Survey and Classification of Hybrid GMPPT Techniques for Photovoltaic System under Partial Shading Conditions

Faiza Belhachat and Cherif Larbes

Abstract−A maximum power point tracking process is a very important task to harvest the maximum power available from a photovoltaic generator. For this reason, resorting to the development of new and more effective methods is an absolute necessity. Numerous advanced methods have been successfully employed to extract the real maximum point, such as neural networks and metaheuristic techniques. These techniques deal effectively in such conditions. However, the use of the algorithm alone has some limitations. In order to solve these drawbacks, the combination of two or more different techniques provides more advantages over single MPPT algorithms and improves the performance of the overall system. This paper mainly focus in reviewing the most important and recent hybrid global MPPT techniques proposed in the literature and proposes a classification of these methods with a comparison of their performances. All surveyed hybrid GMPPT methods are divided into four categories according to algorithms types involved in the MPPT method. This review study intends to make it easier for the user to make the convenient selection of which method to adopt especially in the presence of a variety of methods which are continuously developing in the literature.

***Keywords*− Photovoltaic, Hybrid, conventional algorithms, soft computing algorithms, GMPPT, Partial shading.**

NOMENCLATURE

PV	Photovoltaic.
PSC	Partial shading conditions.
HGMPPT	Hybrid Global Maximum Power Point Tracking.

I. INTRODUCTION

Partial shading (PS) causes significant reduction in power production in photovoltaic (PV) systems. The reduced effectiveness of partially shaded photovoltaic arrays is still a big barrier in front of the fast development of photovoltaic energy systems. Thus, reducing the mismatch of the output power and the partial shading effects is a primary task.

Extracting the maximum power from partially shaded photovoltaic array has been extensively studied in the literature. The negative effects of partial shadings can be resolved through different techniques. The most frequently used techniques to reduce the impact of partial shading are: bypass diode insertion to prevent PV cells from hotspot, PV system architecture, configurations and reconfiguration PV array schemes and maximum power point tracking (MPPT).

The maximum power point tracking strategy is considered a necessary means to gain the maximum energy in photovoltaic (PV) systems.

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In fact, conventional methods have been widely used to extract the MPP, such as the P&O and INC algorithms. These algorithms work well under normal climatic conditions and find the MPP without difficulty since there is only one maximum. Nevertheless, the presence or the occurrence of the phenomenon of shading causes several maximum peaks in the characteristics of the PV module, which complicates the tracking task, therefore the need for the development of more efficient techniques able to differentiate the real maximum among the local maximums.

Partial shading in PV array makes conventional MPPT inefficient.

Different techniques GMPPT have already been developed in literature aiming to track in effective way the global maximum power point (MPP) under PS conditions.

In recent years, the application of bio-inspired and soft computing algorithms has been widely used thanks to their high efficiency in dealing with the problem of extracting the maximum power whatever the climatic operating conditions [1-2],[4], [6]. However, the use of the algorithm alone has some limitations which leads us to look for other more efficient algorithms.

In order to improve the performance of the algorithm and therefore the efficiency and yield of the whole system, the mixture of two or more algorithms makes it possible to increase them considerably since the disadvantage of an algorithm is compensated by the advantage of the other.

A variety of hybrid techniques have been proposed in the literature, each has its particularity, its own advantage and disadvantage and for which application was designed.

For this reason, this paper deal with the review of hybrid global MPPT techniques (HGMPPT) proposed in the literature and at the same time proposes a classification based essentially on the type of algorithms applied in the employed technique.

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The reviewed HGMPPT is classified into four main categories: hybrid methods combining conventional algorithms, hybrid methods combining soft computing algorithms, hybrid methods combining conventional and soft computing techniques and other HGMPPT techniques.

Subsequently, all the reviewed methods will be discussed and their performances will be also evaluated in terms of different criteria's. The analysis of the different hybrid methods has made it possible to draw several observations concerning the use of the applied techniques.

This review helps the researchers to acquire comprehensive and precise information about the application of the different hybrid algorithms and furthermore help them to choose an efficient way to harvest maximum power from the PV systems during partial shading conditions (PSC) by applying the appropriate and suitable HGMPPT algorithms.

This paper is arranged as follows: Section 2 explains partial shading effect on photovoltaic module characteristic, while section 3 introduces partial shading mitigation methods for PV systems. Section 4 describes and classifies the selected hybrid techniques, the analysis and discussion are described in section 5 and the conclusion is provided in the section 6.

II. PARTIAL SHADING EFFECT ON PV MODULE CHARACTERISTIC

A PV module is usually connected in series to form a string. When the PV module is subjected to the shading effect, the exposed part of the solar cell to shading will no longer generate power and the module become as a load.

The shaded module current will force the output current of the whole string. In extreme cases, the shaded modules will generate excess heat due to reverse current flow. The excessive heat generated in certain part of PV modules leads to creation of the hot spots. In order to overcome this problem, bypass diodes are connected in parallel with group of PV cells. The bypass diode will bypass the cell current subjected to shading and protect the module failure due to hot spots [3-4].

Fig.1 shows P-V characteristics of two PV modules connected in series under STC and PSC.

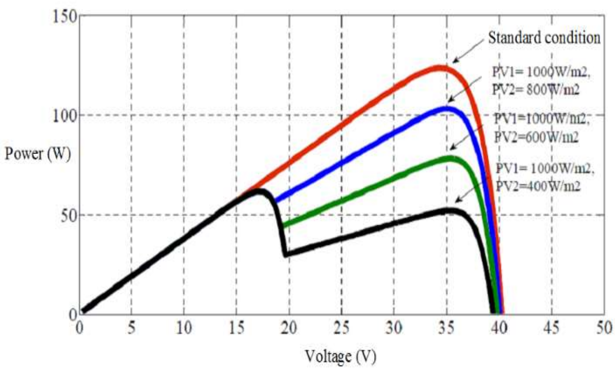


Fig.1: P-V characteristics curves obtained under STC and PSC.

III. PARTIAL SHADING MITIGATION METHODS FOR PV SYSTMES

Partial shading causes considerable power losses which affects the performance of the overall system, which has led researchers to develop numerous solutions which make it possible to remedy this problem and consequently reduces losses due to the shading. Several solutions are available to reduce this negative effect and therefore maximize the power supplied. Among the available solutions, we mention the bypass diode employment, the PV systems architecture, the PV array configuration and reconfiguration and MPPT techniques. A brief classification of shading mitigation techniques is presented in this section.

III.1. By-pass diode employment

Bypass diodes are electronic components that prevent problems associated with shading. They are associated with groups of PV cells within a single panel and allow current to flow by isolating the shaded cell in order to avoid drops in production (Fig.2). The insertion of the bypass diode with groups of cells causes the appearance of several peaks on the PV characteristics.

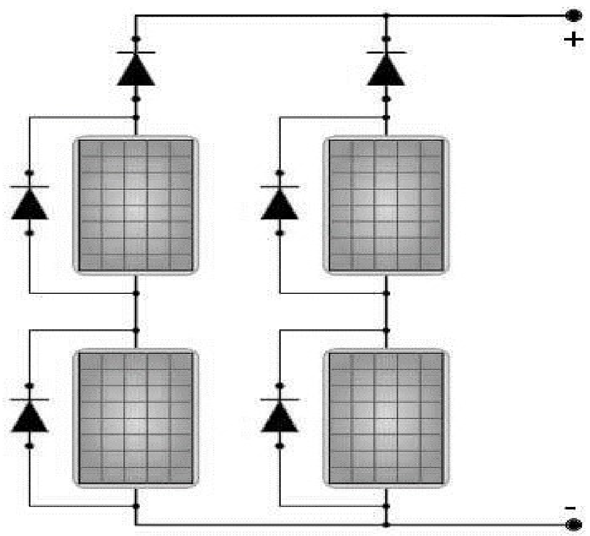


Fig.2: 2x2 PV array with bypass diodes across each PV module and blocking diodes.

III.2. PV System architecture topologies

The PV system architecture topologies describe how the power electronics converters are linked to the configuration of the photovoltaic panel. The most commonly used architectures are central inverters, string inverter, multi-string inverter and micro inverter system.

