A Comprehensive Review on Recent Maximum Power Point Tracking of a Solar Photovoltaic Systems using Intelligent, Non-Intelligent and Hybrid based Techniques

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Abstract:- **The uncertainty associated with modelling and performance of solar photovoltaic systems could be easily and efficiently solved by using Maximum power point techniques. During the past decade of 2010 to 2021, the classification of techniques based on intelligent, non-intelligent and their hybrid models are found as potential techniques for detecting the maximum power point of a photovoltaic system. In addition, for this decade there is no extensive and comprehensive review on applicability of intelligent, non-intelligent and their hybrid models for performance prediction and modelling of solar photovoltaic systems. Therefore, this article focuses on extensive review on design, modelling, maximum power point tracking, advantages, disadvantages of each technique, evolutionary trend, convergence and tracking speed, and output efficiency prediction of solar photovoltaic systems under partial shading conditions and non-partial shading conditions using intelligent, non-intelligent and their hybrid techniques. Furthermore, a total of 77 selected articles on the solar PV tracking technique and their hybrid models together with the PV technology were reviewed. Total of 22 articles are reviewed and summarized in this review paper for the period of 2010 to 2021 with 12 articles in non- intelligent technique, 7 articles in intelligent technique and 3 articles in their hybrid form. The review showed the suitability and reliability of intelligent, non-intelligent and their hybrid models for accurate detection of maximum power point and the performance characteristics of solar photovoltaic systems. Finally, this review presents the guidance for the researchers and engineers in the field of solar photovoltaic systems to select the suitable techniques for enhancement of the performance characteristics of the solar photovoltaic systems and the utilization of the available solar radiation.**

Keywords:- *Hybrid, Intelligent Technique, Maximum Power Point Tracking, Non-Intelligent Technique, Performance, Solar Photovoltaic.*

I. INTRODUCTION

The conversion of solar energy into electricity has been conventionally used for some years now. The IEA's comprehensive and comparative study of the world energy consumption reviewed that in 2050, more than 45% of necessary generated and transmitted energy in the world will be exclusively produced by solar PV arrays [1]. IEA also stated that as regional energy consumption falls by 7%, the new generation will grow by 41% with renewable sources providing 81% of total output by 2050 which is the largest share in the world [2].

The major component of a solar photovoltaic (PV) system is the PV module which is made up of solar cells. A solar cell converts the energy in the photons of sunlight into electricity by the means of the PV phenomenon found in certain types of semiconductor materials such as selenium (Se) germanium (Ge) and silicon (Si). In isolated operation, Photovoltaic cell produces a negligible amount of power. To produce substantial electrical output power, solar cells are connected in series and parallel to form a PV module. PV cells are connected in series to increase voltage output and connected in parallel to increase the current output [3].

The efficiency and performance of solar PV module depends on factors such as: geographical factors (latitude, longitude and irradiation), Environmental factors (pollution, humidity, wind, temperature, Dust and rain) and Photovoltaic technology (crystalline, monocrystalline, polycrystalline and thin film). So, for PV solar energy to be efficiently and economically used, there is a need to study the environmental parameters that can negatively affect the performance of the PV system and also to deploy the best method to minimize it. However, the solar modules are rated

under Standard Test Conditions (STC) with irradiance of $1000W/m^2$, ambient temperature of 25˚C and Air Mass of 1.5 [4].

II. CLASSIFICATIONS OF SOLAR PHOTOVOLTAIC TECHNOLOGY

The Solar PV cell technologies are generally classified as thin-film solar PV cell technology, Wafer-based crystalline solar PV cell technology and other recently emerging technologies.
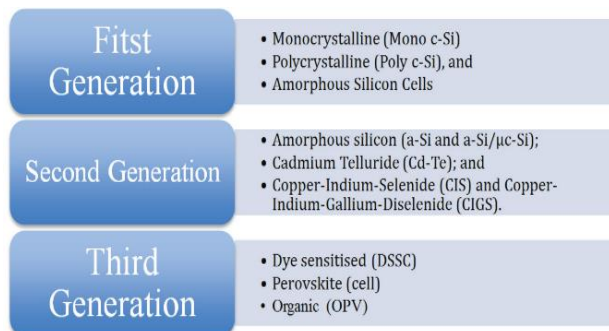

Figure 1: Classification of Solar Cell Technologies [5]

The two major commercial photovoltaic technologies being used by the PV designers due to their trending availability in the renewable energy market as in figure 1 are:

(a) Wafer-based Solar cells made from crystalline silicon either as single or polycrystalline wafers.

(b) Thin-film products typically incorporate thin layers of PV active material placed on a glass/metal substrate using vacuum deposition. The disadvantage of commercial thin-film materials is that there is huge loss in the output thickness of the PV array [6].

2.1 Crystalline Silicon (c-Si)

Crystalline silicon (c-Si) is the most used semiconductor material for the manufacturing of photovoltaic solar cells. These cells are arranged in parallel and series into a solar panel to produce solar power from the sunlight. Electronically, a monocrystalline silicon is used in the production of microchips. Crystalline silicon is also known as the first generational solar cells, as they were the first silicon wafer and rampant type with good quality. The c-Si known as wafer based silicon solar cells are made from wafers with characteristics such as thickness of 160/190μm, efficiency of 25.6± 0.5%, areas of $143.7cm^2$ and Voc of 0.740V [7][5].

2.2 Polycrystalline Solar Cell (Multi-Si)

Another name for polycrystalline silicon is Polysilicon (Poly-Si) and it is a highly purified type of silicon used by solar PV companies as raw material. Siemen process is a method of producing polysilicon from high grade metallurgical silicon using chemical purification processes. This process is directly cast into multi-crystalline ingots to grow single boule of silicon crystals. The crystals are then sliced into wafers, assembled for the production of solar PV cells. The advantage of Polysilicon cells used in

photovoltaics is that it is less expensive. The disadvantage is that it is less efficient compare to those made from monocrystalline silicon [8][9].

2.3 Amorphous Silicon Solar Cells (a-Si)

Amorphous silicon is one of the most well-developed of the thin-film technologies for over the years. Amorphous silicon comprised of non-crystalline or microcrystalline form of silicon. The high band gap (of 1.7eV) of amorphous silicon materials made it an outstanding type of silicon technology which gave it an advantage over c-Si of 1.1eV energy. The visible light spectrum was absorbed by top cells of the amorphous silicon while the infrared spectrum of the bottom cells will be taken care of by Nc-Si. An a-Si is widely used in the production of pocket calculators and also to power some private homes and thin-film transistor in LCDs [10][9][11].

2.4 Multi-Junction Solar Cell (M-J)

Multi junction solar cell consists of different semiconductor materials that were made of multiple p-n junctions. The type of p-n junction material and the wavelengths of light absorbed by the cell will determine the quantity of electric current to be generated. The use of multiple semi-conducting materials improves the efficiency and rate of conversion of sunlight by the cell to electrical energy. Furthermore, each layer of the junction has different band gap which allows it to absorb electromagnetic radiation over different portions of the spectrum. The Advantage of M-J cells is that it is used in special application such as space exploration and satellite. It is also used in Concentrator Photovoltaics (CPV) to focus sunlight on a small highly efficient M-J solar cells [12] [9].

2.5 Quantum Dot Solar Cells (QDSC)

A QDSC was designed to make use of quantum dots as a PV absorbing material. With the rapid growth of QDSC, if no characteristic defect is detected in nearest feature it will replace other bulky materials such as Copper Indium Gallium Selenide (CIGS) or CdTe and Silicon. The excellent characteristics of changing the dots' size of QDSC due to its tunable band gap makes it attractive for multi junction solar cells. This is because varieties of materials are used to improve the efficiency of QDSC by effectively harnessing M-J portions of the solar [9][13].

2.6 Dye-Sensitized Solar Cells (DSSC)

Dye-sensitized solar cell (DSSC) is a third generational PV solar cell that converts visible light into electrical energy. DSSC is a disruptive technology that is very sensitive to light that it produces electricity at indoors and outdoors. Its high sensitivity to light enables it to rapidly converts both natural and artificial light to a reasonable quantity of electrical energy. A DSSC is a thin-film PV formed between electrolyte and photo-sensitized anode to yield photo-electrochemical system. The advantage of DSSC is that it is less expensive compare to conventional solid state electronic solar cell designs [14][9]. Another advantage is that, it also converts artificial light into electrical energy even at indoor state.

2.7 Perovskite Solar Cells (PSC)

Perovskite cells are lead-halide based with crystal structures. A perovskites material is a hybrid solar cell material known as organic-inorganic solar cell material [15][16]. The general chemical formula for perovskite material is given by ABX3 where A is organic or inorganic Cation (Na$^+$, CH$_3$NH$_3$$^+$ etc), B is inorganic Cation (Pb^{2+}, Sn^{2+}, Fe^{2+} etc) and X is inorganic Anion (Cl$^-$, I$^-$, O^{2-}) [17] [18] [19]. It is produced from the by-products of crude oil (methyl ammonium and ethyl ammonium) and inorganic compounds (lead iodide, tin iodide) [20]. The advantages of Perovskite materials are (a) direct optical band gap (b) broad light absorption (c) bipolar transport (d) long carrier diffusion length and finally its flexibility [11] [21][22].

III. MAXIMUM POWER POINT TRACKING (MPPT)

Maximum Power Point (MPP) can be defined as the point along PV curve where the output power has the maximum value with minimum conductance. An embedded device that continually searches and locates the MPP of a photovoltaic panel is called Maximum Power Point Tracker (MPPT) [23].

