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AN EVALUATION OF THE MOST RECENT MPPT OPTIMIZATION TECHNIQUES FOR A PV SYSTEM

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Abstract- Green energies have become an alternative in the energy sector, especially solar energy, which is attracting a lot of attention and is the subject of research to improve its efficiency. Weather changes and irradiation conditions have an impact on the photovoltaic system. In partially shaded conditions (PSC), a photovoltaic (PV) system represents multiple maximum power points (MPP), so tracking the peak power is challenging. Most recently, optimization techniques for MPP under shading conditions have seen enormous development. One of the most advanced of these techniques is the Horse Herd optimization (HHO) algorithm. This paper aims to extract the best algorithm among the most recent algorithms: horse herd optimization and flying squirrel search optimization (FSSO). This paper evaluates these algorithms under partial shading conditions, a conventional algorithm to assess a complete evaluation of the two recent techniques is introduced, and the simulation results under MATLAB/Simulink reflect that the Horse Herd Optimization algorithm performs better.

Keywords: Photovoltaic System, HHO, FSSO, Incremental Resistance (INR), Maximum Power Point Tracking (MPPT).

1. INTRODUCTION

The energy produced and consumed comes from fossil fuel deposits (oil, gas, coal), uranium, and renewable sources (hydraulic, wind, solar). Fossil energies provide more than 80% of greenhouse gases responsible for climate change [1]. Energy forecasts predict an increase in global energy production, which has a dangerous impact on the environment: an increase in the earth's temperature, drought, floods, storms, and rising sea levels. Therefore, it is necessary to replace fossil energies with green energies that are accessible and ecological.

Photovoltaic energy occurs through semiconductor materials: We refer to photovoltaic modules composed of cells connected to produce electricity [2]. The current produced is a direct current that can be transformed into an alternating current using an inverter. Temperature and irradiation [3] affect the linearity of the P-V characteristic in a photovoltaic system and influence the maximum power output. Several MPPT algorithms exist to solve this problem derived from different families: conventional algorithms and meta-heuristic [4]. Each algorithm is characterized by complexity, tracking speed, response time, and other factors.

The conventional algorithms [5] most used because of their simplicity of implementation, speed of response, and ease of implementation are Perturber and Observer (P&O), Incremental Conductance (INC), Incremental Resistance (INR), Voltage Fraction Algorithm V_{co} (FCO), and Current Fraction Algorithm I_{cc} (FCC). The third categories are artificial intelligence (AI) techniques such as fuzzy logic control (FLC), artificial neural networks (ANN), and evolutionary computation (EC) based on genetic algorithm (GA) [6] and differential evolution (DE).

The solution of various optimization problems using meta-heuristic algorithms has developed considerably because these algorithms are simple and suitable for solving complex problems. The [7] proposed a new meta-heuristic algorithm called the Horse Herd Optimization Algorithm (HOA), based on the gregarious nature of horses for the most complicated high-dimensional optimization problems by mimicking the social performance of horses in races. It stands out for its accuracy and efficiency compared to other algorithms.

The [8] proposed a meta-heuristic optimization algorithm called Flying Squirrel Search Optimizer (FSSO) based on the behavior of squirrels flying from tree to tree in the wild, stepping on the floor, or standing on a branch of a tree to get food. The results showed that the FSO algorithm works well for problems with unknown search space. In our study, we will evaluate the performance of HHO by comparing it with another recently developed optimization technique based on the algorithm (FSSO).

The structure of the paper is as follows: Section 2 provides a brief outline of photovoltaic system modeling. Section 3 describes the different algorithms used in our study to design the MPPT controller. Section 4 illustrates with curves the performance of the MPPT techniques investigated in the case of irradiation changes. Finally, section 5 concludes the study.

2. MODELING OF A PV MODULE

A photovoltaic cell [4] made of semiconductor materials converts solar energy into electricity by electron delocalization in the material. The design of a PV module relies on a diode, a photoelectric current source represented by I_{ph}, an ideal diode connected in parallel with I_{ph}, and two resistors. Figure 1 shows the practical PV pattern.

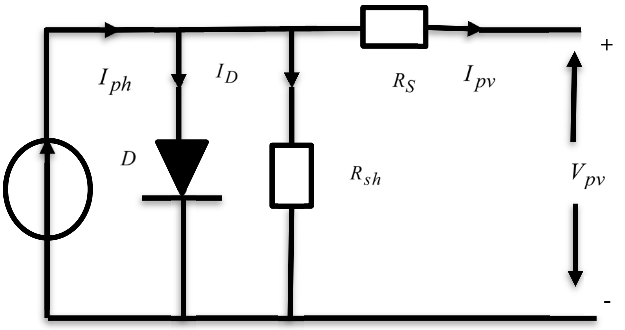


Figure 1. PV cell model with a single diode [4]

The Equation (1) represents the current generated by a solar cell, the Shockley Equation (2) is helpful to calculate the current circulating in the diode, and equation (3) determines the current flowing through the shunt resistor I_{sh}. Equation (4) defines the characteristic of the current and voltage of a solar cell [4].

$$I_{pv} = I_{ph} - I_D - I_{sh} \quad (1)$$

$$I_D = I_0 \left[\exp\left(\frac{q}{nkT} \left(V_{pv} + I_{pv} R_S \right) \right) - 1 \right] \quad (2)$$

$$I_{sh} = \frac{V_{pv} + I_{pv} R_S}{R_{sh}} \quad (3)$$

$$I_{pv} = I_{ph} - I_0 \left[\exp\left(\frac{q}{nkT} \left(V_{pv} + I_{pv} R_S \right) \right) - 1 \right] - \frac{V_{pv} + I_{pv} R_S}{R_{sh}} \quad (4)$$

where,

I_{pv} : The output currents

I_{ph} : Photoelectric current

I_D: The diode current

I_{sh} : The shunt currents

q : The electron charges

I_0 : The reverse saturation current of the diode

V_{pv} : The voltage across the diode

R_s , R_{sh} : The series and shunt resistors of the solar cell

T : The temperature at the junction

k : The Boltzmann's constant

n : The ideality factor of the diode

2.1. Photovoltaic System Overview

This system is composed of photovoltaic panels feeding a charge that operates at maximum power using a boost converter and a controller (MPPT). The total PV solar cell is composed of three models connected in series. Figure 2 shows the Simulink model of our study.