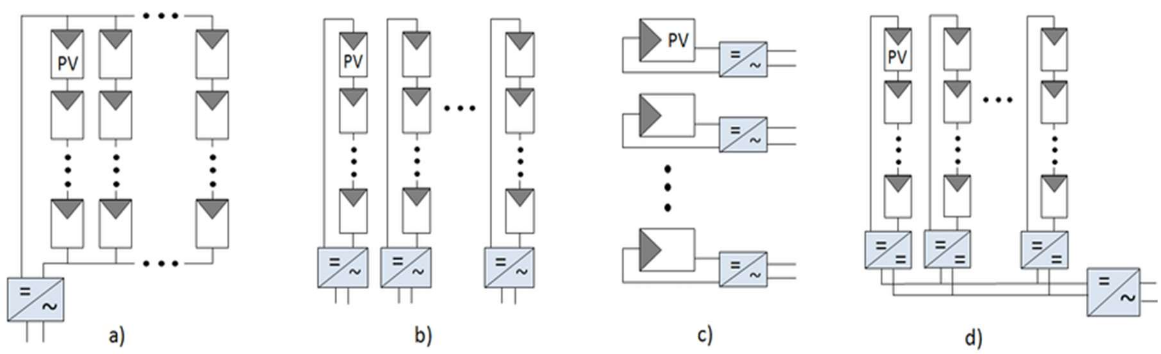


Fig.3: PV system topologies: (a) Central inverters; (b) String inverters; (c) Module inverters; (d) Multi-string inverters

III.3. PV array interconnection topologies

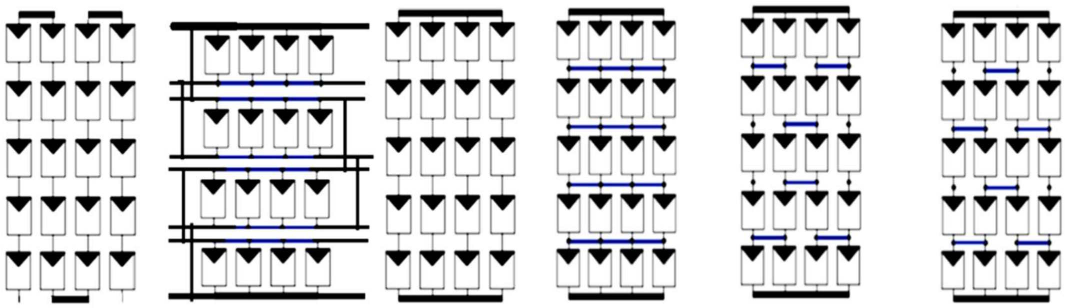
PV array configuration describes the way of the interconnection of the PV modules inside the PV array. There are the conventional configurations which are the Series (S), Parallel (P) and Series-Parallel (SP) configurations and the alternative configurations which are the Total-Cross-Tied (TCT), BL Bridge-Linked (BL) and Honey-Comb (HC) configurations. Several works have been studied and analyzed the performance of different PV configurations under PS conditions. The TCT configuration has been shown to provide the best performances compared to other PV configurations [3].

III.4. PV array reconfigurations

PV array reconfiguration process is considered as one of the most efficient solution to minimize the negative effect of PS to improve the extracted power. It aims to equalize the generated currents in different electrical rows.

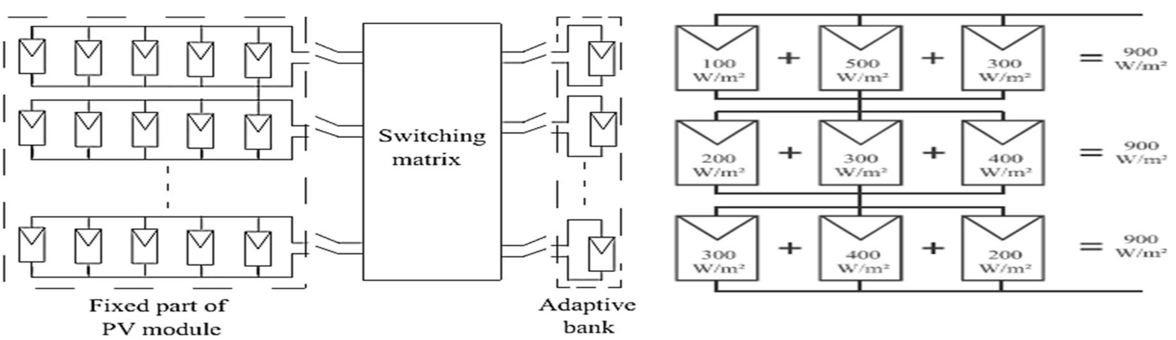
Reconfiguration techniques are divided into two classes: static and dynamic reconfigurations. Several static and dynamic reconfiguration techniques and control algorithms to alleviate the negative effect of PS have been developed in the literature [5].

Fig 5 and 6 show examples of some static and dynamic reconfigurations techniques proposed in the literature.



(a) (b) (c) (d) (e) (f)

Fig.4: PV array configurations scheme: (a) Series (S), (b) Parallel (P), (c) Series-Parallel (SP), (d)Total-Cross-Tied (TCT), (e) Honey-Comb (HC), (f) BL Bridge-Linked (BL).



(a) (b)

Fig. 5: Dynamic reconfigurations techniques examples: (a) Adaptive bank method, (b) Irradiance equalization principle for 3x3 TCT PV array.

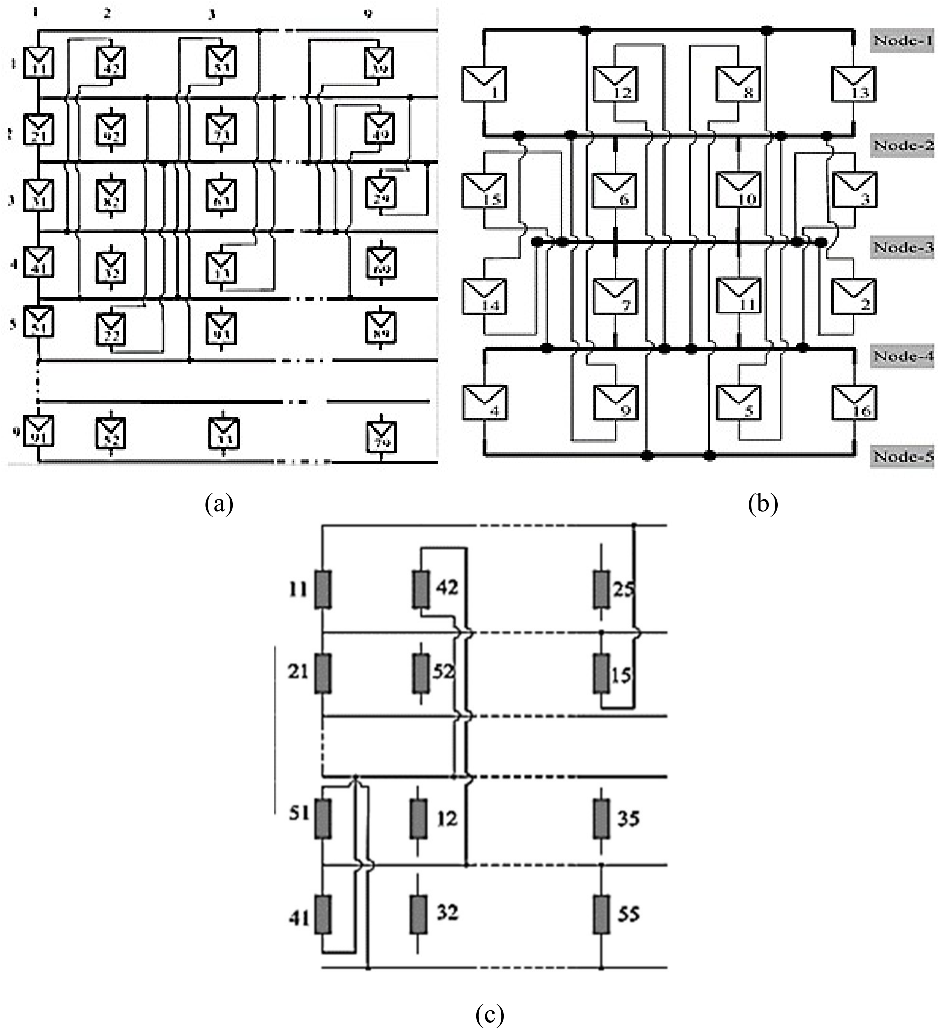


Fig.6: Examples of some static configurations proposed in the literature. (a) Su Do Ku arrangement, (b) Futoshiki arrangement, (c) Magic square arrangement.

*III.5. Maximum power point tracking (*MPPT) *techniques*

MPPT is a technique commonly used with PV systems to maximize power extraction under all climatic conditions. Fig.7 depicts a model of photovoltaic system integrated with MPPT [6]. .

In the literature, numerous paper proposed control algorithms performing a maximum power point search under partial shading conditions (PSC).

In this paper, we are only interested in hybrid global MPPT techniques (HGMPPT).

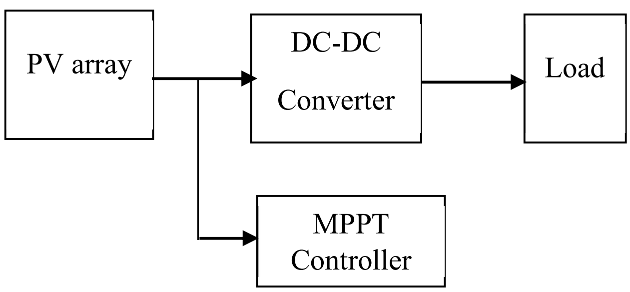


Fig.7: A model of photovoltaic system integrated with MPPT.

The most important strengths and weakness of each strategy can be summarized as follows: The use of the bypass diodes across one or series of PV modules avoids hot spots effect. However, its employment under PS conditions creates multiple local maximum power points. The appearance of these multiple peaks on the characteristics of PV array makes the tracking more difficult under these conditions and requires the integration of a more efficient power control system which is able to distinguish between local and global maxima to harvest the maximum possible energy and therefore, increase the efficiency of the entire system.

