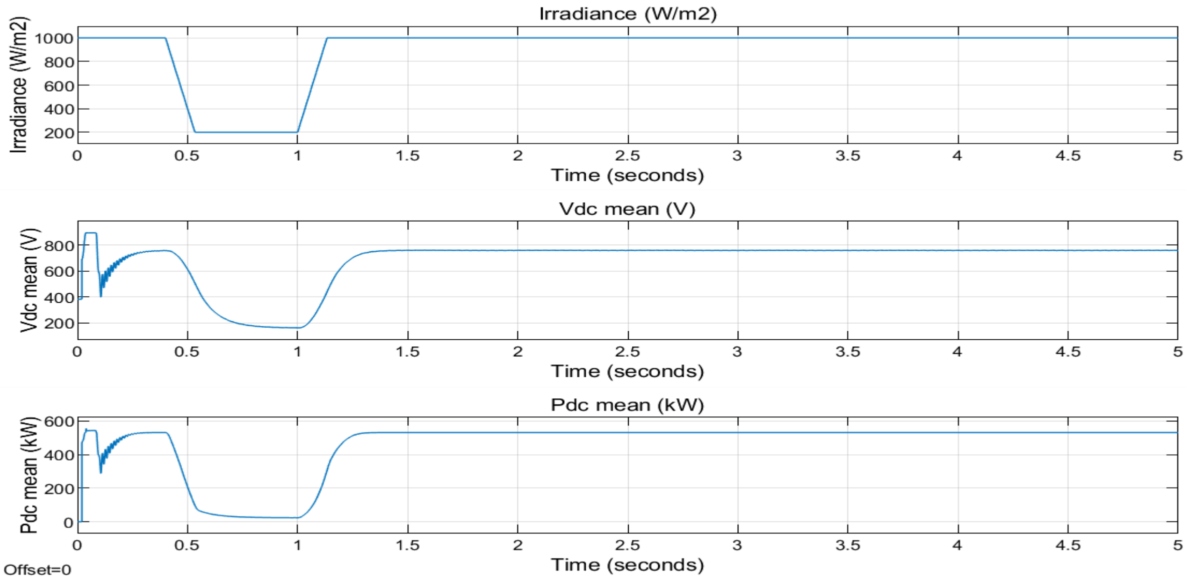


**Figure 9b:** Irradiance, Voltage and Power of the SHPS under WOA method

As shown in Fig. 4, when the switch is toggled to $S_2$, the system is under the P and O control method, and on WOA-based MPPT control technique when the toggle is on $S_1$ respectively. As shown in Fig. 9a, at an irradiance of 1,000 W/m$^2$, an output power of 466.2 kW, current of 674.5 A and a voltage of 734 V is attained over a simulation period of 5 seconds. Between 0.5 seconds and 1 second, irradiation dropped, solar irradiation varies directly to power of a PV system. As irradiation drops, power also drops as low as 104.2 kW. From 1 second, as irradiation raises, power also raises back and maintains a power of 466.2 kW throughout the simulation period. Fig. 9b shows the dynamic behaviour of the system under WOA-based MPPT control technique. An output power of 530.4 kW is obtained at 1,000 W/m$^2$ irradiance, while current and voltage stood at about 683.6 A and 774.7 V respectively. As could be seen, solar irradiation varies directly proportionally to the output power of the PV system, between 0.5 seconds and 1 second, power drops as per irradiation. From 1 second throughout the period of simulation, a steady irradiance of 1,000 W/m$^2$ and power of 533.6 kW is maintained.