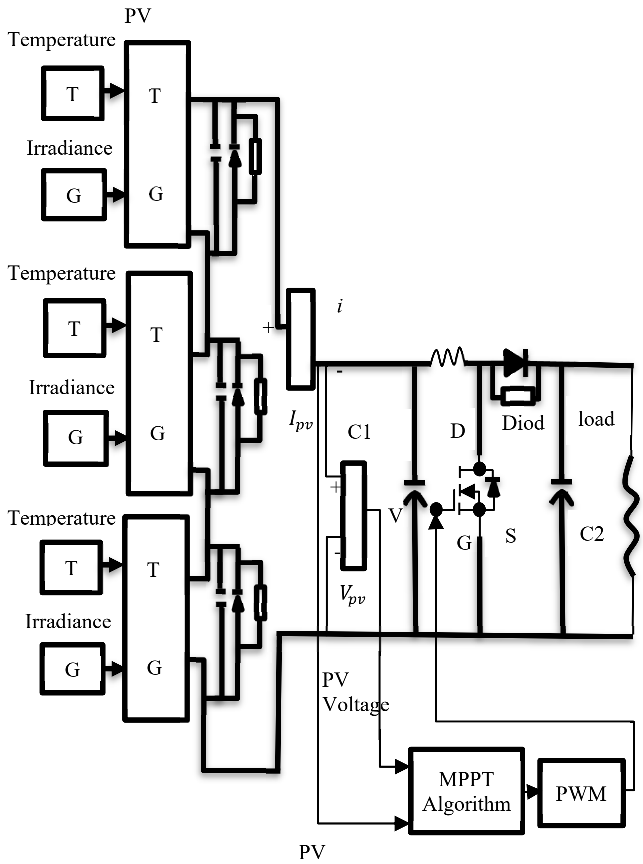


Figure 2. The PV system block diagram

The photovoltaic system contains three modules connected in series and a boost converter. The inductance value is 4 mH while the output capacitor value is 187 µF, the input capacitor has a value of 45 µF, the resistive load is equal to 60 Ω and the switching frequency of the converter is 10 kHz. The photovoltaic system in Figure 2 operates by sensing the voltage and current under (PSC) conditions that get passed to the MPPT block to look for the duty cycle that derives the maximum global power.

2.2. PV Array Characteristics under Partial Shading Conditions

Partial shading [9] has a detrimental effect on the PV system, leading to a decrease in power output and several peaks in the *P-V* characteristic. The number of MPP on the *P-V* plot is proportional to the total of modules. Our study focuses on two cases with different shading. The figure below shows the *I-V* and *P-V* characteristics for the solar PV model in the various shading cases considered. The two *P-V* curves have three peaks. The peak shown by (point B) represents the GMPP in both cases:

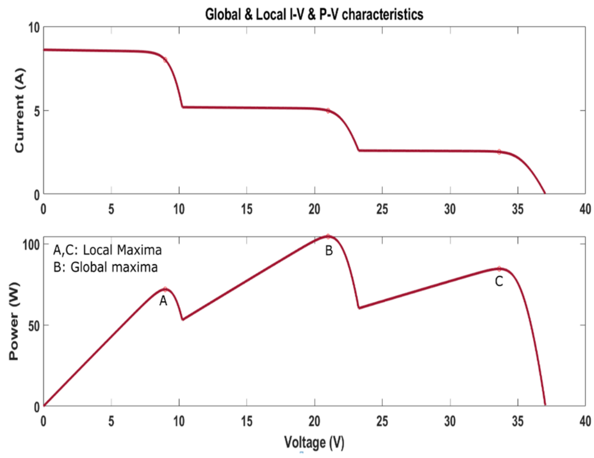


Figure 3. *P-V* and *I-V* plots for the studied photovoltaic system using the first model shading of 1000 W/m^2, 300 W/m^2, and 600 W/m^2

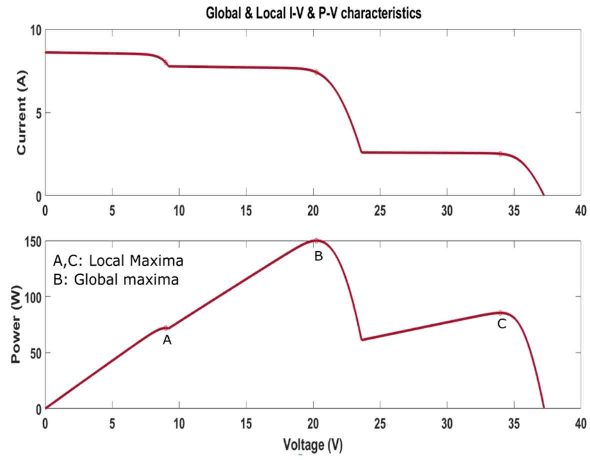


Figure 4. *P-V* and *I-V* plots for the studied photovoltaic system using the second model shading of 1000 W/m^2, 300 W/m^2, and 900 W/m^2

3. MPPT TECHNIQUES

The algorithms used in our study as explained in detail in the following paragraphs:

3.1. Horse Herd Optimization Algorithm

A novel swarm intelligence optimization algorithm, firstly proposed by ref. [7] is HOA. It relies on imitating neighboring behavioral models of horses within their existing environment. Horse behavioral models are Graze (G), Hierarchical (H), Social (S), Imitative (I), and Defensive device (D) in addition to Roaming (R). Horse movement in each iteration follows the equation [7]:

$$X_m^{Iter,A} = V_m^{Iter,A} + X_m^{(Iter-1),A} \quad , A=\alpha,\beta,\gamma,\delta \tag{5}$$

where,

$X_m^{Iter,A}$: Position of *m*th horse

A: Age group of the horse considered

$V_m^{Iter,A}$: Velocity vector of the horse

The average age of the horse is about 25-30 years old. Therefore, *A* is a requirement that δ and γ indicate the age bracket of 0-5-year-old and 5-10-year-old horses, β the age bracket of 10-15 years old, and α shows horse over 15 in age.