Additionally, the shading effect can be further mitigated by using alternative PV arrays' configurations such as TCT, BL and HC. The TCT configuration presents the best performances under most cases of PSC. However, TCT configuration does not provide the maximum possible power under PS and the extracted output power can be further improved. PV array reconfiguration strategy has been adopted as an alternative solution to optimize the power output under PS conditions. Many reconfiguration static techniques suffer from ineffective shade dispersion which reduces their reliability while. While, the dynamic technique requires a monitoring reconfiguration algorithm to identify the optimum configuration and the switching matrix to make connections between PV modules.

A variety of photovoltaic power system topologies and their control schemes exist and the way in which are arranged varies in term of complexity, efficiency and cost.

IV. HYBRID GLOBAL MPPT (HGMPPT) METHODS CLASSIFICATION

In this study, the reviewed HGMPPT techniques are divided into four main categories according to the type of the used algorithms in tracking as shown in Fig.8. The four groups are hybrid methods combining classical algorithms, hybrid methods combining soft computing algorithms, hybrid of classical and soft computing methods and other HGMPPT techniques.

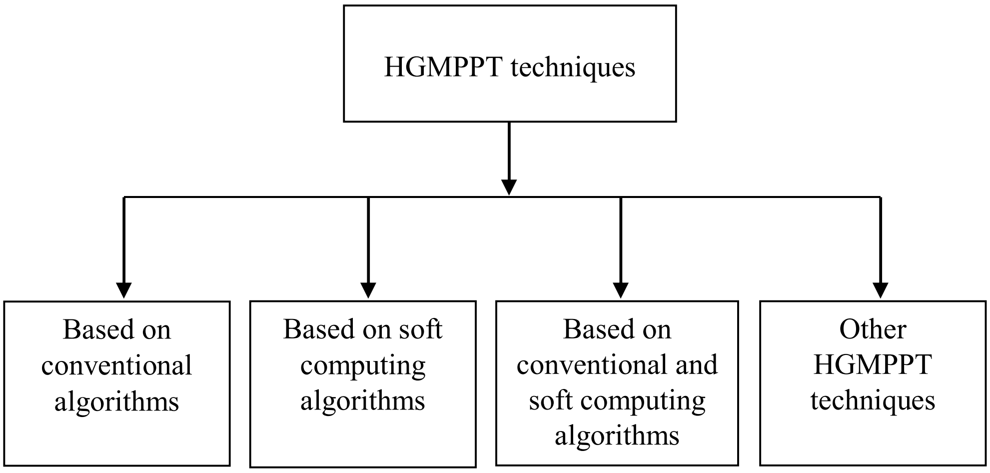


Fig.8: Proposed classification of the HGMPPT techniques.

IV.1. HGMPPT combining conventional algorithms (conventional-conventional algorithms based methods)

This category comprises the list of HGMPPT methods that integrates two or more classical algorithms. The conventional algorithm can be: perturb & observe (P&O), incremental conductance (INC), fractional open circuit voltage (FOCV), fractional short circuit current (FSCC), or power increment technique (PIT).

IV.1.1. Fractional open circuit voltage with perturb and observe (FOCV-P&O)

The FOCV approach is simple and effective, nevertheless it accuracy is low. Whereas P&O algorithm, is more accurate, but induces oscillations around MPP. Therefore, a fractional open circuit voltage is integrated with P&O algorithm to improve the performance in [7].

The weakness of an individual MPPT algorithm is overcome by the advantage of another with which it is combined. In this technique, the FOCV method situates general position a global maximum while the P&O method exactly locate it.

The proposed hybrid method *FOCV-P&O* is experimentally validated by implementing two PV panels connected in series using buck converter and compared the single P&O and FOCV.

IV.1.2. Power increment technique with perturb & observe (PIT-P&O)

For the same purpose, the same authors in [7] proposed hybrid method which combines the power increment and P&O techniques. Similarly, the proposed hybrid method PIT-P&O is experimentally validated by implementing two PV panels connected in series using buck converter and compared the single P&O and PIT technique [7].

*IV.1.3. Fractional open circuit voltage with i*ncremental conductance *(FOCV- INC)*

This hybrid technique combine the FOCV and INC algorithms. This algorithm works in two steps. First, FOCV technique finds global maximum region. Whereas, the variable step sized incremental inductance reaches global maximum power point. According the authors, this efficient technique has quick response time and easy to be implemented [8].

IV.1.4. Improved 0.8 V_{OC} model with smart power scanning procedure (I0.8 V_{OC} model –SPSP).

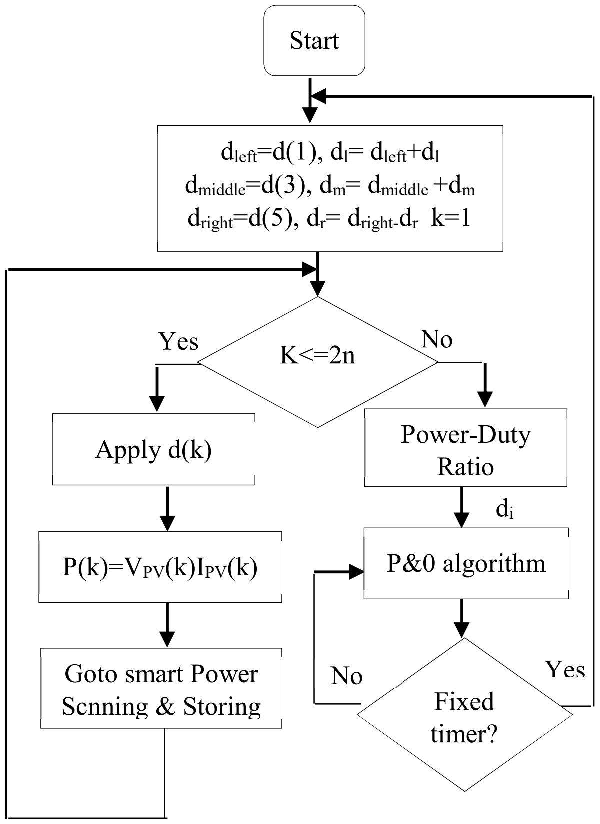
In this study, [9] used an improved 0.8 V_{oc} model and P&O algorithm for module level MPPT applications. The improved 0.8 V_{oc} model employs a power scanning procedure, which is based on the sign of PV module power change.

Figs.9 and 10 depict the flowchart and block diagram of the I0.8 V_{OC} model –SPSP technique.

The proposed HGMPPT was experimentally validated. The results obtained show higher tracking efficiency of the proposed technique compared to other techniques. This hybrid algorithm is used for module-integrated converters (MICs), PV power optimizers and module level distributed MPPT applications.

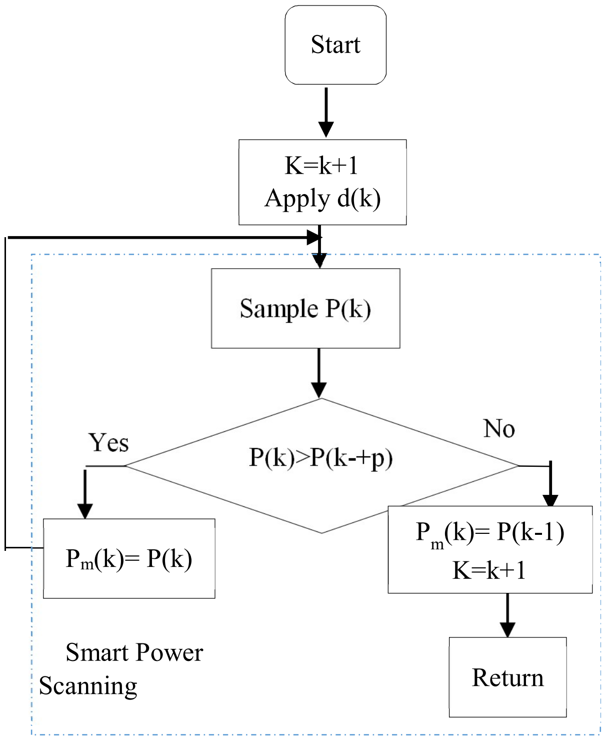
IV.1.5. Open circuit voltage and short circuit current based method (OCV-SCC)

In [10], a combination of the OCV and SCC techniques has been realized. The modified SCC is employed under normal conditions whereas the modified OCV method is used during PSC. The flowchart of proposed OCV-SCC technique is depicted in Fig.11.



(a)

Smart Power Scanning & Storing



(b)

Fig.9: (a) The flowchart of the I0.8 VOC model –SPSP.(b) Smart Power Scanning & Storing procedure [9].

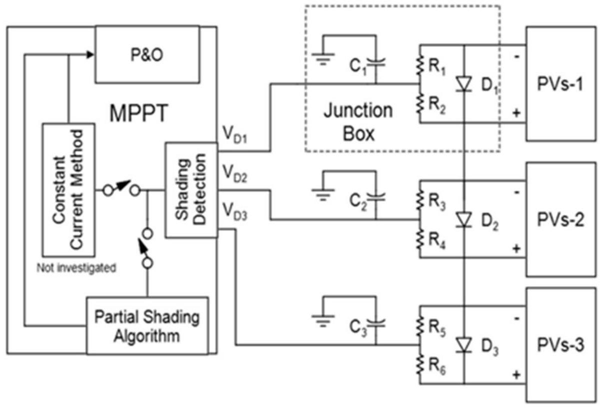


Fig.10: Block diagram of the I0.8 VOC model –SPSP [9].

