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A Comprehensive Review on Maximum Power Tracking of a Photovoltaic System Under Partial Shading Conditions

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Abstract- This paper presents a comprehensive review on the different methodologies of a Photovoltaic (PV) system under Partial Shading Conditions (PSC) which improves the output voltage and power. Numerous publications report on PV regarding power improvements and its implementation. But, confusion arises while selecting a methodology that performs under all climatic situations. Therefore, an indispensable review of PSC techniques is considered, which is based upon maximum power point tracking (MPPT) at Standard Test Conditions (STC). These MPPT techniques can track the Global Peak (GP) at PSC. Extensive research has been explored in this field and many techniques have been reported. In this paper, a detailed narration and classification on different techniques of PV at PSC have been made in terms of control variables, structure and circuitry used in practical and commercial applications.

Keywords Global Peak (GP), Maximum Power Point Tracking (MPPT), Partial Shading Conditions (PSC), Photovoltaic (PV) system.

1. Introduction

Household power consumption rises exponentially as linked to the power generated due to increase in demand of numerous home appliances. Pursuit for a low cost, low maintenance and pollution free power source propels the need for renewable energy. Due to the abundance of solar energy, Photovoltaic (PV) is the best substitute for standalone and grid connected modes [1]–[5]. To track the maximum power from PV at any climatic situations, Maximum Power Point Tracking (MPPT) technique was developed. At normal climatic conditions or Standard Test Conditions (STC) the basic MPPT techniques [6]–[10] are efficient to track maximum power. Converter topologies play an important role in order to maximize the solar energy capabilities. Power converters for PV systems have to be designed for high efficiency, accurate MPPT, and voltage/current performance [11]–[14]. Rapid alteration in weather situations and/or Partial Shading Conditions (PSC) on PV increases the number of maxima and thus tracking for Global Peak (GP) is difficult for conventional MPPT. Several authors proposed several techniques to track the maximum power from PV with and without MPPT at PSC [15]–[66]. Unfortunately, limited review articles [15], [16] are offered in these fields that include discussions on PSC until 2003.

Basically, during partial shading condition, the PV system is very liable due to substantial alteration of MPPT point of PV system, which can considerably decrease the energy of the PV system [17]. Consequently, the complexity and cost of the PV system are increased. During the partial shading condition, several maxima points are generated, which are comprised of local and global peaks. Among all these peaks the highest peak is represented as global peak, whereas others peaks are represented as local peaks. However, searching the global peak point is one of the complex tasks for MPPT control strategies [18]. Conversely, the perceptivity of partial shading condition to a PV array is continuous. The perceptivity of partial shading to a photovoltaic array can be altered with different time instances [19]. It is illustrated in [20] that if the design pattern of partial shading is identical, then the shading immensity is increased with time and the resultant maximum power of PV array is dropped at continuous rate. As a result, the partially shaded PV structure is always subjected to the shading immensity, when the partial shading pattern is identical.

Therefore, many new techniques such as DIRECT search algorithm, a Particle Swarm Optimization (PSO) approach, interconnections between the cells, blocking and bypass diodes at series connected PV cells, parallel connected PV arrays, identification of the micro cracks, etc., have been reported. Hence, it is essential to organize a review that includes all effectual methods of PV refining the power at PSC before 2003 and until 2018. In this review, an attempt has been made to compare the techniques on the basis of benefits, detriments, control variables, circuit complexity, applications and implementation cost. Several review challenges have been made on MPPT at STC, but very limited attempts have been attained for MPPT at PSC. So, we are concerned about a review on PV at PSC.

In this paper, Section II deals with description on various techniques at PSC through several literatures till 2018. In Section III, a relative assessment of various techniques has been organized. Section IV comprises of application, competence, efficiency and quality computation. The future scopes and challenges are prescribed in section V. Finally the review paper is summarized in section VI.

2. Review on PSC Techniques

The PV modules are generating power from sunlight. The I-V and P-V characteristic curves of PV modules at different temperatures are revealed through Fig.1 in normal conditions. When PV modules are partially shaded, hot-spot condition occurs; this is termed as thermal breakdown of the diode. The characteristic curves of PV modules to calculate GP are shown in Fig. 2. To save PV module from hot-spots "bypass diode" concept was introduced [16], [21]. The number of bypass diodes connected to a PV module depends on the breakdown voltage of the diode [22], [23]. Power flow of PV modules bypass diodes with and without shading is shown in Fig. 3, and the power losses of PV at shading are calculated in [24] – [26]. The following techniques are some of the widely used techniques to improve PV power with modified MPPT, when any change in climatic conditions occurs.

2.1. *Parallel Connected Solar (PCS) PV System*

Partially shaded PV modules generate less energy and traditional systems cannot collect that energy due to presence of fewer number of bypass diodes [27]. Parallel connected PV modules give better performance in shading conditions approximately twice that of a conventionally configured series system [28]–[30]. For identifying the global maxima with an optimum speed, an MPPT controller is required [31]. In this technique [27], each parallel connected module will give its own Maximum Power Point (MPP) and within a few milliseconds V_{mpp} is calculated.