Maximum power point tracking is a tracker enhancement incorporated into a charge controller that isolates the charging equipment output power from the restrictive effect of the battery, for effective utilization of the output maximum power of the charging equipment. MPPT can also be described as an electronic system that operates the photovoltaic modules in a sequential and chronological manner that permits the module to transfer nearly all the generated power to the load.

3.1 Theory of Maximum Power Point Tacking

MPPT is not a mechanical form of tracking where there is a physical move of the panel to make it point directly at the direction of the rays of the sun. **Solar tracking system** was one of the popular ancient manual ways of tracking, that involves aligning Photovoltaic solar panels to the direction where the solar irradiation is at highest. The disadvantage of this conventional technique is that it consumes times, power losses during manual panel transfer from low irradiance position to higher irradiance position. However, the aforementioned drawbacks of solar tracking technique led to introduction of MPPT. Furthermore, MPPT technique was embraced to effectively and efficiently transfer the generated power from the Photovoltaic panel to the load with minimal power loss. Despite the use of MPPT not all the power generated by the photovoltaic panel were transferred to the load due to losses as a result of hysteresis.

MPP is a point along P-V curve where the photovoltaic module transfers the highest percentage of the power generated to the load. It can also be described as the point along P-V characteristic curve where the impedance of the load is equivalent to the impedance of the solar photovoltaic panel. At this mentioned point the generated power is nearly transferred to the load with negligible loss. The quantity of

power transferred from the solar PV panel to the load depends on the available maximum power harvested form the PV panel and also on the efficiency of the MPPT [24][25].

3.2 Maximum Power Point Tracking Technique

MPPT technique is one of the various tracking techniques that has been validated and adopted to ensure that almost all the generated power from the solar photovoltaic panel are transferred to the load with minimal energy loss. Many techniques have been used in MPPT to ensure effective power transfer. MPPT technique is broadly classified into intelligent and non-intelligent techniques. Some of the non-intelligent techniques are Fractional Short Circuit Current (FSCC) Technique, Fractional Open Circuit Voltage (FOCV) Technique, Perturb and Observe (P&O) technique, Adaptive Perturb and Observe (AP&O) technique, Incremental Conductance (INC) technique, Improved Incremental Conductance (IINC) technique, Random search method, DIRECT Search (DIRECT SA) method [26] and Optimized Adaptive Differential Conductance (OADC) technique. Intelligent MPPT techniques comprises Particle Swarm Optimization (PSO), Takagi-Sugeno (T-S) Fuzzy technique, Artificial Neural Network (ANN) and Fuzzy logic techniques, scanning particle swarm optimization [27][28].

3.2.1 Non-Intelligence Maximum Power Point Tracking Technique

The non-intelligence MPPT technique is one of the conventional tracking techniques with little improvements. They have excellent performance with fast response without overshoot and less fluctuations/oscillation at MPP when experiencing rapid atmospheric change. It is implementable at low cost and with high efficiency. Examples of Non-intelligence MPPT techniques are Perturb & Observe (P&O), Improved Incremental Conductance (IINC), Dividing Rectangle Search (DIRECT SA), Incremental Conductance (INC), Fractional Open Circuit Voltage (FOCV), Random Search Method (RSM). Centralized, Distributed and Reconfiguration Technique for Mismatching Conditions, Variable Indicator and Scaling Factor, Fractional Short Circuit Current (FSCC), Adaptive Perturb & Observe (AP&O) and Optimized Adaptive Differential Conductance (OADC) [29] [30] [31].

3.2.1.1 Fractional Short Circuit Current (FSCC) Technique

Fractional Short Circuit Current under varying atmospheric conditions is determined when current at its maximum power point is equivalent to the product of proportionality constant and short circuit current in a PV arrays as shown in (1).

$$I_{mpp} = K_2 * I_{sc} \qquad (1)$$

Where: K_2 = proportionality constant; I_{sc} = short circuit current

The proportionality constant determined from the PV array range from 0.78 to 0.98 [32]. Boost converter is used to enhance the efficiency of the technique because the

switching elements in the power converter acts as switch to short down the circuit [33]. At STC short circuit current is equal to current of the photovoltaic.

The main advantage of fractional short circuit current technique is its low cost of implementation and simplicity. The drawback of this technique is its inability to track the real MPP due to parametric approximation. Secondly, power losses due to periodical shortening of the solar PV array using additional switches in control of I_{sc}

3.2.1.2 Fractional Open Circuit Voltage (FOCV) Technique

Fractional open circuit voltage technique is one of the simplest MPP techniques that is used to determine the MPP of a PV array at constant voltage. This technique makes use of linear relationship between Voltage Maximum Power Point (Vmpp) and Open circuit Voltage (Voc) of the PV array under varying temperature and irradiance as expressed in equation (2) [33].
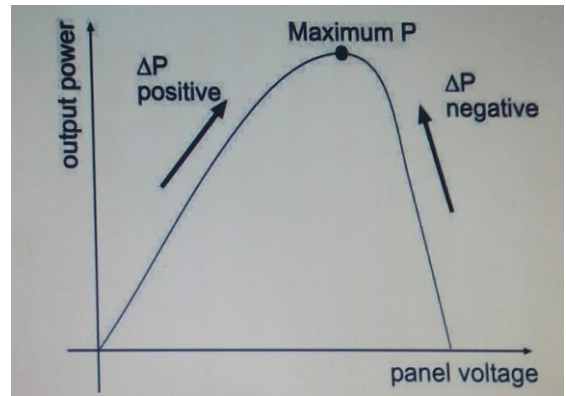
$$V_{mpp} = k_1 * V_{oc} \qquad (2)$$

Where; k_1= proportionality constant (0.71≤k1≤0.78);
V_{oc} = Open Circuit Voltage
V_{mpp} = Maximum Power Point Voltage

The proportionality constant is dependent on the PV array characteristics in use as it is computed by dividing V_{mpp} by V_{oc} at different temperature and irradiance [32]. V_{mpp} can be obtained by measuring V_{oc}. Intermittently.

The advantage of this method is that it is easy to implement because of the use of analog devices which is simple and cheap unlike digital components. The drawbacks of FOCV are; it has low algorithm efficiency due to power loss during the measurement of V_{oc} and the error in k_1. Secondly, inability to tracking the real MPP due to the use of approximation to determine the relationship between V_{oc} and V_{mpp} [33].

3.2.1.3 Perturb & Observe (P&O) Technique

The P&O technique makes use of operating voltage modification concept to modify the operating voltage of the photovoltaic panel until the maximum power is harnessed. The PV array operating voltage is perturbed by small increment which results to observable change in power [34]. The positive change in power led to voltage perturbation moving closer to the MPP which further voltage perturbation along same direction will make the MPPT to locate the maximum power point. Furthermore, the negative change in power shows that the OP has moved away from the MPP and the direction of the voltage perturbation should be reversed to return back towards the maximum power point as shown in figure 2 [34].

Figure 2: P-V Characteristics for P&O Algorithm [34]**.**

Equation (3) and table 1 showed the working principle of P&O algorithm. The algorithm continuously decrements or increments with respect to reference voltage based on the previous data until the MPP is attained. When $\frac{dP}{dV} > 0$, the operating voltage of the Photovoltaic array will be perturbing within a specified direction, that means that the perturbation has moved operating point of Photovoltaic array towards the MPP and reverse is the case when $\frac{dP}{dV} < 0$. Perturb & Observe technique therefore, will continue to hover the PV voltage in the direction of the MPP [35].

$$When\ \Delta P < 0, \& V(j) < V(j-1), then\ Vref = V(j+1) = V(j) + \Delta V \quad (3)$$

Table 1: Truth Table Summarizing P&O Algorithm
[36][37][38]

Sign of Δv	Sign of ΔP	Direction of next step
Positive	Positive	+C
Negative	Negative	+C
Negative	Positive	-C
Positive	Negative	-C

The two approaches used for successful modelling of perturb and observe algorithm are the **Reference Voltage Perturbation** which is used as control parameter together with PI controller to regulate the duty ratio of the MPP output power converter and **Direct Duty Ratio Perturbation** that is used as control parameter to limit the need for a Proportional-Integral controller which enhanced stability and minimized circuit complexity of the system. This technique led to better energy utilization and enhance stability characteristic at lower transient response but was worse performance achieved at rapid atmospheric change [36].

The advantage(s) of P&O technique is inexpensive, simple and ease of implementation. The main drawback of this technique is the inability to determine the real MPP and its deviate from MPP during rapidly atmospheric change such as shading [39] [40]. This drawback has caused a lot of problem in MPPT and that leads to improvement in P&O technique to adaptive perturb and observe.

3.2.1.4 Adaptive Perturb and Observe (AP&O) Technique

The Adaptive Perturb and Observe technique is developed to sort out the pitfalls of conventional P&O [41]. In this technique the current perturbation is considered instead of voltage perturbation unlike the conventional P&O. Two algorithms are developed for this technique which are Current Perturbation Algorithm (CPA) and Adaptive Control Algorithm (ACA). ACA is developed to set the operating point closer to MPP by estimating optimal proportional constant (Ksc-opt) and the Short Circuit Current (Isc). Sudden change in irradiance (ΔS) or PV current (ΔI_{ph}) activates ACA. **CPA** was developed based on tracking current perturbation by increasing tracking speed. ACA is developed using a concept where the new operating point is ascertained based on its nearness to MPP. The new operating point is obtained by multiplying k_{sc_opt} with I_{sc}. This algorithm will be activated when there is sudden change in irradiance. The AP&O algorithm is calculated using equation (4)

$$I_{ref} = I_{pv}(k) + sign\left(I_{pv}(k) - I_{pv}(k-1)\right) *$$
$$sign\left(p_{pv}(k) - p_{pv}(k-1)\right)\Delta I \qquad (4)$$

Where; $I_{pv}(k)$ = PV panel current at kth iteration;
$p_{pv}(k)$ = PV panel power at kth iteration
ΔI = Change in current perturbation size; Sign = Polarity (± 1) of the inside value.