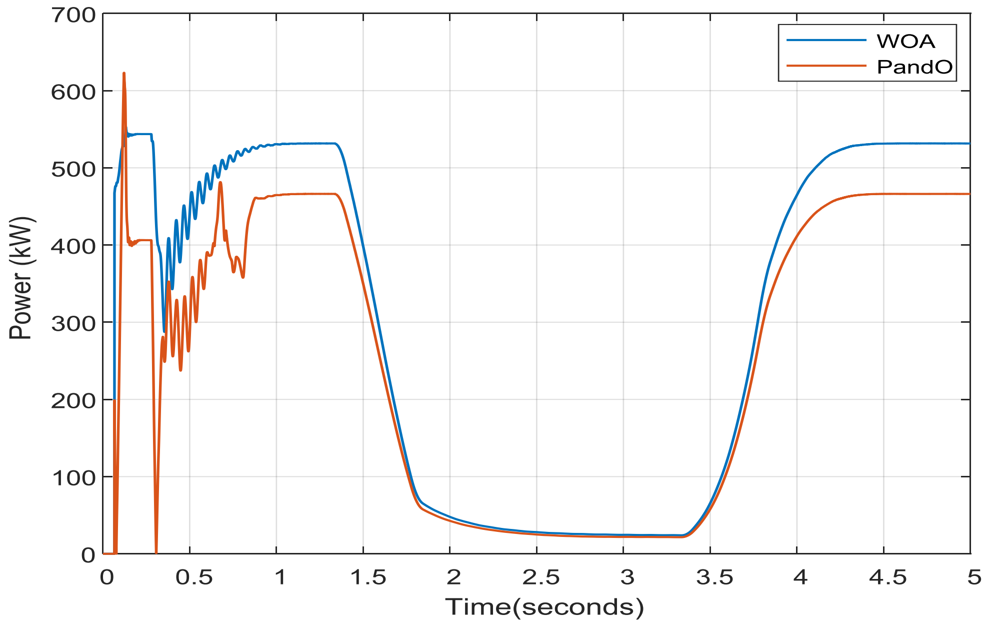


**Figure 10a:** Comparism of P and O, and WOA method with respect to output power of the array

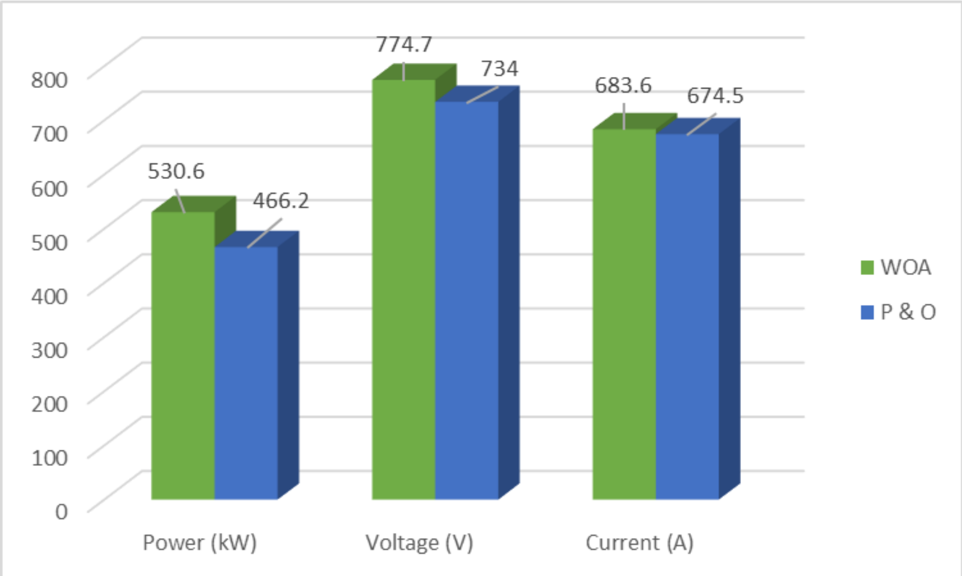


**Figure 10b:** Comparism of P and O, and WOA method with respect to output power, voltage and current of the array

Fig. 10a and 10b represent the comparism of P and O, and WOA-based MPPT control techniques with respect to respect to output power, voltage and current of the array. These two MPPT control technique were tested on the same system with similar input parameters. The P and O MPPT controller tracked up to 466.2 kW of power at the output of the PV array, while the WOA-based MPPT controller obtained up to 530.4 kW. From Fig. 10a, over damping, a slow rise time and settling time are present on the curve representing the P and O control, as compared to that of the WOA-based controller. It could also be seen that, oscillation which causes power loss at MPP is one of the major drawbacks using the P and O method, while on the curve representing the WOA-based MPPT control method, the superiority of the WOA over P and O could be seen as it eliminates oscillations, rises and settles faster correspondingly tracking the maximum amount of power.

## V. Conclusion

Following the assessment of P and O, and WOA-based MPPT controllers on the 500 kW SHPS, it can be concluded that the WOA-based MPPT controller has tacked the highest power at the output of the PV array, and hence offers an improvement in the system dynamics, steady-state performance, and efficiency of the microgrid system.

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