The movement coefficient of horses at various times is describable as shown below under the Equations (6)-(9) [7]:

$$V_m^{iter,\alpha} = G_m^{iter,\alpha} + D_m^{iter,\alpha} \tag{6}$$

$$V_m^{iter,\beta} = G_m^{iter,\beta} + H_m^{iter,\beta} + S_m^{iter,\beta} + D_m^{iter,\beta} \tag{7}$$

$$V_m^{iter,\gamma} = G_m^{iter,\gamma} + H_m^{iter,\gamma} + S_m^{iter,\gamma} + I_m^{iter,\gamma} + D_m^{iter,\gamma} + R_m^{iter,\gamma} \tag{8}$$

$$V_m^{iter,\beta} = G_m^{iter,\beta} + H_m^{iter,\beta} + S_m^{iter,\beta} + D_m^{iter,\beta} \tag{9}$$

where, are the main steps of the horse herd algorithm:

3.1.1. Gazing

Horses look in a pasture for 16 to 20 hours per 24 hours. The gaze becomes mathematically expressible in Equations (10)-(11) [7]:

$$G_m^{iter,A} = g_{iter}\left(\mu + \rho l\right)\left[X_m^{iter-1}\right], \quad A=\alpha,\beta,\gamma,\delta \tag{10}$$

$$g_m^{iter,A} = g_m^{(iter-1),A} \times \omega_g \tag{11}$$

$G_m^{iter,A}$ represents the parameter of motion within the i^{th} equine. It is suggested to consider $\mu = 0.95$, $l = 1.05$ and $g = 1.5$ of various age ranges.

3.1.2. Hierarchy

The equine population spend their lives following a leader. In wild horse herds, according to the law of hierarchy in a herd of horses, there is an adult manager among them leading. The coefficient *h* expresses the tendency of the herd of horses to follow the strongest and oldest one. Horses follow the law of hierarchy in the average years between β and γ. Equations (12)-(13) determine the hierarchical stratum [7]:

$$H_m^{iter,A} = h_m^{iter,A}\left[X_*^{iter-1} - X_m^{iter-1}\right], \quad A=\alpha,\beta,\gamma \tag{12}$$

$$h_m^{iter,A} = h_m^{(iter-1),A} \times \omega_h \tag{13}$$

where, $H_m^{iter,A}$ shows the effect of the location of the highest ranked animal upon the speed-setting, while X_*^{iter-1} indicates the position of the highest ranked horse.

3.1.3. Sociability

Sociability is one of the criteria of horses since they do not like solitude, so it is better to live in a herd for their safety. It shows the evolution towards an average position of the other horses expressed using factor *s*. Equations (14)-(15) describes sociability characteristic of horses [7]:

$$S_m^{iter,A} = s_m^{iter,A}[(\frac{1}{N}\sum_{j=1}^{N} X_j^{iter-1} - X_m^{iter-1}, \quad A=\beta,\gamma \tag{14}$$

$$s_m^{iter,A} = s_m^{(iter-1),A} \times \omega_S \tag{15}$$

where,

$S_m^{iter,A}$: Vector of the social movement of *i*th horse

$s_m^{iter,A}$: Direction of horses involved in the herd in *iter*th iteration,

N : The overall number of horses.

3.1.4. Imitation

One of the characteristics of horses is that they imitate each other. Young horses imitate others. They do this until they reach full maturity. The mimicking activity is stated by the factor i in this algorithm [7]:

$$I_m^{iter,A} = i_m^{iter,A}[(\frac{1}{\rho N}\sum_{j=1}^{\rho N} X_j^{iter-1}) - X^{(iter-1)}],\ A=\gamma \tag{16}$$

$$i_m^{iter,A} = i_m^{(iter-1),A} \times \omega_i \tag{17}$$

where,

$I_m^{iter,A}$: Movement coefficient of ith horse to the best mean horse with X position.

ρN : The number of horses with the highest niches.

ρ : About ten percent of the total number of animals.

ω_i : The cycle reducing ratio.

3.1.5. Defense Mechanism

The defense characterizes horses that fight for several reasons: to obtain food and water from rivals and against a hostile or dangerous environment. The HOA algorithm describes the escape of horses that react inappropriately. During the lifetime of a horse, the defense mechanism is always presented by Equations (18)-(19) [7]:

$$D_m^{iter,A} = -d_m^{iter,A}[(\frac{1}{qN}\sum_{j=1}^{qN} X_j^{iter-1} - X^{(iter-1)},\ A=\alpha,\beta,\gamma \tag{18}$$

$$d_m^{iter,A} = d_m^{(iter-1),A} \times \omega_d \tag{19}$$

where,

$D_m^{iter,A}$: The exhaust vector from ith equine of the average of certain equines with the lowest slots coming from the vector X.

qN : The number of horses having the lowest position.

q : Twenty percent from the entire number of horses.

ω_d : The cycle reducing ratio for d_{iter}.

3.1.6. Roam

Horses roam in search of food. They change location to graze out of curiosity, to discover their neighborhood, or experience new pastures. With the attainment of maturity, roaming begins to disappear gradually, as described Equations (20)-(21) [7]:

$$R_m^{iter,A} = r_m^{iter,A}\,\rho X^{(iter-1)},\quad A=\gamma,\delta \tag{20}$$

$$r_m^{iter,A} = r_m^{(iter-1),A} \times \omega_r$$

where,

$R_m^{iter,A}$: Vector of speed randomized by the i^{th} horse in a local research and an exhaust in terms of relative minimums.

ω_r : The cycle reducing ratio of $r_m^{iter,A}$.