2.2. *Real MPPT (RMPPT) Method*

To track the global peak from multiple peaks of a PV system under PSC, a Real MPPT (RMPPT) technique was developed in [32]. An incremental conductance MPPT technique is used with variable step size in RMPPT.
The modeling of the controller is as follows:

$$\Delta V_{pv} = V_{pv}[n] - V_{pv}[n-1] < \Delta V_{SET} \tag{1}$$

$$\frac{\Delta I_{pv}}{I_{pv}[n-1]} = \left|\frac{I_{pv}[n] - I_{pv}[n-1]}{I_{pv}[n-1]}\right| < \Delta I_{SET} \tag{2}$$

Here ΔV_{SET} is the predetermined voltage range.

$$V^*_{pv} = \left(V_{o,rms} / I_{o,rms}\right) x\ I_{pv}[n] \tag{3}$$

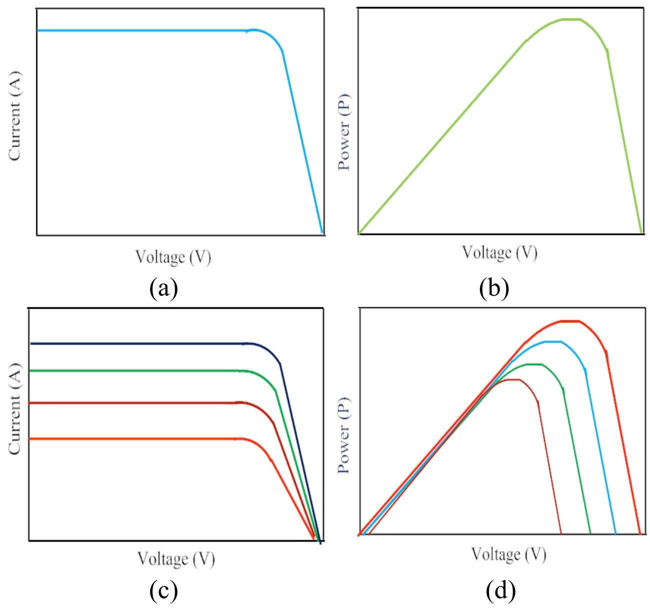

Fig. 1. Characteristic curves of PV array under no shading (a) I-V curve at 25^0 C, (b) P-V curves at 25^o C, (c) I-V curve at different temperatures, (d) P-V curves at different temperatures.

Equation (3) moves the operating point level. After the operating point has arrived at the reference point, the MPP is tracked again by the RMPPT method [32], which is based upon equations (1) and (2). When a PSC is detected, the proposed MPPT method changes the voltage reference by the linear function. This method operates as conventional incremental conductance method after the operating point. From the experimental results, it was confirmed that the power loss was lower than the conventional incremental conductance MPPT method by 15%. The reliable issues of a PV array at PSC are calculated in [33].

2.3 *Feed Forward Control Scheme (FFCS) with MPPT*

In order to accelerate the tracking speed, feed forward control scheme [34] for operating DC-DC converter and a reference voltage are used to get MPPT [35] – [37]. A duty cycle (D) is arranged and a new duty cycle (D*) is set to operate MPPT technique [34] described as follows:

$$D + \Delta D = 1 - \frac{(V_{pv} + \Delta V_{pv})}{V_o + \Delta V_o} \tag{4}$$

$$D^* = \frac{1 - V_{ref}}{V_o - \Delta D} \tag{5}$$

$$\Delta D = k\, X\left(V_{ref} - V_{in}\right) \tag{6}$$

where ‘k’ is a constant.

A P&O MPPT algorithm is used to track the Maximum Power Point (MPP). In this technique, GP tracking speed is ten times faster than a conventional controller.

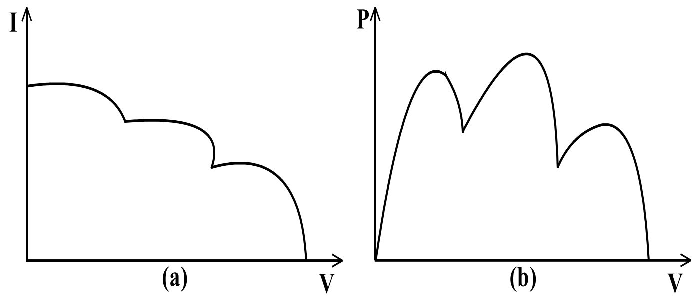

Fig. 2. I-V and P-V curves when shading occurs

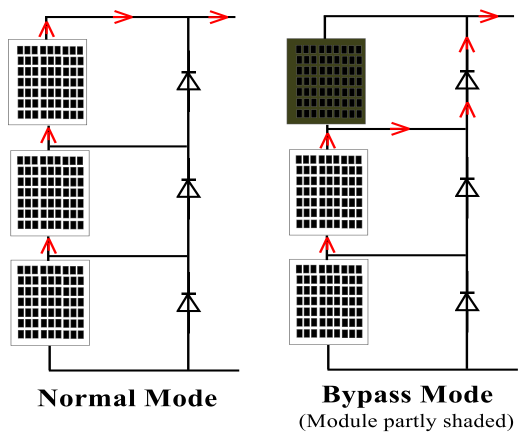

Fig. 3. Power flow of a PV with and without shading.