The major advantage of AP&O technique is that the oscillation around the MPP is drastically reduced due to variable current perturbation [39]. The drawback of AP&O technique is its expensiveness, circuit complexity and inability to locate the real MPP at rapid atmospheric change which led to development of incremental conductance technique.

3.2.1.5 Incremental Conductance (INC) Technique

Incremental conductance technique based its technology on adjustment of MPP voltage to suit the terminal voltage of the grid [42]. This technique deals with the incremental and instantaneous conductance of the photovoltaic module. From equation (5) and figure 3, it showed that at MPP the slope of the Photovoltaic array power curve is zero, and equation (6) showed that when the incremental conductance is greater than the instantaneous conductance the MPP is located at the left-hand side and when the incremental conductance is less than the instantaneous conductance the MPP is located at the right-hand side. The equations were based on $\frac{\partial i}{\partial v}$, where V and I are the output voltage and output current respectively. The direction at which the MPPT operating point tracks is calculated based on the relationship between $\frac{dI}{dV}$ $and -\frac{I}{V}$. This relationship is glean from the fact that $\frac{dP}{dV}$ is always negative when the algorithm needs to track back because the MPP is located at the right hand side and when positive reverse is the case [43]. The left-hand side and the right-hand side of equation (6) were the incremental conductance and instantaneous conductance of the solar photovoltaic module respectively. In this technique, both current and

voltage are sensed simultaneously and it reduced tracking error due to rapid atmospheric change. The drawback of this technique is its circuit complexity and high cost of implementation [44][32]. Secondly the accuracy is low as it kept on tracking and re-tracking
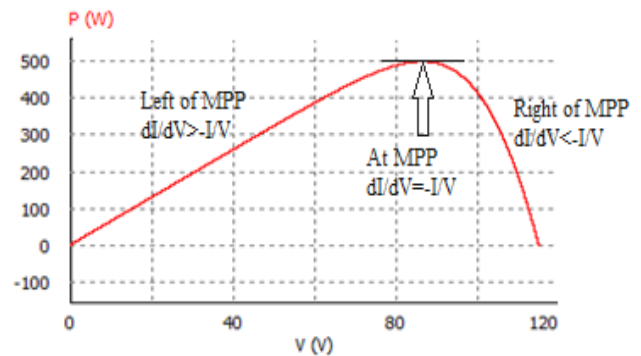
$$\frac{dI}{dv} = -\frac{I}{v} \qquad At\ MPP \qquad (5)$$

$$\left.\begin{array}{l} \frac{dI}{dv} > -\frac{I}{v} \qquad left\ of\ MPP \\[2mm] \frac{dI}{dv} < -\frac{I}{v} \qquad Right\ of\ MPP \end{array}\right\} \qquad (6)$$

The working principle of this technique makes use of hypothetic ideology that takes the cognizant of the differential of output power with respect to output voltage to be equal to the output instantaneous conductance. Power transferred to the load from the solar PV panel is expressed by (7) [36].

$$P = VI \qquad (7)$$

Differentiating with respect to V and equate dp/dv to zero at MPP equation (4) will be obtained.

$$\frac{dI}{dV} = -\frac{I}{V} \qquad (8)$$

Figure 3: P-V Characteristic for Incremental Conductance Algorithm [42]

Incremental conductance technique follows the photovoltaic curve as expressed in figure 3 and it follows the working procedures of increasing and decreasing as: when the present sensed power is greater than the previous sensed power, the operating voltage increases and vice versa. And when the present sensed power is equal to the precious sensed power, the operating voltage remains constant [25]. The control signal of the INC output is used to adjust the reference voltage of the PV array by either increasing or decreasing a constant change in voltage to the previous reference voltage [45].

The advantage of this technique is that it has good tracking efficiency and also the ability to extracted/harvest power from the panel effectively. Therefore, Incremental conductance technique solved the drawback of P&O which is the inability to track MPP under rapid atmospheric change. INC technique curbed this aforementioned pitfall of

P&O by having the ability to determine when MPP has attained with better accuracy despite the rapid atmospheric change. The drawback of INC technique is that its control circuitry is expensive and it oscillates within the MPP. The MPP is inaccurately determined under low computation of incremental conductance due to low tracking speed. Hence, this drawback lead to another technique called improved incremental technique (IINC) [46].

3.2.1.6 An Improved Incremental Conductance (IINC) Technique

In [46], an Improved Incremental Conductance (IINC) technique was developed to solve the problem of conventional INC technique. This method was achieved by computing the differential of power to voltage as in (9).

$$\frac{dP}{dV} = \frac{p(k) - p(k-1)}{v(k) - v(k-1)} \qquad (9)$$

Furthermore, incremental conductance and constant voltage (CV) algorithms were combined for the estimation of the Voltage Maximum Power Point (Vmpp) which limits the search space for incremental Conductance algorithm. The Constant Voltage technique makes use of operating voltage at the MPP which is linearly proportional to the Voc of the solar PV panels with rapid change in irradiance and temperature. The ratio of V*mpp* to (Voc) is commonly used for INC technique. The IINC technique is implemented by dividing the PV characteristic into three areas where area 1 is from 0 - 70%Voc, area 2 is from 70%Voc - 80%Voc, and area 3 is from 80%Voc – Voc. The area 2 is the area of major interest as shown in Figure 4. The IINC technique searches for the MPP within the mapped area of interest as in equation (12)

$$V_{ref} = (70\% - 80\%)Voc = (V_1 - V_2) \quad (12)$$

The MPPT algorithm of IINC sets the solar photovoltaic panel current momentarily to zero and allowed it to measure and record the panels' Voc.

The advantage of this method over conventional INC and P&O is the increase in convergence speed which improves the accuracy of the tracking. The drawbacks of this technique is that it operates under ideal condition where shading and irradiance were not considered as a factor and it has a complex circuitry. This drawback leads to more research work by researchers to improve MPP tracking technique.

3.2.1.7 Random Search Method (RSM)

RSM technique is developed to curb the problem of MPPT under Partially Shaded Condition (PSC)[47]. Random Search Method is a direct search and gradient-free model with mathematical analysis. The Power generated by PV systems under PSC are largely non-linear and multimodal in nature and as a result of that, global optimization technique is required to maximize the power generated and transferred to the load. In RSM, random numbers were used to locate the global optima and gradient independent of the system. This technique works by

generating and moving a sequence of improved functions towards a better solution. Consider a function, with n variables $f(x_1, x_2, \dots, x_n)$, this function is to be maximized using RSM step by step technique.

Therefore, iteration number k= 1. Assign a random number to each variable X_i^k ($X_{i,min}$, $X_{i,max}$). For n – dimensional function $f^k = f(X_{1,}^k X_{2,}^k, \dots, X_{n,}^k) = f(X^k)$. This generates a set of n random numbers $r_1, r_2 \dots, r_n$ each lying within the range [-1, 1] and unit vector u as given in (11)

$$u = \frac{1}{(r_1^2 + r_2^2 + \dots + r_n^2)^{(1/2)}} \begin{Bmatrix} r_1 \\ r_2 \\ . \\ . \\ . \\ r_n \end{Bmatrix} \qquad (11)$$

For the next iteration, a new vector X^{k+1} is computed and the corresponding function values is as given in (12) and (13)

$$X^{k+1} = X^k + u\lambda \qquad (12)$$

$$f^{k+1} = f(X^{k+1}) \qquad (13)$$

Where: λ = initial step length

The microcontroller embedded in this technique continuously monitors PV output power and ensure that the deviation is not beyond 0.4% of the rated power else the microcontroller reinitiate the RSM [47][48].

The advantage of RSM is its less memory requirement and simple computational steps. The drawback is that the MPP accuracy is not guaranteed as the compiler has a random computer generator library that can generate wrong values/data.

3.2.1.8 Dividing Rectangular Search Algorithm (DIRECT SA) Technique

The Dividing Rectangular Search Algorithm (DIRECT SA) was developed to solve the problems of Perturb and Observe and Incremental conductance techniques [26]. DIRECT SA has the same ease of implementation, better performance and fast-tracking speed, especially during PSC as P&O and INC techniques. The approach is based on the DIRECT SA algorithm which was developed for searching the global maxima of a Lipchitz function with a specified interval. The flowchart and working principles were as shown in in figure 5a. The advantage of DIRECT SA is its fast and better tracking speed. The disadvantage is inability to detect the real MPP during tracking which lead to introduction of optimized adaptive differential conductance.
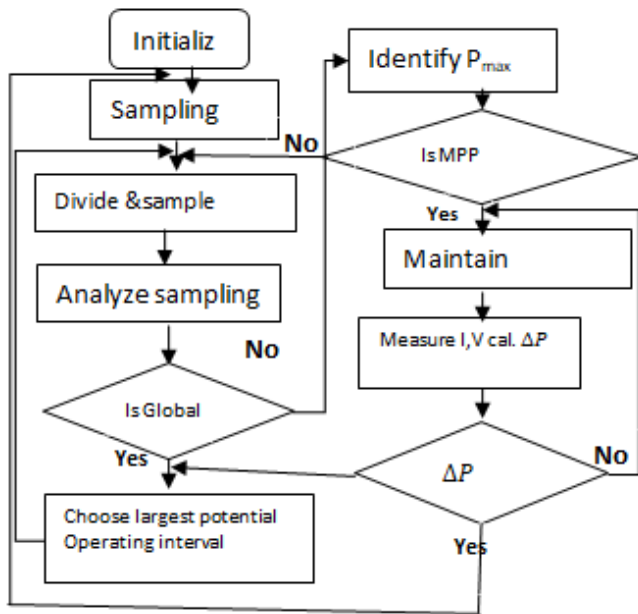
Figure 5a: Flowchart of DIRECT SA Technique.

