A conceptual framework and a Review of AI-Based MPPT Techniques for Photovoltaic Systems

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Abstract. Several Maximum Power Point Tracking (MPPT) techniques based on various Artificial Intelligence (AI) algorithms were recently developed due to the current availability of powerful computation controllers and adaptability of AI algorithms and their characteristic in handling non-linear problems. AI algorithms are perfectly suited to handle the problem of adverse conditions of rapid irradiance change and partial shading that the PV systems suffer. This paper presents a conceptual framework of the MPPT for photovoltaic systems and a comprehensive review of the current AI-based MPPT techniques. The paper also covers MPPT components, modeling, characteristics, affecting factors, and categories. The performance of different AI algorithms is evaluated and categorized based on many criteria including system complexity, tracking speed, cost, efficiency, accuracy, hardware implantation, sensory parameters, response to Partial Shading Conditions (PSC), etc. Finally, a summarizing comparison of performance of the main MPPT techniques is presented.

Keywords: MPPT; PV system; Solar; partial shading conditions; artificial intelligence

1. Introduction

Solar energy is considered a renewable energy due to the sun availability. The sun emits energy in the form of electromagnetic radiation. Current energy generation relies on fossil fuels such as oil, gas, and coal. For nearly 300 years at most, Fossil fuels are expected to continue to be deposited through combustion [1]. The problem is that humans are consuming this fossil fuel rapidly. Therefore, these fuels are not considered as a sustainable energy source. The greater the consumption of fossil fuels, the less readily available gas and oil resources. The pollution of the atmosphere and the environment due to the intensive exploitation of fossil fuels in most human activities has resulted in undesirable phenomena not previously observed in human history. These types of phenomena are global warming and its impacts, climate change, ozone depletion, and acid rain [2].

The impacts of these phenomena can be avoided by improving the quality of fossil fuels, which in turn will reduce atmospheric harmful emissions, or replacing the use of fossil fuels as much as possible with environmentally friendly and clean energy sources. Solar power
generation is renewable and it is considered as the ultimate abundant and distributed in nature as compared to other energy sources. Other renewable sources are geothermal energy, wind, hydropower, waves, tidal energy sources, and biomass. The known limits of fossil fuels are pushing the world's societies to leave them and use renewable energy instead of improving its quality. Solar energy is expected to play an important role and dominating other sources of energy in the near future [1].

Due to the continuous decreasing costs of PV arrays and their control systems, 50% less in the last five years, the use of photovoltaic (PV) systems has gained a remarkable momentum. The use of PV arrays in standalone local power generation and smart buildings with storage battery and back-up hybrid systems and the advancements on control systems are increasing the PV system usage as the emerging form of alternative renewable energy source [3].

2. Main Components of a Solar System

Solar panels are the heart of the solar electrical system and are available in different types. PV panels generate electricity from the sun and when the power of solar energy increases, we get more energy, and in the shade, solar panels generate less electricity. Solar panels consist of individual PV cells, linked together. A typical PV cell produces approximately a half volt and when linked in series together on the inside of the panel, this leads to obtaining a more useful voltage. Smaller solar panels of 150 watts or less are classified as 12 volts panels and larger panels are 24 volts panels. Under load condition, the 12 volts panels generate approximately (14-18) volts, allowing one panel to charge 12 volts battery [4].

Charge Controller consists of an internal circuit breaker for damage protection of the PV cells in short circuit situations. It purifies and stabilizes the voltage received from the PV cell to the system that operates using constant DC voltage. It regulates the charging process of the batteries as the charging process differs in its mechanism from simply providing a continuous power source connected to the battery. Also, it ensures no returning current from the battery to the PV cell, which may damages it [2]. Three types of charge controllers are available including: on/off, pulse width modulation [PWM] and MPPT. MPPT is characterized by its high efficiency and its ability to extract energy from solar panels [5].