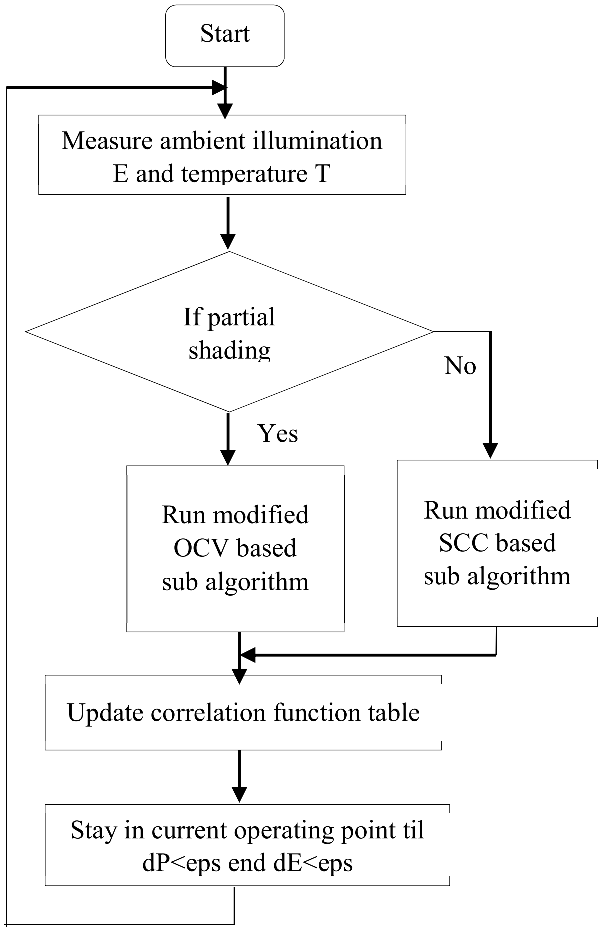


Fig.11: The flowchart of the OCV-SCC method [10].

IV.2. HGMPPT combining soft computing algorithms (soft computing - soft computing algorithms based methods)

This group contains all the methods which combine two or more algorithms belong to the soft computing algorithms such as PSO, DE, WOA, JAYA, SA, GWO, FFA, FWO and Beta algorithms, etc. …

IV.2.1. Differential evolutionary and particle swarm optimization algorithms (DEA-PSO)

The DEA and PSO algorithms are combined to track the GMPP under PS conditions in [11].

Simulation and experimental validation are investigated to verify the performance of the proposed technique under different PSC. According the authors, this method offers several advantages including reliability, system independence, and accuracy in GMPP tracking under PSC.

IV.2.2. Whale optimization and differential evolution algorithms (WOA-DEA)

The *WOA* algorithm was integrated with DEA technique to track global MPP. The WOA-DEA technique track the GMPP in short time and less number of searching agents [12]. The WOA allows to searches the global best in an efficient way while the DEA improves the performance of the WOA.

IV.2.3. Jaya and differential evolution algorithms (JAYA-DEA)

The hybrid method JAYA-DEA was introduced in [13] by hybridizing the Jaya with differential evolution to cut down the excessive number of iteration and searching delay.

The combined performance of Jaya and DE algorithms enhances the searching ability and reduces the number of iteration with the minimum computational burden [13].

The algorithm generates duty cycle from three values, the best and worst in these three values is chosen in accordance with the performance. After that, Jaya updates all values by using (1) and transmit all updated data the DE algorithm after evaluating best and worst.

$$D_{i,j}^{k+1} = D_{i,j}^{k} + rand_1 x(D_{i,best}^{k} - |D_{i,j}^{k}|) - rand_2 x(D_{i,worst}^{K} - |D_{i,j}^{k}|) \quad (1)$$

Where, $D_{i,j}^{k}$ is the value of the i^{th} variable for the j^{th} candidate during the t^{th} iteration, $D_{i,best}^{k}$ is the value of variable 'i' for the best candidate during the k^{th} iteration, $D_{i,worst}^{K}$ is the value of variable.

DE algorithm, by means of searching process (mutation, crossover and selection process) generates the best place for all candidates of the Jaya algorithm.

Afterwards, all duty cycles are mutated by using wavelet mutation, which notice the variations and consequently modify the obtained duty cycles. The wavelet mutation process is described as,

$$D_i^{k+1} = \begin{cases} D_i^k + \xi x(D_{max} - D_i^k), & \text{if } \xi > 0 \\ D_i^k + \xi x(D_i^k - D_{min}), & \text{if } \xi \leq 0 \end{cases} \quad (2)$$

Where, D_{min} and D_{max} are the minimum and maximum value of the duty cycle. ξ is wavelet mutation operator.

According the authors, the proposed method is accurate in tracking GMPP and faster in comparison to others published methods. In addition, it has a good dynamic and steady state responses under different conditions.

IV.2.4. Simulated annealing and particle swarm optimization algorithms (SAA-PSO)

In another study, a SAA algorithm and PSO algorithm are combined to reach much faster and more accurate tracking to the global MPP [14]. The SAA-PSO algorithm quarries the core part of the PSO algorithm with the stepwise change pattern, which is integrated into the SAA method. The algorithm can reduce the tracking time and increase the tracking accuracy. The proposed SAA-PSO exhibits better performances under PSC compared to the SA and PSO algorithms.

IV.2.5. Modified genetic and firefly algorithms (MGA-FFA)

The GA has complicated calculations and poor accuracy under PSC. [15] combined a modified GA with FFA and added a differential evolution (DEA) algorithm to further improve the calculation process. GA calculations are simplified by the integration of the DEA mutation process and FFA attractive process. The flowchart of the proposed MGA-FFA algorithm is illustrated in Fig.12.

Both the simulation and experimental evaluation show that the MGA-FFA algorithm presents a fast response time and high accuracy under PS.

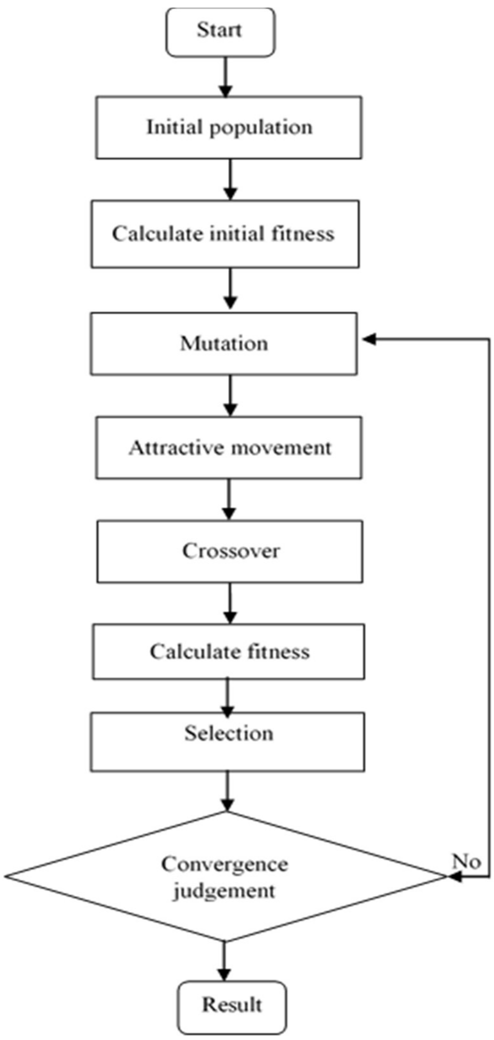


Fig.12: The flowchart of proposed *MGA-FFA* algorithm [15].

IV.2.6. Grey Wolf Optimization and Golden-Section Optimization algorithms (GWO-GSO)

The GWO has been used to track GMPP. Wherever, it requires numerous iterations resulting in significant power losses.

A hybrid search algorithm (GWO-GSO) integrating GWO and GSO to extract GMPP for photovoltaic systems was applied in [16]. Initially, MGWO is activated for the global search. In conventional GWO, wolf leaders possess the same impact on decision-making. In this technique, the decision weights of wolf leaders are automatically tuned with hunting progression to accelerate hunting. After that, the algorithm is switched to GSO for the local search, which play a crucial role to avoid useless search and reduce the tracking time. Additionally, a novel restart judgment based on the quasi-slope of the power-voltage curve is introduced to improve the reliability of MPPT systems. Simulation and experiment results reveal that the proposed GWO-GSO technique track the GMPP quickly and accurately with higher accuracy under different PSC.

According the authors, the proposed GWO-GSO exhibits better performance compared to the P&O, PSO, GWO and GWO-P&O algorithms under different conditions in terms of tracking time and output power,

IV.2.7. Grey wolf optimization and Beta algorithms (GWO-β)

[17] proposed a HGMPPT which combines the GWO algorithm with β method to enhance the convergence speed and reduce the power oscillations around MPP. The proposed algorithm employs the GWO technique to reach the GMPP, whereas, at the same time, the β method calculates the MPPT reference based on the PV voltage and current at GMPP. Then, only the Beta method which is activated to track the MPP reference, ensuring the GMPP in that specific operating point. The effectiveness of the proposed GWO-β algorithm was evaluated by means of simulation results, in which the proposed technique was compared to the P&O, β and GWO methods.