3.2.1.9 Optimized Adaptive Differential Conductance (OADC) Technique

This involves analytical method that uses single diode model for its derivation. It deals with comparing and balancing the impedance of the load with the impedance of the solar PV panel with respect to their respective conductance. The major difference between this technique and the existing conventional INC technique was that conventional INC differentiated the current and the voltage while OADC differentiated current and voltage at its maximum power points.

Equation (12) is the analytical equation of OADC which through its recursive nature solved curbed the inaccuracy in tracking under partial shading conditions.

$$
\begin{aligned}
&= \left(\frac{\left(\frac{AnKT}{qR_s} \log_e\left(1 + \frac{1}{1000I_o}\right) \left[1 + k_i(T - T_{ref})\right]\frac{G}{G_{ref}}\right)}{V_{mpp}} \right. \\
&\quad \left. \frac{- \text{Io}\left[exp\left(\frac{qV_{mpp}}{AnKT}\right)\right]}{V_{mpp}} \\
&\quad - \frac{I_o q}{AnKT} \exp\left(\frac{Vq}{AnKT}\right) \right) \quad (12)
\end{aligned}
$$

From equation (12), the right-hand side is the panel impedance and the left-hand side is the load impedance. The tracking involves balancing the impedance of the load with that of the panel by driving the operating point as close as to the maximum power point.

Form the graph of figure 5b it was observed that the degree of accuracy of the technique was very high as the MPP was detected at an exact point along the P-V curve where the resultant conductance is nearly zero. This show the degree of accuracy of the technique but some factors where not considered during analytical development such as the module saturation current which leads to low power computation of the technique.

The advantage of OADC is that it accurately detects the MPP without much delay but it has a major drawback of low power conversion. This low power conversion has led to more research in this area to improve the power generated and transferred to the load by considering the module saturation current (Io) mathematically not by assigning constant value to it [30].

3.2.1.10 High Gain DC-DC Converter with Model Predictive Control (HGCMPC) Technique

In [49], this technique proposed the improvement of the power delivery to the load by designing a high DC-Dc converter which will serve as a booster to the Panel. The contribution of this author in this research paper is the development of model predictive control maximum power powering tracking (MPC-MPPT) control algorithm with optimum number of sensors based on fixed and adaptive step-size and implementation of a new high step-up without transformer DC- DC converter. The DC-Dc converter was designed with two inductors, three diodes, one output capacitor and two power switches.
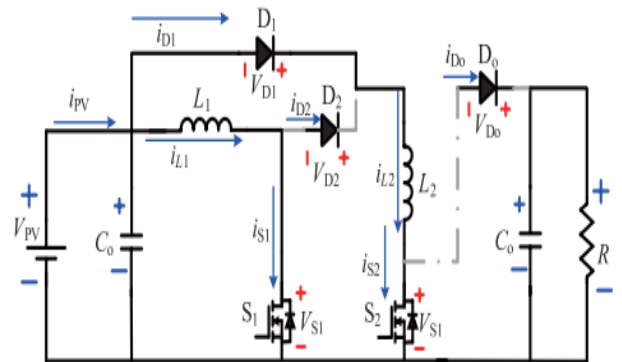

Figure 6: Typical diagram of the new high gain DC-DC under first condition.

Under continuous conduction mode (CCM), the converter has two modes of operation depending on the switch status (0 or 1). The new DC-DC converter was designed to operate successfully under two conditions as detailed below. The first conditions occur when the two switches are triggered on with high pulse signal. once the switches are turned on, diodes D2 and Do are turned off and inductors L1 and L2 are being charged from the DC source. The characteristics equations and diagram of this first condition is as shown in equation (13) and Figure (6).

$$\left.\begin{array}{c} V_{L1}(t) = V_{PV} \\ i_{PV}(t) = c_{PV}\frac{dVV_{PV}}{dt} + 2i_{L1} \\ V_{L2}(t) = V_{PV} \\ c_o\frac{dV_0}{dt} = i_{Co} = \frac{V_o}{R} \end{array}\right\} \qquad (13)$$

Second condition occurs when two switches a trigged off at low pulse signal and that turns D2 and Do on to provide a path for the inductor currents and diode D1is turned off. Furthermore, inductors L1 and L2 discharges energy in series to the output capacitor. These conditions were repeated every switching cycle for effective operation. Inductor volt-second balance and capacitor charge balance are the base criteria where the input-output voltage was obtained. The characteristic equation and figure of second condition were shown as in equation (14) and figure (7).
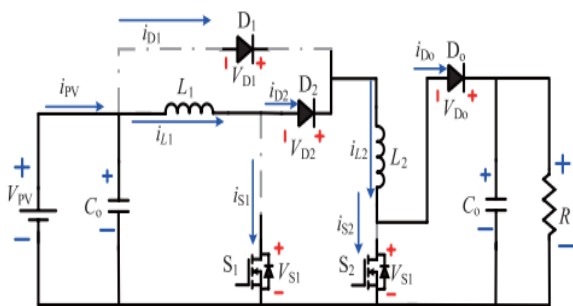

Figure 7: **Typical diagram of new high gain DC-DC under second condition**

$$\left.\begin{array}{c} V_{L1}(t) = V_{L2}(t) = \left(\frac{V_{PV} - V_o}{2}\right) \\ i_{PV}(t) = c_{PV}\frac{dVV_{PV}}{dt} + i_{L1} \\ c_o\frac{dV_0}{dt} = i_{Co} = i_{L1} - \frac{V_o}{R} \end{array}\right\} \qquad (13)$$

From the deduced equations and techniques, it was observed that the technique fulfilled its objectives and was validate in figure (8).

From figure 8 it was deduced by the author that the DC-DC converter has an outperforming efficiency compared to other techniques used for the validation

The advantage of this technique is that its output voltage sensor was replaced by an observer to optimize the system cost and at the same time maintain the same performance. Secondly, the developed algorithm work with fixed and adaptive step-size that makes it to operate within a specified region.

The disadvantage of this technique is that working with variable switching frequency uneased the optimum design of the power converter and it has complex circuitry.

3.2.1.11 Control Strategies for Optimum Utilization (CSOU) technique

This technique made use of three strategic methods to achieve high efficiency. The three strategies are extraction of maximum power from PV system under fast varying irradiance method, extraction of high voltage gain with DC-DC converter method and development of efficient power management scheme between SPV and Energy Storage System (ESS) for reliable storage. The new MPPT algorithm developed in this review paper makes use of slope detection method and variable step perturbation and observation algorithms to effectively detect the real MPP.

In this technique a variable step size was used to decreases the step size and modified INC algorithm to increase the converging speed with fast varying irradiance. The interception between the load line and I-V curve is used to determine the MPP as shown in figure 10. The new algorithm did not consider dp/dv =0 rather considered dI/dV+I/V<0.06 as a fixed point. The high voltage gain was configured with Soft Switch Interleaved Boost Converter and the voltage gain was expressed as in equation (14) and figure 9 is the Soft Switch Interleaved Boost Converter (SSIBC) for high voltage gain applications.
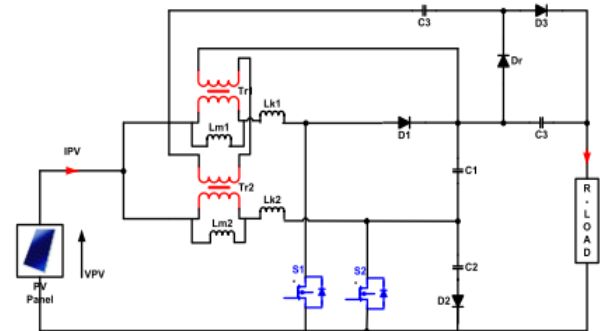

Figure 9: Block Diagram of SSIBC for High Voltage Gain Applications

Figure 9 operates in four modes of operation and the switches are operated in any one of the three ways as shown in table 2.

Table 2: Switching Sequence for Proposed SSIBC

S/N	1	2	3
S1	ON	ON	OFF
S2	ON	OFF	ON

$$M = \frac{Vo}{Vpv} = \frac{2}{1-D}[1+N] \qquad (14)$$

After the node and branch mathematical analysis in [50], equation (14) was obtained which helped curtail the leakage currents and improve the duty circle for fast tracking.
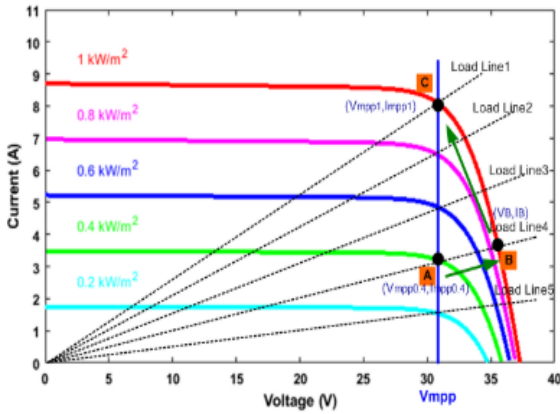
Figure 9: I-V Curve at Difference Irradiance with Load Line

Points A, B, C in figure 9 are the intercepting points between the load line and the current-voltage curve where the MPP is located. It was all so stated that Vmpp multiply by Impp gives MPP.

