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A REVIEW ON MPPT ALGORITHMS FOR SOLAR PV SYSTEMS

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ABSTRACT

In past few decades, solar energy plays a vital role in energy production among the different renewable energy resources. In shaded/unshaded photovoltaic (PV) systems, tracking of maximum power under different environmental conditions is provided by maximum power point tracking (MPPT). In recent years many works available on different types of MPPT techniques to track maximum power from PV systems with own pros and cons. This article comprehensively reviews the different traditional methods like perturb and observation (P&O), open circuit voltage (OCV), short circuit current (SCC), hill climbing (HC), incremental conductance (IC). Also recall the advanced MPPT techniques like particle swarm optimization (PSO), grey wolf optimization (GWO), cuckoo search (CS), artificial neural networks (ANN), fuzzy logic controller (FLC) available in literature. This review is conducted based on implementation, accuracy, tracking speed, cost, merits, and demerits of each technique. Traditional MPPT methods can't able to track global maximum power point under partial shaded conditions and exhibits less efficiency when compared with advanced soft computing methods. Hybrid methods provide good efficiency and performance than traditional and advanced methods. Authors powerfully confirm that this article offers convenient information's to enthusiastic engineers and new researchers those who are all working in solar PV systems.

Keywords: Solar Energy, Photovoltaic, MPPT, Conventional Algorithms, Evolutionary Algorithms, Hybrid Algorithms

1. INTRODUCTION

Recent decays of research shows that the earth temperature increases rapidly due to many reasons like increases in population density, civilization, and increase in usage of fossil fuels which emits more carbon dioxides, as results in unnatural behavioural in earth atmosphere. To avoid the increasing temperature in earth temperature, from past few decades, renewable energy resources attract many researchers mind towards resources like solar, wind, geothermal etc., Among many available renewable resources, solar sources attract more due to its abundant availability in major parts of the world and especially environmental friendly. Now much research works going all around the world in converting sun light into energy with different techniques such as solar cells, modules, and panels Shaikh et al. (2017). Voltage generated from a single solar photovoltaic (PV) cell is around 0.5 to 0.8 volts based on the semiconducting material technology used for fabrication. In order to get usable value of voltage level, many solar cells is interconnected usually in the range of 36 to 72 cells is named as solar PV modules. To get higher values modules are inter-connected in series and parallel called PV panels Salmi et al. (2012). Solar PV can be utilized to generate power in the ranges from mille watt to Giga watt based on the required applications.

The major challenge of using solar energy is the conversion efficiency from light into electricity is very poor. The energy conversion from sun light is majorly depends on proper trapping of incident light. I-V and P-V characteristics of PV systems are non-linear and can be affected by solar irradiations and temperature Herbazi et al. (2019), Nayak et al. (2012), Mohan and Senthilkumar (2022), Senthilkumar et al. (2022), Nathangashree et al. (2016), Senthilkumar et al. (2014). The performance of PV systems may be affected by factors like dust, leafs, trees, buildings, cloud, bird's droppings etc., which leads to multiple peaks in I-V and P-V characteristics Mao et al. (2020). Under partial shaded conditions Salem and Awadallah (2016), Djalab et al. (2018), Teo et al. (2018). PV systems exhibits multiple peaks in I-V and P-V characteristics which leads to drop in performance. In order to catch the global peak from multiple peaks, maximum power point tracking (MPPT) is proposed. These challenges are the major motivations to the authors to prepare this review article for the benefits of research community.

This article is structured as chapter 1 describes the introduction; modelling of solar PV is summarized in chapter 2. Chapter shows the different types of MPPT in solar PV systems; Chapter 4 reviews various traditional MPPT algorithms, and in chapter 5 optimization based MPPT algorithms are presented. Chapter 6 summarizes different intelligent based MPPT algorithms, hybrid MPPT methods are presented in chapter 7. In chapter 8, major challenges and issues are discussed. Finally in chapter 9, Conclusion and future scope of this work are presented. Figure 1 shows the structure of this article. In this review article 1280 articles from 2004 to 2023 are considered to provide a quality article. PRISMA style reorientation of this review article is shown in Figure 2.

Figure 1

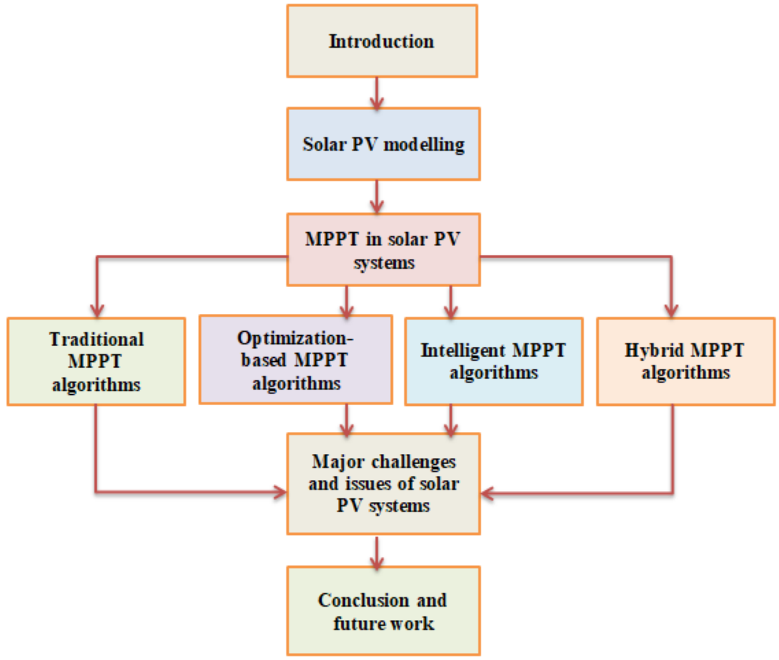

Figure 1 Flow Chart for Structure of The Article

Figure 2

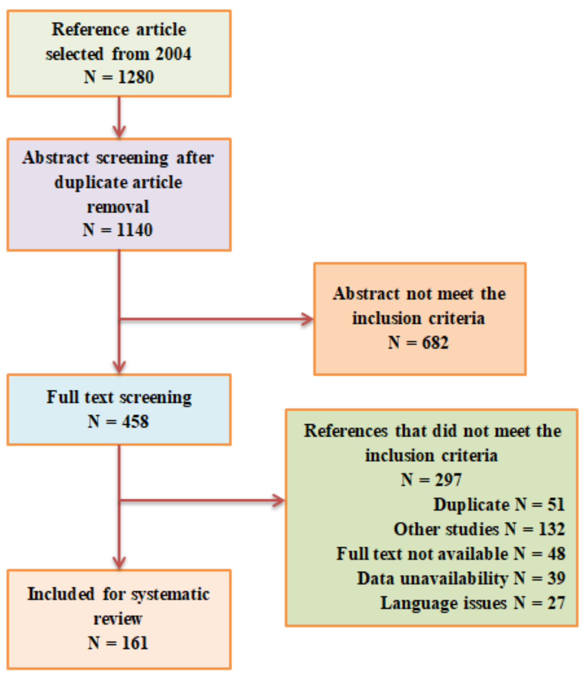

Figure 2 PRISMA Representation of this Review Article

Table 1 shows the installed renewable energy capacity in India as on 28.02.2022. Figure 3 shows renewable energy installed capacity in India as on 28.02.2022. Figure 4 shows the simple form of solar energy generation systems.

Table 1

Table 1 Installed Renewable Energy Capacity in India as on 28.02.2022 From MNRE (MW)

S. No.	Renewable energy source	Contribution in MW
1	Solar Power	50778
2	Wind Power	40130
3	Biomass	10176
4	Hydro Power	4840
5	Waste to Energy(off-grid)	237
6	Waste to Power	214
	Total	**106375**

Figure 3

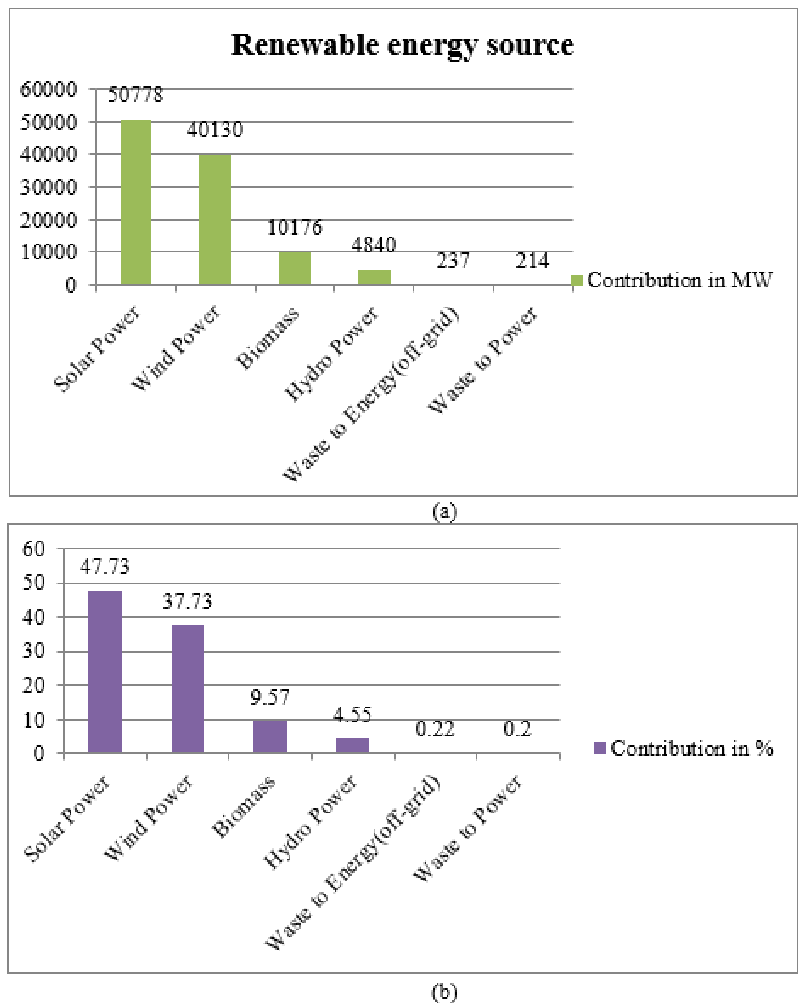

Figure 3 Renewable Energy Installed Capacity in India (A) Contribution in MW, (B) Contribution In %