Batteries are responsible for storing and discharging energy as required. There are many types of batteries, but the majority of the batteries used with solar systems are of the type of lead acid and lead acid panels, and most of the batteries used for this purpose have a voltage in the range of 12 volts, 24 volts or 48 volts. To obtain diverse current and voltage values, Batteries are connected in different topologies, similar to solar cells. The electricity generated from the solar panels is direct current, DC. Also, the value of the voltage is 12 or 24 volts. In order to take advantage of the resulting electricity and operate home appliances or any devices that work on voltage 220 or 110 volts, an inverter or current transformer is used [4]. It converts electricity from direct current DC to AC.

Solar panels generate electricity through the photoelectric effect, as this phenomenon was explored in 1839 while the scientist Edmund Becquerel realized the materials, which when exposed to light, produce an electric current. In order to create this effect, a semiconducting material of two layers are combined.. When they are subjected to sunlight, photons will be absorbed by the layers of material. As a result, electrons will be excited, and this leads to some "jumping" from one layer to another, which will result in the generation of an electrical charge.

In the construction of solar cells, silicon is used as a semiconductor material, which is cut into skinny wafers. Some chips are doped to contaminate them, resulting in an imbalance in chips. The purpose of forming a solar cell is to do this by aligning the chips together. The electrical current takes conductive metal strips that are attached to the cells. When a photon collides with a PV cell, it can be reflected from the PV cell, directly passed through the cell, or absorbed by the PV cell. In the case of silicon absorbing a photon, the process of generating an electric current occurs. By increasing the number of photons (meaning an increase in light intensity), which are absorbed by the PV cell. This leads to an increase in the generated current. PV cells generate most of the electricity by direct sunlight, but the cells can also
generate electricity in cloudy days. Some systems can generate a small electricity amount in moon nights. Individual PV cells usually produce small amounts of electrical energy. For the purpose of obtaining useful quantities of electricity, so to make a solar unit, this is done by connecting these cells together, also called solar panels or, more precisely, a photoelectric unit [4].

3. MPPT Role in PV Systems

Usually MPPT is used at the PV module / array level. Using the I-V curve, it is possible to perceive the behavior of the solar luminescent cell. Connecting several PV cells in parallel or in series results in an increase in the total voltage and / or current only. However, it does not alter the shape of the I-V curve. To understand MPPT, it suffices to consider the I-V curve of a single solar cell where the I-V curve is based on the amount of radiation and also the temperature of the unit. For example, with increasing irradiance, the current increases as well as leads to a small increase in voltage, as shown in Fig.1. Also, the same figure shows that the harmful effect on the voltage is when the temperature increases to it.

![Figure 1. PV Module I-V curve demonstrating the effect of irradiance (GM) or temperature (T).](image)

Maximum operating point is specified by current and voltage at which the solar module operates at a specified time. At pre-defined irradiance and temperature, a unique pair [I, V] that represent operating point lies on the IV curve. At this point, the output power is calculated by:

\[ P = I \times V \] (1)

The maximum point [I, V] represents the highest power point on the power-voltage curve [P-V], as depicted in Fig. 2. To obtain the maximum output power, maximum power point MPP, at a specified temperature and radiation, the maximum [P-V] curve and the operating point must coincide. If an electrical load is directly connected to a solar unit, that load dictates the operating point. To extract highest power out of the unit, the unit must be forced to operate at the maximum point of power. To force the unit to operate at MPP in the simplest way is by forcing the PV module voltage to be in MPP called [VMPP].
However, MPP depends on changes in surrounding conditions. If the temperature or radiation changes, then the properties of $[P-V]$ and $[I-V]$ will modified. The MPP position may also changes. Thus, it is necessary to monitor all changes in the $[I-V]$ curve continuously in order for the operating point to be adjusted to become MPP by making changes in the surrounding environment. The process is defined as Maximum Power Point Tracking (MPPT). MPP trackers are called to the systems that perform this process. Two different classes of MPPT are available including: indirect MPPT, as it is possible to estimate the position of MPP through a coded algorithm, and MPPT Direct, for MPP positioning uses actual $I-V$ data. Some MPPT algorithms are based on finding and adjusting voltage to find $V_{MP}$. Other algorithms are based on force search rather than effort and their purpose is to find $I_{MP}$ [2].

