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Review and Comparative Analysis of Metaheuristic MPPT Algorithms in PV Systems Under Partial Shading Conditions

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***Abstract*—The power efficiency of photovoltaic energy systems mainly depends on climatic conditions such as solar irradiation and temperature. Therefore, several types of maximum power point tracking (MPPT) algorithms have been proposed to get the maximum efficiency. However, traditional algorithms perform insufficient response for reaching global maximum power points (GMPPs) under partial shading conditions. In order to improve this issue, this paper investigates and compares the tracking capability of particle swarm optimization (PSO), gray wolf algorithm (GWO) and dragonfly optimization algorithm (DFO) methods at first. Results show that DFO responds faster and operates with less error in tracking GMPPs than others. Furthermore, a hybrid PSO-DFO algorithm is proposed in the paper by using the best position of the particle in the PSO algorithm and the best position of the swarm into the dragonfly algorithm. It is observed that the maximum power point tracking performance of this proposed hybrid algorithm is better than DFO, GWO and PSO algorithms.**

Keywords—mppt, partial shading, metaheuristic algorithms

I. INTRODUCTION

In the last few decades, it has become inevitable to focus on sustainable renewable energy production due to environmental problems such as the rapid growth of the population, the increase in energy consumption, the decrease in fossil fuel reserves and the greenhouse gas emissions of fossil fuels. In terms of providing unlimited supply, solar is one of the most preferred renewable electricity generation sources [1].

Solar panels consist of solar arrays formed by grouped solar cells. These arrays generate DC power using solar radiation from sun [2]. Under constant temperature and constant solar radiation conditions, the power generated in PV increases in direct proportion to the load connected to PV. After the panel reaches the maximum power point (MPP), the power starts to decrease even as the load increases. This MPP may shift due to changing atmospheric conditions (such as temperature and solar radiation), panel pollution and shading. Therefore, the power optimization is necessary to ensure maximum efficiency from the PV panels [3]. The power optimization made to get maximum efficiency from solar panels is called maximum power point tracking (MPPT). The fundamental principle of MPPT is to adjust the duty cycle of the power electronics converter at the output of the PV panel so that the PV panel operates at the maximum power point continuously. Many MPPT applications have been proposed recently [4]. The most common of these applications is the traditional perturb and observe (P&O) application. In this application, the power obtained with a reference current and voltage is compared with the PV power obtained with the PV current and voltage. According to the difference, the power is tried to be kept at the maximum with the voltage increase and decrease technique in constant step [5].

Various other methods such as Incremental conductance (IC / IncCon) method, constant voltage method and variable step P&O method which are traditional applications used for MPPT, have also been examined in many studies. However, it has been determined that almost all these methods have delayed response problems [6]. At the same time, more intelligent methods have been needed, as it has been seen that the classical algorithms did not provide sufficient efficiency in tracking the global maximum points (GMPP) and they may lodge in local maximum points (LMPP) formed under partial shading conditions [7]. For this reason, fuzzy logic [8-13], artificial neural networks [12-16] and metaheuristic methods [17-23] have been discussed by many researchers. The main purpose of the intelligent algorithms is to guarantee the tracking of the GMPP regardless of the partial shading and variable temperature conditions [19].

Metaheuristic algorithms have been presented by many authors as a viable solution for tracking GMPP with much higher efficiency in literature. Therefore, in this paper, an analysis has been made on the tracking performance of the most widely used metaheuristic algorithms. Furthermore, a hybrid PSO-DFO algorithm is proposed by using the best position of the particle in the PSO algorithm and the best position of the swarm into the dragonfly algorithm.

The rest of this paper is organized as follow: in the second part, general structure and theoretical background of the PV system including the characteristic V-I curve of the PV panel and the effect of partial shading conditions is explained. Third part examines the MPPT techniques and optimization methods such as particle swarm optimization algorithm, gray wolf optimization algorithm and dragonfly optimization algorithm, which are the most used metaheuristic methods for MPPT. These methods are compared in Simulink in the fourth part where a hybrid particle swarm-dragonfly optimization algorithm is also proposed. Finally, the results are evaluated and a general conclusion is made in the last part.