The velocities of horses under the categories $\delta,\gamma,\beta,\alpha$ are described by Equations (22)-(25) [7]:

$$\begin{aligned} V_m^{iter,\delta} &= \left[g_m^{(iter-1),\delta}\omega_g(\mu+\rho l)X_m^{(iter-1)}\right] \\ &+\left[i_m^{(iter-1),\delta}\omega_i\left[\frac{1}{\rho N}\sum_{j=1}^{\rho N}X_j^{iter-1}\right]\right] \\ &+\left[r_m^{(iter-1),\delta}\omega_r\rho X^{(iter-1)}\right] \end{aligned} \tag{22}$$

$$\begin{aligned} V_m^{iter,\gamma} &= \left[g_m^{(iter-1),\gamma}\omega_g(\mu+\rho l)X_m^{(iter-1)}\right] \\ &+\left[h_m^{(iter-1),\gamma}\omega_h\left[X_*^{iter-1}-X_m^{iter-1}\right]\right] \\ &+[s_m^{(iter-1),\gamma}\omega_s\left[\frac{1}{N}\sum_{j=1}^{N}X_j^{iter-1}-X_m^{(iter-1)}\right]] \\ &+[i_m^{(iter-1),\gamma}\omega_i\left[\frac{1}{\rho N}\sum_{j=1}^{\rho N}X_j^{iter-1}-X^{(iter-1)}\right]] \\ &-[r_m^{(iter-1),A}\omega_r\left[\frac{1}{qN}\sum_{j=1}^{qN}X_j^{iter-1}-X^{(iter-1)}\right]] \\ &+\left[r_m^{(iter-1),A}\omega_r\rho X^{(iter-1)}\right] \end{aligned} \tag{23}$$

$$\begin{aligned} V_m^{iter,\beta} &= \left[g_m^{(iter-1),\beta}\omega_g(\mu+\rho l)\left[X_m^{(iter-1)}\right]\right] \\ &+\left[h_m^{(iter-1),\beta}\omega_h\left[X_*^{iter-1}-X_m^{iter-1}\right]\right] \\ &+\left[[s_m^{(iter-1),\beta}\omega_s\left[\frac{1}{N}\sum_{j=1}^{N}X_j^{iter-1}-X_m^{(iter-1)}\right]\right] \\ &-\left[[d_m^{(iter-1)}\omega_d\left[\frac{1}{qN}\sum_{j=1}^{qN}X_j^{iter-1}-X^{(iter-1)}\right]\right] \end{aligned} \tag{24}$$

Velocity of α horse over 15 years old:

$$\begin{aligned} V_m^{iter,\alpha} &= \left[g_m^{(iter-1),\alpha}\omega_g(\mu+\rho l)\left[X_m^{(iter-1)}\right]\right] \\ &-\left[d_m^{(iter-1)}\omega_d\left[\left(\frac{1}{qN}\sum_{j=1}^{qN}X_j^{iter-1}\right)-X^{(iter-1)}\right]\right] \end{aligned} \tag{25}$$

The HOA algorithm [7] sorts the local maxima and accelerates the search speed based on the horse movement factors. Thus, it reduces the complexity of solving the problem. The main parameters influencing the HOA algorithm are: Hierarchy factors, Sociability factors, limiting factors, Defense factors, and Wandering factors, the flowchart in Figure 5 allows us to derive the HHO algorithm.

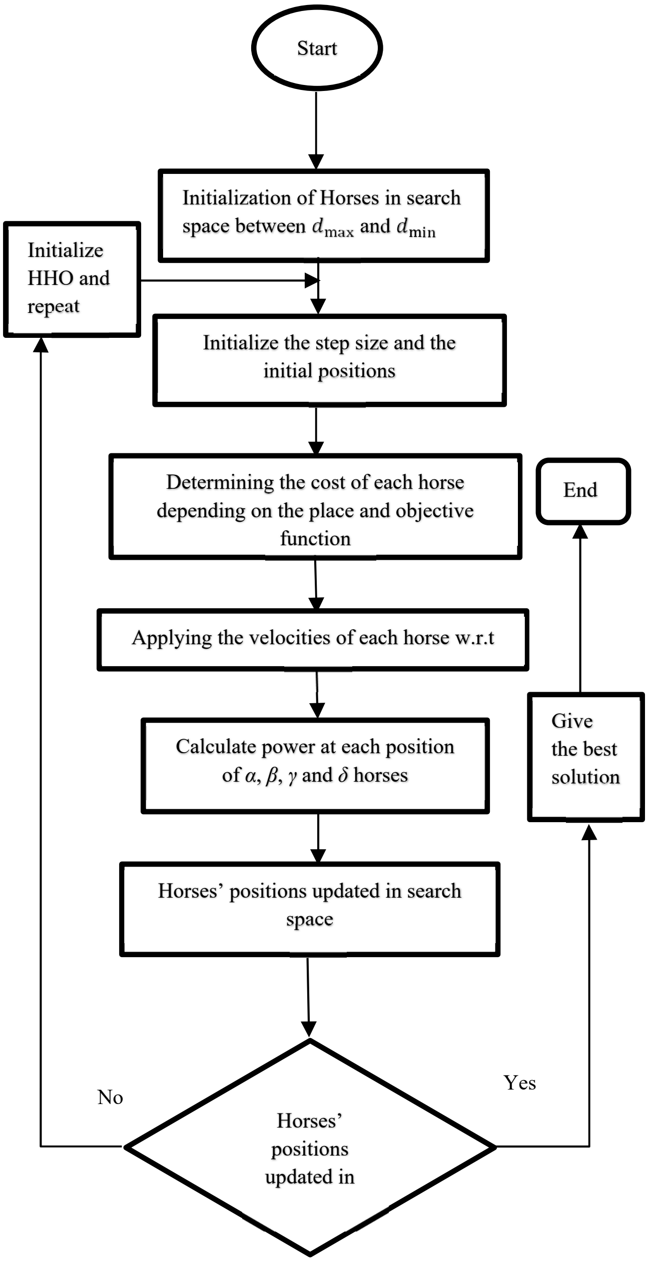


Figure 5. Flowchart of the HHO algorithm

3.2. Incremental Resistance Algorithm

Among the best conventional algorithms for the optimization of MPPT is the Incremental Resistance (INR) [10]. The INR algorithm has a duality relationship with the Incremental Conductance algorithm (INC), which is simple and widely used because of its low cost. Figure 6 shows the Matlab simulation for the INR tracker.