4. The characteristics curve of the PV module

One of the crucial characteristics of a PV cell is the short-circuit current ($I_{sc}$). This current arises in a lightened, short-circuited PV cell. Open-circuit voltage ($V_{oc}$) is another the crucial characteristics of the PV cell that describes the tension at open circuit (when no current is taken). The theoretical attainable optimal power ($P_{opt}$) is the product of $I_{sc}$ and $V_{oc}$ [6]:

$$P_{opt} = I_{sc} \cdot V_{oc} \tag{2}$$

The maximum power ($P_{max}$) is computed from the maximum possible $V$ and $I$ at a given operating point. The Maximum Power Point (MPP) is obtained by [6]:

$$P_{max} = P_{mpp} = I_{mp} \cdot V_{mp} \tag{3}$$
5. Factors Affecting Solar Energy Production

The properties of the PV system depend on the sun radiation intensity, amount of cell temperature, etc. Some factors that change continuously during the day, such as radiation and temperature, and the characteristics of the cell change. The following factors that affect solar energy generation are [7]:

- Temperature: a rise in temperature yields a reduction in voltage and almost constant current as illustrated in Figure 4.

- Intensity of sunlight: a rise in radiation intensity yields a rise in current and constant voltage approximately as illustrated in Figure 5.

- Structure of the matrix: the matrix performance depends on the cells type as well as on the quality of manufacture.

- Shadows may be complete or incomplete and are formed by clouds, communication towers, electricity, trees, buildings, etc. In semi-shadow conditions, it is difficult to trace the extreme point as several local maximum points are created in addition to the general maximum so the properties of the PV array becomes complex.

![Figure 3. P-V / I-V characteristic curve of the PV cell.](image)
6. **MPPT Techniques**

The constant voltage method (fixed voltage), for instance, is a method for the solar module adjusts the operating voltage on a seasonal basis. The method assumes that for the same amount of radiation, during winter the MPP voltages are expected to be higher compared to the summer. This method is not considered very accurate; it works best at locations of minimal radiation changes on different days.

Two of the most widespread indirect MPPT technique are the fractional open circuit voltage method and open circuit partial voltage method. These methods have good approximation and exploit the fact that VMPP,

\[ VMPP = K \times VOC \]  

(4)
occurs in terms of constant k. For crystalline silicon, values between 0.7 and 0.8 usually take k. K depends on the PV cell type. This is because changes in are easily tracked and implemented and VMPP is calculated by multiplying open circuit voltage by k. However, there are some disadvantages. First, only constant k factor is allowed for an estimate of an approximate MPP. Therefore, the playback point usually will not be exactly on MPP but close to it. Second, system needs to react repeatedly to changing lighting conditions; the volatile compounds must be measured. For this measurement, the solar module should be disconnected for a short time from the load resulting in reduction in the overall PV system output. When production loss increases, the more often the organic volatile compounds are determined. By slightly modifying the method, it is possible to overcome this disadvantage. An experimental solar cell is needed for this modification that is extremely compatible with module cells. Like the rest of the PV module, experimental cell receives same radiation, the measurement of organic volatile compounds of the experimental cell gives the PV unit a precise presentation of the module. Thus, it is used for (VMPP) estimation. Therefore, it is possible to adjust the operating point of the unit without the necessity to disconnect the PV module.