Figure 4

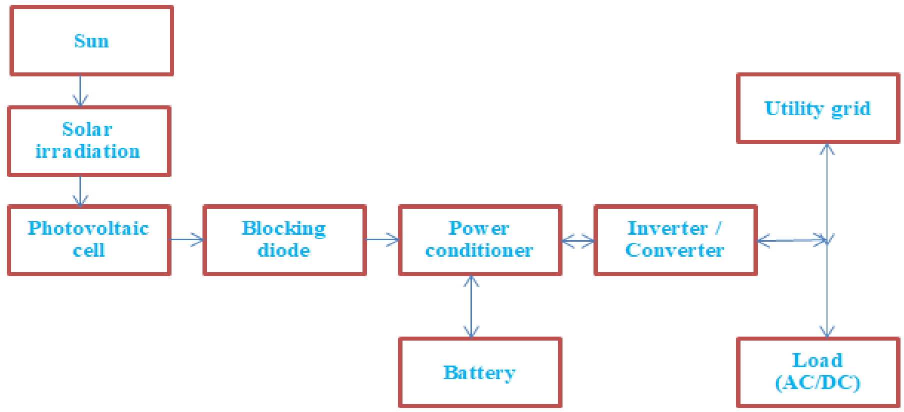

Figure 4 Solar Energy Generation

2. SOLAR PV MODELLING

The working and I-V characteristics of solar PV systems are majorly depends on modelling solar PV cell. The following are the major contributors for accurate modelling solar PV systems.

- PV current (Ipv)
- Diode saturation current (Id)
- Series resistance (Rs)
- Shunt resistance (Rsh)
- Diode ideality factor (a)
- Open circuit voltage (Voc)
- Short circuit current (Isc)
- Voltage at maximum power (Vmp)
- Current at maximum power (Imp)

Three types of solar PV cell modelling available in literature namely single diode model (SDM) Rasheed and Shihab (2020), Mehta et al. (2019), Marish et al. (2015), Ma et al. (2013), Park et al. (2016), double diode model (DDM) Ndi et al. (2021), Ćalasan et al. (2019), Li et al. (2019), Yaqoob et al. (2021), Prakash et al. (2021) and triple diode model (TDM) Elazab et al. (2020), Rezk And Abdelkareem, (2021), Khanna et al. (2015), El Dabah et al. (2021). Figure 5 depicts the mathematical model of a solar cell.

Figure 5

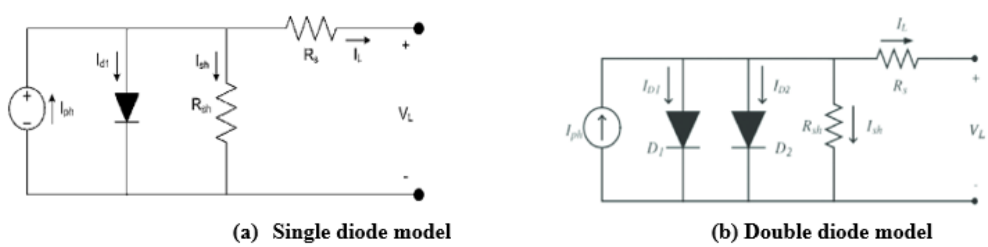

Figure 5 Mathematical Model of Solar Cell

Output current from SDM circuit is written as shown in Equation 1.

$$I_L = I_{ph-} I_0(\exp\left(\frac{V_L+I_L R_s}{aV_T}\right) - 1\Big) - \left(\frac{V_L+I_L R_s}{R_{sh}}\right)$$ Equation 1

Here diode current is written as shown in Equation 2.

$$I_{d1} = I_0(\exp\left(\frac{V_L+I_L R_s}{aV_T}\right) - 1\Big)$$ Equation 2

(2)

Output current from DDM circuit is written as shown in Equation 3.

$$I_L = I_{ph} - I_{D1} - I_{D2} - I_{sh}$$ Equation 3

Current through diodes in DDM is written as shown in Equation 4 and Equation 5.

$$I_{D1} = I_{01}(\exp\left(\frac{V_L+I_L R_s}{a_1 V_T}\right) - 1)$$ Equation 4

$$I_{D2} = I_{02}(\exp\left(\frac{V_L+I_L R_s}{a_2 V_T}\right) - 1)$$ Equation 5

Shunt resistance in DDM is calculated by the following Equation 6.

$$I_{sh} = \left(\frac{V_L+I_L R_s}{R_{sh}}\right)$$ Equation 6

A solar cell should be operated to get a maximum power obtain from short circuit current and open circuit voltage Afghan et al. (2017).

3. MPPT IN SOLAR PV SYSTEMS

Cost involving in converting light into energy and storage of converted energy consumes more and on the other side efficiency of the solar PV cells is somewhat poor. Partial shading also plays a major role in solar PV power production Aljafari et al. (2022), Satpathy et al. (2022), Kumar Pachauri et al. (2022), Wan et al. (2019), Aljafari et al. (2022), Yang et al. (2019), Mohammed et al. (2022), Suresh et al. (2022), Satpathy et al. (2022). So, proper tracking of incident light on the PV cells are most important to increase the efficiency of that particular cells is referred MPPT. MPPT is always trying to operate the solar PV systems in peak or values closer to the peak power from the incident radiation on solar cells under different environmental conditions. Considering current research scenario, lot of research activities going on in MPPT to track maximum power from the PV cells and increase the efficiency too. Different types of algorithms developed in recent times for MPPT available in literature Mohapatra et al. (2017).

This article gives a clear review and focused idea about different available MPPT algorithms in literature.

3.1. DIFFERENT TYPES OF MPPT ALGORITHMS

This chapter summarizes different algorithms developed for MPPT available in literature and gives a clear-cut idea to the new researchers in the field of MPPT optimization. Figure 6 illustrates the different types of MPPT available in literature for solar PV systems.

Figure 6

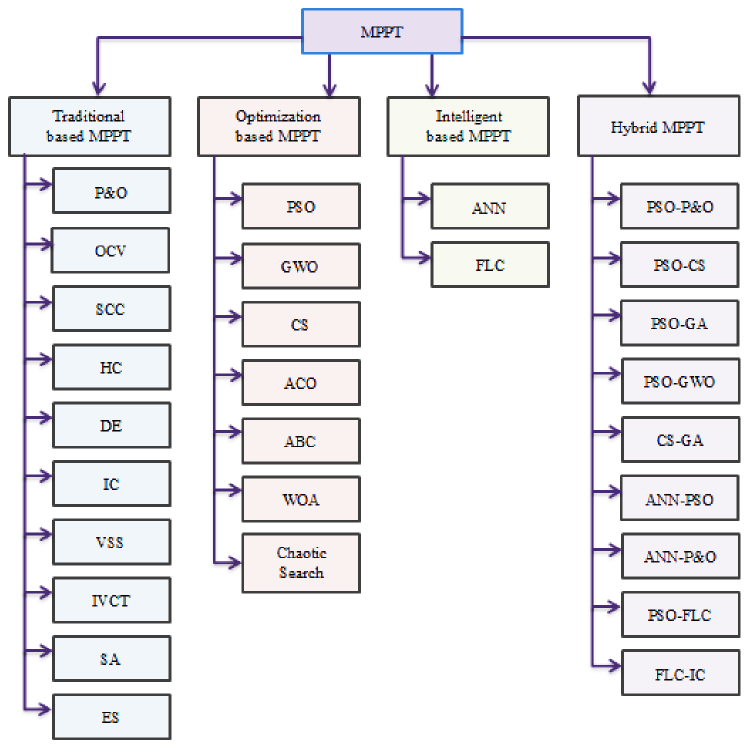

Figure 6 Different Types of MPPT Algorithms

3.1.1. TRADITIONAL ALGORITHMS

- perturb and observation (P&O)
- Open circuit voltage (OCV)
- Short circuit current (SCC)
- Hill Climbing (HC)
- Differential Evolution (DE)
- Incremental Conductance (IC)
- Variable step size (VSS)
- I-V curve tracer
- Simulated annealing (SA)
- Extremum seeking (ES)

3.1.2. OPTIMIZATION ALGORITHMS

- Particle swarm optimization (PSO)
- Grey wolf optimization (GWO)

- Cuckoo search (CS)
- Ant colony optimization (ACO)
- Artificial bee colony (ABC)
- Whale optimization algorithm (WOA)
- Firefly algorithm (FA)
- Chaotic search

3.1.3. INTELLIGENT ALGORITHMS

Poor response for rapid changes in solar irradiations and temperature are major drawbacks of conventional methods. To overcome these drawbacks intelligent based MPPT methods are developed to track global maximum power point (GMPP) and some of the methods are given below.