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II. PV System Description and Modeling

A. PV Modeling

The fundamental element of PV systems are cells formed with diodes which can be made from various semiconductor materials [23]. Fig. 1 shows the photovoltaic cell which is modelled using single diode connected in anti-parallel to a current source.

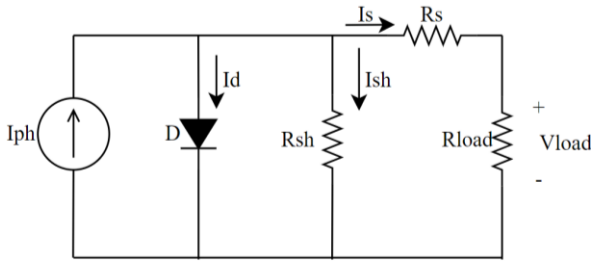


Fig. 1. Solar cell one diode equivalent circuit [23].

The output current according to this electrical circuit can be obtained by Kirchhoff's current law as [23]:

$$I_s = I_{ph} - I_d - I_{sh} \quad (1)$$

I_{ph}: Current generated by solar cell

I_d: The saturation current

I_{sh}: Parallel resistor current

Equation (1) is rearranged using the Shockley equation for an ideal diode as follow [23]:

$$I_s = I_{ph} - I_0 \left[\exp\left(\frac{q(V+R_sI_s)}{nKT_k}\right)-1\right] - \frac{V+R_sI_s}{R_{sh}} \quad (2)$$

I_s: Current of PV cell *V: Voltage of PV cell*

I_0: Diode saturation current *n: Diode ideality factor*

R_s / R_{sh}: Parallel /series resistors *T_k: Cell temperature*

K: Boltzmann constant with value $1.38x10^{-23}$ J / K

Q: Charge amount of an electron with value $1.602x10^{-19}$ C

Solar cells come together to form cellular groups. These cellular groups are connected in series to increase the generated voltage and connected in parallel to increase the generated current and thanks to these connections, PV modules are formed. Modules are also connected in series and parallel to form PV arrays for higher power generation [23]. This formation is shown in Fig. 2.

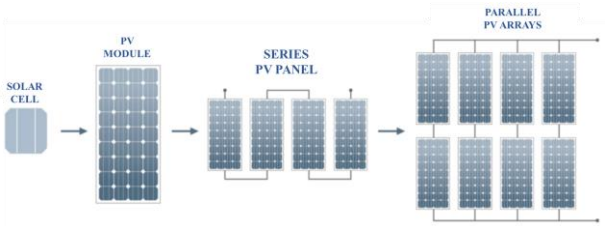


Fig. 2. PV array formation stages.

B. V-I Characteristic of PV arrays

In PV arrays, the output power also varies with temperature and solar radiation, apart from the load connected to the PV panel. As solar radiation increases, the current generated increases, and as the temperature increases, the generated voltage decreases [23]. The changes in current, voltage and output power according to solar radiation and temperature are given in Fig. 3. and Fig. 4, respectively.

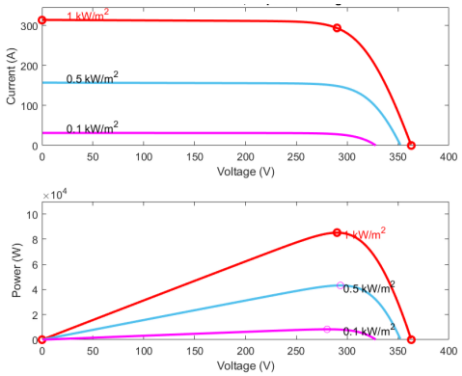


Fig. 3. Effects of solar irradiation on P-V and I-V curves.

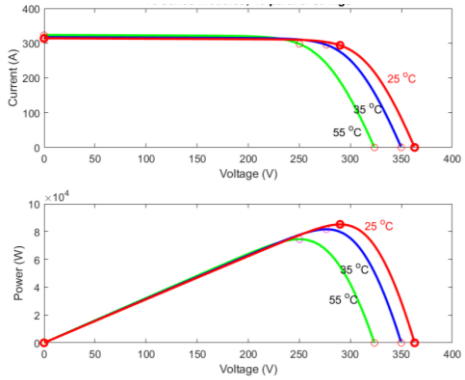


Fig. 4. Effects of temperature on P-V and I-V curves.