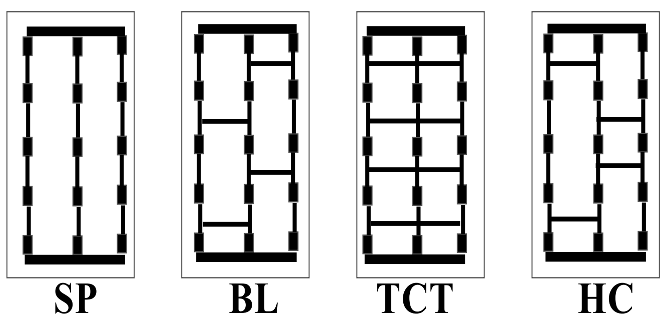

Fig. 4. PV interconnection topologies

2.4. Interconnections among Modules (IM)

Connection among the modules of a PV plant is called a topology. Various topologies in Fig. 4 are described below: SP stands for “Series-Parallel” [28], BL means “Bridge Link”, TCT stands for “Totally Cross Tied” and HC is described as “Honey Comb”. The objective of this technique is to establish a clear relationship between topologies, shadows and MPP of the PV plant [38].

In literature shadow shape is described by the number of strings (width, N) and modules per string (length, M), where each string is starting from the top side. This is known as shadow identification code [38]. Mismatch losses are indicated by the following equations:

$$Mismatch = \frac{\Delta P}{P_{theoritical}} \tag{7}$$

$$\Delta P = P_{theoritical} - P_{simulated} \tag{8}$$

$$P_{theoritical} = \sum_{i=1}^{M.N} P_{max}(i) \tag{9}$$

where Pmax(i) is the maximum power of the module ‘i’.

2.5. TCT with Hill Climbing MPPT

In this technique, single PV block includes 18 solar cells with single bypass diode [39]. Hill climbing MPPT is widely used because of simpler structure. Oscillations are observed on output power of PV array. Increase in the step size maximizes the oscillation; on the other hand, the dynamic performance reduces if step size decreases. This reduces the negative effect of mismatch losses of PV array and is useful to improve PV efficiency, but delivers no assurance to track GP at all weather conditions [40].

2.6. Irradiance Estimation (IE) Method

The basic principle of IE method consists of two parts: i) Approximation of the obstacles outline or the local horizon by a set of linear functions, ii) Irradiance on the PV panel is estimated using Perez model [41]. Obstacles approximation by a set of linear functions is described by the following relationship:

$$\Gamma_{ob,i} = \underbrace{\frac{\Upsilon^{i+1}_{ob} - \Upsilon^{i}_{ob}}{\Psi^{i+1}_{ob} - \Psi^{i}_{ob}}}_{a}\Psi + \underbrace{\frac{\Upsilon^{i}_{ob}\Psi^{i}_{ob} - \Upsilon^{i+1}_{ob}\Psi^{i}_{ob}}{\Psi^{i+1}_{ob} - \Psi^{i}_{ob}}}_{b} \tag{10}$$

where $\Upsilon^i_{ob}, \Psi^i_{ob}$ are the altitude and azimuth angles of the considered obstacles points, ‘a’ is the function slope and ‘b’ is the second term. Calculation of irradiance [42] – [44] of a PV system (unshaded and shaded) is as follows:

$$G_t = B_t + D_t + R_t \tag{11}$$

where Bt and Dt are the direct and diffuse irradiances on a tilted plane, and Rt is the ground reflected diffused component.

$$G_{t,sh} = G_t - \Delta G_{t,sh} \tag{12}$$

where $\Delta G_{t,sh}$ is the irradiance loss due to shading.

2.7. Different Computing Platforms for Global MPPT

Different computing platforms such as microcontroller, digital signal processor (DSP) and field programmable gate array (FPGA) are utilized as controller for tracking the Global MPPT algorithm. These controllers generate the pulse width modulation (PWM) signal for controlling a DC-DC converter, which is connected at the output of PV array for tracking the maximum output power. The Microcontroller Based Global MPPT (MC-MPPT) method [12] can be applied either in standalone or grid-connected PV systems. To operate this model, only microcontroller interfacing with converter is sufficient [45]. A block diagram of its implementation is depicted in Fig. 5. The following equation [45] explains the power calculation.

$$P_{pv} = V_c^{'} V_o - \frac{V_o^2 T_s}{2L} \tag{13}$$

Where $V_c^{'}$ is a DC control signal of adjustable amplitude produced by the control unit according to the global MPPT algorithm, Ts is the switching period, L is the inductor.