Direct MPPT is more involved (requirement for power, current or voltage measurements) than indirect MPPT. A system should also respond faster and more accurately than indirect MPPT. The most popular types of algorithms: Anxiety and Observation (P&O) algorithm it is also called a "hill climb" algorithm. This algorithm provides a disturbance in the voltage at which the unit is occupied. A change in the power output is what the voltage disturbance will cause. The operating point is less than this maximum power point if the power increases due to the increased voltage and this requires more voltage disturbance towards higher voltages in order to reach the MPP. On the other hand, if the power decreases due to increased voltage, more turbulence towards the less voltages is needed to approach MPP. Thus, the algorithm will approach MPP by several perturbations. This principle is summarized in the following table

| Prior Perturbation | Next Perturbation | Change in Power |
|--------------------|------------------|-----------------|
| Positive           | Positive         | Positive        |
| Positive           | Negative         | Negative        |
| Negative           | Negative         | Positive        |
| Negative           | Positive         | Negative        |

The drawback of the algorithm is that the trigger point is not fixed at MPP but rather is meandered around MPP. This aliasing can be minimized if we use very small perturbation steps around the MPP. The P&O algorithm also combats fast lighting changes. For example, the algorithm essentially fails in convergence efforts if there is a change in illumination and consequently radiation between two sampling moments in the convergence process as shown
In the figure. 6. In the last disturbance of the algorithm it was determined that the MPP is located at a voltage higher than that of point B, and therefore the disturbance converges towards MPP accordingly is the next step. If the illumination is steady at C, it is over and the algorithm will deduce MPP is still a higher voltage that is correct. But before next turbulence, the illumination rapidly changes, the next disturbance performs the process of moving the operating point from C to C′.

\[ P_C < P_B \]  \hspace{1cm} (5)

While MPP is still located right to the C′, P&O algorithm considers it is left to C′. So, it moves to point D′. This error in assumption is detrimental to the P&O algorithm in terms of speed of convergence which is one of the important MPPT technologies. Severe changes in weather conditions will significantly affect the effectiveness of the algorithm.

\[ \frac{dI}{dV} \approx \frac{\Delta I}{\Delta V} \]  \hspace{1cm} (9)

is deployed. Auxiliary connection, recalling \( \Delta I/\Delta V \) and \( I/V \). Thus, we get.

\[ \frac{\Delta I}{\Delta V} = \frac{-I}{V} \quad \text{if} \quad V = V_{\text{MPP}} \]  \hspace{1cm} (10)

Incremental conductance method an additional transport method for an electrical component. The conduction G is defined as

\[ G = \frac{I}{V} \]  \hspace{1cm} (6)

That in MPP the P-V curve has a slope of zero

\[ \frac{dP}{dV} = 0 \]  \hspace{1cm} (7)

\[ \frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} \]  \hspace{1cm} (8)

After which it is possible to write whether the sampling steps are sufficiently small, so that approximation

\[ \frac{dI}{dV} \approx \frac{\Delta I}{\Delta V} \]  \hspace{1cm} (9)

is deployed. Auxiliary connection, recalling \( \Delta I/\Delta V \) and \( I/V \). Thus, we get.
\[ \frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad \text{if} \quad V < V_{\text{MPP}} \quad (11) \]
\[ \frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad \text{if} \quad V > V_{\text{MPP}} \quad (12) \]

The instantaneous voltage is the controllable parameter. While the parameters of the instantaneous voltage and current can be observed, \((V_{\text{ref}})\) is the value of the PV unit imposed by the MPPT device. It is the most recent approximate estimate of \((V_{\text{mpp}})\). The instantaneous algorithm is compared to the incremental conduction values of any change in the operating point. The operating current is left to the MPP in case the increased behavior is greater than the negative of the instantaneous conduction then the \(V_{\text{ref}}\) must be increased. In contrast, the operating current point is to the right of the MPP if the auxiliary conduction is less than the negative conductivity of the instantaneous conduction and hence \(V\) decreases. This process is repeated until the additional conduction becomes the same as the passive instantaneous conduction, in this case \((V_{\text{ref}} = V_{\text{MPP}})\).