Some solar cells in PV systems may generate lower power due to partial shading caused by external factors such as clouds, pollution, buildings [24]. This causes a decrease in the output power and therefore reduces the performance of the system. Fig. 5. shows the P-V curves of changes in output power under non-uniform solar irradiation levels conditions [25]. When each cell of the solar panel can absorb solar irradiation equally, only one maximum power point (MPP) occurs on the P-V curve.

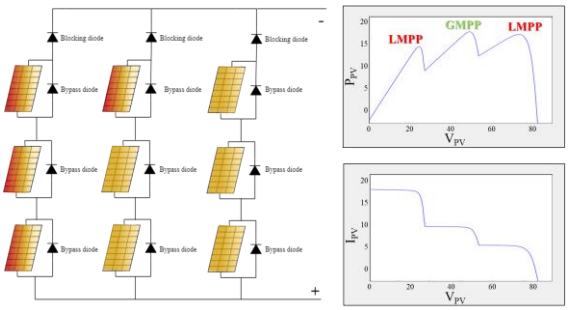


Fig. 5. P-V curves of changes in output power under partial shading conditions.

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If the modules are exposed to different solar irradiation because of partial shading, multiple MPPs are formed, the largest of which is the global MPP (GMPP), and the others are local MPPs (LMPPs) [25]. In PV systems under partial shading conditions, the shaded panel emits heat while consuming the power supplied by other non-shaded panels and limits the current of other panels connected in series to it with its own current. To overcome this dilemma, bypass diodes are connected in parallel to each PV panel. In uniform irradiation conditions, these diodes are reverse biased and there is no effect due to these. However, under partial shading conditions, it becomes forward biased and carries the current of the shaded panel and limits the currents of others. Apart from the effects of shading conditions on the P-V curve, the presence of bypass diodes also complicates the characteristic curve of the PV module. So, under conditions of partial shading, traditional MPPT algorithms fail to determine GMPP and can move to one of the LMPPs and remain at that point [26,27,28].

III. MPPT ALGORITHMS

A general block diagram of the MPPT control in PV systems is given in Fig 6. DC-DC converters, which are very important for use in PV systems, are used in applications where a linear average output voltage is required, which can be higher or lower than the input voltage. The selection of the appropriate DC - DC converter for both the operation of the MPPT system and the integration of the solar panel into the grid are important for the productive operation of the photovoltaic system [29]. Point $dP=0$ where the slope of the P-V characteristic curve is zero namely the derivative of power is zero is defined as the maximum power point (MPP). It has been explained in the previous sections that the voltage or current value that will create the maximum power point may differ depending on external effects. Therefore, it is necessary to constantly monitor the voltage and current parameters and compare them with the previous situation [30]. As given in Fig. 7, when comparing a power $P_{(t)}$ measured at time (t) with a $P_{(t-1)}$ measured at the time $(t-1)$, if the derivative of the measured power is positive ($P_{(t-1)} < P(t)$), the power is on the left side of MPP and the MPP has not yet been reached. Otherwise, if the derivative is negative ($P_{(t-1)} > P(t)$), means that power exceeds MPP [31].

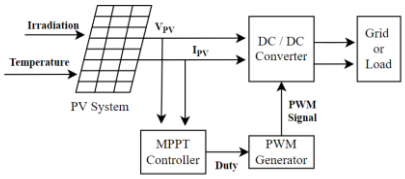


Fig. 6. The block diagram of MPPT control [1].

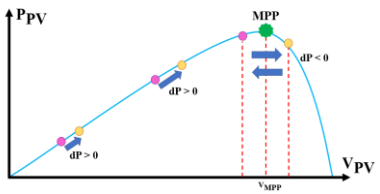


Fig. 7. The fundamental principle of traditional MPPT algorithm [31].

In much research presented in recent literature, the most used classical and metaheuristic MPPT techniques are explained in detail and their advantages and disadvantages are presented [32-35]. Some of the most common of metaheuristic MPPT algorithms PSO [36-41], GWO [42-46] and DFO [47-51] which is just becoming widespread, are examined, and compared in this paper.