- Artificial neural network (ANN)
- Fuzzy logic controller (FLC)

3.1.4. HYBRID ALGORITHMS

- PSO-P&O
- PSO-CS
- PSO-GWO
- CS-GA
- ANN-PSO
- ANN-P&O
- PSO-FLC
- FLC-IC

4. TRADITIONAL MPPT ALGORITHMS

4.1. PERTURBATION AND OBSERVATION ALGORITHM

P&O algorithm perturbs operating voltage of a PV system to ensure maximum power from the varying incident radiation. In P&O algorithm, the output power from the solar PV module is continuously measured with respect to change the voltage to the solar PV module and compare currently measured power with previous one and input voltage gets increased or decreased according to the comparison result. Much research work has been carried out for the development of MPPT algorithm for solar PV models Patel (2013). The performance of the P&O MPPT algorithm is improved by controlling the electronic buck converter Villalva and E. R. (2019). The efficiency of the P&O MPPT can increase by optimization of sampling intervals based on dynamics of its converters Femia et al. (2014). A MPPT charge controlled for 200W standalone PV systems is developed using P&O algorithm and test the designed model with lead acid battery and showed that the proposed algorithm significantly improves the solar PV model while compared with other available charge controllers Salman and Wu (2018). An enhanced adaptive P&O MPPT algorithm for solar PV systems is proposed successfully to tracks global peak under different partial shading conditions, tracking speed is increased by 2 to 3 times and achieved more than 99% efficiency Ahmed and Salam (2018). A modified P&O MPPT algorithm for solar PV array is proposed and observed improvement in steady state and dynamic state response under various atmospheres conditions and verified the performance of proposed algorithm in simulation using Matlab/Simulink software Thakurta (2020), Zhao et al. (2021), Senniappan and Umapathy (2021). A modified P&O MPPT proposed for solar PV systems under partial shading conditions and found a significant improvement in accuracy and simple implementation Sarfo et al. (2020). The major drawbacks of P&O algorithm is failure in rapidly changing environmental conditions. Common flow chart for P&O algorithm is given Figure 7.

Figure 7

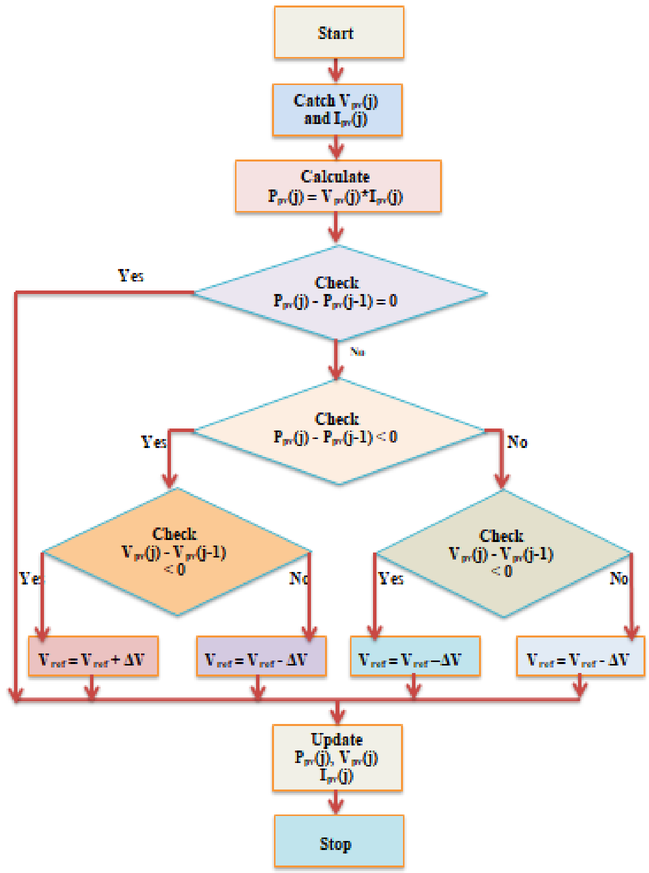

Figure 7 Flow Chart for Conventional P&O MPPT Algorithm

4.2. FRACTIONAL OPEN CIRCUIT VOLTAGE ALGORITHM

The basic idea behind in this algorithm is maximum power point of a solar PV models are proportional to open circuit voltage. Fractional open circuit voltage algorithm (FOCV) delivers an accurate Vmpp voltage estimation under different environmental irradiations and temperature, since Kv remains constants for all given conditions. The relationship between Vmmp and Voc are linear and mathematically written as shown in Equation 7 Baimel et al. (2019).

$$Vmpp = Kv*Voc \quad \text{Equation 7}$$

Here,

Vmpp = Volatage at MPP

Kv = Voltage factor constant normally in lies between 0.7 to 0.9.

Voc = open circuit voltage

In this method, a periodical sampling of open circuit voltage is done by quick removal of the load from the circuit. In order to get good accurate value for Vmpp, the frequency and duty cycle selected for this algorithm should be in higher value.

From the available literatures Bharath and Suresh (2017), Motahhir et al. (2019), Das (2016), Ahmad (2010). FOCV algorithm has many advantages when compare with other methods like P&O, IC, and HC are simple implementation and lower cost. The main drawback associated with this algorithm is sudden power loss due load disconnection. To overcome these drawbacks improved FOCV algorithms proposed and available in literatures Hmidet et al. (2021), Baroi and Sarker (2017).

4.3. FRACTIONAL SHORT CIRCUIT CURRENT

FSCC is working similar to FOCV, here the relation between current at MPP (Impp) and short circuit current (Isc) is linear and mathematically written as shown in Equation 8 Husain et al. (2017).

I_mpp=kI_sc Equation 8

Here,

k – Current factor constant normally in lies between 0.7 to 0.9.

FSCC have similar advantages of FOCV like easy design and low cost for implementation. But major drawback is measuring of Isc when the PV system in working is very difficult.

4.4. HILL CLIMBING ALGORITHM

HC is a MPPT algorithm with simple design and easy implementation since any mathematical model or studies are doesn't required, it uses duty cycle of the converter to find MPPT. Figure 8 shows the flow chart for HC MPPT algorithm.

Figure 8

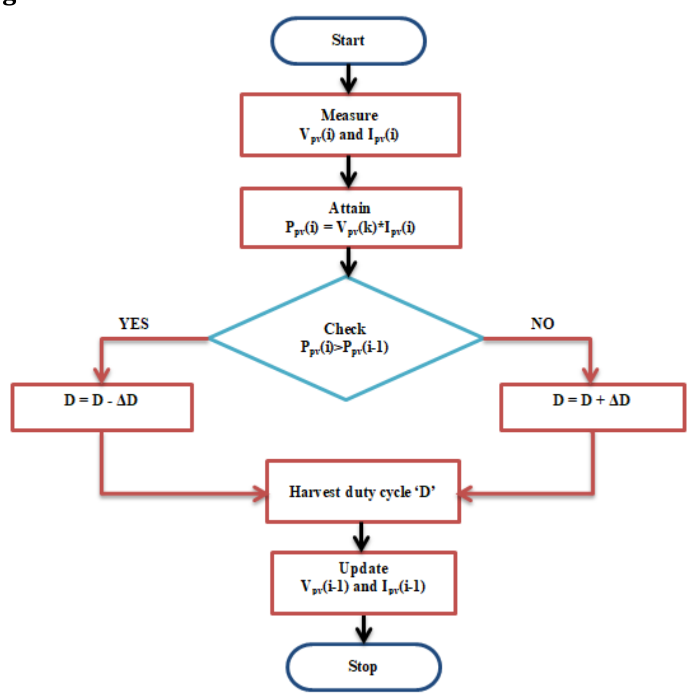

Figure 8 Flow Chart for HC MPPT Algorithm

Working of HC is as following Bahari et al. (2016), Jately et al. (2021).

1) Measuring the PV array voltage (Vpv(k)) and PV array current (Ipv(k)).
2) Now compare newly calculated Vpv(k) and Ipv(k) with latest iteration value.
3) Based on the comparison result, optimum pulse width modulation (PWM) is obtained.

The major negatives of HC algorithm are the adjustment between the PV systems is in a periodic of continuous solar radiation and can't able to response for a rapid changes in environmental conditions. To overcome these drawbacks some modified and enhanced HC MPPT algorithms available in literature Fapi et al. (2019), Kjær (2012).