The additional conductivity algorithm is more efficient than P&O algorithm. This is because it does not circumvent the MPP at steady state conditions. It is less prone to changing light conditions because small sampling times make it this way. Under partial shading and during highly variable conditions the additional delivery method becomes less efficient. The complexity of implementing its hardware is the main drawback of this algorithm. Simultaneous and incremental conductors must be calculated and compared, not just currents and voltages to be measured.[2]

The PSO algorithm is a global multifunctional improvement method by simulating foraging behavior in birds developed. Researchers have recognized that it widely performs excellent in a multivariate system by solving multiple climax problems. PSO aims to find the best particle that represents the optimum universal solver, ie GMPP for the PV array. The output current may be the particle and the output energy may be the objective function. Assuming a transformer installed, the operating ratio is the control variable. Major impact on their performance is through the group setting and changing environment. That is why in current years PSO algorithms are enhanced and used by researchers in PSCs.

Three strategies were used to realize the PSO algorithm and conducted in non-uniform lighting, improving effective tracking performance. In addition, PSO was combined with ANN and RBF for the purpose of optimizing traceability for the algorithm. An innovative overall distribution PSO algorithm (ODPSO) that serves to determine the voltage of the potential peak point to the elemental particle position by OD-MPPT. This ensures only the PSO algorithm requires to obtain MPP efficiently and quickly in a small search domain. The hybrid is a new hybrid, distributed, and central. The enhanced PSO that acts as the main controller, which is deployed to control the power of the sources by controlling the link transformer. There is another optimized algorithm IPSO that takes local and global modes to determine the maximum power point.

In ACO algorithm, similar search principle is used as in PSO. The modification is in the algorithm works to save location information. For the first time, Dorigo and Gambardella presented the ACO and relied on the foraging behavior of real ants and how they find the best way to eat. The main advantage is his ability to adapt to it. Change in real time and work
continuously. An extension has been made from ACO to continuous areas. Dynamic and MPPT-inspired console based on improved ant colony algorithm with new pheromone update strategy ACO_NPU MPPT. It saves calculation time, with very good tracking and accuracy, great durability, and no vibration. Although the algorithm demonstrates maximum processing and good performance in the special problems in controlling MPPT tracing. Also, the statistics show that ACO gave better results compared to GA.

ABC algorithm for swarm intelligence algorithms is a new application, suggested by Karaboga in 2005. It relies on the behavior of the Bees through the following characteristics: foraging, memory, information sharing, and learning. It mimics leader, follower, and explorer searching for honey. Repetition is used continuously for the purpose of finding the optimal source for honey and it is appropriate for the optimum value of the parameters variations. Comparing with other available traditional and/or smart algorithms, the algorithm has a better negative and positive feedback mechanism as well as random behavior of group cooperation. This leads to giving it good durability and fast convergence. Also, the computational complexity is low, the accuracy is high, and the stability does not depend on its ability to deal with harsh local conditions and initial conditions. P&O was merged with ABC to improve stability of the algorithm. The ABC algorithm was also applied for the purpose of controlling MPPT for a PV system that was not uniformly illuminated, and the process of comparing it with performance to track the PSO algorithm. This makes ABC algorithm is an excellent candidate in MPP Trace Control. An improved ABC version was proposed that optimizes constraint equations for solar modules to reduce the effect of uneven illumination.

Some researches use FA in MPPT (modified Firefly algorithm within PSCs that GMPP can be extracted accurately and quickly. The concept of the algorithm focus on local and global firefly densities at each iteration, and contains two disposal mechanisms for adaptive adaptation to the firefly population. There is a proposal to improve Firefly's algorithm for the purpose of compensating for the shortcomings of the Firefly population. Conventional coil. Through powerful firefly algorithm gain control unit one by one improved.

In the last period, a new algorithm was developed inspired by biology, SSA. It is categorized by a simple search mechanism as well as good efficiency. By comparison with the other algorithms, SSA only has to update one parameter. It has similar limitations as MH algorithms like slow convergence, however, its ability not fully explored. An MPPT controller has been proposed to combine SSA with GWO (that's SSA-GWO). To enhance global search capacity, the pioneering architecture of the GWO algorithm has been introduced into the core SSA. A new optimization method has also been proposed, a biologically inspired method known as the mimetic salp swarm algorithm (MSSA). The algorithm was developed from SSA with multiple independent salp chains. It is deployed to modernize the existing solution using the switching modes of SSA and PSO, which in turn creates a balance in SSA exploration.