A. Particle Swarm Optimization Algorithm (PSO)

Particle Swarm Optimization algorithm (PSO) has been developed by Kennedy and Eberhart in 1995 [23]. This algorithm is based on a swarm that moves stochastically in the search space. Each element in the swarm is called a particle, and the velocities and positions of these particles are recorded. Particles move at a certain speed to reach the best position of the swarm. According to the best position of the particles and the best position of the swarm, the values are updated in each iteration to reach the optimum solution. Position update and velocity equations of particles are given below [23].

$$V_i(k+1)=\omega V_i(k)+c_1r_1(P_{best(i)}-x_i(k)+c_2r_2(G_{best}-x_i(k)) \quad (3)$$

$$x_i(k+1)=x_i(k)+V_i(k+1) \quad (4)$$

$V_{i(k)}$: *Velocity for the i^{th} particle at the k^{th} iteration*

$X_{i(k)}$: *Position for the i^{th} particle at the k^{th} iteration*

$P_{best(i)}$: *Best value for the i^{th} particle*

G_{best}: *Best global value ever of swarm*

ω *:Constant of weight function*

c_1 , c_2: *Positive constant determined in the range of [0 -2]*

r_1 , r_2: *Uniformly random constant in the range of [0 -1]*

The algorithm basically consists of the following steps [52]:

	Basic Steps of PSO Algorithm
1	*Determine the objective function of the optimization problem*
2	
3	*Generate starting positions, velocities, and swarm with uniformly random values within determined lower and upper limits*
4	
5	*k=1*
6	***While*** *(k < Maximum_iteration)*
7	*Calculate the fitness values of all particles in the swarm*
8	*Calculate the best value (P_{best}) for each particle*
9	*Select the global best value of the swarm (G_{best}) from among the best of the particles (P_{best})*
10	*Update positions and velocities of each particle*
11	*k=k+1*
12	***end*** *(when all P_{bests} approach G_{best} or the iteration reaches maximum)*

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B. Gray Wolf Optimization Algorithm (GWO)

Gray wolf optimization (GWO) has been developed inspired by the hunting behavior and social hierarchy of gray wolves [53]. In this social hierarchy has shown in the pyramid in Fig. 8, alpha (α) wolve is the leader and decision maker, beta (β) and delta (δ) wolves that help α in decision making, and omega (ω) wolves which must obey all other wolves.



Fig. 8. Social hierarchy pyramid of gray wolves

The algorithm basically consists of the following steps [53]:

	Basic Steps of GWO Algorithm
1	*Determine boundary conditions and objective function*
2	*Generate uniformly random positions vector of wolves and a, r_1, r_2 parameters*
3	*Identify alpha (α), beta (β) and delta (δ) wolves and their position vectors*
4	*t=1*
5	***While*** *(t < Maximum_iteration)*
6	*Calculate fitness function for each searching wolves*
7	*Update positions and update a parameter linearly decreases from 2 to 0*
8	*t=t+1*
9	***end*** *(when the iteration reaches maximum)*

During hunting, the position of the prey and the approach and encircling behavior of the wolves are expressed as position vectors in the equation given below [53].

$$\vec{D}=\left|\vec{C}.\vec{X_p}(t)-\vec{X_p}(t)\right| \quad (5)$$

$$\vec{X_i}(t+1)=\vec{X_p}(t)-\vec{A}.\vec{D} \quad (6)$$

t: Iteration $\vec{D},\vec{A},\vec{C}$*: Coefficient vectors*

$\vec{X_p}$*: Position vector of prey* $\vec{X_i}$*: Position vector of* i^{th} *gray wolf*

The vectors A and C are calculated as follows:

$$\vec{A}=2\vec{a}.\vec{r_1}-\vec{a} \quad (7)$$

$$\vec{C}=2.\vec{r_2} \quad (8)$$

$\vec{a}$*: linearly decreases from 2 to 0 during iterations*

$\vec{r_1}$ *and* $\vec{r_2}$ *: Uniformly random constant in the range of [0 -1]*

C. Dragonfly Optimization Algorithm (DFO)

Dragonfly algorithm is a metaheuristic algorithm that has been first proposed by Seyedali Mirhalili in 2015, based on the behavior of dragonflies seeking food sources and escaping from enemies [54]. First step in the dragonfly algorithm, a uniformly random swarm generated, and a step vector is created which expressing the substitution request. The substitution request is initially considered zero. Then, the fitness function is calculated for each dragonfly in swarm. The best solution is considered the position of food source and the worst solution is considered the position of enemy. Dragonfly swarms have two basic behaviors in nature. These are the actions of searching and reaching food and escaping from the enemies. The mathematical models of these actions are given below [54].