4.5. DIFFERENTIAL EVOLUTION ALGORITHM

In 1995, Price and Storn suggest DE algorithm for problems with non-differentiable, non-linear and multi-dimensional and this algorithm utilized for MPPT in solar PV systems due to its non-linear behavior with different environmental conditions and this algorithm have benefits like simple design with good efficiency, only few parameters required for tuning. Normally four steps of optimization used in DE algorithm namely (a) initialization, (b) differential mutation (c) crossover and (d) selection Qing and Lee (2010), Tey et al. (2014). Flow chart for DE algorithm is shown in Figure 9.

Figure 9

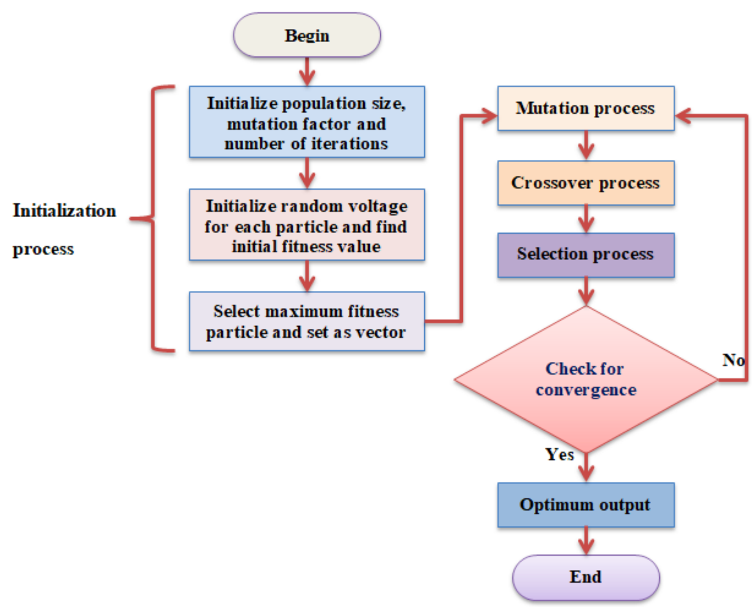

Figure 9 Flow Chart For DE Algorithm

4.6. INCREMENTAL CONDUCTANCE (IC) ALGORITHM

In this algorithm, maximum power point is determined from instantaneous rate of change in power with respect to input voltage to the solar PV module and performs a good job by covering large irradiations changes when compared with other algorithms like P&O. This algorithm contains more mathematical modeling equations and electrical component compare with some other algorithms Putri et al. (2015), Babaa et al. (2014), Safari and Mekhilef (2011), Shang et al. (2020). The main drawback of this conventional IC algorithm is that this algorithm does not provide an accurate respond when irradiation is changes. Solar PV systems are modelled with modified IC algorithm especially for rapid changes in solar irradiance. Simulation results of this modified IC algorithm are compared with conventional IC algorithm and suggested design provides better accuracy for sudden changes in environmental conditions Motahhir et al. (2018), Anowar and Roy (2019). An improved IC MPPT algorithm is developed to make improvement in efficiency and economy of solar PV models and simulated the developed system using Matlab/Simulink software. As a result, the developed model provides significant improvements in tracking efficiency and response time when compared with conventional IC MPPT algorithm Shang et al. (2020). An adaptive step size IC based MPPT is proposed; in this method step size is adaptively changed after completion of each iteration and achieves a fast convergence without affecting the value of accuracy Kim et al. (2020). Major drawback in this IC algorithm is increment and decrement of voltage is done manually by trial-and-error method. Figure 10 shows the flow chart for IC algorithm.

Figure 10

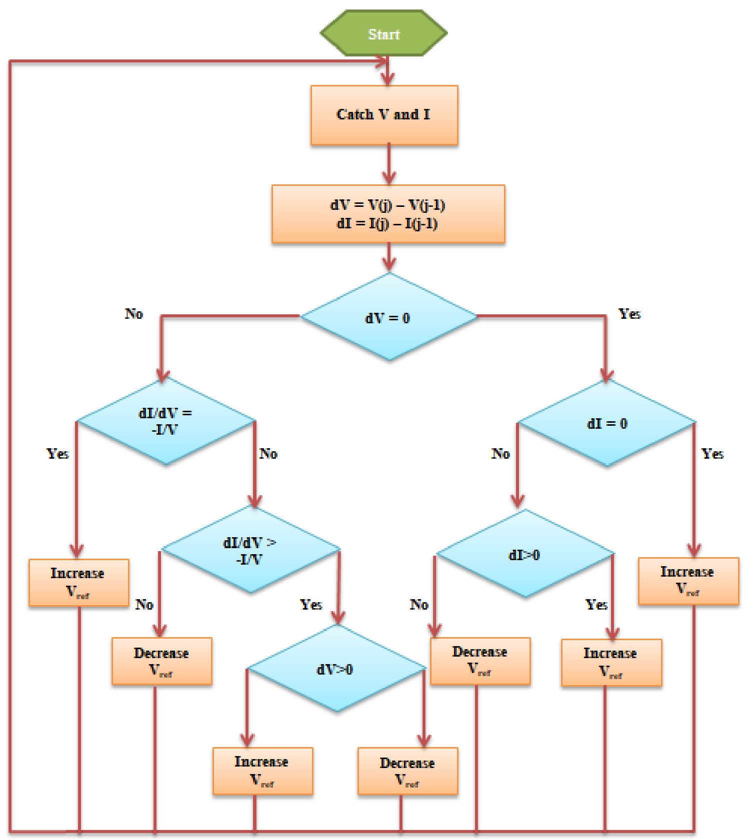

Figure 10 Flow Chart – IC Algorithm

4.7. VARIABLE STEP SIZE MPPT ALGORITHMS

Even conventional MPPT algorithms with fixed step size provides a better performance, have some setbacks like slower in convergence speed, exhibits oscillating behavior around maximum power point (MPP) and unsuccessful to find/track MPP under varying environmental conditions especially partial shading.

To achieve more speed, large step is needed but if step gets increased means steady state oscillations can't be avoided. Steady state oscillations can be reduced by reducing the step size, but system tracking speed gets slower down if step size gets reduced Messalti et al. (2017). Many research contributions available in literature to overcome these issues with the introduction of variable step size MPPT algorithms Hosseini et al. (2013), Alkhawaldeh and Bhuiya (2021), Liu et al. (2008), Tian et al. (2014), Husain et al. (2017), Chuang et al. (2020), Suntio and Kuperman (2019), Kumar et al. (2019), in which step size is regularly changed according to the environmental conditions and provides a simple and quick response with low oscillations. The step size of this method is mathematically written as shown in Equation 9 and Equation 10.

$$D(i) = D(i-1) \pm N * d_{pv} \qquad \text{Equation 9}$$

$$d_{pv} = P(i) - P(i-1) \qquad \text{Equation 10}$$

Where,

D(i) – Duty cycle of iteration i

D(i-1) – Duty cycle of iteration i-1

N – Scaling factor

dpv – PV output power

An enhanced VSS incremental resistance MPPT for solar systems is proposed, in which the benefits of INC and automatic changes in step size with respect to solar irradiations to track MPP of the PV systems are utilized. And also, the performance of proposed algorithm is verified with simulation as well as experimental setup with dc boost converter and observed a good performance in steady state and dynamic states on a wide range of operating points Mei et al. (2011).

4.8. I-V CURVE TRACER ALGORITHM

This type of MPPT algorithm utilizes I-V curves of solar PV systems to track the MPP accurately with low cost of design. Here I-V characteristics of solar PV is captured by I-V curve tracer mechanism under different environmental conditions and evaluate the generated power from PV panel and also used to find fault conditions. This mechanism provides a good accuracy with quick convergence time. This I-V curve tracer mechanism has three parts Zhu and Xiao (2020) namely (a) Data acquisition system which sense current and voltage from the solar PV panel (b) Power conditioner which is used to capture full I-V characteristics of solar PV and (c) Control strategy is used for controlling the power conditioning. Different types of methods used in I-V curve trace MPPT algorithm is listed below

Capacitance load I-V curve trace method Spertino et al. (2015), Chen et al. (2020)

Variable resistive load I-V curve trace method Willoughby et al. (2014)

Electronic load I-V curve trace method Willoughby and Osinowo (2018)

DC-DC converter type I-V curve trace method Pereira et al. (2021)

Four-quadrant power supply based I-V curve trace method Zhu and Xiao (2020)

4.9. SIMULATED ANNEALING ALGORITHM

Optimum solution to a problem finds out from SA algorithm by the process of annealing in metals i.e cooling the metals under control to pursued out minimum energy Lyden and Haque (2016), Nishat et al. (2019). SA algorithm used to find out GMPP instead of local MPP with global searching characteristics. The requirements of SA algorithm are initial and final temperature and cooling rate. SA algorithm performs operations on each operating voltage and measure power corresponding to each operating voltage. Obtained power is compared with reference power; obtained power is high means it will be acted as a new operating point.