3.2. FSSO Flying Squirrel Search Optimization Algorithm

FFSO is a recently developed algorithm [11] based on mimicking the feeding style of southern FS and their hovering movement. The elimination of the predator to save time to reach the global maximum power point is a rule that this algorithm uses. Below is a diagram that explains the different phases of this algorithm for monitoring the (GMPP) in Figure 7.

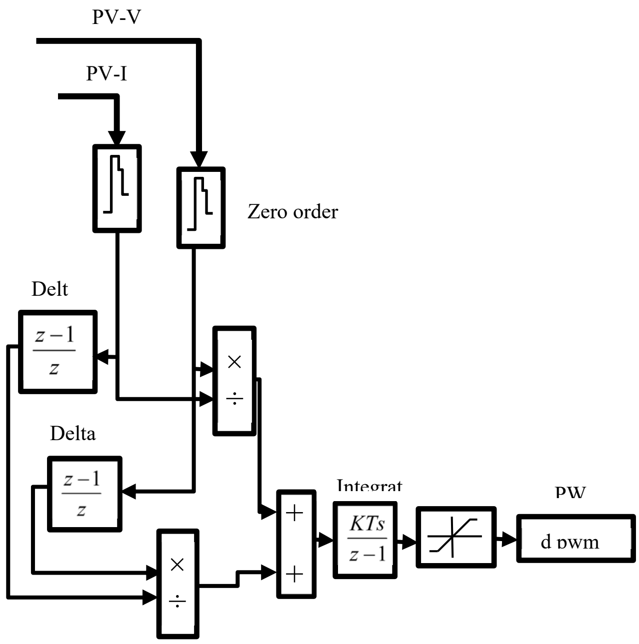


Figure 6. Configuration of the INR tracker in MATLAB

4. SIMULATION RESULTS

The detailed results (power, voltage, and duty cycle) of the simulation with different MPPT techniques under (PSC) are shown in Figures 8 and 9. The evaluation of the most recent HHO and FSSO techniques by comparing them with the INR technique is done by considering the tracking speed of each algorithm, the efficiency, and the performance in each case studied.

Figure 10 shows the superposition of the power curves of the three algorithms in the different irradiance cases studied. The results show that all the algorithms succeeded in reaching the GMPP with performance, and we observe superiority and high efficiency of the HHO algorithm in the two cases.

In the first case of the irradiance model (Figure 8) 1000W/m^2, 300W/m^2, and 600W/m^2, the value of GMPP is 104 W. The HHO algorithm extracts the GMPP with a tracking delay of 0.23s for the FSSO algorithm the GMPP extraction time is 0.37s. Therefore, the HHO algorithm reduces the monitoring time by 37.83% relative to FSSO algorithm. We remark further that HHO accesses the GMPP at extremely high monitoring performance. In contrast, INR technique failed to reach the GMPP value since it is a conventional algorithm.

The solar irradiances for the second case (figure 9) are 1000W/m^2, 900W/m^2, and 300W/m^2. The HHO tracker reaches the GMPP with a tracking time of 0.2s, FSSO with a time equal to 0.3s and INR at 0.4s. The HHO tracker initiated the cycle at 0.2s followed by the values 0.3s, 0.4s and 0.58s successively, whereas FSSO initiated the duty cycle of the boost converter at 0.2s followed by the values 0.3s, 0.4s, and 0.56s progressively, later the cycle values change. These results show us that using the HHO algorithm is still the best choice to reduce the tracking time compared to FSSO by 33.34%.

The number of iterations and the tracking time in the two cases studied under partial shading conditions show that the MPPT based on the HHO algorithm performs better than FSSO and INR.