$$F= X^{+} - X \quad (9)$$

$$E= X^{-} + X \quad (10)$$

F: Food X^{+}*: Position of food* *E: Enemy*

X^{-} *Position of enemy*

X_i*: Position of current* i^{th} *dragonfly*

Unlike other swarm algorithms, the dragonfly algorithm has a concept which is called neighborhood. In the algorithm, it is examined whether there is another neighboring dragonfly nearby to the current dragonfly. The neighborhood area has a radius. The radius of the neighborhood is chosen small at first step. It is enlarged with each iteration. The updating position of current dragonfly is determined with two different ways; has at least one neighbor in the neighborhood or not. If there is a neighborhood relationship between dragonflies, there are three factors that related to position update of these neighboring dragonflies [54]. Separation *(S)* ensures that neighboring dragonflies do not bump into each other. Alignment *(A)* allows that neighboring dragonflies to move at synchronous velocity. Cohesion *(C)* allows that neighboring dragonflies to move in close positions without being too far from each other and attraction of all dragonflies towards the center of swarm. The equations for calculating these factors are as follow [54]:

$$S_i= -\sum_{i=1}^{N} X-X_j \quad (11)$$

$$A_i=\frac{\sum_{j=1}^{N} V_j}{N}-X \quad (12)$$

$$C_i=\frac{\sum_{j=1}^{N} X_j}{N}-X \quad (13)$$

i: Iteration

N: Number of neighborhoods

X: Position of current dragonfly

X_j*: Position of the* j^{th} *neighboring dragonfly*

V_j*: Velocity of the* j^{th} *neighboring dragonfly*

Searching and reaching mechanism depends on the factors *S, A, C, F, E* and their weight coefficients *s,a,c,f,e* which randomly determined and inertia moment ω.

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The step and position vector are updated as below [54]:

$$\Delta X_{t+1}=(sS_i+aA_i+cC_i+fF_i+eE_i)+\omega\Delta X_t \quad (14)$$

$$X_{t+1}=X_t+\Delta X_{t+1} \quad (15)$$

ΔX_i: Step which is at the t^{th} moment displacement request

X_i: Position at the t^{th} moment *ω: Inertia moment*

s,a,c,f,e : Weight coefficients of S,A,C,F,E

If the current dragonfly has no neighbors, random motion methods are used to determine its new position. The most used random motion methods in the dragonfly algorithm are Lèv'y flight and Brownian motion [55]. The Lèv'y equation and position equation that will be discussed in this paper are as shown below [54]:

$$\text{Lèv'y(d)}=\frac{1}{100}\times\frac{r_1\times\left(\frac{\Gamma(1+\beta)\times\sin\left(\frac{\beta\pi}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right)\times\beta\times2^{\left(\frac{\beta-1}{2}\right)}}\right)^{1/\beta}}{|r_2|^{1/\beta}} \quad (16)$$

$$X_{t+1}=X_t+(X_t\,.\,\text{Lèv'y(d)}) \quad (17)$$

X_i: Position at the t^{th} moment β: Randomly constant

d: Dimension of the search space

r_1 ,r_2: Uniformly random constant in the range of [0 -1]

Γ: Gamma function as $\Gamma(z)=\int_0^\infty t^{z-1}e^{-t}dt$

if z=integer $\Gamma(n)=(n-1)!$

The algorithm basically consists of the following steps [56]:

	Basic Steps of DFO Algorithm
1	*Determine boundary conditions and objective function*
2	*Generate random position, velocity, and step vector*
3	*iteration=1*
4	***While*** *(t < Maximum_iteration)*
5	*Calculate fitness function for each dragonfly, update positions of food source and enemy*
6	*Generate uniformly random constants w,s,a,c,f and e, Calculate S, A, C, F, E using equations*
7	*Update neighborhood radius*
8	***If*** *(the current dragonfly has at least one neighboring dragonfly)*
9	*Update the velocity vector using S, A, C,F,E*
10	*Update the position vector using step vector*
11	***else***
12	*Update the position vector using Lev'y flight eq.*
13	***end***
14	*iteration=iteration+1*
15	***end*** *(when the iteration reaches maximum)*

In the literature, specified that metaheuristic algorithms no matter how intelligence they are, do not well perform independently. Therefore, hybrid metaheuristic optimization algorithms have also been suggested for MPPT [57-63].