The probability of acceptance is written in the following Equation 11 Lyden and Haque (2016).

$$P_A = \exp\left(\frac{P_i - P_j}{T_c}\right) \quad \text{Equation 11}$$

Where,

Pi – Current power

Pj – Previous best power

Tc – Current temperature

Cooling schedule for SA algorithm is written as shown in Equation 12

$$T_c = \alpha T_{c-1} \quad \text{Equation 12}$$

Where

α – Constant

Following steps have to be used in SA algorithm

Step 1: Initialization of cooling rate, size, initial and final temperature

Step 2: Random voltage selection Vj

Step 3: Calculate power Pj corresponding to Vj

Step 4: If temperature is higher that threshold (Tmin), then following steps have to be followed

1) Random voltage selection Vi
2) Power calculation (Pi) for Vi
3) If Pi>Pj, Vi will be the new operating point ie (Vj = Vi)
4) Else, agree the working point from Equation 12.

Flow chart for SA algorithm is given Figure 11.

Figure 11

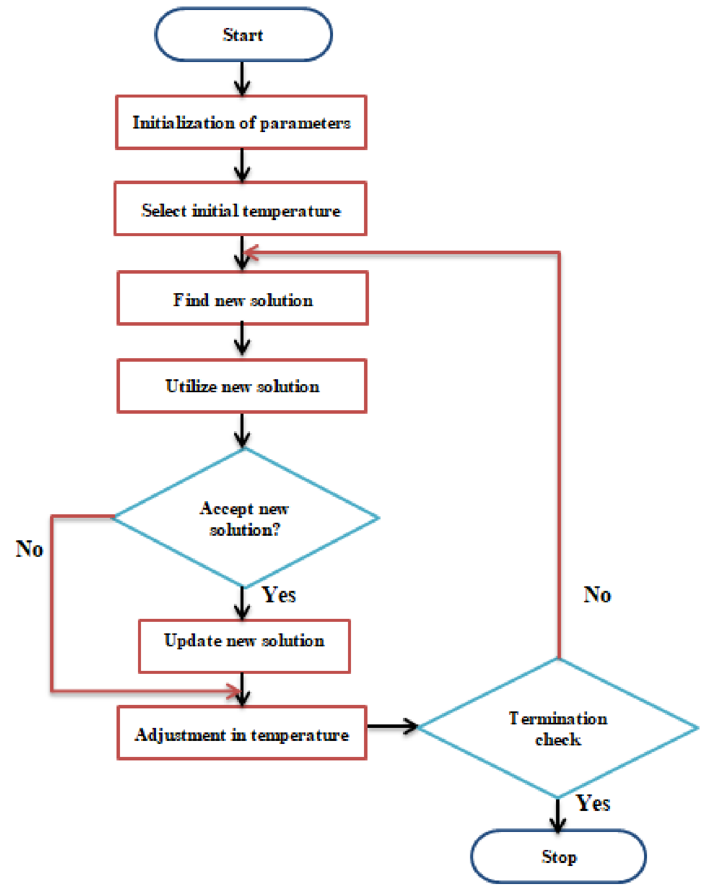

Figure 11 Flow Chart for SA Algorithm

4.10. EXTREMUM-SEEKING ALGORITHM

Leblanc proposed ES control technique to an electromechanical system for searching resonance peak value. The working principle of ES algorithm in solar PV array is with varying the terminal voltage force the system to attain MPP Leyva et al. (2006). As many as works are available in literature Leyva et al. (2006), Li et al. (2014), Yau and Wu (2011), Kirubasankar and Senthilkumar (2015), Hu et al. (2019) and find the following observations from this method. ES exhibits good enactment than other existing conventional methods in literature like HC method, track the Pmpp quickly when compared with artificial based methods and provide a good performance under dynamic locations of environment. Another highlight of this algorithm is, in steady state the oscillations around MPP is almost negligible Sajadian et al. (2018).

5. OPTIMIZATION BASED MPPT ALGORITHMS

5.1. PARTICLE SWARM OPTIMIZATION

PSO provides an optimized solution to a problem by iteration method to get a better solution with high tracking speed and operated in different weather conditions. PSO have good capability to find global optimal solution, system independency, few tuning parameters and good computational efficiency without any complicate derivative mathematical calculations. The working principle of PSO algorithm is depicted in Figure 12.

Figure 12

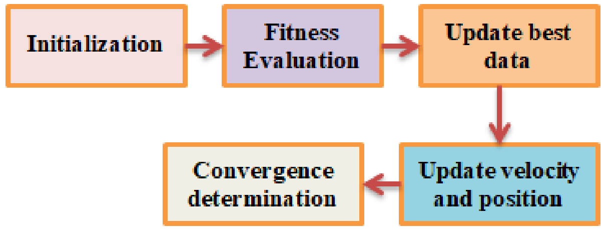

Figure 12 Working Principle of PSO Algorithm

A detailed review on PSO algorithm MPPT in solar PV systems are provided and analysis-based criteria's like convergence speed, search space, initial parameters, efficiency and performance of the system with and without partial shading conditions Díaz Martínez et al. (2021). Conventional PSO based MPPT have weakness in high convergence and some oscillations while searching is takes place. In order to overcome these issues some advance/improved PSO has been developed in recent years. A novel MPPT for solar PV systems is presented using PSO algorithm and simulate this algorithm using Matlab/Simulink software and compared the results with P&O, IC method and concluded that the proposed algorithm provides fast tracking and stability over rapid change in environmental conditions Koad et al. (2017). A novel 2-stage PSO for MPPT control of solar PV systems is suggested using buck converter obtained a higher power when compared with conventional P&Oand PSO algorithms Mao et al. (2017). An improved PSO based MPPT for solar PV systems are available in literature and simulate the suggested algorithm using Matlab/Simulink and the observed performance was better than other methods Abdulkadir et al. (2014), Ishaque et al. (2012), Obukhov et al. (2020).

5.6. GREY WOLF OPTIMIZATION ALGORITHM

Hunting nature of Grey wolfs is considered in GWO algorithm. A GWO based MPPT algorithm is developed with single ended primary-inductor converter for solar PV systems and simulated in Matlab/Simulink software, obtained results prove that fast response and improvement in performance of steady state Atici et al. (2019). Figure 13 depicts the flow chart for GWO algorithm. Two different algorithms namely PSO and GWO are considered to track maximum power from the solar PV model under shading areas. The mentioned algorithms were tested in Matlab/Simulink software to measure the performance of the PSO and GWO algorithms Kraiem et al. (2021). A MPPT design of solar PV systems is offered using GWO algorithm to overcome some limitations in P&O algorithm such as oscillations in steady state, tracking efficiency and transients in partial shading conditions and concluded that the proposed model provides a good results in MPT when compared other two mentioned algorithms Mohanty et al. (2016). An enhanced GWO is projected to track maximum from a solar PV system under partial shaded conditions. The proposed algorithm track the maximum power with good accuracy and reduced computational time compared with other mentioned algorithms Cherukuri and Rayapudi (2017). Two new MPPT algorithms for solar PV systems are suggested namely WOA and GWO. The newly developed algorithms provide a better performance than other conventional methods in terms of ripple, overshoot and response time Abderrahim et al. (2021), Senthilkumar et al. (2022).