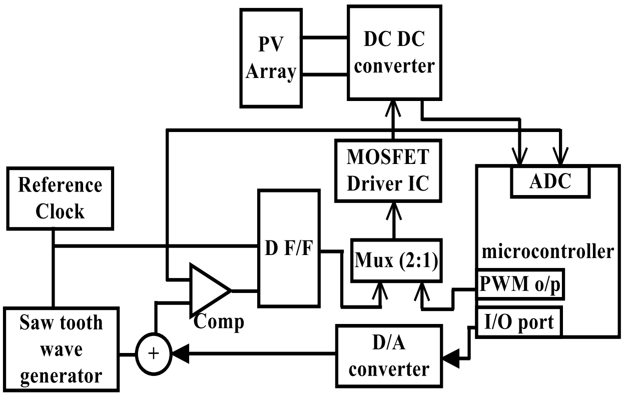

Fig. 5. Block Diagram of Microcontroller based MPPT

2.8. Upper Bound Technique (UBT)

Estimating the PV power losses by identifying micro cracks defines UBT; this technique is useful at both shaded and unshaded conditions [46] – [48]. Because of these micro cracks 8% power is being wasted. Identifying the micro cracks with the help of electroluminescence method is presented in [46]. The PV power is developed with four scenarios: (i) Power loss of one PV module is calculated with one defective cell and that defective cell is disconnected. (ii) Defective cell is connected in series with active cell and the corresponding power loss of PV module is calculated. (iii) More than one defective cells are in a double string with constant and varying cell area. (iv) Single defective cell is connected with 19 intact PV modules. It is verified that the PV module consists of 60 cells in series and 3 bypass diodes each in parallel with 20 solar cells. Identifying micro cracks [47] in PV modules and modifying with upper bound technique reduces 50% to 12% of inactive area of a single cell and increases the PV power in a reputable amount.

2.9. Soft Computing (SC) Approaches

Soft computing is a word applied to a field whose output is unpredictable and uncertain. Different types of SC techniques like Neural Computing (NC), Evolutionary Computing (EC), Fuzzy Systems (FS), etc., are available in literature. In EC, the PSO and Genetic Algorithm (GA), etc., were used to estimate the output of PV arrays under PSC. SC takes very less time to calculate the output at critical conditions and recursively execute the algorithm till final results are obtained.

A PSO is a computational method that optimizes a problem by iteratively trying to improve the candidate's solution. PSO was proposed to control several PV arrays with one pair of voltage and current sensors [49], a block diagram of which is shown in Fig. 6. This scheme is a multidimensional search based technique, applied to a multivariable function optimization [49] – [51] having many local optimal points. The PSO algorithm reinitializes whenever the following two conditions are satisfied.

$$\left|v_{i+1}\right| < -\Delta V \tag{14}$$

$$\frac{\left|P(s_{i+1}) - P(s_i)\right|}{P(s_i)} > \Delta P \tag{15}$$

Continuously executing the above conditions, the authors [49] are able to find the global MPP under complex shading conditions and take 1 to 2sec to find the global MPP.

2.10 Dividing Rectangles (DIRECT) Algorithm

In this technique, the power/voltage relationship of a PV cell is described in Lipschitz function in order to track the global MPP. The Lipschitz condition is as follows [52].

$$\left|p(v_1) - p(v_2)\right| \le M\left|v_1 - v_2\right| \tag{16}$$

where 'M' is the maximum value. The original DIRECT algorithm divides all potential optimal to search for the GP globally and locally at the same time. But the dividing strategy is different [53], [54], thus the conditions are explained mathematically [52].

$$f(x_j) + \overset{:}{K}\frac{\left(a_j - b_j\right)}{2} \ge f(x_i) + \overset{:}{K}\frac{\left(a_j - b_j\right)}{2} \tag{17}$$

$$f(c_j) + \overset{:}{K}\frac{\left(a_j - b_j\right)}{2} \ge f_{\max} + \varepsilon\left|f_{\max}\right| \tag{18}$$

The tracking efficiency and speed of the MPPT are changing with respect to the duty cycle (D) of the converter. The buck-boost converter topology, duty cycle boundaries $D_{\min\_abs}$ and $D_{\max\_abs}$ are calculated as follows:

$$D_{\min\_abs} = \frac{\sqrt{\eta_{bb} R_{load\_\min}}}{\sqrt{R_{pv\_\max}} + \sqrt{\eta_{bb} R_{load\_\min}}} \tag{19}$$

$$D_{\min\_abs} = \frac{\sqrt{\eta_{bb} R_{load\_\max}}}{\sqrt{R_{pv\_\min}} + \sqrt{\eta_{bb} R_{load\_\max}}} \tag{20}$$

With the help of change in duty cycle (19) and (20), the tracking efficiency and speed of partially shaded conditions are 0.5% less than the STC. If number of cycles are more per second then the efficiency and tracking speed are more [54].