The advantage of this technique is that it reduces the steady state oscillations which improves the dynamic performance of the whole system. Secondly at medium duty ratio a very high voltage gain is obtained. The disadvantage of this technique is that there are a lot of power loss during switching and secondly, the system compilation is slow in action.

3.2.1.12 Enhanced Adaptive Extremum-Seeking Control (EAESC) Algorithm

This makes use of Tylor expansion to find the optimum of the extremum and it makes use of two methods [51] This is the most recent non intelligent based MPPT as of the compilation of this review paper.

This technique developed a new MPPT algorithm based on the adaptive Extremum Seeking Control (ESC) method to track the Global Maximum Power Point (GMPP) while improving tracking efficiency, convergence time, and accuracy in a PV system. An adaptive loop is utilized to yield variable perturbation signal amplitude by using the measured power of the PV system. This technique overcome the problem of low computational complexity by using the quantity of ESC- based MPPT algorithm to add perturbation adaptation. The perturbation amplitude of this new MPPT changes only when the power variation of the system is greater than the reference value. With this new technique, small change on the amplitude are sufficient to guarantee that the system does not achieve Local Maximum Power Point (LMPP) and to avoid large oscillations in the output response. Hence, convergence time, power oscillations in steady state, and accuracy in tracking the GMPP considering partial shading condition was evaluated in this technique.
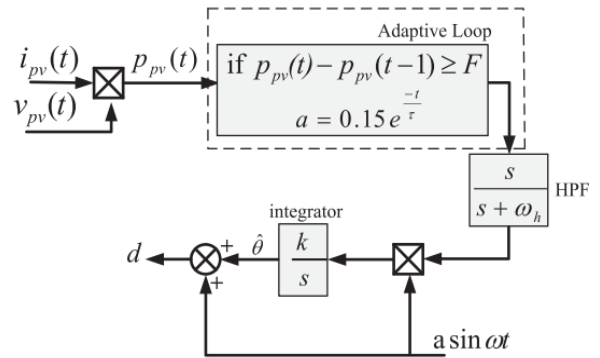

Figure 10: Schematic Working Diagram of MPPT Algorithm of Adaptive ESC

This technique was achieved by analyzing the figure 10 by adding a sinusoidal perturbation signal at the plant input (modulation) and multiplying the output by the same signal (demodulation) after a high-pass filter (HPF). Using Taylors expansion rule around θ*, the function (f) within the loci will be written as in equation (15).

$$\theta - \theta^* = a \sin wt - \tilde{o} \qquad (15)$$

Therefore, after all the necessary analytical processes the result signal is given as in equation (16)

$$\xi = \frac{a^2 f''}{2} \tilde{o} + \frac{a^2 f''}{2} \tilde{o} cos2wt + \frac{af''}{2} \tilde{o}^2 sinwt + \frac{a^3 f''}{8}(sin3wt - sinwt) \quad (16)$$

The adaptive ESC equation was given as in equation (17) for effective and efficient tracking

$$Ppv(t) - Ppv(t-1) \geq F \qquad (17)$$

Where: $Ppv(t)$ = immediate calculated PV power, $Ppv(t-1)$ = previous calculated power, F=predetermined value of power variation. The working principle is that, if the power variation is greater than a predetermined value (F), the amplitude is increased during a short time to help the ESC algorithm escape from a local optimum and get close to the global maxima. The amplitude (a) will be set as in equation (18).

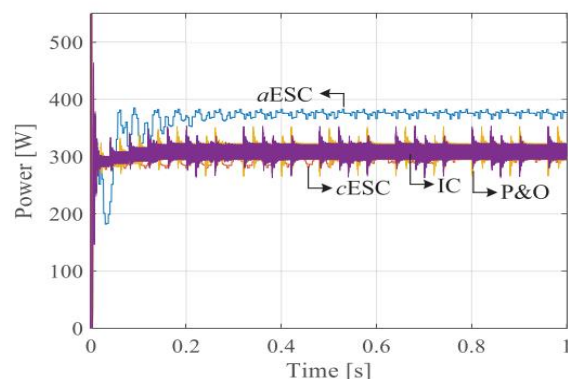$$a = 0.15e^{-\frac{t}{r}} \qquad (18)$$

Figure 11: Validation Result of the Developed Technique

This reviewed technique involved both theoretical and practical work, from the validation it was observed that the technique is outperforming others used in the validation.

This reviewed paper has advantages over the other non-intelligent based MPPT technique such as its ability to locate the global maxima in a very short time and the less circuit complexity due to the use of already ESC developed algorithm. As of the time of this review it was observed that Enhanced MPPT Algorithm Based on Adaptive Extremum-Seeking Control Applied to Photovoltaic Systems Operating under Partial Shading has the best MPPT tracking speed, convergence time and excellent performance based on MPPT tracking under partial shading conditions.
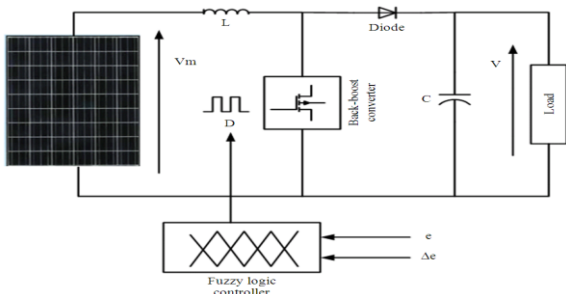
3.2.2 Intelligent MPPT Techniques

The introduction of intelligence in maximum power point tracking of a PV systems is very promising and a lucrative area for researchers. The technique has a very good MPP tracker with excellent performance in terms of accuracy and speed during PSC. Examples of intelligence MPPT techniques are Fuzzy Logic (FL), Particle Swarm Optimization (PSO), Artificial Neural Network (ANN), Improved Particle Swarm Optimization (IPSO) [39], Scanning Particle Swarm Optimization (SPSO).

3.2.2.1 Fuzzy Logic Control (FLC) Technique

Fuzzy Logic (FL) was introduced by L. Zadeh in 1965 and the concept was based on approximate reasoning technique [52]. FL was used to curtail the unsolved MPP tracking problem such as inability to track the real MPP and tracking delay or oscillation within the MPP region. Microcontroller makes artificial controlling technique so easily because it allows embedment of complicated programs, codes and algorithm for a specific target. FLC can also be applied in biometric and series predictions applications. The five operational fuzzy rule-based system is expressed as show below:
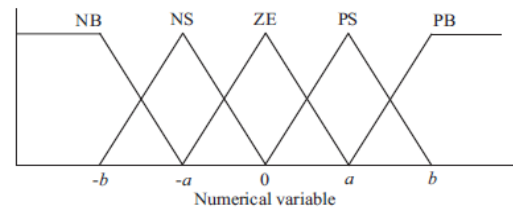
- A database which defines the membership functions of fuzzy sets is used in the fuzzy rules.
- A fuzzification interface which transforms the crisp inputs into degrees of match with linguistic values.
- A rule base containing a number of fuzzy IF THEN rules.
- A decision-making unit which performs the interference operations on the rules.
- Defuzzification interface which transforms the fuzzy results of the inference into a crisp output.
-

Figure 12: Block Diagram of Designed Fuzzy Logic MPPT System [53]

Figure 12 is a diagrammatic representation of designed fuzzy logic MPPT with Fuzzy Inference System (FIS) operational techniques [54]. The three stages of Fuzzy logic control system are; *fuzzification, defuzzification and fuzzy rule base table* [33].

Fuzzification: Fuzzification is the process of converting crisp inputs to fuzzy memberships, transforming numerical crisp inputs into linguistic variables for it to be used in fuzzy interference system [54] [55]. The number of membership function in use will determine the level of accuracy of the fuzzy. Therefore, the higher the number of membership functions, the better the controller accuracy. Membership function varies between 5 and 7 [8, 16, 20, 47]. Figure 13 is the five fuzzy functional levels where acronyms were represented as positive Small (PS), Positive Big (PB), Negative Big (NB), Negative Small (NS) and Zero (ZE). The variables a and b are the values covered by each of the membership function and in some situations made less symmetric to prioritize and optimize the particular fuzzy level for better accuracy [33] [55].

Figure 13: Membership Functions of FLC [56]**.**

The fuzzy controller solar MPPT inputs are error (E) and change in error (ΔE). The selection of error input is dependent on the designer's professionalism and solar PV system. Error equation can be chosen as the slope of P-V curve, $\frac{dP}{dV}$ because it is zero at the MPP as expressed in (19). The error change can be defined as in (20) [33][52].

$$E(k) = \frac{P(k) - p(k-1)}{V(k) - V(k-1)} \qquad (19)$$

$$\Delta E(k) = E(k) - E(k-1) \qquad (20)$$

The fuzzy logic controller output is the duty cycle, which is used to drive the DC-DC converter or change in reference voltage. Secondly, rule base table is computed based on the combination of error and change in error which the outcome depends on the type of converter being used and the designer's professionalism [33].

The rule base is also called **rule base lookup table** or fuzzy rule algorithm as shown in table 3,this associates the fuzzy inputs to the fuzzy output based on the converted power and the designer's level of expertise [55]. Using table 3 as an example, if the operating point is not close to the right of the MPP, as in (19), the error E notification symbol is NB. Furthermore, within a short time change of error, ΔE notified with PB will occur which means that the system perturbed further away to the right of the MPP. At this point, the system will automatically introduce a negative sign to

re-track back NB (moving the OP to the left) to locate the maximum power point [33] [53].