Figure 13

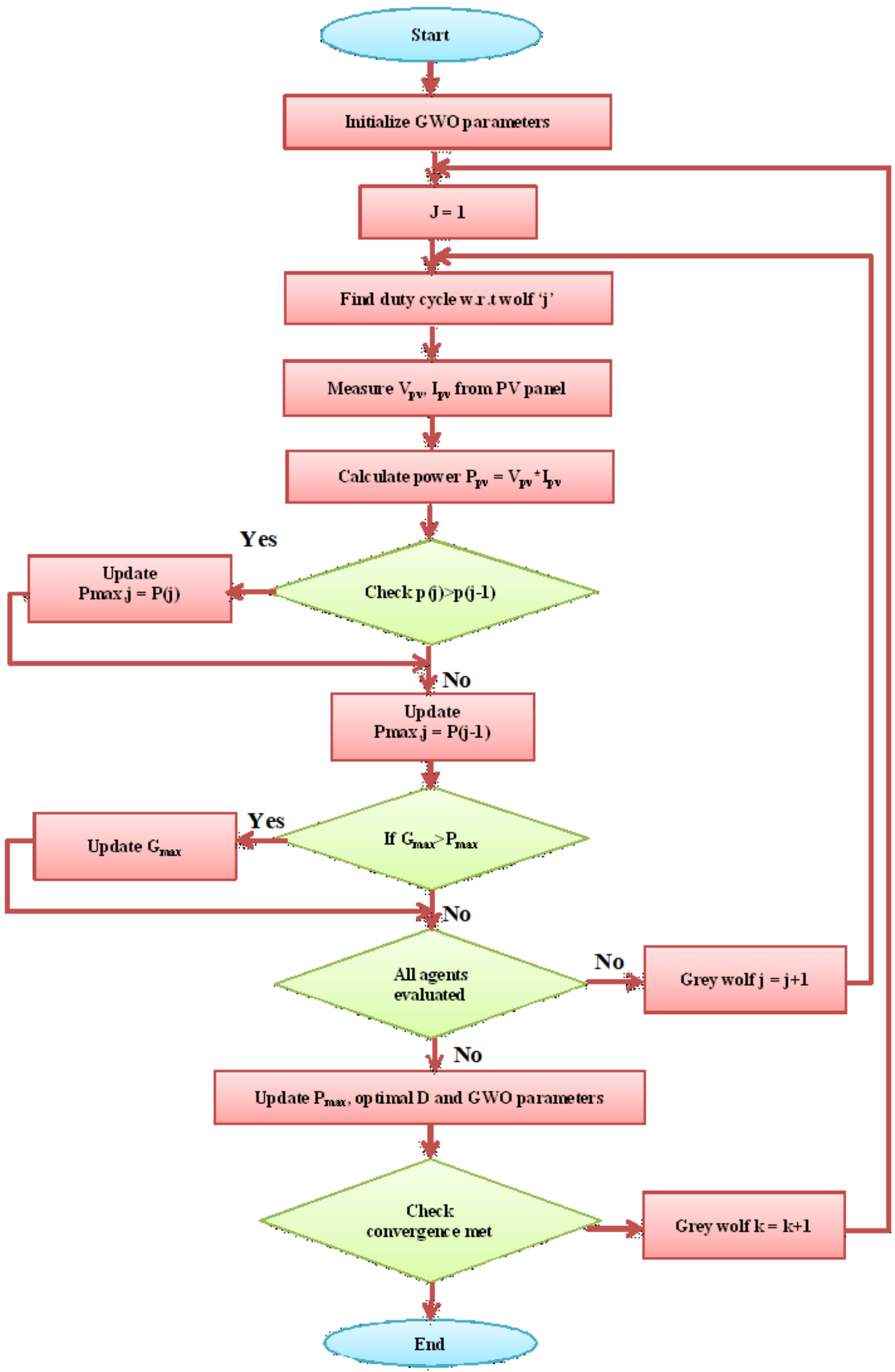

Figure 13 Flow Chart for GWO Algorithm

5.3. CUCKOO SEARCH ALGORITHM

Yang and Deb proposed CS algorithm from the inspiration of cuckoo bird's characteristics as a metaheuristic algorithm. Cuckoos used other bird's best nest for lay their eggs in a good position for new generation of cuckoos. Flow chart for CS algorithm is showed in Figure 14.

Figure 14

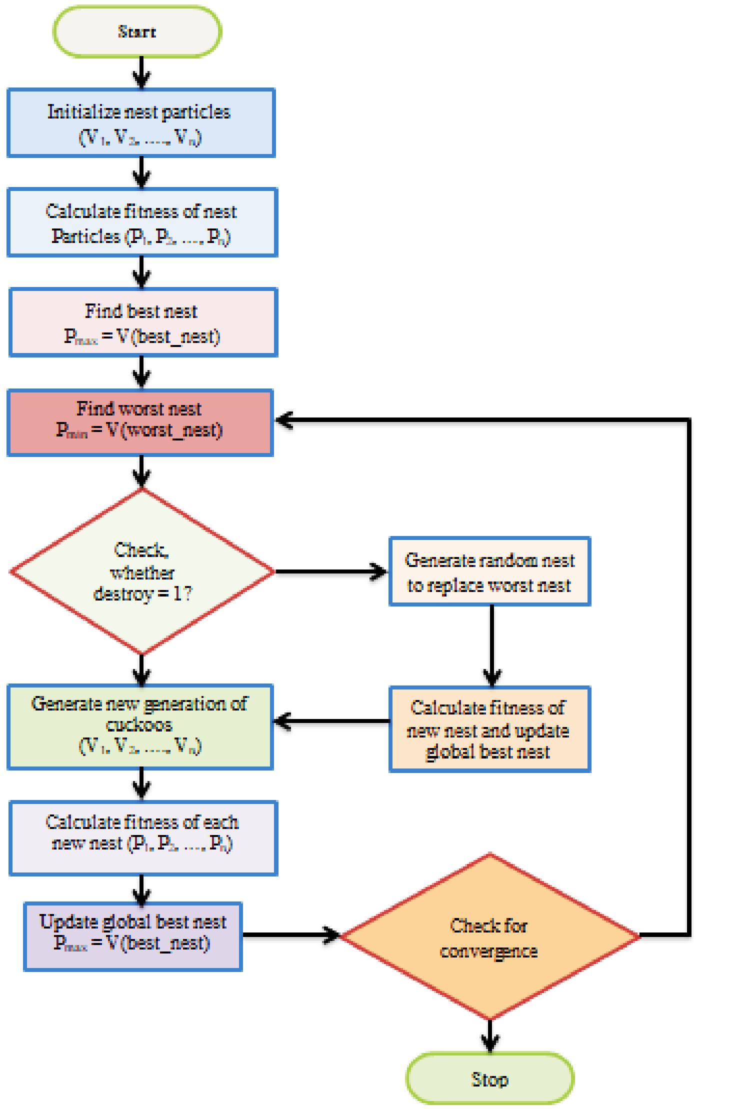

Figure 14 Flow Chart for CS Algorithm

Implementation of CS algorithm is based on the following three rules Nugraha et al. (2019), Mosaad (2019), Shi et al. (2016), Gude et al. (2022).

1) Each and every cuckoo will lay only one eggs in a randomly selected other bird's nest.
2) The nets with good quality eggs (best solution) will take cuckoo birds into next generation.
3) Due to only fixed number of availability of nests, the probability for host bird to discover the cuckoo bird egg is Pc, where $0 \leq Pc \leq 1$.

The assumption needs to be made in CS algorithm is that each and every egg available in host nest is a solution and a new solution is represented by cuckoo's egg available in that particular nest.

CS has many advantages like global convergence and optimum solution, simple implementation and easily hybridized with other algorithms based on swarm Kaur and Jaryal (2019).

5.4. ANT COLONY OPTIMIZATION ALGORITHM (ACO)

ACO algorithm is introduced in the year of 1991 based on real behavior of ants for searching their foods from their colony by means of shortest path using pheromone trial is a chemical responds from same species of members. Lot of research works available in literature on ACO based MPPT algorithm for solar systems under partial shading conditions Rajalashmi and Monisha (2018), Sridhar et al. (2016). The pheromone path thickness gets increased when more ants follow the same path and if another shortest path identified means current pheromone starts to disappear. The working procedure for this algorithm is given below Pathy et al. (2019).

Step 1: Initialization of ants and evaluation of random solutions

Step 2: Fitness evaluation

Step 3: Find new solution

Step 4: Check for global best position

Step 5: Update pheromone trail

Step 6: Check whether termination condition reached or not

Step 7: If condition is true, current position is global best solution, else go to step 3.

Formula to find pheromone concentration is written as

$$Pi = \rho Pi(k-1) + \Delta Pi \quad \text{Equation 13}$$

Where,

Pi = Revised pheromone concentration

ρ = Pheromone concentration rate

ΔPi = Pheromone concentration change

k = 1,2,3,..,T.

ACO algorithm nicely tracks the global maximum point for MPPT with high computational speed within less iteration Sahoo et al. (2017).

5.5. ARTIFICIAL BEE COLONY ALGORITHM

ABC is a swarm based stochastic algorithm developed to solve multimode and multidimensional problems based on honeybee characteristics of food searching and have advantage that convergence not depends on initial conditions Baba et al. (2020). In this algorithm, three types of bees are used namely employed bees for searching food source, onlooker bees for decision making and scout bees for improving food sources by number of trails Verma et al. (2021), Motahhir et al. (2020), Gonzalez-Castano et al. (2021). In this algorithm, communication between bees takes place through pheromone and joggle dance. Steps have to be followed to track GMPP in ABC algorithms are Hassan et al. (2017).

Step 1: Initialization phase

Step 2: Employed bee phase

Step 3: Onlooker bee phase

Step 4: Scout bee phase

Step 5: Conclusion phase

In the final conclusion step, the ABC process ends if there is no change in output power otherwise the process continued from step 1 until reach a steady output power. The changes in solar insolation is represented by the following Equation 14.

$$\left|\frac{P_{pv}-P_{pv,old}}{P_{pv,old}}\right| \geq \Delta P_{pv} \times 100\ \% \qquad \text{Equation 14}$$

5.6. WHALE OPTIMIZATION ALGORITHM

WOA is proposed in 2016 from inspiration of hunting behaviour of Humback Whales and provide better optimization solutions to non-linear problems Mirjalili and Lewis (2016). Recently many research works available in literature on WOA Ebrahim et al. (2019), Elazab et al. (2017), Diab (2020), Helal et al. (2019), Salgotra et al. (2019). The biggest Whale in the world is Humback Whale and it uses a special chasing method for bubble-net feeding. Preys are enclosed by Humback Whales during the progression of hunting. Two phases of process used in this method for searching best solution namely exploration and exploitation. Search space is explored globally in exploration phase in two steps namely encircle a prey and bubble-net attacking. The flow chart for WOA algorithm is given in Figure 15. Mathematically encircle of a prey is written as shown in Equation 15, Equation 16, Equation 17, Equation 18.