Genetic Algorithm (GA) is a stochastic and heuristic search algorithm. It mimics the natural selection of the biological revolution and develops an ideal solution to the problem taking place using genetics, replication, crossover and anisotropy. It is suited especially for problems that are real-time non-linear and complex objective functions. This is because it has great durability and widespread applicability. Despite this, GA is unstable and sometimes it is trapped on an optimal local solution. The algorithm can be improved by combining GA with
FA, and its calculation optimization is done through DE. This is to simplify computations needed for the results of the genetic algorithm. The DE mutation process and the FA absorption process are combined. A meta-approach based on a genetic enhanced algorithm (RCGA) was proposed for the purpose of regulating the DC-link voltage according to the adaptive reference voltage to enhance PV system dynamic behavior running under voltage variation.

DE, an evolutionary algorithm, is used to find the global optimization. For the purpose of solving problems that do not accept differentiation, as well as non-continuous, non-linear, flat, noisy, or random, local, multi-dimensional, which contains many minimum limits and constraints, this algorithm is used. Unlike PSO, DE has only two setting parameters to achieve precise MPPT tracker. This is to reduce the complexity of adjusting the parameters. In principle, DE depends more on the randomness of the primary population as compared to GA. Selection, intersection and mutation are implemented to optimize the candidate solution. The standard DE algorithm is used to find maximum global power point within PSCs. Although high tracking is achieved, it depends on several objective constant functions to find a specified P-V characteristic. The actual P-V characteristics of the array always vary with temperature and solar irradiance. In addition, maximum power tracking is a time-varying and non-linear problem. Addressing this issue, the conventional DE algorithm is improved. Due to the importance of trace time for the MPPT controller, the introduction of convergence into the enhanced algorithm DE occurs so that search approximation with the best particle direction occurs in each computation cycle. To reduce the MPPT tracking time further, a comparison of experimental vectors and donors occurs before the start of the tracking process. Moreover, it may happen that the optimized algorithm responds to the load change process quickly and this ultimately reduces the unwanted fluctuations when the PV array is output[8]. By reviewing and summarizing the main MPPT technologies for PV systems, it is possible to divide them into three groups as illustrated in Fig. 7 and Table 2 and 3 [9-44].

| MP | Trac | Accu | Compl | Effici | Circ | Hard | Cost | Ap | Senso | wit | Type of |
|----|------|------|-------|--------|------|------|------|----|-------|-----|---------|

**Figure 7.** Main categories of the MPPT algorithms for PV systems.

**Table 2.** Comparison of the performance of common MPPT techniques for PV systems.
| PT | king speed | racy | exity | ency | uity | ware Imple. | p. | r parameter | h PS C | MPPT |
|----|------------|------|-------|------|------|-------------|----|-------------|-------|------|
| CV T | Medium | Low | Low | <90% | A,D | Easy | Low | SA | V | Unable |
| O V T | Medium | Low | Low | <90% | A | Easy | Low | SA | V | Unable |
| S C T | Medium | Low | Low | <90% | A,D | Easy | Low | SA | I | Unable |
| C S | slow | Low | Low | <90% | A,D | Easy | Med ium | SA | V,I | Unable |
| P & O | Medium | Medi u m–low | >95% | A,D | Easy | Med ium | SA, GT | V,I | Unable |
| I C | Medium | Medi um–high | Medi um | Mediu m | Mediu m | Mediu m | Mediu m | Mediu m | Mediu m | V,I | Unable |
| P C | Medium | Medi um–high | Medi um–high | >97% | A,D | Diffi cult | High | SA | V | Unable |
| R C C | Medium | Medi um | Medi um | >97% | A | Easy | Med ium | GT | V,I | Unable |
| P F | Slow | Medi um–low | Medi um–low | >90% | D | Easy | Med ium | SA | V,I | Unable |
| F L C | Fast | Medi um–high | Medi um–high | >98% | D | Medi um | High | SA, GT | Varie s | Abl e |
| N N | Fast | Medi um–high | High | >98% | D | Diffi cult | High | SA, GT | Varie s | Abl e |
| S M C | Fast | Medi um–high | Medi um | >98% | A,D | Medi um | High | SA, GT | V,I | Abl e |