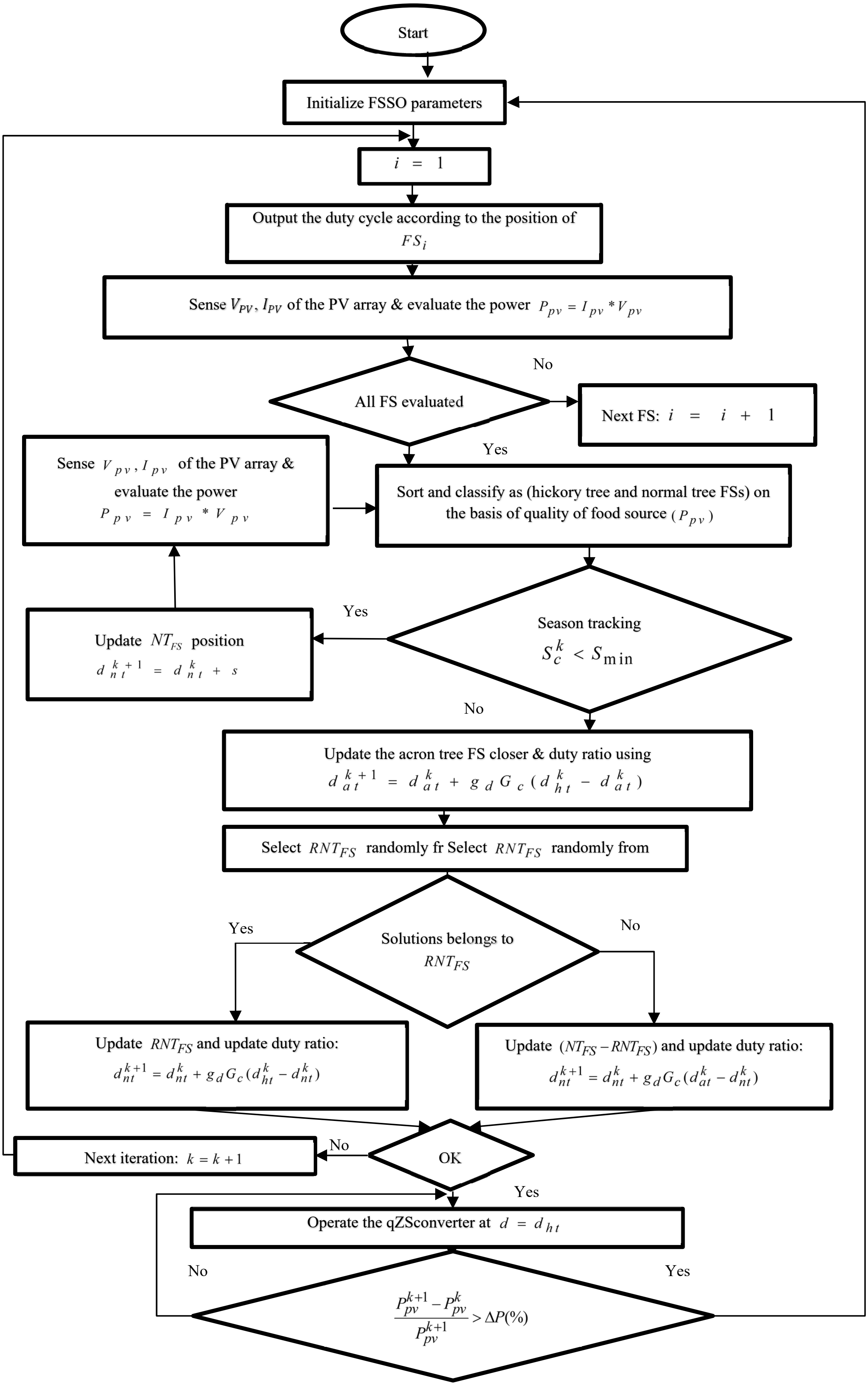
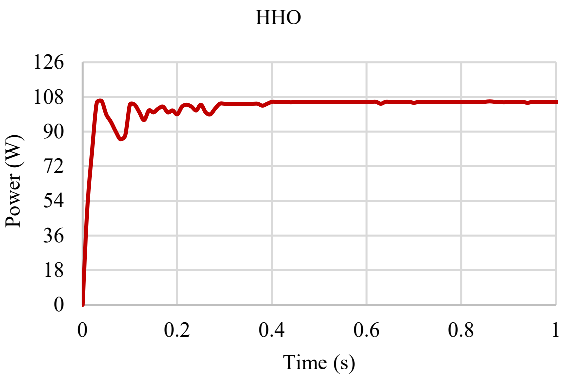
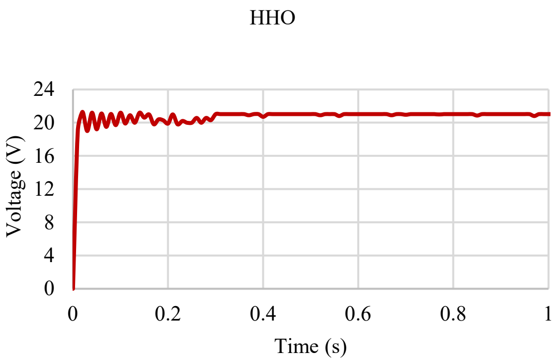
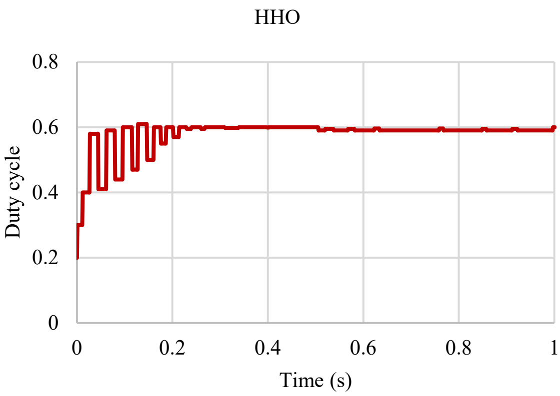


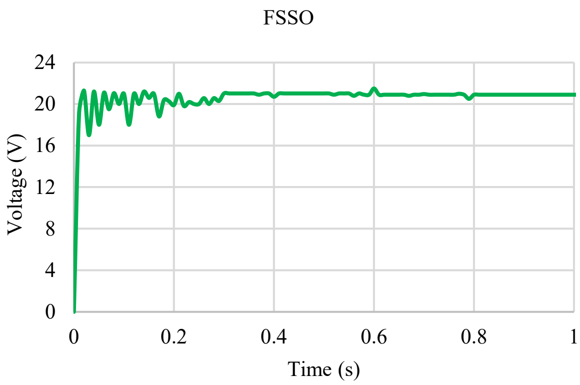
Figure 7. Flowchart of the FSSO algorithm

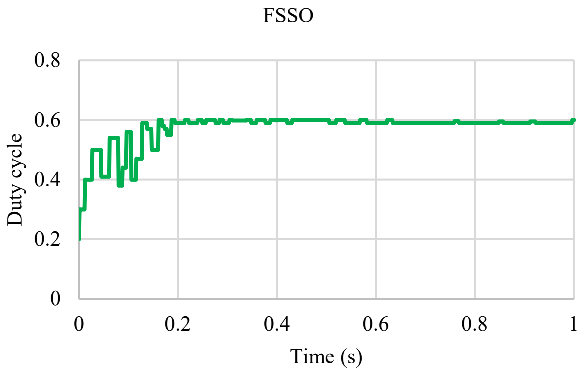

HHO
Power (W)
Time (s)


HHO
Voltage (V)
Time (s)

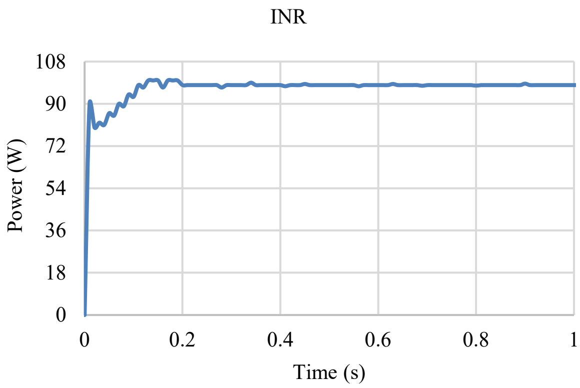

HHO
Duty cycle
Time (s)