Figure 15

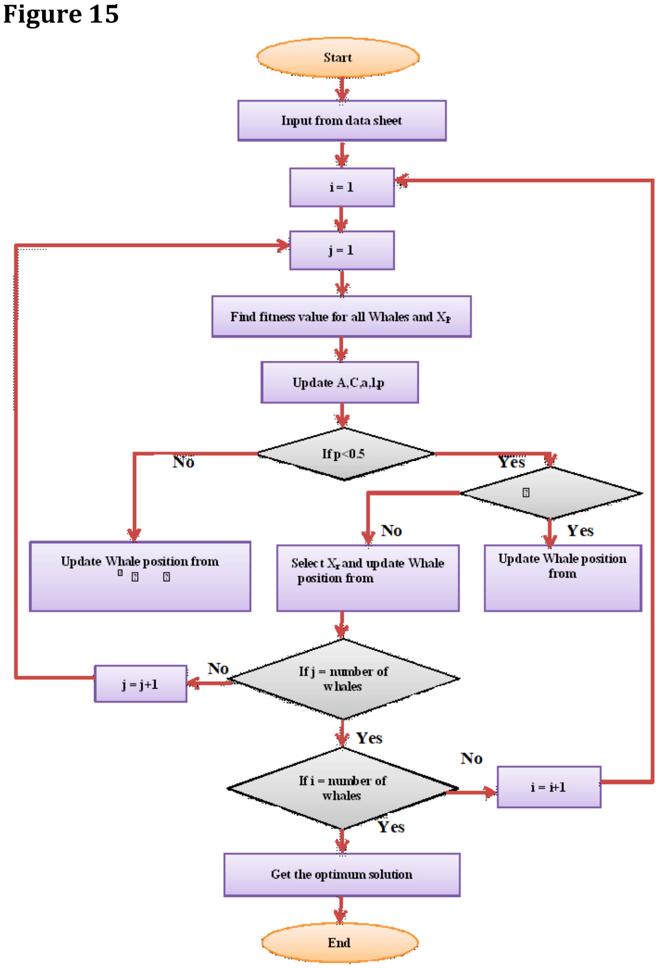

Figure 15 Flow Chart for Woa MPPT Algorithm

$P = |C.X(t) - X(t)|$ Equation 15

$X(t+1) = X^*(t) - A.P$ Equation 16

$A = 2m * r - m$ Equation 17

$C = 2 * r$ Equation 18

Where,

A,C	- Coefficient vector
t	- Current iteration
X*	- Best solution position vector
X	- Position vector
m	- Variable linearity
r	- Random number between 0 and 1

The spiral position of Whale is written as shown in Equation 19

$X(t) = \{P.e^{bl}.\cos(2\pi l) + X^*(t)\}$ Equation 19

Here

b	- Constant
l	- Random number between -1 to 1

The updated position of bubble-net attacking is written as shown in Equation 20

$$X(t) = \begin{cases} X^*(t) - A.P & if\ p < 0.5 \\ P.e^{bl}.\cos(2\pi l) + X^*(t) & if\ p > 0.5 \end{cases}$$ Equation 20

p - Random number between 0 to 1

Now the optimum solution is mathematically written from exploitation phase as shown in Equation 21 and Equation 22.

$P = |C.X_r - X|$ Equation 21

$X(t+1) = X_r - A.P \qquad A > 1\ for\ exploration$ Equation 22

WOA have many advantages like fast tracking in partial shaded conditions, easy implementation and quick convergence without oscillations in the output Maniraj and Peer Fathima (2020).

5.7. FIREFLY ALGORITHM

The fast, robust, flexible and low cost FA was introduced by Yang in 2007, working in accordance with attraction between two fireflies based on their brightness. In FA, optimization process is completed based on the optimum position finding from fireflies movements. Three idealized steps have to be followed in FA algorithm

1) Unisex fireflies have to be considered, and then only attraction between the fireflies takes place.
2) The firefly attraction is proportional to their brightness.
3) An objective function has to be used to find brightness of firefly.

By considering FA for PV systems, voltage and current of PV is represented by firefly position, PV power is represented by brightness and global maximum power is represented by brightness of brightest firefly Zhang et al. (2019).

Firefly attraction is mathematically written as shown in Equation 23

$$\beta = \beta_0 e^{-\gamma r^2} \quad \text{Equation 23}$$

Where,

r – Distance between two fireflies

β_0 – Initial attraction

γ – Absorption coefficient (Lies between 0.1 to 1)

And Cartesian distance is find out from the following Equation 24 and Equation 25

$$r_{ij} = \left|\left|x_i - x_j\right|\right| \quad \text{Equation 24}$$

$$= \sqrt{\sum_{k=1}^{d}(x_{i,k} - x_{j,k})^2} \quad \text{Equation 25}$$

Where

d – Dimension number

$x_{i,k}$,$x_{j,k}$– k – component of spatial coordinator of ith and jth firefly.

The movement of firefly i attracted to another brighter firefly j is written as shown in Equation 26

$$x_i(t+1) = x_i(t) + \beta\left[x_j(t) - x_i(t)\right] + \alpha(rand - \tfrac{1}{2}) \quad \text{Equation 26}$$

Where,

rand – random number [0,1]

α € [0,1]

$x_i(t)$– ith firefly position

$x_j(t)$– jth firefly position

$x_i(t+1)$– New position of ith firefly

Much research works available in FA algorithm Palupi et al. (2020), Dhivyaand Kumar (2017), Mohanty et al. (2019), Sundareswaran et al. (2014), Goswami and Kumar Sadhu (2020) and confirmed the above said positives of this algorithm.

5.8. CHAOTIC SEARCH ALGORITHM

It is a phenomenon used for complex non-linear problems and has good characteristics like ergodicity, regularity and randomicity. Here first two characteristics provide chaos can go non-repetitively over each state in an assured area. The sensitivity and initial conditions are represented by randomicity Wang et al. (2014). Working of this algorithm has three steps. (a). In first step, chaos variable is produced by single carrier. (b). in second step, chaos variable is transformed into solution space from chaos space. (c). in last step, optimum solution is find out from chaos characteristics namely ergodicity, regularity and randomicity. The traditional chaos search algorithm has some drawbacks. Searching ability is poor since it uses only one carrier and it will take more time to find MPP Piccirillo et al. (2009). To overcome these drawbacks some new articles available in literature with two stage carrier and obtained an improvement in efficiency when compared with conventional chaos search algorithm. Normally logistic mapping method is used to create chaos variable and mathematically written as shown in Equation 26

$$p_{i+1} = \mu p_i(1 - p_i), \quad i = 1,2,3, \ldots \qquad \text{Equation 27}$$

Here μ – Control parameter

6. INTELLIGENT MPPT ALGORITHMS

6.1. ARTIFICIAL NEURAL NETWORK

Main objective of ANN is to provide a new duty cycle value even for a small change in solar irradiations and temperature to get MPP with training from Levenberg-Marquardt algorithm without any mathematical modeling for complex and non-linear problems Jyothy and Sindhu (2018). ANN with Levenberg-Marquardt algorithm trained from 1000 datasheets with two layer networks and exhibits a better performance Roy et al. (2021). An ANN algorithm with three layer network to track maximum voltage from solar PV panel is suggested Ocran et al. (2005), Sedaghati et al. (2012), Suganya et al. (2014) without voltage sensors, current sensors, and complex mathematical calculations and got higher efficiency. A cascading two layer ANN is proposed Sherif and Seshadri (2018) to track MPP from solar PV with an assumption of 10 neurons per layer and duty cycle generated from binary outputs are responsible for switching operations of inverter Chitrakala et al. (2017), Mohan et al. (2017), Krithiga and Mohan (2022), Sivamani and Mohan (2022), Chitrakala et al. (2017).

6.2. FUZZY LOGIC ALGORITHM

To handle the systems with non-precision inputs and non-linearity's, fuzzy logic is a suitable method. In fuzzy logic, an accurate mathematical modeling is not necessary one and this method is fast and quickly response to rapid changes in atmosphere. In this method PV current and voltage are inputs and duty cycle will be the output and membership functions are determined by on controller accuracy level usually 5 to 7 Canny and Yusivar (2018). Three stages namely fuzzification, rule evaluation and defuzzifications are used in this method Rezk et al. (2019). The basic fuzzy logic controller block diagram is given Figure 16 Dabboussi et al. (2020).

Figure 16

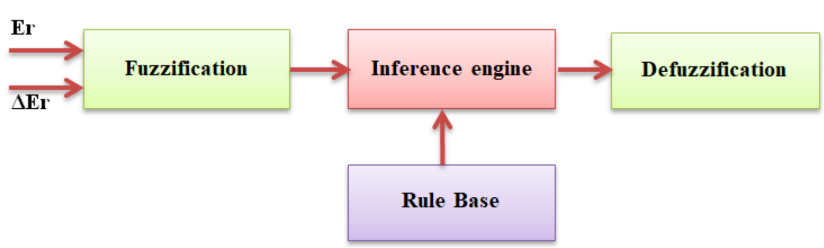

Figure 16 Block diagram of FLC

In fuzzy logic, error and change in error are inputs and change in reference voltage (duty cycle) will be the output Corcau and Dinca (2019). Error, output power, change in error and change in reference voltage are written in Equation 28 Equation 29, Equation 30, and Equation 31 respectively.

$$Er = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \qquad \text{Equation 28}$$

$P(k) = V(k) * I(k)$ Equation 29

$\Delta Er = Er(k) - Er(k-1)$ Equation 30

$\Delta V = V(k) - V(k-1)$ Equation 31

Where,

Er – error

P(k) – output power

V(k) – output voltage

ΔEr – change in error

ΔV – change in output voltage

Basic working principle of fuzzy logic algorithm is described in Figure 17.