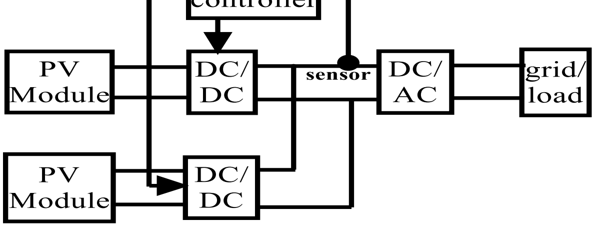

Fig.6. Multiple arrays controlled by a single MPPT controller

2.11 Module Integrated PV and Converter (MIPC) Technique

MIPC is a good technique for achieving maximum power generation for mismatching or partially shaded PV modules [55]. Multiple units of PV system controlling are difficult, because the operation of each unit is required to be regulated to generate the maximum power according to its light level [56] – [60]. Fig. 7 and Fig. 8 show the loop control scheme for a particular MIPC system [55]. The output power at load without considering the losses is given below .

$$P_T = V_T I_T = V_{p1} I_{p1} + V_{p2} I_{p2} \tag{21}$$

$$P_T = V_T I_T = \left(V_{p1} + V_{p1} \left(\frac{K_{11}}{1 - K_{11}} \right) \right) \left(I_{p1} \left(1 - K_{11} \right) + I_{p2} K_{11} \right) \tag{22}$$

where K_{11} is the duty ratio. Executing the above equations power will be calculated and this approach [55] enables independent control of individual PV modules according to insulations at partial shading conditions.

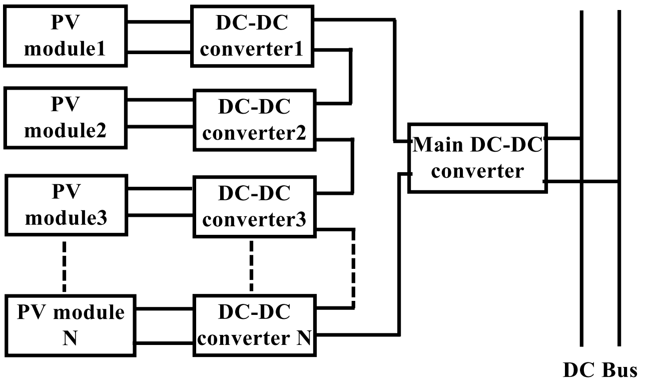

Fig. 7. MIPC system using cascaded converter approach

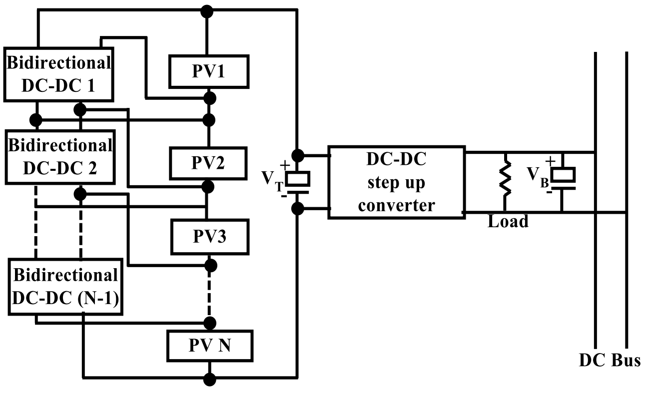

Fig.8. MIPC system using bypass approach

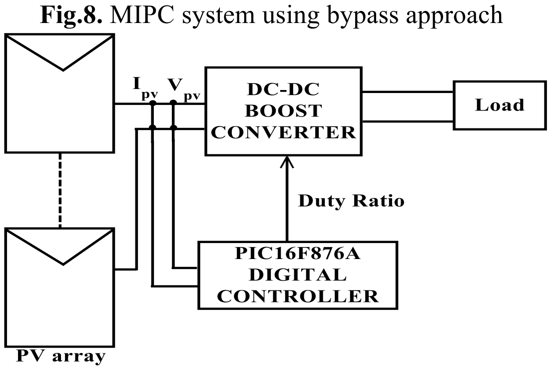

Fig.9. Block diagram of FA-based MPPT scheme

2.12 Mobile Solar Power (MSP) Technique

Till today, MSP is the only option for portable power applications like solar blanket, solar tent, etc. Mobile PV is a technology especially useful for armed forces and trekking people to reduce the usage of fuel and battery resupply [61]. Solar cells are laminated between two sheets of transparent fluoropolymer film [47], [61]. The laminated cell array was then attached using a thick black plastic, which provided a stiffness to protect the cells. For portable solar applications mismatching and partial shading are the main drawbacks [62] –[65]. To overcome this problem, interconnections between the cells and bypass diode concepts were implemented [66]. The panel design [61] consists of a 30 solar cells array that is of 10.25x15.5 inch size with 270g in weight.

2.12 Multilevel DC-link Inverter and Control (MDCIC) Algorithm

The application of multilevel DC-link inverter is used [67] - [69] for a series connected PV system to overcome the partial shading effect on individual PV modules. The permutation algorithm is used in the inverter control to extract maximum power from each PV source under PSC. This algorithm is based on the combination of pulse width modulation (PWM), sequential permutation and output generation. Here, PWM reduces the computational time compared with space vector PWM (SVPWM). The direct normalized reference voltage is given by

$$\bar{V}_{ref}(i) = \frac{v_{ref}(i)}{v_{MPP}/n} \tag{23}$$

where V_{mpp} is the value of MPP at irradiance 1000 W/m^2, n is the total number series connected PV modules.

The offset voltage is defined as $V_{offset}(\mathrm{i}) = \mathrm{int}[\bar{V}_{ref}(i)]$ (24)

Total on time period is calculated as follows:

$$t_{on}(i) = T_s(\bar{V}_{ref}(i) - V_{offset}(i)) \tag{25}$$

where T_S is the switching cycle period.