According to the authors, the simulation results show that the proposed MPPT algorithm converge quickly to the GMPP. Moreover, in, low power oscillations occur at MPPT in steady state as well as higher tracking efficiency compared to the other MPPT methods.

IV.2.8. Overall distribution and Particle Swarm Optimization algorithms (OD- PSO)

The authors in [18] proposed a OD algorithm to rapidly found the area near the global maximum power points, which is further mixed with the PSO algorithm to improve the MPPT accuracy

In this algorithm, the OD algorithm is first used to rapidly obtain the particles, which are within a small region that contains the GMPP. The obtained particles will be used as the initial particles for PSO algorithm, and finally the PSO algorithm captures the GMPP. The effectiveness and accuracy of the OD-PSO algorithm are demonstrated through simulations and experimentations.

IV.2.9. Particle swarm optimization and gravitational search algorithm (PSO-GSA)

Hybrid of PSO and GSA techniques have been proposed to track GMPP in [19].

The PSO-GSA algorithm combines the capability of social evolution of PSO and the local search ability of GSA. Results obtained from proved efficiency of PSO-GSA technique compared to other techniques.

IV.2.10. Particle swarm optimization (PSO) and ANFIS (PSO-ANFIS)

[20] proposed hybrid technique combining an adaptive neuro-fuzzy inference system (ANFIS) and PSO technique. The PSO-ANFIS method efficiently tracks the global maximum with a fast time. Simulation results prove that the PSO-ANFIS is more efficient and has higher speed tracking compared to the PSO and FFA algorithms.

IV.2.11. Grey wolf optimization algorithm and fuzzy logic controller (GWO-FLC)

[21] combined the GWO witch fuzzy logic controller (FLC) to solve the problem of oscillations around the global MPP. The hybrid of GWO and FLC exploits the advantages of both techniques where GWO is fast and reliable in tracking GMPP under PSC and FLC presents low oscillations around the GMPP. In addition, two initialization techniques are proposed to re-initialize the GWO to achieve the dynamic or variant GMPP. The initialization techniques are based on predefined time or PSC changes. Simulation results demonstrates that the proposed technique has superior performance in case of time variant PSCs.

IV.2.12. A general regression neural network trained with sailfish optimizer (GRNN-SFO)

[22] proposed a highly effective HGMPPT technique which consists of a general regression neural network trained with meta-heuristic sailfish optimization algorithm (GRNN-SFO). To verify the performance of the proposed technique, a comparison was made with the GRNN-PSO and GRNN-P&O methods. The comparison shows that GRNN-SFO tracks the global maxima with great efficiency and faster tracking time under fast varying irradiance and partial shading condition compared to the two methods.

IV.3. HGMPPT combining conventional and soft computing algorithms (conventional - soft computing algorithms based methods).

In this group, the classical algorithms such P&O, INC, FOC are combined with soft computing methods such ANN, FLC, PSO, SA, and ACO…

IV.3.1. Artificial neural network and P&O algorithms (ANN-P&O)

Several works have adopted this technique, combining the artificial neural network and the P&O [23-25].

In [23] and [24], the ANN predicts the region of the global MPP and then a P&O method searches real global MPP within the local region. The general process of the proposed ANN-P&O technique is depicetd in Fig.13. According to the author, this method has simple structure and provide a fast convergence speed.

In another study, this method combines P&O with the ANN technique. The ANN predicts the global MPP region by estimating its voltage boundaries. The P&O algorithm identifies the MPP in the estimated region [25].

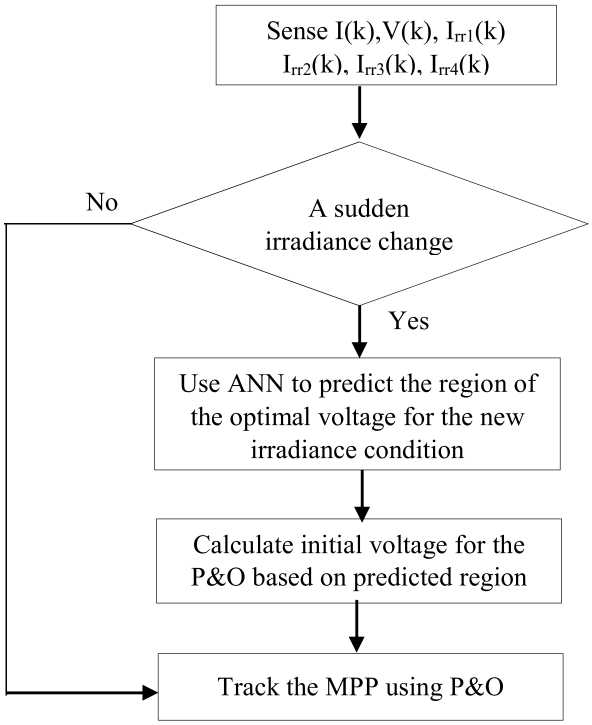


Fig.13: The general process of hybrid ANN-P&O MPPT [23].

IV.3.2. Artificial neural network and a hill climbing method (ANN-HCA)

In the study carried out in [26], an artificial neural network and a hill climbing method is combined to achieve global MPP. Initially, the hybrid method uses the ANN to provide a first GMPP estimation. Then, a HCA find the estimated optimal one. In this approach, the computational burden is reduced due to a good ANN structure and its training process.

IV.3.3. Fuzzy logic control and Perturb and observe and (FLC-P&O)

This hybrid algorithm combines P&O and fuzzy logic control (FLC) algorithms. The proposed algorithm starts MPPT with P&O and switches to FLC algorithm when the transient operating point is close to the global MPP [27]. According to the authors, this algorithm reach quickly the global MPP with less oscillation.

Simulation results show that the proposed method exhibits more harvested energy compared to single P&O and FLC algorithms. The flow chart of the proposed hybrid *FLC-P&O* MPPT method is shown in Fig.14.

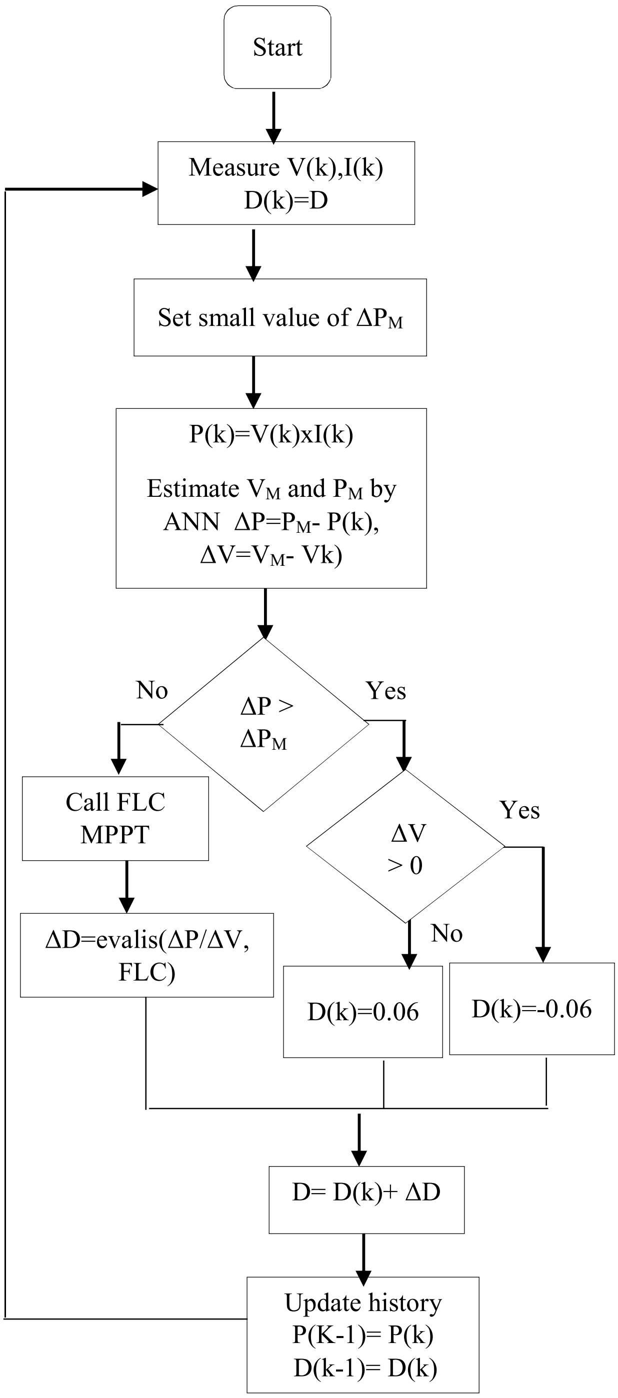


Fig.14: The flowchart of the proposed hybrid FLC-P&O MPPT method [27].

IV.3.4. Particle swarm optimization and incremental conductance (PSO-INC)

The PSO has been widely applied in MPPT tracking in PSC however; this algorithm suffers sometimes from a slow convergence speed and large search space. Several works listed in the literature combined the PSO algorithm with other algorithms such as P&O, INC and HC algorithms. A hybrid technique combining PSO and INC is proposed in [28]. In this method, first, the INC algorithm find the closest local maximum; then, the PSO method searches the global maximum point.