Table 3: Fuzzy Rule Base Table [38].

E ΔE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

Defuzification: This is a process where fuzzy output is being converted to crisp values. The fuzzy outputs of the system are aggregated with union operator before defuzzifing the output [54]. The most popular defuzzification technique in use is the Centre of gravity (COG), which is expressed mathematically in (21).

$$\Delta D = \frac{\sum Y(k) * F(k)}{\sum Y(k)} \qquad (21)$$

Where; ΔD = change of duty cycle;
$\sum Y(k)$ =Ssummation of weight factor
$F(k)$ = the multiplying coefficient based on membership function [33]. This technique tracks intelligently and was programmed and implemented with micro controller chips.
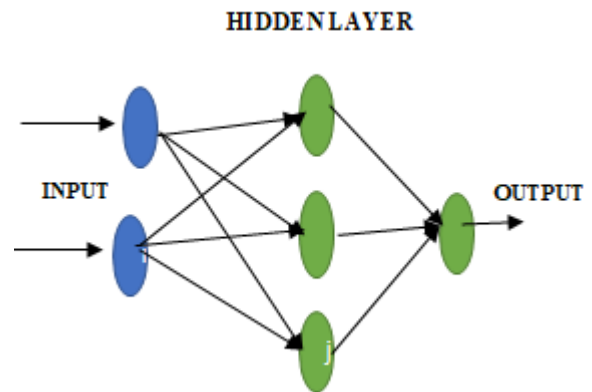
The major advantage of this technique is its fast convergence and minimal oscillation around the MPP. The disadvantage of this technique is that its effectiveness depends on the designer's skill and its mathematical complexity [55]. This drawback leads to Takagi–Sugeno (T-S) fuzzy-model.

3.2.2.2 A Takagi–Sugeno (T-S) Fuzzy-Model

Takagi-Sugeno fuzzy model directly drives the system to the maximum power point and measure isolation without searching the maximum power point [57]. According to T-S fuzzy model representation, nonlinear systems can be described by IF-THEN fuzzy rules that have local linear dynamic subsystems in the subsequent part. One of the advantages of this is that the linear matrix inequality (LMI) technique can be used to design controller gain. The major advantage is that it is effective and efficient in controlling complex nonlinear systems. The main drawback of this technique is that the operational point of the MPPT must be defined and known which is not obtainable in the technique [57].

3.2.2.3 Artificial Neural Network (ANN)

ANN is another intelligent based MPPT technique that uses microcontroller and digital signal processor for its implementation [32]. Figure 14 shows the basic structure of a single neural network which consists of three different layers known as input layer, hidden layer and output layer.

Figure 14: Neural Network Technique [56].

The characteristics of a neural network such as the number of input nodes and hidden layers are dependent on the designer expertise. The higher the number of hidden layers, the better the accuracy of the system. In using neural network to detect the MPPT of a PV system, the input of the neural network can be in any kind of combination depending on the designer's choice, such as weather condition (irradiance and temperature) or photovoltaic parameters such as open circuit voltage and short circuit current. The output power of the system can either be driven by duty cycle or reference voltage in order to draw it closer to the MPP [33]. The efficiency and effectiveness of the algorithm used by the hidden layer and how best the neural network has been trained will determine how close the operating point gets to the MPP [38]. The links between nodes i and j is a product of the two nodes (*wij*) as shown in Figure 14. The *wij's* have to be carefully determined through a training process that may last for a long time (months or years) to accurately locate/identify the MPP and the input/output pattern recorded. Neural network algorithm will be trained based on the characteristic of a particular PV array. The change in PV array which occurs as a result of PSC, which implies that the neural network has to be periodically trained to guarantee accurate maximum power point tracking detection [38].

The advantage of ANN technique is that it has high accuracy and fast convergence speed. The main pitfall of ANN technique is that it takes time to be achieved and also prone to error as it has a large data and takes years to be trained [33].

3.2.2.4 Particle Swamp Optimization (PSO) Technique

Particle Swarm Optimization (PSO) is an evolutionary computational technique that deals with problem optimization by iteratively improving a particle solution by mimicking or imitating the flocking patterns of birds and fish. Furthermore, during particle swarm optimization algorithm iteration, each single solution in search of space is optimized and evaluated based on its fitness function. The velocity of the Particles gives direction towards the optimal solution [58]. According to Kennedy and Eberhart in [59], PSO is an evolutionary computation technique that is used to optimize a continuous nonlinear function and for multi PV array structure with partial shading conditions (PSC). PSO model was employed to minimize the problem of

multivariable with multiple maxima which is caused by PSC [39] [60]. The algorithm has a number of particles where each particle can be a candidate solution particle which can copy the success of nearby particles, and get to their own success. The position of a particle is dependent on the nearby best particle and also best solution searched by the particle. Particle position, x_i, are found using:

$$x_i{}^{k+1} = x_i{}^k + v_i{}^{k+1} \qquad (22)$$

In (22) the velocity component, v_i, represents the step size. The velocity is calculated as in (23).

$$v_i{}^{k+1} = wv_i{}^k + c_1 r_1 \{p_{best\ i} - x_i{}^k\} + c_2 r_2 \{G_{best\ i} - x_i{}^k\} \qquad (23)$$

Where; w = initial weight; K = iteration number; i = 1, 2,…,N, (swarm size). $c_1 c_2$ = Acceleration coefficients; p_{best} = Personal best position of particle; G_{best} = Global best position of the swarm; $r_1 r_2$ = random variable (0, 1); x_i = Particle position; v_i = Velocity of the particle

PSO algorithm can also be used to predict and track the true maximum power point of a photovoltaic system [61].

The advantages were ease of implementation and fast in convergence under PSC. The disadvantage is that it is highly expensive, complex and not yet implemented. This complexity and expensive based drawback of PSO leads to another technique called Improved Particle Swarm Optimization (IPSO).

3.2.2.5 Improved Particle Swarm Optimization (IPSO)
This technique operates by using two positions known as updating strategies and a mutation operation which helps in improving performance and efficiency of the PSO. The algorithm works sequentially as stated below:

- *Algorithm Parameters and Problem initialization*
The problem is comprehensively defined and minimized by the algorithm as given in (24)
$$f(x) = x_{dl} \le x_d \le x_{du} (d = 1,2,…,D). \qquad (24)$$

Where;
x_{dl} = lower decision variable; x_{du} = upper decision variable; D = problem dimension size.

IPSO parameters are specified in steps such as the maximum number of iterations (k), decision probability (L) which determines different position updating strategies, the mutation probability (P_m) and as well as the population size (PS).

- *Initialize Swarm*
Every initial particle in the swarm is generated randomly from a uniform distribution that ranges from $[x_{dl}, x_{du}](d = 1, 2…, D)$. Hence the effect of constraints

might not be feasible in some regions because of the conversion of constraints to penalty function.

- *Position Updating and Mutation Operation*
There are two innovative position updating strategies that are introduced in position updating. During early iterations, current position of each particle is adjusted according to its previous and personal best positions with a large probability. Furthermore, in late iteration, current position of each particle is adjusted according to its previous and global best positions with a large probability, which indicates that it prefers to mimic its successful companions at this stage. The two updating strategies based on position is as shown in equation (25).

$$x_{id}^{k+1} = \begin{cases} x_{id}^k + 2 * ran_1 * (P_{id} - x_{id}^k), if\ rand() < L; \\ x_{id}^k + 2 * ran_2 * (P_{gd} - x_{id}^k), otherwise \end{cases} \qquad (25)$$

Where, $rand(), ran_1, ran_2$ = uniformly randomly generated numbers [0,1]. Decision probability (L) can be expressed as in equation (26)

$$L = \sqrt{1 - \frac{k}{K}} \qquad (26)$$

From the working principle if (26) is satisfied, the position of current component x_{id}^{k+1} will be located at a random position in the region $(P_{id} - |P_{id} - x_{id}^k|, P_{id} + |P_{id} + x_{id}^k|)$, which is a region near personal best position component (P_{id}). Else, the position of current component x_{id}^{k+1} will then locate a random position in the region $(P_{gd} - |P_{gd} - x_{id}^k|, P_{gd} + |P_{gd} + x_{id}^k|)$, which is an area near the global best position component $((P_{gd})$. From figure 15, it was observed that when the number of iterations K increases the decision probability (L) decreases slowly till it gets to zero.

3.2.2.6 Modified Adaptive Particle Swarm Optimization (MAPSO)
In PSO, the setting of weighting factors and inertia weights as a constant are meant to be done by experts. These parameters are performing very low in terms of searching speed when set with high or low value. However, with a smaller parameters, the diversity of population will be drawn to lower levels [62]. These are the Major drawbacks of APSO. Due to these pitfalls an improved PSO was introduced which proposed two major solutions such as: An adaptive inertia weights (w') is expressed in equation (25)

$$w' = \begin{cases} \sqrt[1-3]{\dfrac{f(x_i^{(t)})}{f(Pbest_i^t)}}, if\ (x_i^{(t)}) > fmax \\ \sqrt[1-3]{\dfrac{f(Pbest_i^t)}{f(x_i^{(t)})}}, if\ (x_i^{(t)}) < fmin \end{cases} \qquad (25)$$

Where;
$f(Pbest_i^t)$ = function value of best position of ith agent,
$f(x_i^{(t)})$= function value of ith agent
f_{min} = minimum function; f_{max} = maximum function

The current adaptive function value changed the new initial weight of the system because at initial operation, the initial weight is bigger and increases convergence rate which will continue till the global optimum is found. In the operation process of PSO, there will be a reduction in disturbing particles as a result of decrease in mutation rate [63].