The algorithm was successfully tested with a seven-level inverter with separate maximum power point tracking algorithms under non uniform irradiance.

2.14 Firefly Algorithm (FA)

The FA based MPPT block diagram is shown in Fig. 9. Here, the PV system is interfaced to load through the DC-DC boost converter. The digital controller measures V_{PV} and I_{PV} with the help of duty cycle and computes the output power. The algorithm execution [70] is as follows:

a) Parameter setting
b) Initialization of fireflies
c) Brightness evaluation
d) Update the fireflies (duty cycle) position
e) Terminate the program when criteria reached, otherwise go to step 'c'. If the program is terminated once, then the converter operates at the optimum duty cycle corresponding to GMPP.

f) Reinitiate the algorithm if any solar insolation changes, which is detected by the digital controller.

The major advantages of FA method are simple computational approach and faster convergence. Moreover, FA implementation is possible on a low cost microcontroller

2.15 Artificial Bee Colony (ABC) Technique

When partial shading occurs in a PV system, the resultant P–V curve exhibits multiple peaks. ABC algorithm simulates the intelligent foraging behaviour of a honeybee swarm; the block diagram of which is shown in Fig. 10.

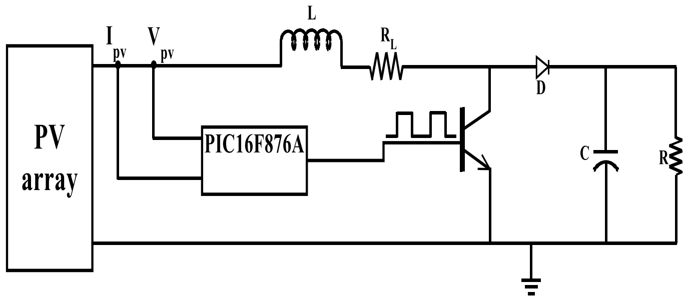

Fig 10. Block diagram of ABC MPPT controller

Table 1. Comparision of different PSC techniques

PSC Technique	Control Strategy	Control Variable	Circuitry	Parameter Tuning	Cost	Complexity Level	Applications	Converters Used	Bypass Diodes
PCS	INC	I	D	YES	INEX	SIMPLE	STAND-ALONE/ GRID TIED	DC-DC	USED (LESS)
RMPPT	INC	V,I	D	YES	EX	MEDIUM	STAND-ALONE	DC-DC	USED
FFCS	INC	V	D	NO	EX	COMPLEX	STAND-ALONE	DC-DC	USED
IM	SM	V,I	A	NO	INEX	COMPLEX	STAND-ALONE	DC-DC	USED
TCT	SM	Irradiance	A	NO	EX	COMPLEX	STAND-ALONE	DC-DC	USED
IE	INC	I	A	NO	INEX	MEDIUM	GRID TIED	DC-AC	NOT USED
MC-MPPT	INC	V,I	D	NO	INEX	COMPLEX	STAND-ALONE/ GRID-TIED	DC-DC	NOT USED
UBT	INC	V,I	D	NO	EX	COMPLEX	STAND-ALONE	DC-DC	USED
PSO	INC	V,I	A,D	YES	EX	COMPLEX	STAND-ALONE/ GRID-TIED	DC-DC DC-AC	USED
DIRECT	INC	V	A	YES	EX	MEDIUM	STAND-ALONE	DC-DC	USED
MIPC	MM	V,I	A	NO	EX	COMPLEX	STAND-ALONE	DC-DC	USED (LESS)
MSP	INC	V	D	YES	EX	SIMPLE	STAND-ALONE	DC-DC	USED
MDCIC	INC	V	A	NO	EX	COMPLEX	GRID-TIED	DC-AC	NOT USED
FA	SM	V,I	D	YES	INEX	MEDIUM	STAND-ALONE	DC-DC	NOT USED
ABC	SM	I	D	NO	INEX	MEDIUM	STAND-ALONE	DC-DC	NOT USED
GWOA	SM	V,I	D	NO	INEX	SIMPLE	STAND-ALONE	DC-DC	NOT USED
GWAPO	SM	V,I	D	NO	INEX	MEDIUM	STAND-ALONE	DC-DC	NOT USED

Note: INC= Indirect Control, SM=Sampling Method, MM=Modulation Method, V=Voltage, I=Current, A=Analog, D=Digital, INEX= Inexpensive, EX=Expensive

In this technique, the total bees are characterized into three different sets namely 1) employed bee, 2) onlookers, and 3) scout bee. The employed bee recognizes the exact food source and shares the information with the other bees waiting in the hive. The onlookers closely look at the information and follow the employed bee, which has identified the best food location. Scout bee carries out random search for discovering new food source. The explanation of ABC technique is as follows:

a) Initialization

$$x_i = d_{\min} + \frac{(i-1)[d_{\max} - d_{\min}]}{N_p - 1} \tag{26}$$

b) Evaluating the quantity: that means calculation of output power with respect to duty ratio.

c) Identifying new food source position. Here two phases are required. (i) Employ phase and (ii) Onlooker phase.

d) Termination criterion

e) Reinitiating the search

2.17 Grey Wolf Optimization Algorithm (GWOA) and Grey Wolf Assisted P&O (GWAPO)

The GWOA is a new optimization method presented in [71], which overcomes the limitations such as lower tracking efficiency, steady-state oscillations, and transients as encountered in P&O and improved PSO (IPSO) techniques. The problem of tracking the global peak (GP) of a PV array under partial shading conditions is attempted employing the GWO-based MPPT technique. The GWO algorithm is tested experimentally with 4S and 2S2P configurations.