The time required for convergence is reduced due to the reduced searching area of the PSO algorithm. Simulation results demonstrate that the proposed hybrid PSO-INC method track the GMPP easily with a faster response time and better dynamic response compared the PSO algorithm. The authors in [29] proposed a dormant particle swarm optimization (DPSO) algorithm. The DPSO algorithm integrated with INC algorithm is simple for implementation and attain GMPP quickly and accurately under partial shading conditions.

IV.3.5. P&O and PSO (PSO-P&O)

Recently, the hybrid technique which integrates the conventional and metaheuristic approaches, is gaining interest [30-34]. A P&O method find the first local maximum point whereas the PSO MPPT methods success to track the global maximum point. However, the PSO algorithm has a long time convergence when the range search space is large. [30] proposed a hybrid method, which combines P&O and PSO methods. First, the P&O gives the nearest local maximum. Then, the PSO searches the global MPP. The main advantage this method is the reduction of PSO search space, which improves the time required for convergence. Simulation and experimental results show that the proposed hybrid PSO-P&O method tracks the GMP successfully with a faster convergence time and better dynamic response compared the PSO method.

Also, in [34] the P&O and the PSO algorithm was combined. Additionally, in order to enhance the tracking GMPP performance under complex shading conditions, an improved hybrid technique which combines a modified P&O and enhanced PSO was proposed in [32].

[35] presented a hybrid enhanced leader particle swarm optimization (ELPSO) assisted by a conventional perturb and observe (P&O) algorithm. The experimental results proved the superiority of the ELPSO-P&O method in tracking the maximum power under all shaded conditions.

IV.3.6. Hill climbing and particle swarm optimization algorithms (PSO-HCA)

The HCA is combined with the PSO. In this method, the MPPT algorithm uses the HCA method to update the position of the best particle and the PSO algorithm is employed to place the rest of particles [36].The effectiveness of the proposed method has been confirmed in simulation studies under partial shading conditions. The computational complexity of the proposed algorithm is low and allowing to its implementation using low cost microcontrollers.

IV.3.7. Particle Swarm Optimization and proportional-Integral (PSO-PI)

This algorithm combines the advantages PSO and proportional integral (PI) control technique [37]. The hybrid method uses firstly the PSO algorithm to find the global peak. Then, the PI controller is activated to increase the tracking precision and to track slow variations in the global peak location. An adaptive sampling time strategy is adopted to accelerate the convergence to the GP. Simulation is carried out using Matlab/Simulink to prove the performance of the PSO-PI algorithm under different partial shading conditions. The results obtained shows fast tracking speed and high accuracy. According to the authors, this algorithm is simple.

IV.3.8. Simulated Annealing and P&O algorithms (SAA-P&O)

SAA has been applied efficiently to track a global maximum with limited implementation complexity. As it was mentioned previously, P&O is simple and easy to be implemented but fails to locate global maxima, and the SA method is unable to carry out continuous searching [38]. The algorithm uses first the SAA algorithm to locate the neighbourhood of the global maxima. Then, the P&O method is applied to perform well tracking to the GMPP.

By merging the two techniques, some of their limitations are overcome such as the failure of the SA algorithm to continuously track and the limited ability of the P&O algorithm to identify global maxima. The effectiveness of the proposed hybrid SAA-P&O technique was demonstrated by simulation results.

IV.3.9. Grey wolf optimization and Perturb & Observe (GWO-P&O)

In this method, the GWO and P&O algorithms are mixed to achieve faster convergence to the GMPP [39]. GWO operates in the initial stages of MPP tracking and the P&O is employed at the final stage to attain faster convergence to the GMPP.

The effectiveness of the proposed hybrid GWO-P&O algorithm has been evaluated through both simulation studies and by experimental studies. The comparative study between the GWO-P&O technique, GWO and PSO-P&O demonstrates that the proposed GWO-P&O exhibits superior performance such as higher tracking speed and faster convergence.

IV.3.10. Whale optimization and Perturb and Observe algorithms (WOA-P&O)

The WOA technique shows more power oscillations when the algorithm tracks the MPP around the GP. To attain the maximum power with less power oscillation and a fast convergence speed, the WOA is combined with the P&O [40]. Thus, this hybrid algorithm overcomes the computational burden encountered in a WOA. In the WOA-P&O technique, the WOA predict the initial global peak and P&O to achieve a quicker convergence to a GP in the final stage. Simulation and hardware results showed that the proposed hybrid WOA-PO technique is efficient in GMPP tracking under various PSC and changes in irradiance level for both the dynamic and steady state conditions.

IV.3.11. An improved P&O and artificial bee colony algorithms (ABC-IMP&O)

In [41], a modified P&O is integrated with ABC algorithm. In the proposed method, GMPP is firstly identified by ABC algorithm and then the P&O algorithm is used for local MPP. The proposed method combines the advantages of both ABC and P&O algorithm.

Therefore, the local search ability of P&O and global search ability of ABC are reliably combined to provide effectively optimum duty cycle to the boost converter. The proposed ABC-P&O algorithm is implemented using Matlab/Simulink model and it is compared to P&O, INC and ABC algorithms. The simulation results demonstrate that the proposed ABC-PO algorithm is more efficient under PSC. Fig.15 depicts the flowchart of the proposed algorithm.

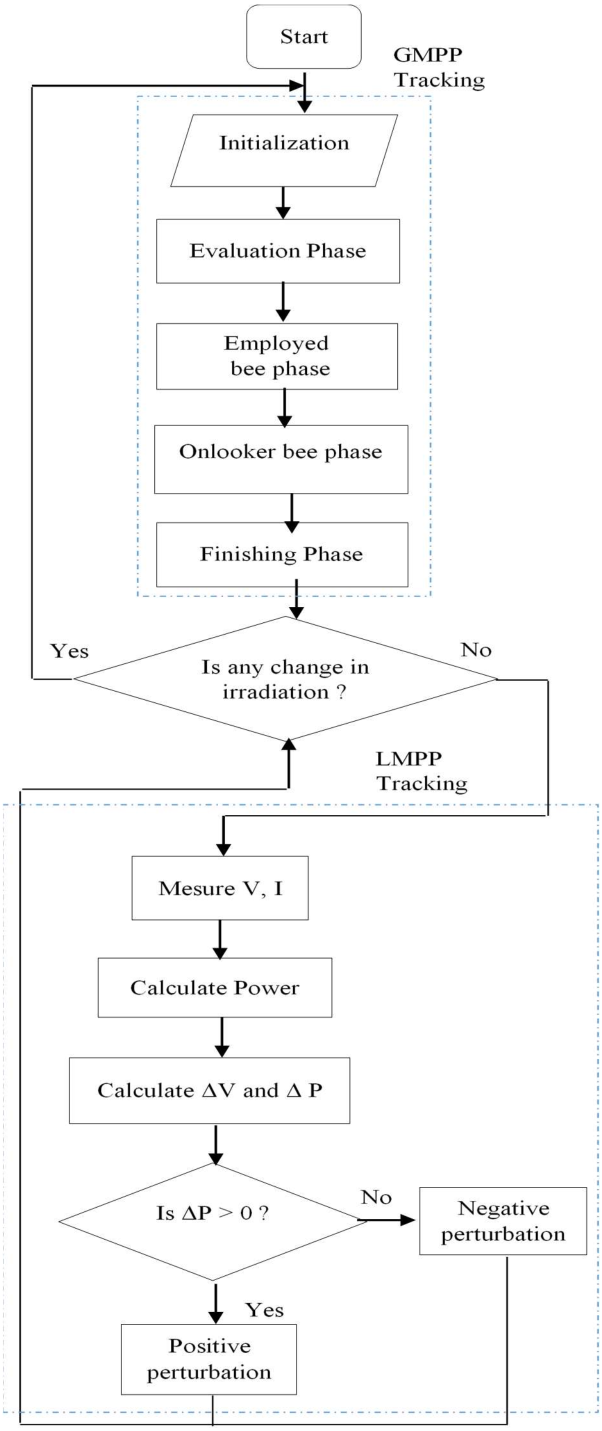


Fig.15: the flowchart of ABC-P&O algorithm [41].

IV.3.12. Ant colony with perturb and observe algorithms (ACO-P&O)

A hybrid MPPT algorithm which combines the ACO and P&O method was introduced in [42]. In this technique, the ACO method tracks a maximum power from PV array under all variations while the P&O achieve faster MPP tracking in final stage. In fact, when the ant colony approaches the MPP, the P&O MPPT begins at the location of the best ACO process.

The proposed ACO-P&O algorithm is validated by both simulation and hardware implementation. This hybrid technique has superior performance and fast tracking speed to track GMPP than other methods such as GWO, ACO and P&O methods.

IV.3.13. Firefly algorithm and incremental conductance (FFA-INC)

The INC and FFA are combined to provide a faster global searching capability and tracking speed [43]. INC algorithm was used for its low-cost implementation and stability under rapidly changing conditions, whereas, FA is very efficient in searching the GMPP.

Initially, the proposed algorithm used INC to find the first local MPP quickly. Next, the initial position and population size of fireflies is determined by the population initialization mechanism. After the initialization, FA searches the global optimal region. Finally, the GMPP is found by the improved INC within global optimal region.