Traditio nal\ Control methods based on paramete r selection |

Direct control methods based on sampled data |

based on intellige nt control methods |

based on intellige nt control methods |

Nonlinea
| Method          | Control | High | High | >99\% | A,D | Difficult | High | SA, GT | V,I | Able                  |
|-----------------|---------|------|------|--------|-----|-----------|------|--------|----|-----------------------|
| AB C-P\& O      | Fast    | High | High | >99\%  | A,D | Difficult | High | SA, GT | V,I | Able                  |
|                 |         |      |      |        |     |           |      |        |    | Improve direct control methods |
| AC O-P\& O      | Fast    | High | High | >99\%  | A,D | Difficult | High | SA, GT | V,I | Able                  |
| PS O-Cl, etc.   | Fast    | High | High | >99\%  | A,D | Difficult | High | SA, GT | V,I | Able                  |
| PS O            | Fast    | High | Medium–high | >98\% | A,D | Medium | High | SA, GT | V,I | Able                  |
|                 |         |      |      |        |     |          |      |        |    | Artificial intelligence methods |
| AC O            | Fast    | Medium–high | Medium–high | >98.5% | D   | Medium | High | SA     | V,I | Able                  |
| AB C            | Fast    | Medium–high | Medium–high | >99\%  | D   | Medium | High | SA     | V,I | Able                  |
| FA              | Fast    | Medium–high | Medium–high | >98.5% | D   | Medium | High | SA     | V,I | Able                  |
| GA              | Fast    | Medium–high | Medium–high | >98\%  | D   | Easy   | High | SA     | V,I | Able                  |
| DE              | Fast    | Medium–high | Medium | >98\%  | D   | Easy   | High | SA     | V,I | Able                  |
| TC T            | Slow    | Medium–low | High   | <90\%  | A   | Difficult | High | SA     | V,I | Able                  |

Here, SA: stand alone, GT: grid tied, A: analogue, D: digital, V: voltage, I: current
The hybrid MPPT demonstrates enhancement in tracking performance, input current ripple, output power ripple and power conversion efficiency. Also the MPPT implementation is easier and cheaper when compared to other traditional MPPT methods [16].

**Table 3.** Comparison of different MPPT techniques.

| Performance Parameters | Traditional MPPT | IA MPPT | Swarm MPPT | Hybrid MPPT |
|------------------------|------------------|---------|------------|-------------|
| Complexity             | Low              | Medium-high | High       | High        |
| Tracking speed         | Slow-Medium      | Fast    | Fast       | Fast        |
| Cost                   | Low-High         | High    | High       | High        |
| Accuracy               | Medium           | High    | High       | High        |
| Efficiency             |                  | High    | High       | High        |
| Hardware Implementation| Easy-Difficult   | Medium  | Medium     | Difficult   |
| with PSC               | Unable           | Able    | Able       | Able        |

**Conclusions**

This paper presented a comprehensive review of AI-based MPPT techniques. The complete conceptual framework of the MPPT was presented including the main aspects of PV systems components, MPPT types, solar modeling, MPPT characteristics, etc. Affecting factors for solar power generation was listed together with the main parameters that were used in the classification of various MPPT techniques. A summary of performance of the main MPPT techniques was incorporated. This paper also includes an important aspect, which is list the techniques that operate under the influence of partial shading so that the researcher can view and take a complete perception of the topic to be able to choose the appropriate tracking technique.

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