D. Proposed Hybrid PSO- DFO Algorithm

In the dragonfly algorithm, the position update action is calculated with two different equations, depending on whether there is a neighborhood or not. However, in DFO algorithm, dragonflies are not programmed for follow previously obtained potential solutions [64]. This may lead to early or late convergence problems. If the best-ever position G_{best} that reached by all dragonflies in the neighborhood and the best position P_{best} that previously reached by the current dragonfly can be recorded, the potential global optimum points can be tracked [64]. For this purpose, a hybrid PSO-DFO algorithm has been developed by us in this study, inspired by the PSO algorithm which the best of the swarm and particle are recorded and updated. In addition, it has been tried to prevent the Lèv'y flight from causing too much divergence in dragonflies by adding the displacement request in the previous iteration to the random Lèv'y motion in the absence of neighborhood. Hybrid PSO-DFO algorithm has been suggested for solution of different problems too in literature [65-68].

The algorithm basically consists of the following steps :

	Basic Steps of Hybrid PSO-DFO Algorithm
1	*Determine boundary conditions and objective function*
2	*Generate random position, velocity, and step vector*
3	*iteration=1*
4	***While*** *(t < Maximum_iteration)*
5	*Calculate fitness function for each dragonfly, Update positions of food source and enemy*
6	*Generate uniformly random constants w,s,a,c,f and e, Calculate S , A, C, F, E using equations*
7	*Update neighborhood radius*
8	***If*** *(the current dragonfly has at least one neighboring*
9	*dragonfly)*
10	*Calculate the best value (Pbest) for each dragonfly Select the*
11	*global best value of the swarm (Gbest) from among the best of the dragonflies (Pbests)*
12	*Update the velocity vector using S, A,C,F,E and position using*
13	*step vector*
14	***else***
15	*Update the velocity vector using velocity of t-1 th iteration and add it to position vector*
16	*Select the global best value of the swarm (G_{best}) from among the best of the dragonflies (P_{bests})*
17	*Update the position vector using Lev'y flight*
18	***end***
19	*iteration=iteration+1*
20	***end*** *(when the iteration reaches maximum)*

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IV. Modelling and Simulation

Metaheuristic MPPT algorithms focused on this paper have been evaluated and compared to each other. The simulation has been carried out on MATLAB R2018a version, with computer that 16GB RAM, 250 GB SSD, 1 TB HDD, Intel(R) Core (TM) i7-4700MQ CPU @ 2.40GHz x64 processor. Fig. 9. shows the Simulink model of MPPT system designed.

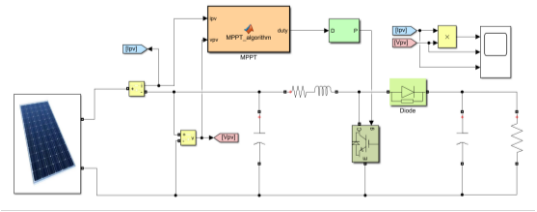


Fig. 9. PV system model designed in Simulink.

Tables I and II show the characteristics of the PV panel and the parameters of the DC-DC boost converter, respectively.

TABLE I. PV PANEL PARAMETERS

Maximum PV Power	P_{MAX} = 213 W
MPP Voltage	V_{MPP}= 29 V
MPP Current	I_{MPP} = 7,35 A
Open Circuit Voltage	V_{OC} = 36,3 V
Short Circuit Current	I_{SC} = 7,84 A
Cells Per Module	N_{CELL}= 60
Parallel Strings	P= 2
Series Connected Modules per String	S= 2

TABLE II. DC-DC Boost Converter Parameters

Input Capacitor	C_{PV} = 470 µF
Boost Inductor	L_B= 2,5 mH
Output Capacitor	C_O = 47 µF
Resistive Load	R_L = 6Ω
Switching Frequency	f_s = 50kHz

A. Simulation Results

The modelled system consists of four panels, each of which has 213 W maximum power. In order to simulate the partial shading condition, while 1000 W/m^2 solar radiation has been applied to two of four panels, 800 W/m^2 and 600 W/m^2 solar radiations have been applied to the other two panels, respectively. Ideally, it is expected to total power of the system reaches up to 852 W if all panels receive 1000 W/m^2 solar radiation. However, in partial shading conditions where significant decreases are occurred on the power generation abilities of PV panels, the MPPT algorithm that keeps the total output power closest to 852 W can be considered as the most performant.