The FFA-INC algorithm is compared to the P&O, FFA and INC MPPT methods under four different conditions. Simulation and experiment results show that the proposed algorithm tracks the GMPP under various conditions with higher speed and accuracy.

IV.3.14. Fireworks algorithm and Perturb and Observe (FWA-P&O)

This strategy exploits the advantages of the P&O and FWA algorithms [44]. Under uniform irradiance conditions, the P&O algorithm is used due to its dynamic tracking capability, where it tracks the unique MPP. During the occurrence of partial shading, the FWA determine the global MPP, due to the good exploration and exploitation characteristics and fast convergence that possess. The FWA-P&O technique is implemented using a low-cost microcontroller and performances are verified through experimentation.

The performance of the proposed technique is compared to the conventional PSO algorithm and has been demonstrated the superiority of the FWA-P&O method terms of dynamic tracking capability and power oscillation during tracking.

Fig.16 shows the flowchart for the proposed GMPPT FWA-P&O algorithm.

IV.3.15. Modified bat and Perturb & Observe algorithms (MBAT-P&O)

In [45], a hybrid search algorithm that consist of modified bat algorithm and P&O algorithm was proposed. The standard bat algorithm has been modified in this hybrid method by adding tabu list avoiding a duplication of unsuccessful solutions, first, a modified bat algorithm determine the global peak area, and then P&O track the MPP in the global peak area.

The simulations results demonstrated that the proposed MBAT-P&O method has superior performances compared to the standard bat and P&O algorithms.

IV.3.16. Gravitational search and P&O algorithms (GSA-P&O)

[46] proposed hybrid GMPPT algorithm combines the GSA with P&O algorithm. Initially, the GSA the scannes a power-voltage (P-V) curve to obtain the best solution which is then transferred to P&O algorithm.

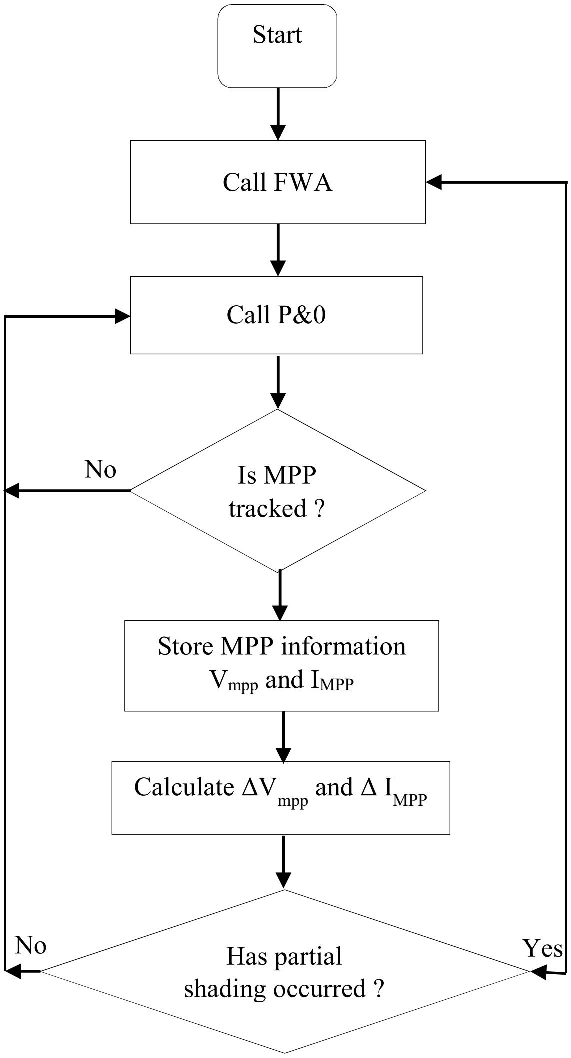


Fig.16: the flowchart of the proposed FWA-P&O [44].

Simulation and experimental results demonstrated that the GSA-P&O performance has been enhanced and it exhibits high efficiency in comparison with GSA and P&O.

IV.3.17. Hill climbing with single current sensor and artificial bee colony algorithms (HC-SS-ABC)

In order to reduce the number of sensors and obtain a good convergence speed, [47] has proposed a hybrid algorithm integrating the single sensor hill climbing (HC-SS) and ABC algorithms. In this technique, the detection of the occurrence of partial shading conditions as well as identification of type of shading pattern are performed by scanning the output current vs. duty cycle characteristics of the power electronic interface.

In addition, the SSHC is employed during normal irradiance conditions, while during partial shading conditions either HC-SS or ABC algorithms according to the PV-curve type.

The performance of this technique is validated by simulation and experimental results. The proposed HC-SS-ABC is compared to the HC algorithm based P-V curve scanning technique and ABC algorithm.

The obtained results show that the proposed hybrid GMPPT technique has a fast convergence speed and high efficiency compared to the two technique mentioned. This hybrid algorithm is used for battery charging applications.

IV.3.18. Adaptive salp swarm and differential evolution-perturb & observe technique (ASSADE-P&O)

[48] proposed a HGMPPT technique named adaptive SSADE–P&O which integrates SSA, DE and P&O algorithms. In the proposed method, the algorithm control parameters are adaptively adjusted to avoid needless power oscillations even after achieving the global peak region (GP) by SSA owing to dependency of the algorithm control parameter on the maximum iteration count. The combination of the SSA with the modified ED results in more accurate GMPP tracking with few search agents. Further in the identified GP region, the tracking is moved to the variable-step P&O, resulting in more accurate GMPP tracking and reduced power oscillations in the steady-state. In order to get the rapid MPP tracking during load changes direct duty ratio calculation is adapted without reinitializing the GP region identification stage.

The proposed algorithm is accurate and fast and has low power oscillations during tracking around MPP.

The proposed hybrid technique is verified with Matlab/Simulink model and by using hardware prototype developed. The superiority of the proposed method is compared the comparison of ASSADE-P&O method with SSA, ASSA, ASSADE MPPT methods which exist confirmed the superiority of the proposed technique in terms of tracking time and accuracy under complex partial shading conditions as well as load changes.

IV.4. Other HGMPPT methods

Various other hybrid techniques can be found in the literature but it is not possible to cover all techniques here. We mention the following:

IV.4.1. Direct adaptive neural control and voltage traverse (DANNC-VT)

An adaptive neural network control is combined with the feedback load voltage traverse (VT). Initially, the feedback load VT method achieve the reference voltage, and next the DANNC learning algorithm stabilize the maximum value [49].

The simulation results demonstrate that the proposed hybrid method track efficiently the GMPP under PSC. The proposed hybrid DANNC-VT technique is simple and more accurate and stable than other traditional algorithms.

IV.4.2. PSO algorithm and intermediate power point tracking algorithm (PSO-IPPT)

This hybrid technique integrates the PSO method and intermediate power point tracking algorithm (IPPT). The PSO technique is employed to track the global MPP under partial shading conditions whereas the IPPT algorithm is used to reach any other set point [50].

IV.4.3. Modified perturb and observe and checking algorithm (MP&O-CHECKA)

An enhanced P&O is mixed with a checking algorithm in [51]. In this method, the checking algorithm is introduced into a modified P&O algorithm. The checking algorithm detect the global maximum power by comparing all existed peak points, the modified P&O algorithm identify the voltage at MPP, required to calculate the duty cycle of the boost converter.

The Simulation results proved that the proposed technique track effectively the GMP. This method has many advantage such as the accuracy and simplicity of the algorithm and hence the possibility of implementation using low cost microcontroller.

IV.4.4. Gaussian process regression and Jaya algorithm (GPR-JAYA)

A hybrid of GPR and Jaya algorithm was proposed for photovoltaic system operating under PSC in [52].

To improve the tracking performance with Jaya algorithm, a GPR model is added into the iterative updates of candidate solutions (operating voltages).

The GPR model has the role of a predictor of PV power generations. Candidate solutions that do not improve PV power generations considered by the GPR model will be rejected during iterative updates, which reduce worse updates.

The effectiveness and efficiency of the proposed method is validated by simulation. Results obtained from simulation show that the GPR-Jaya outperforms standard Jaya algorithm and particle swarm optimization (PSO) algorithms in terms of dynamical efficiency and convergence speed.

IV.4.5. Hybrid P&O based multi-peak MPPT algorithms (P&O-MPT)

[53] presented a hybrid GMPPT algorithm under PSC combining five methods which includes the global scanning method, the filtering method, the binary searching method, the three-point method, and the anti-restarting method. The global scanning method finds all the local intervals, the filtering method reduces the search area, the binary searching method reduces the search time, the three-point method track the GMPP dynamically, and the anti-restarting method prevents restarting the algorithm.

The proposed P&O-MPT algorithm is illustrated in Fig.17.
The integration of benefit of all this methods allows to improve the efficiency and tracking speed, reduce the oscillation, and avoid restarting.

The results show that the proposed algorithm has a high performance such as system oscillation, tracking efficiency and speed. In addition, this algorithm is accurate and has fast respond fast in case of dynamic changes of irradiance (or temperature).

According the authors, the proposed algorithm is easily to be implemented using a low-cost microcontroller.