Secondly, the rate of convergence is being improved by introducing a new competition operator which is evolutionarily populated to compete with a random population. Furthermore, by effectively and efficiently applying this technique, the object function value will converge to the global optimum and reduces the degree of the MPP settling at the local maxima.

In [64] Four benchmark functions Rastrigin, Rosenbrock, Grievank and Sphere are used to test the optimization performance of APSO technique for solving complex optimization problems. The advantage of APSO is its ability to effectively overcome the stagnation phenomenon and also enhance global search. The drawbacks are delay, complexity in circuitry design and cost effectiveness.

3.2.2.7 Scanning Particle Swarm Optimization (SPSO) Technique
Scanning Particle Swarm Optimization (SPSO) is one of the most recent metaheuristic techniques that has shown its accuracy and excellent performance in detecting the Global Peak (GP) and avoidance of being trapped at Local Peak (LP) as compared to conventional PSO techniques as of the time of this review. During PSC, the Global Peak point varies which affects it position in the P–V curve and makes it difficult for the PSO technique to capture the new GP unless it reinitializes. There is always delay in tacking during reinitialization which may led to premature convergence. In [31], an SPSO technique which tracks the new GP position without reinitialization was introduced. The design approach of SPSO is to be sending a particle to the anticipated places of peaks to search for any peak with power greater than the current Global Peak and when it locates a new Global Peak greater than the current global peak, it will move the PSO operating point directly to the new Global Peak. But when the current GP is less than the previous GP it discards it and maintain the old GP. The advantage of this technique is that it avoided premature convergence associated with conventional PSO techniques but never solved the problem of delay in convergence speed. The main pitfall of this technique is that the convergence speed is delayed and also programming complexity.

3.2.3 Hybridized MPPT techniques
This is a new technique that was adopted to ensure that this problem of inability to detect real MPP of a solar photovoltaic module during PSC. It involves the combination of two techniques to ensure better harness of power from the PV panel and this combination may be intelligent technique and non-intelligent technique, two non-intelligent technique or two intelligent techniques for better and effective tracking. The hybridizations techniques are as detailed below.

Hybridization of PSO and other techniques simply means the technical know-how of combining PSO and other MPPT techniques in a sequential and chronological order following the technical rule that guides the MPPT tracking techniques. This involves the integration of other MPPT technique into PSO for efficient and effective tracking and reliable power output.

3.2.3.1 Hybridization of PSO and P&O
In [65] Particle Swarm Optimization and Perturb and Observe techniques were hybridized for better performance. This technique works by first calculating the range of possible duty cycles and several duty cycles that will be tested and the power corresponding to each point will be calculated by the converter. In the absences of shading, the algorithm sets the duty cycle constant at optimum point, and then switches to non-intelligent mode (P&O) waiting for atmospheric change [66]. This will continue till shading is detected, then the algorithm switches to intelligent mode (PSO) to find the Global MPP. When the PSO technique detects the MPP it will settle there but at small changes in P-V curve it will switch to non-intelligent mode and maintain the MPP at that point. The algorithm restarts and PSO is employed to detect the P-V curve maxima when large changes are detected. This algorithm tests the power output at the location of each particle and the particles communicate with each other to know which of the location has the best power output. The previous location of the swarm was determined by the particle's movement along the power curve. Every time a system found an MPP, the tracked point will be noted and installed in the memory for feature use. The system will take cognizant of the specific operating or irradiance condition at which the MPP was recorded. As a result of this awesome observation by the tracker, this technique builds up a database and uses it to predict the location of the MPP.

Moreover, one of the major problems with P&O algorithm is that it oscillates within MPP region and takes time to locate the exact MPP during rapid change in irradiance. The advantage of this technique is that the time taken to locate the MPP is drastically reduced by decreasing the duty cycle increment or decrement step size. The disadvantage(s) of this technique is that the speed of convergence reduced drastically because of the time it takes it to switch from PSO to P&O and vice versa. This technical design is complex and expensive.

3.2.3.2 Hybridization of PSO with Adaptive Genetic Operator (AGO)
In [67] Hybridization of Particle Swarm Optimization with adaptive Genetic Algorithm operators are introduced. This is one of the PSO hybridization techniques that deal with the adoption of exploration of the strengths of

hybridization and adaptive strategies in improving Particle swarm optimization performance. It also focuses on combining inertia weight PSO with adaptive crossover and the rate of mutation that may eventually occur during the test for an effective adaptive approach to be employed during PSO hybridization. This research technique was meant to serve two important purposes which involves the identification of the most effective adaptive PSO hybridization approaches and to also compare the performance of the hybridized adaptive PSO and the adaptive inertia weight PSOs [68][62].

This technique compares four possible combinable sets of adaptive algorithms which are adaptive mutation rate (AMR), adaptive crossover rate (ACR), adaptive inertia weight without hybridization (AIW) and adaptive crossover and mutation rate (ACMR). These algorithms were combined one after the other and the most successful combination is subsequently used for a comparison between ACR, AMR and ACMR. In [69][70], analyses have proven that adaptive parameterization and hybridization algorithms have a significant improvement and a good performance. Regardless of the type of hybridization, the most effective adaptive parameterization method is ascertained based on *pbest* and *gbest* not based on their fitness.

The advantage is that it exploits different algorithm and selected the best combination among all, thereby serving as gang chart for designers who wants to use different algorithms. The drawback of this research is that it didn't put in consideration the exploitation of position (*pbest* and *gbest*) in adaptive parameterization which leads to inaccuracy in detecting GMPP.

3.2.3.3 Adaptive PSO with Artificial Neural Network (ANN)

In this technique the weights and biases of the Neural network neurons are joined together to create a single vector. A particular set of vectors can be identified as the best optimized solution among other sets of singly formed vectors. One of these vectors is found to have the best operating point using an Adaptive Particle Swarm Optimization (APSO) technique [71].

Artificial neural networks are mainly used for different kind of complicated problems because of its powerfulness, flexibility and ability of learning from examples [72][70]. A Neural Network Adaptive Particle Swarm Optimization (NNAPSO) input for a particular experiment is Velocity, Speed, and Displacement of air blower, the first network is trained by using training samples. The impact of textual indication of the learning process is presented on the standard output during the learning. A database that gathered from industry was used in the research and the data recorded and trained with NNAPSO. This technique through the application of all the necessary principle as in [72], yielded an excellent performance in terms of tracking speed and convergence.

The major advantage of artificial neural networks is that there is no need to prepare any algorithms to perform any task or to understand the structure or mechanism of the network before being applied that is its ease of use. The adaptive particle swarm optimization (APSO) approach was used to solve the complex condition monitoring problems [73]. The drawback of this technique is that it has complex program and mechanism.

3.2.4 Comparison of the Existing MPPT Techniques

The reviewed MPPT techniques will be compared based on reliability/accuracy, efficiency, advantages and drawbacks. The drawback of the conventional MPPT leads to the development of new MPPT technique. The new technique solves the problem of the old MPPT techniques and as time goes on the new MPPT needs to be improvement based on the observed pitfalls. The tables below show the comparison of different MPPT techniques reviewed in this paper. table 5 is the summary of all the reviewed techniques based on all the mentioned characteristics[38][32][33][34][74][64][75][76][27]. Table 4 summarized the MPPT techniques and also showed their evolutionary trend. The trend of evolves from the up to down. The problem reduces down the trend and increases up the table. The evolvement of the techniques was established in order to solve the problem that the old technique couldn't solve. However, sometimes the new techniques may curb the problem(s) of the old technique but t at the same time have one of the problems that the old technique that it improved on has solved.
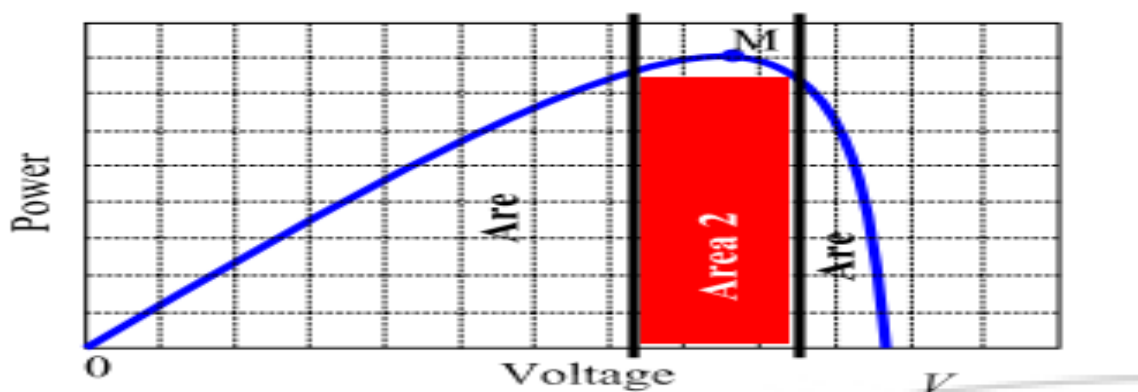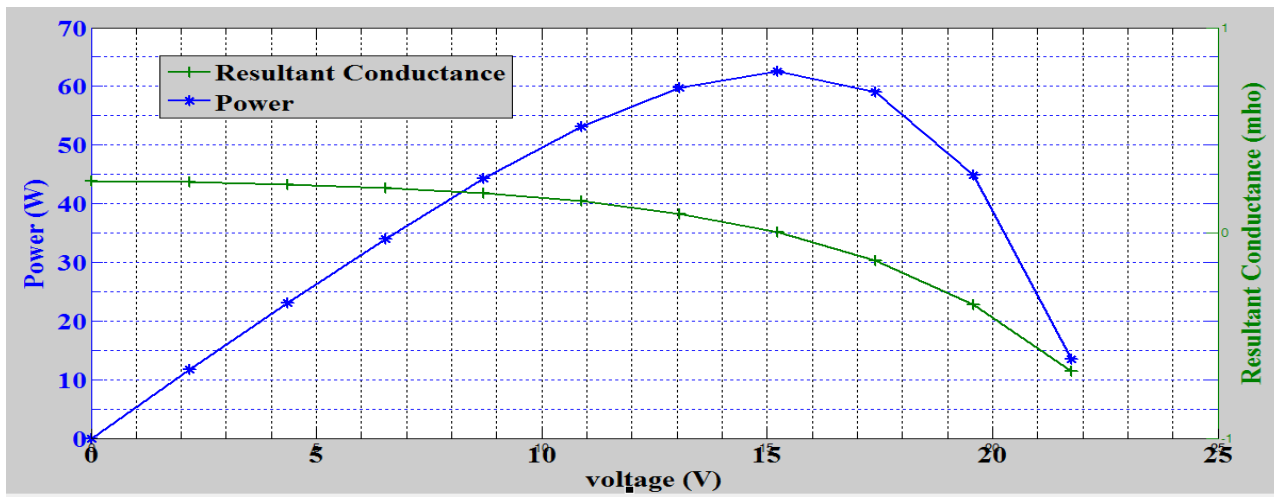