The tracking factor of each algorithm focused in this study has been examined taking into account the difference between the required power and the actual steady-state power and it has been observed that the hybrid DFO-PSO algorithm gives better result than others with a score of 97%. Figure 10 and Table III present the details of results for all algorithms including the peak value of the power, the actual power in steady-state conditions, the percentage of the power fluctuation range, the percentage of tracking factor. During simulations, it has been noticed that when the number of individuals in the swarm is increased, there is a stuck to the local maximum point. However, power fluctuations have occurred when the number of individuals has been reduced. Therefore, it may be required to find the number of individuals and iterations separately as specific to each algorithm.

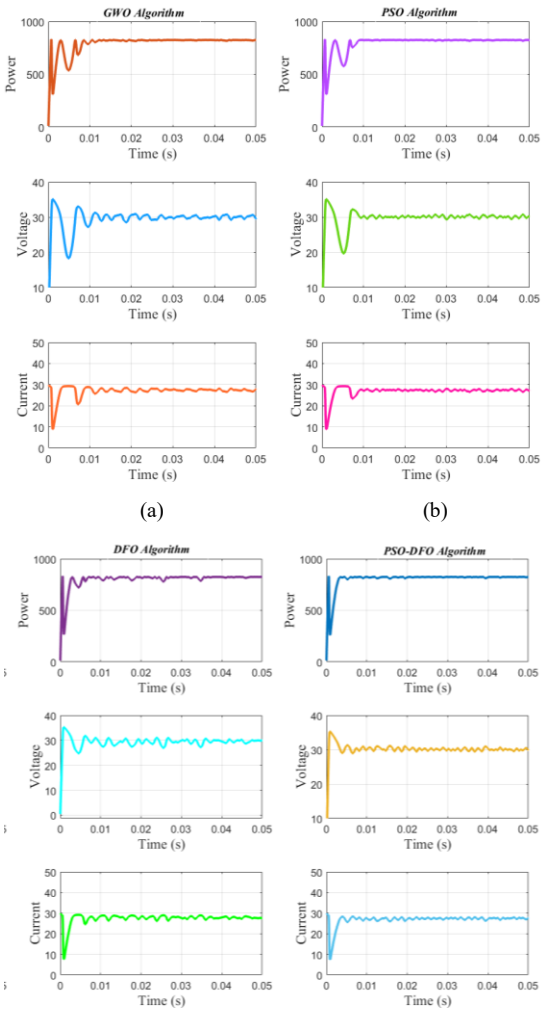


Fig. 10. Power, voltage, current curves for (a) GWO, (b) PSO, (c) DFO and (d) hybrid PSO-DFO

TABLE III. Simulation Results

MPPT Algorithm	*Maximum Power (W)*	*Steady-State Average Power (W)*	*Power Oscillation (%)*	*Tracking Factor (%)*
GWO	*828 W*	*818 W*	*%1.79*	*%92*
PSO	*825 W*	*820 W*	*%2.07*	*%90*
DFO	*833 W*	*813 W*	*%1.492*	*%94*
PSO-DFO	*835 W*	*825 W*	*%1.231*	*%97*

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V. CONCLUSION

In this study, firstly, PSO, GWO and DFO metaheuristic MPPT algorithms, those have a wide usage area in the literature, have been compared in order to analyze their performance for MPPT tracking capability. Then, a hybrid algorithm combining PSO and DFO has been proposed for better performance. To make a comparative analysis, the behavior of the PV system under various irradiations and partial shading has been considered. Each algorithm has been tested on the same model that consists of four PV panels and a DC-DC boost converter. Although all three of the analyzed algorithms yielded successful results for following GMPP, output powers in the steady state conditions have been found lower and high oscillations have been occurred. The proposed hybrid method has not only given the best result for tracking ability but also provided the higher output powers.

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