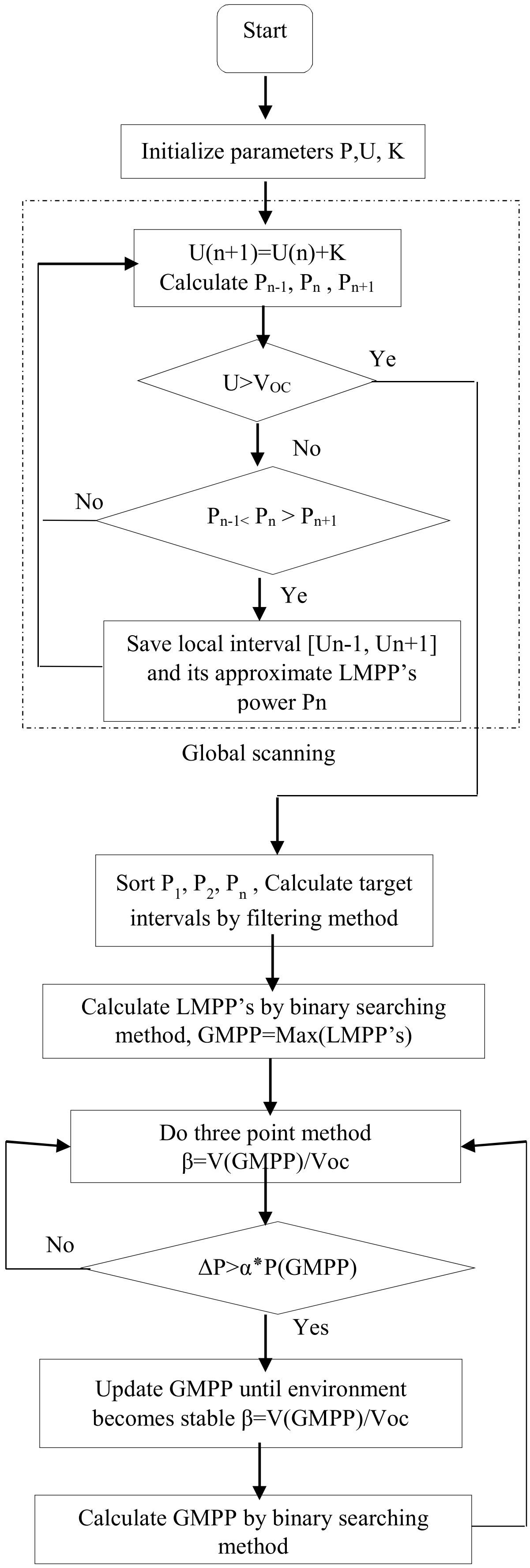


Fig.17: The flowchart of the proposed Hybrid P&O-MPT algorithms [53].

IV.4.6. Artificial neural network algorithm and segmentation algorithms (ANN-SEG)

[54] implemented an easy and cost effective HGMPPT technique to ensure a fast tracking of the global MPP. The proposed technique comprises a two stages searching method. The first stage combines an algorithm based on standard segmentation and an artificial neural network to identify the best operating point of the PV array subjected to continuously

variable environmental conditions. The second stage uses a hill-climbing method to finely track the precise GMPP location. The proposed method exploits a simple neural structure which consists only of six neurons in the hidden layer integrated with segmentation technique avoiding a complex ANN structure.

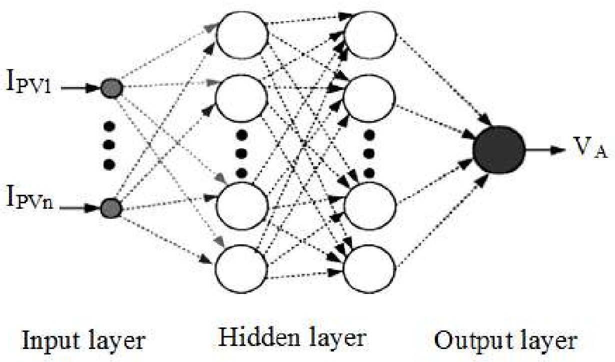


Fig.18: Neural network structure [54].

V.COMPARISON AND DISCUSSION

Availability of great number of techniques, impose to have a rigorous comparison to select the best one for a particular application. In this section, the following table depicts a performance comparison of different HGMPPT methods according the following parameters: convergence speed, complexity level, experimental implementation, efficiency, etc.

The analysis and evaluation of different HGMPPT techniques under PSC according to previous reviewed studies show that the hybrid techniques are the most useful methods in comparison with other MPP tracking methods.

- All hybrid control methods are efficient in tracking GMPP under PS and all weather conditions.
- The hybrid algorithms contributes to the improvement of PV array accuracy and efficiency under partial and changing environmental conditions.
- Hybrid methods based on classical algorithms are simple compared to hybrid methods based on conventional-soft computing and soft-computing soft computing based methods.
- Hybrid methods based on classical algorithms are less effective under partial shading compared to hybrid methods based on conventional-soft computing and soft-computing soft computing based methods.
- Hybrid methods based on conventional-soft computing and soft-computing- soft computing based methods are more effective in GMPP tracking.
- The use of two or more MPPT algorithms helps to overcome the drawbacks of individual MPPT algorithms when used alone.

Table I

PERFORMANCES OF DIFFERENT HGMPPT TECHNIQUES UNDER PSC.

Refs	HGMPPT	Complexity level	Tracking speed(s)	Efficiency (%)	converter	Appl-ication	Experimental Validation
[7]	FOCV-P&O	Simple	12.91	73.75	Buck	SA	Yes
[7]	FOCV-PIT	Simple	11.27	68.22	Buck	SA	Yes
[8]	FOCV-INC	Simple	<0.2	NA	Boost	SA	No
[9]	I0.8 V_{OC} mode-SPSP	Medium	5	97.39	SEPIC	GC DMPP	Yes
[10]	OCV-SCC	Simple	NA	NA	Buck	NA	Yes
[11]	DEA-PSO	Simple	<0.5	~98	SEPIC	SA	Yes
[12]	WOA-DEA	High	1.23	99.10	Boost	SA	Yes
[13]	JAYA-DEA	High	0.44	NA	Boost	SA	Yes
[14]	SAA-PSO	High	0.13	NA	Boost	SA	No
[15]	MGA-FFA	Medium	0.036	99.26	Buck	SA	Yes
[16]	GWO-GSO	High	0.64	99.99	Boost	SA	Yes
[17]	GWO-β	High	0.46	99.98	Boost	SA	No
[18]	OD-PSO	Medium	1.86	97.74	Buck	SA	Yes
[19]	PSO-GSA	Medium	8.75	99.99	Boost	SA	No
[20]	PSO-ANFIS	Medium	0.15	99.43	Boost	SA	No
[21]	GWO-FLC	High	NA	99.99	Boost	GC	No
[22]	GRNN-SFO	Medium	0,066	99.9%	Boost	SA	No
[24]	ANN-P&O	Medium	NA	NA	Buck	SA	Yes
[26]	ANN-HC	Medium	NA	NA	NA	NA	NA
[27]	FLC-P&O	Simple	1	>99.9	NA	SA	No
[28]	PSO-INC	Medium	~1	>99	NA	SA	No
[33]	PSO-P&O	Medium	0.9	NA	Boost	SA	No
[32]	PSO-P&O	Medium	NA	NA	Buck-boost	SA	Yes
[36]	PSO-HC	Medium	NA	NA	NA	SA	No

[37]	PSO-PI	Low	0.42	99.94	Buck-boost	SA	No
[38]	SAA-P&O	Medium	NA	NA	NA	SA	No
[39]	GWO- P&O	Medium	0.015	100	Boost	SA	Yes
[40]	WOA-P&O	Medium	NA	>96.7	NA	SA	Yes
[41]	ABC-P&O	Medium	0.08	99.93	Boost	SA	No
[42]	ACO-P&O	High	NA	>99.90	Boost	SA	Yes
[43]	INC-FFA	Medium	0.38	99.99	Boost	SA	Yes
[44]	FWA-P&O	Medium	NA	NA	Boost	SA	Yes
[45]	MBAT- P&O	Medium	NA	99.85	Buck-boost	SA	No
[46]	GSA-P&O	Medium	3	99.90	Boost	SA	Yes
[47]	HC-ABC	High	1.03	99.17	Boost	GC	Yes
[48]	ASSADE-P&O	Medium	1.36	99.68	Boost	SA	Yes
[49]	DANNC-VT	Low	0.0389	99.98	Boost	SA	
[50]	PSO-IPPT	Medium	NA	NA	Boost	SA	Yes
[51]	P&O-HECKA	Low	NA	100	Boost	SA	
[52]	GPR-JAYA	Medium	<2	>99		SA	No
[53]	P&O-MPT	Medium	~0.1	>99	NA	SA	No
[54]	ANN-SEG	Simple	NA	NA	Full bridge Power converter	SA	Yes

SA: Standalone, NA: Not Available, GC: Grid Connected

VI. CONCLUSION

In the literature, there are a large number of studies dealing with GMPP tracking under PSC. Thus, it is extremely delicate to pick the proper method by the designer with existence the huge studies number. For this reason, this review selected the studies that concern the most important HGMPPT methods published in the literature, revealing the advantages and drawbacks of each reviewed technique.

In addition, this work classifies different hybrid methods from the literature in four main categories. After the relevant evaluations of all surveyed methods, a table summarizing the performance has been presented, which makes it possible to choose the adequate HGMPPT technique for any application.

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