Furthermore, the GWAPO is a Hybrid MPPT algorithm, which combines GWOA and P&O techniques for efficient extraction of maximum power from a PV system subjected to rapid variation of solar irradiance and PSCs. GWOA handles the initial stages of MPP tracking followed by application of the P&O algorithm at the final stage in view of achieving faster convergence to the global peak GP. The GWAPO MPPT algorithm [72] overcomes the computational overhead as encountered in the case of a GWO based MPPT algorithm. An experimental setup is prepared for practical implementation. Comparing GWAPO MPPT technique with other fast converging techniques, it can be envisaged that the GWO-PO Hybrid-MPPT exhibits superior performance such as higher tracking speed and faster convergence towards the GP.

2.18 Maximum Power Trapezium (MPT) and High-Speed MPPT Module (HS-MPPT)

The trapezoidal area, entitled as maximum power trapezium (MPT) is proposed in [73]. GMPPT algorithm is employed here initializing the MPT and the minimum voltage difference between nearby local peaks. Thus, the proposed technique follows the GMPP of a string PV array with severe PSC degrading not only its voltage track but also its tracking time. Simulation and experimental results exhibit the superior performance of the proposed algorithm as compared to the conventional algorithms in terms of tracking time, energy loss, and total voltage track during the search for the GMPP.

Further, the fast significance of GMOP under PSCs employing a proposed high-speed MPPT module [74] operates in combination with boost converter. Through the high speed MPPT module, the tracking time of the MPPT controller is effectively dropped. This idea is first employed on a PV structure simulation model and the results are validated through a prototype experimental set-up of a 300W PV fed boost converter operated with various PSCs. Lastly, the results were verified with installation of a 2.5 kW PV System. These results exhibit that the proposed high speed MPPT controller overtakes both duty sweep and PSO-based MPPTs.

2.19 Overall distribution (OD) MPPT algorithm and search space differential evolution algorithm

A novel overall distribution (OD) MPPT algorithm [75] rapidly approaches the area near the global MPP. The OD MPPT technique can be further combined with other intelligent techniques to achieve the global maximum power point (MPP) perfectly in this paper. Particle swarm optimization (PSO) technique is preferred as combined algorithm due to its simpler approach. Then, the OD-PSO MPPT technique is applied into the global MPPT of a PV structure. The simulation and experimental results demonstrate the efficacy and accuracy of the proposed OD-PSO MPPT method by assessing with the present PSO MPPT technique. As a consequence, this paper indicates a good approach for the MPPT of PV structures towards partial shading conditions.

An improved global search space differential evolution algorithm is introduced in [76] for tracking the GMPP. The key contributions of the proposed technique are: a) tracking capability and faster response against load variations, b) optimization algorithm technique can be searched within a larger operating range as it is employed by utilizing a single-ended primary-inductor converter. The feasibility of the proposed method is validated through the experimental set-up. It can be shown from the results that the proposed technique can track the GMPP within 2 s with an accuracy of 99% and also can respond to load variation within 0.1 s.

3. Comparison of PSC Techniques

In this paper, classification of PSC techniques has been considered with respect to control variables, circuitry, and approximate cost.

3.1 Based on Control Variables

The combined (Voltage, current) or (irradiance, temperature) parameters are the control variables to achieve the maximum power at STC or PSC. According to the control variables, the controllers are divided into two types, single variable techniques and double variable techniques. Comparatively, voltage sensing techniques are easier than current sensing techniques in aspects of modeling, implementation and cost in PV power systems.

3.2 Based on Circuitry

Two types of circuit techniques are involved in developing PV systems, analog and digital; depending upon the user, one can develop techniques according to their own wish. As per the present developments many users are interested to develop the circuit in a digital manner, but, it is difficult when compared with an analog implementation.

3.3 Based on Cost

Accurate and fast working systems are always costly; these types of systems have been used in industries, solar vehicles etc. Some systems such as residential applications and street lights need cheap and simple techniques. We have set a cost line of US$1000. Below this line, it is inexpensive and vice versa. This categorization has been described in Table 1.

4. Applications, Efficiency and Quality Calculation

A brief history of PV is as follows: 'Edmond Becquerel' accidentally discovered photovoltaic effect when he was working on solid state physics on 1839. In 1883, 'Fxitz' fabricated the first thin film solar cell. In 1941 'Ohl' fabricated silicon PV cell, but that was very inefficient and finally 'Chopin, Fuller and Pearson' fabricated a PV cell with efficiency of 6% at Bell labs in 1954. There are several applications of PV under partial shading condition by considering global MPPT.