Figure 17

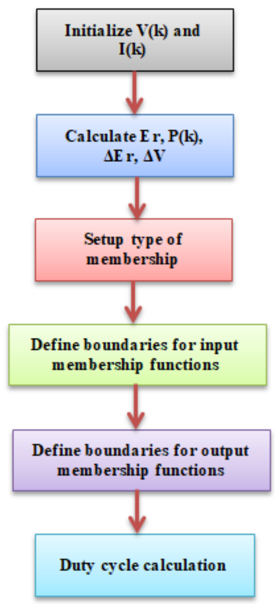

Figure 17 Flow Chart for FL Based MPPT Algorithm

A FL based MPPT algorithm is proposed for standalone PV solar systems under different atmosphere and load conditions with a PI controller and simulated the proposed system with Matlab/Simulink software. The proposed algorithm effectively solves instability in system voltage under different environmental conditions with an accuracy about 95.5% to 99.5% Fapi et al. (2019) The main setback of FL is rules can't be reformed, once it is well-defined. The overall performance comparison of different MPPT algorithms is summarized in Table 2.

Table 2

Table 2 Performance Comparison of Different MPPT Algorithms

MPPT algorithm	References	Efficiency	Accuracy	Complexity	Tracking speed	Implementation	Ability of tracking in partial shading
P&O	[13,14,154].	>95%	Medium	Low	Medium	Easy	No
Open circuit voltage	[10]	<90%	Low	Low	Medium	Easy	No

Short circuit current		<90%	Low	Low	Medium	Easy	No
Differential Evolution		>98%	Medium	Medium	Fast	Easy	Yes
Incremental Conductance		97%	Medium	Medium	Medium	Easy	No
PSO		>98%	High	Medium	Fast	Medium	Yes
GWO	[95]	>99.5%	High	Medium	Fast	Fast	Yes
CS	[109,155,156]	>99%	High	Medium	Fast	Easy	Yes
ACO	[10]	>98.5%	High	Medium	Fast	Medium	Yes
ABC		>99%	High	Medium	Fast	Medium	Yes
WOA	[128,157]	>99.95%	High	Low	Fast	Easy	Yes
GA	[10]	>98%	Medium	Medium	Fast	Easy	Yes
FA		>98.5%	High	Medium	Fast	Medium	Yes
ANN		>98%	Medium	High	Fast	Difficult	Yes
FLC		>98%	Medium	Medium	Fast	Medium	Yes

7. HYBRID MPPT ALGORITHMS

In previous section, several MPPT techniques presented with their merits and demerits. If two algorithms combined together, the benefits of individual algorithms gets combined and results in improvement of efficiency, tracking speed, reduced oscillations, power loss and less convergence time. Several hybrid MPPT algorithms available in literature like hybrid PSO-CS, PSO-P&O, WOA-SA, PSO – SA, GWO-P&O and SA-P&O etc., In this section, a hybrid PSO-CS MPPT algorithm is reviewed in details.

7.1. HYBRID PSO-CS

PSO-CS is used to solve complicated non-linear optimization problems by combining the PSO iteration strategy and CS searching technique Ding et al. (2019) [158]. Figure 18 explains the flow chart of PSO-CS hybrid MPPT algorithm. In this hybrid method, optimization problem is decomposed into a number of sub-components, which are enhanced by regular CS method Wang et al. (2015) . In order to expand the performance of PSO algorithm, random search in PSO is replaced by Levy frights and modified/improved PSO is called PSO-CS (hybrid) algorithm. In this algorithm, searching is done by random 1, random 2, w1c1 and w2c2 values are fixed. In this method length of random step is varied by Levy flight. Velocity and position functions of PSO-CS algorithm is written as shown in Equation 32 and Equation 33.

$$v_{ij}(t) = w \times v_{ij}(t) + \left(c_1 \oplus Levy(\lambda)\right) \times \left[P_{bestij}(t) - x_{ij}(t)\right] + \left(c_2 \oplus Levy(\lambda)\right) \times \left[G_{bestij}(t) - x_{ij}(t)\right] \quad \text{Equation 32}$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \quad \text{Equation 33}$$

Here, the hybrid PSO-CS provides great consistency and efficiency than PSO and CS algorithms from the findings of global optimal solution to non-linear problems. All the works available in literature confirms that hybrid PSO-CS exhibits a better performance like convergence speed, accuracy, and efficiency than PSO and CS algorithms Prajapati and Shah (2018), Ibrahim and Mohammed (2017), Senthilkumar et al. (2023), Krithiga et al. (2023).

Figure 18

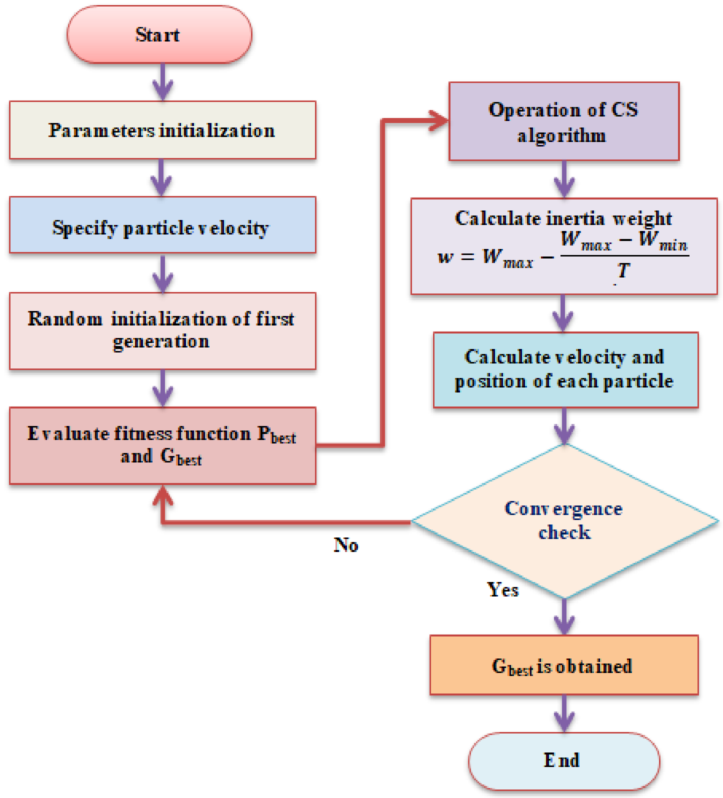

Figure 18 Hybrid PSO-CS

8. MAJOR CHALLENGES AND ISSUES OF SOLAR PV SYSTEMS

Some of the major challenges in solar PV systems are listed below

- Irregular availability
- Installation cost is high
- Required more area for installation
- Conversion efficiency is poor
- Proper trapping of incident light under partial shaded condition

9. CONCLUSION AND FUTURE WORK

In this article, a detailed review was conducted on different types of MPPT techniques available in literature. First, classification of MPPT techniques was presented. Then based on the characteristics like implementation, accuracy, tracking speed, cost, merits and demerits of MPPT algorithms are reviewed and summarized clearly. From this conducted review it is found that swarm based optimization MPPT methods like, PSO, GWO, and CS etc., have a better performance with respect to tracking speed, accuracy and searching ability than other methods. Finally few hybrid methods are discussed which have benefits of two methods. This review article will provide a clear idea for researchers in the field of MPPT methods.

In future, wide range of scope for integrating the solar PV MPPT algorithms with internet of things technology for proper tracking of incident light under partial shaded conditions.

CONFLICT OF INTERESTS

None.

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None.

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APPENDIX I

S. No.	Abbreviation	Description
	a	Diode ideality factor
	ABC	Artificial bee colony
	ACO	Ant colony optimization
	ANN	Artificial neural network
	CS	Cuckoo Search
	DDM	Double Diode Model
	DE	Differential Evolution
	ES	Extremum seeking
	FA	Firefly algorithm
	FLC	Fuzzy logic controller
	FOCV	Fractional open circuit voltage algorithm
	GMPP	Global maximum power point
	GWO	Grey Wolf Optimization
	HC	Hill Climbing
	IC	Incremental Conductance
	I_d	Diode saturation current
	I_{mp}	Current at maximum power
	I_{pv}	Photovoltaic current
	I_{sc}	Short circuit current
	MPP	maximum power point
	MPPT	Maximum Power Point Tracking
	OCV	Open Circuit Voltage
	P&O	Perturb And Observation
	PSO	Particle Swarm Optimization

PV	Photovoltaic
PWM	Pulse Width Modulation
R_s	Series resistance
R_{sh}	Shunt resistance
SA	Simulated annealin
SCC	Short Circuit Current
SDM	Single Diode Model
TDM	Triple Diode Model
V_{mp}	Voltage at maximum power
V_{oc}	Open circuit voltage
VSS	Variable step size
WOA	Whale optimization algorithm