Figure 4: Area Partitioning of the P-V Characteristics [46]

Figure 5b: The P-V and Conductance Characteristics of OADC Algorithm.
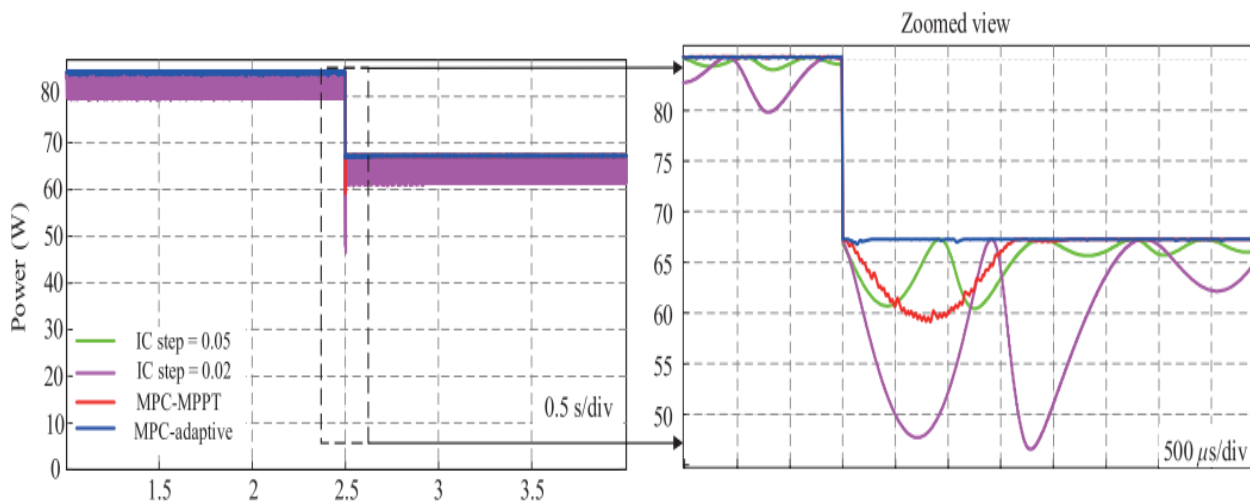

Figure 8: Validation using other MPPT Techniques under partial irradiance conditions
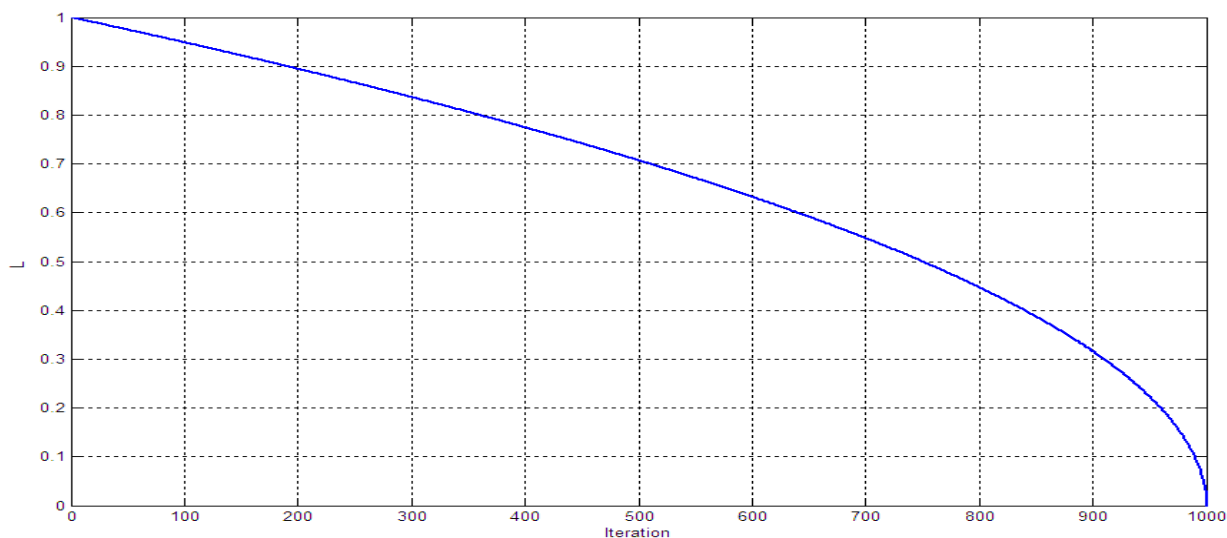

Figure 15: Decision Probability L and Iteration K [59]

Table 4: Summary of the Characteristics of MPPT Techniques Reviewed in this paper

MPP Technique	Efficiency	Convergence speed	Oscillation	Cost	Implementation complexity	Sensed parameters	Track real MPP	Reliability
FSCC	Poor	Medium	Yes	Inexpensive	Medium	Current	No	Low
FOCV	Poor	Medium	Yes	Inexpensive	Low	Voltage	No	Low
P&O	Medium	Varies	No	Relatively lower	Low	Voltage	Yes	Low
AP&O	Medium	Fast	No	Expensive	High (Digital)	Current	Yes	High
INC	Max	Varies	No	Expensive	Medium	Voltage, Current	Yes	Medium
IINC	Max	Varies	No	Expensive	Medium (Digital)	Voltage, Current	Yes	High
RSM	Medium	Varies	No	Inexpensive	Digital	Multi-variable	Yes	Medium
DIRECT SA	Medium	fast	yes	moderate	Medium (digital)	Multi-variable	Yes	High
OADC	max	Very fast	No	Moderate	Digital	Vmpp, Impp	Yes	High
HGCMPC	Max	Fast	No	Expensive	Digital	Current Voltage	Yes	Medium
SCOU	Max	Varies	Yes	Inexpensive	Digital	Multi-variable	Yes	High
EAESC	Max	Very fast	No	Expensive	Digital	Multi-variable	Yes	High
FLC	Max	Fast	Yes	Expensive	High (Digital)	Varies	Yes	Medium
T-S fuzzy	Max	Fast	Yes	Expensive	High (Digital)	Varies	Yes	Low
ANN	Max	Fast	Yes	Expensive	High (Digital)	Varies	Yes	Medium
PSO	Max	Fast	No	Expensive	Medium (Digital)	Multi-variable	Yes	High
IPSO	Max	Fast	No	Expensive	High (Digital)	Multi-variable	Yes	Medium
MAPSO	Max	Fast	No	Expensive	High (Digital)	Multi-variable	Yes	Low
SPSO	max	fast	No	Expensive	High (Digital)	Multi-variable	Yes	Medium
PSO & PO	Max	Fast	No	Expensive	Digital	Multi-variable	Yes	High
PSO & AGO	Medium	Fast	Yes	Expensive	Digital	Multi-variable	Yes	Medium
APSO & ANN	Max	Medium	No	Moderate	Digital	Multi-variable	Yes	Low

IV. CONCLUSION

The comprehensive review above, showed and elaborated that MPPT is classified basically into intelligent and non-intelligent MPPT techniques. The review also showed that two algorithms can be combined to form MPPT techniques in hybridized form which also curtail some of the problems of MPPT with high performance. However, for non-intelligence based MPPT techniques reviewed in this paper it was discovered that Enhanced Adaptive Extremum-Seeking Control (EAESC) has the best performance as it is easily implemented and involves less programming language with high degree of accuracy. EAESC tracks the real MPP at a very recommendable speed with high degree of accuracy. Hybridized techniques also have an excellent tracking accuracy of which among the reviewed hybridized technique APSO & ANN has the best performance because of its ability to detect real Global Maximum of a panel under partial shading condition. It was also discovered that among all the MPPT techniques in existence as at the time of this review, intelligent based technique is the best of all the MPPT technique. Then, within the intelligent based MPPT technique reviewed in this paper, scanning particle swarm optimization (SPSO) technique is the best because of its ability to dissipate real tracking with excellent accuracy as well as its ease of implementation under rapidly PSC. Finally, SPSO, APSO & ANN and EAESC has the best performance in tracking the MPP of a panel under shaded condition with high accuracy and good convergence speed respectively. This reviewed paper will serve as a guide for researcher with respect to prone and cons of the recent twenty-two MPPT techniques.

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