In Building Integrated Photovoltaic (BIPV) system [77], the entire building roof and facade are integrated with PV with PSC system; therefore, it can save the electricity cost. Similarly, in transport system such as solar vehicles utilize the PV for charging the vehicle battery banks [78]. In contrast when PV with PSC system is utilized for utility interactive purpose, it supplies the power to different household appliances, street lights, parking meters and water pumping. Additionally, the PV with PSC module exhibits vital roles in communication system as it provides power back up to the signal towers, which are situated at remote areas [79].

During natural calamities condition PV with MPPT algorithm is one of the attractive solutions as it often reduces the electricity crisis [80]. Furthermore, Emergency health care clinics choose PV based PSC power system in contrast to conventional power systems because of problems associated with fuel transport [81]. Correspondingly, PV with PSC module can be efficiently utilized to perform the scientific activities in remote areas. Also, in navigational systems, for example aircraft warning signals, light houses and highway can be far away from the power grid [82]. PV with PSC systems is a reliable power source for these essential applications. PV with PSC module can be a suitable candidate for reducing the corrosion effect in pipelines [83]. The corrosion effect is occurred in the water and oil pipeline due to the electrolytic process of metals. In this process metal can lose ions while making contact with water or oil. The corrosion effect of Pipelines can be reduced by applying small external DC voltage, which can avert the ion loss from the metal surface. This external DC voltage is applied through PV module.

Mono crystalline, poly crystalline and amorphous materials provide an efficiency of 12-14%, 12% and 6-8% respectively. Efficiency calculations of grid tied PV systems are required to get the maximum profit. The efficiency (η) of a cell is defined [68] as the ratio of peak power to input solar power given below,

$$\eta = V_{mpp}\,\mathrm{I}_{\mathrm{m}pp} / I(\mathrm{k}W/m^2).A(m^2) \tag{27}$$

where I= insolation and A= Area of the cell.

Every PV cell has a life expectancy. As time progresses, the quality of the cell goes down. So, it is necessary to check the quality of the cell whether it is functioning in certain level or below level. Calculation of quality is also called as Fill Factor (FF), described as ratio of the peak power to the product of open circuit voltage and short circuit current, as shown below:

$$FF = \frac{V_{mpp}\,\mathrm{I}_{\mathrm{m}pp}}{V_{oc}\,\mathrm{I}_{sc}} \tag{28}$$

Ideal fill factor should be 1 or 100%, but, a good panel has a fill factor in the range of 0.7 to 0.8.

5. Future Scope and Challenges

Numerous of researchers have proposed several MPPT control algorithms for PSC system. However, MPPT for PSC system is an amenable research area where many future scopes are still there. Therefore, various metaheuristic optimization methods for MPPT under PSC systems are proposed, many of these techniques are also considered in this paper. But various techniques are still available, which explore MPPT algorithms are Pareto multi objective optimization (PMOO), shuffled frog leaping (SFL), Artificial immune system optimization (AISO), invasive weed optimization (IWO), cuckoo search algorithm (CSA), fish optimization (FO), raindrop optimization (RO), tabu search continuous optimization (TSCO), seeker optimization algorithm (SOA) and flower pollination algorithm (FPA). All these evolution approaches may be utilized for enhancing the MPPT tracking performance and suggested for future scope of research in MPPT with PSC system. During PSC, instance evolutionary algorithm (EA) carries a significant role by enhancing its performance. The performance enhancements are carried out by reducing the algorithm complexity and computational time of EA. These factors are reduced by reducing the search space of algorithm by choosing the appropriate control parameter.

Additionally, Artificial intelligence supported MPPTs may be organized in dSPACE platform where the coding complications are significantly diminished and it also helps researchers to emphasis on enhancing the efficiency through novel converters. The other features of upcoming investigation can be of organizing robust control algorithms such as advanced sliding mode control for tracking extreme power. Similarly a multidimensional search through distributed MPPT (DMPPT) converters in partially shaded PV array will expand the power extracting structure as the multidimensional search with DMPPT creates each panel to activate at its topmost power. Moreover, a hybrid technique should be encouraged based upon environmental parameters as well as other economic parameters. An improved model based MPPT technique may be suggested, which can take the advantage of lower cost and simplicity in hardware implementation. Achieving easier, quicker and inexpensive MPP tracker with improved efficiency and reliability is suggested. In near future PSC becomes a barrier and immense peril to PV installations. Therefore, reconfiguration methods are important considerations in installation of PV array, which can alleviate the shading effect on PV panels. In future aspect soft computing methods are important consideration for reconfiguring PV panels to reduce the shading effect.

6. Conclusions

This review paper provides a clarification of available PSC techniques based on control variables, circuitry, efficiency and cost. This classification is useful for selecting the technique for particular application, it also provides an idea about standalone or grid connected mode and type of converter used. This paper covers many recent hybrid PSC techniques along with benefits and detriments, with or without MPPT. This article gives the information about the PV system working at STC also and gives an idea about commercial and/or residential usage of the product. This review paper is helpful for research purpose as well as commercial purpose to select the best alternative among the available techniques.

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