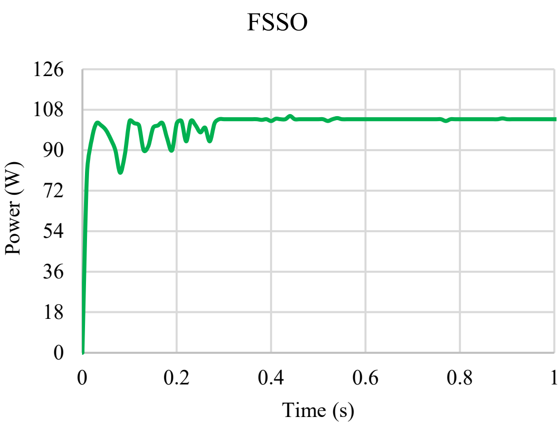
(a)

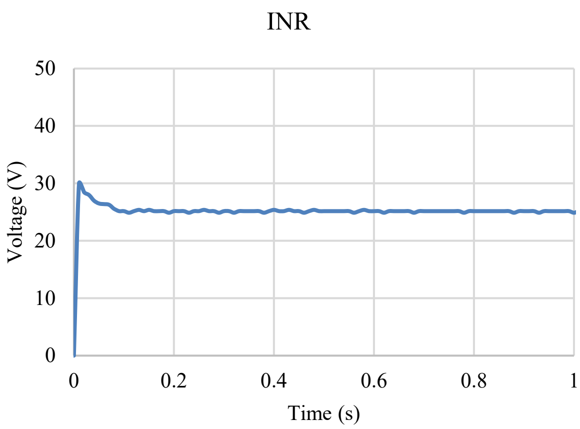

FSSO
Voltage (V)
Time (s)

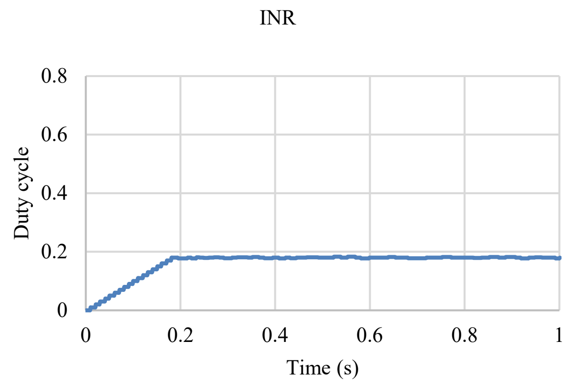

FSSO
Duty cycle
Time (s)

(b)


INR
Power (W)
Time (s)

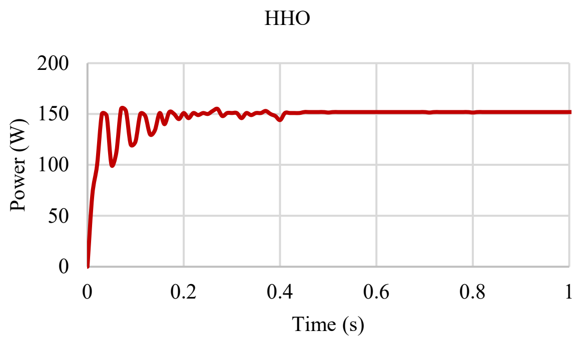

FSSO
Power (W)
Time (s)

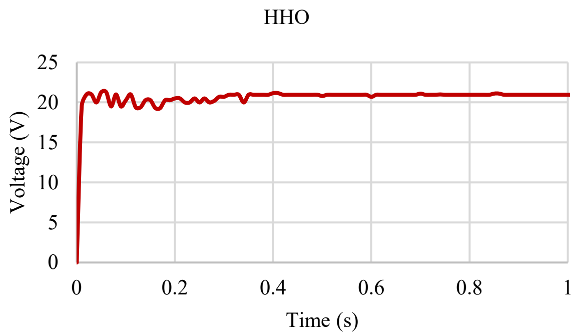

INR
Voltage (V)
Time (s)

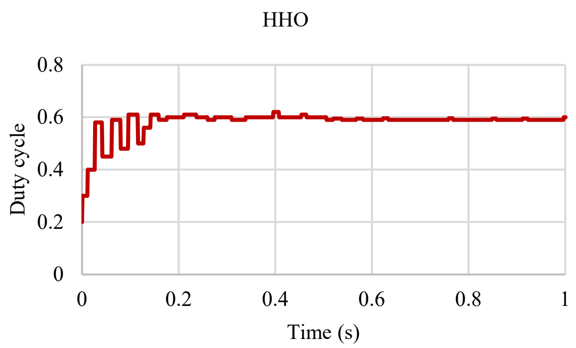


(c)

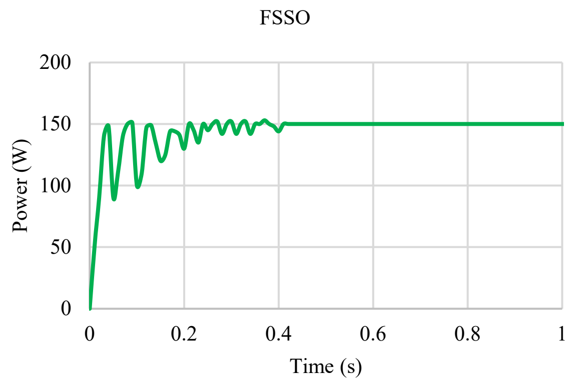
Figure 8. Simulation result details for the PV system under the first shading model of 1000 W/m², 300 W/m², and 600 W/m² (a) HHO-based tracker, (b) FSSO and (c) INR

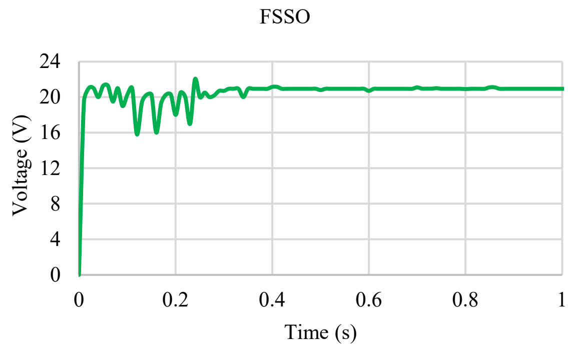


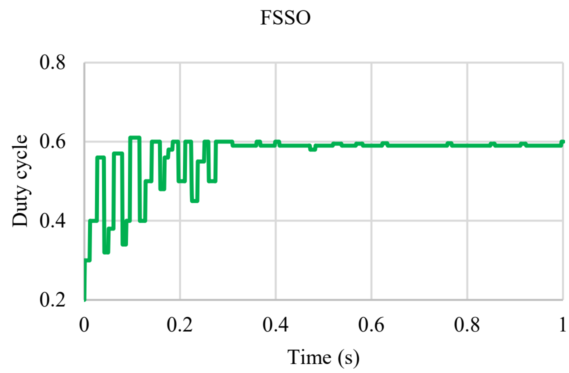




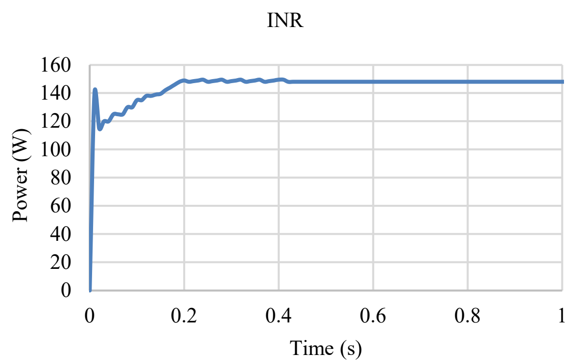
(a)

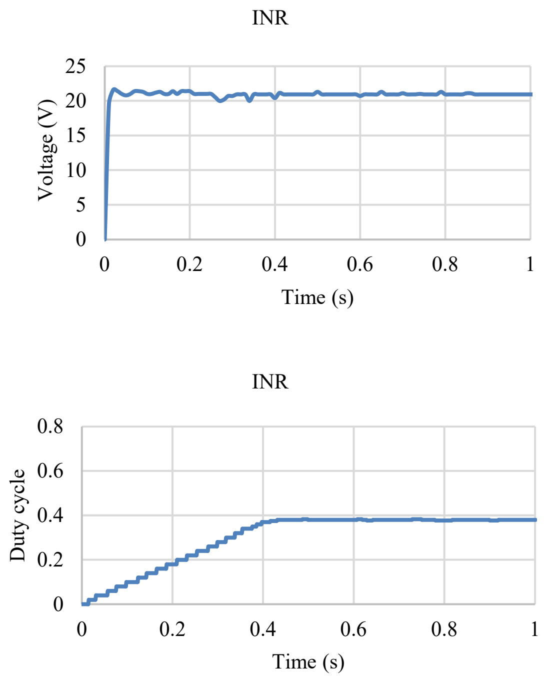






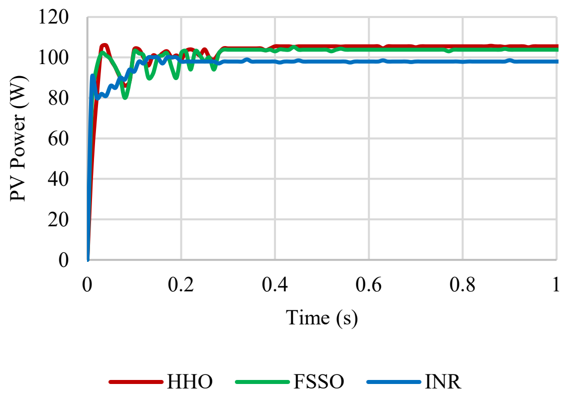
(b)



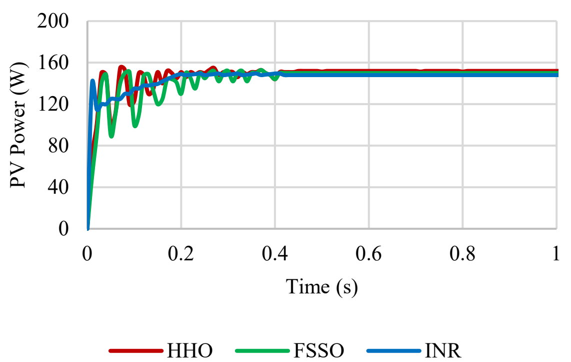


(c)

Figure 9. Simulation result details for the PV system under the second shading model of 1000 W/m2, 300 W/m2, and 900 W/m2 (a) HHO-based tracker, (b) FSSO and (c) INR



(a)



(b)

Figure 10. The power output of the PV system for the HHO, FSSO, and INR techniques under the different partial shading models investigated (a) the first shading model 1000 W/m^2, 300 W/m^2, and 600 W/m^2, (b) the second shading model 1000 W/m^2, 300 W/m^2, and 900 W/m^2

5. CONCLUSIONS

This paper reports on the two most efficient algorithms: Horse Herd Optimization and Flying Squirrel Search Optimization, compared to the INR algorithm. A detailed analysis between conventional and meta-heuristic optimization techniques is performed using MATLAB software under different partial shading conditions. The results confirm that the HHO algorithm is more efficient in terms of accuracy, speed of maximum power tracking, and reduced oscillation frequency. It is possible to conclude that the HHO algorithm remains a better choice for a PV system even under disturbing weather conditions, so this study can be considered a reference for researchers to select the most suitable MPPT technique among the most recent ones.

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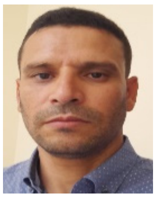

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