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Review article

Classification and summarization of solar photovoltaic MPPT techniques: A review based on traditional and intelligent control strategies

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ABSTRACT

The output power–voltage (P–V) curve of a solar photovoltaic (PV) power system shows a single peak under an even irradiation environment, nevertheless, but often exhibits seriously nonlinear multi-peak characteristics under partial shading conditions (PSCs). Then, traditional maximum power point tracking (MPPT) control methods may fail to find the maximum power point (MPP). Many different MPPT control methods have been proposed to adjust the peak power output and improve the generating efficiency of the PV system. In this paper, the main MPPT techniques for PV systems are reviewed and summarized, and divided into three groups according to their control theoretic and optimization principles. Especially, the advantages and disadvantages of the MPPT techniques for PV system under PSCs are compared and analyzed. Finally, possible future research directions for MPPT are discussed.

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1. Introduction

In the 21st century, improving energy efficiency, optimizing energy structure and developing various new energy sources have become the key to sustainable worldwide development (Poompavai and Kowsalya, 2019; Seyed, 2019; Yang et al., 2019a,b; Tang et al., 2019, 2018b,a). PV power generation has the advantages

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Abbreviations

MPPT	Maximum power point tracking
LMPP	Local maximum power point
GMPP	Global maximum power point
PSCs	Partial shading conditions
PV	Photovoltaic
RPV	Re-configurable PV
CCM	Continuous conduction mode
CVT	Constant voltage tracking
OVT	Open-circuit voltage tracking
LT	Look-up table method
CS	Current scanning method
CF	Curve fitting method
SCT	Short-circuit current tracking
P&O	Perturb and observe
IC	Incremental conductance
PC	Parasitic capacitance
RCC	Ripple correlation control
PAC	Photovoltaic array combination
AM	Actual measurement
PF	Power feedback
FLC	Fuzzy logic controller
RBF	Radial basis function
NN	Neural network controller
SMC	Sliding mode control
SS	Simple series
FWA	Firework algorithm
SWS	Switching set
Z-Z	Zig-Zag
BA	Bate algorithm
TCT	Total cross tied
SP	Series parallel
HC	Honey-comb
BL	Bridge link
BIPV	Building integrated PV
IE	Irradiance equalization
DPST	Double-pole single-throw
SPST	Single-throw type switches
SPDT	Single-pole dual-throw
GA	Genetic algorithm
DE	Differential evolution
PSO	Particle swarm optimization
ACO	Ant colony optimization
ABC	Artificial bee colony algorithm
SSA	Salp Swarm Algorithm
FA	Firefly algorithm
OD-PSO	Overall distribution-PSO
IPSO	Improved PSO
NPU	New pheromone updating
MH	Metaheuristic
GWO	Gray wolf optimizer
MSSA	Memetic salp swarm algorithm
SSM	Segmentation search method
FLS	Fibonacci linear search algorithm
RCGA	Real coded improved GA
CCP	Common coupling point
VO-MPPT	Voltage-oriented MPPT
DS	Dominance square
VF	Voltage feedback method

of being universally available, pollution-free and easy to use. It is effectively inexhaustible. According to the global photovoltaic market outlook 2019–2023, demand is predicted to rise by 12% in 2020 to reach 144 GW, to reach 158 GW in 2021, 169 GW in 2022, and 180 GW in 2023. and the installed capacity of solar power generation in the world may reach 1610 GW in 2023. However, many factors are restricting the development of PV generation technology, among which the inherent PV cell generation efficiency is the most critical. One important technique to maximize the efficiency of a given PV cells technology is to use MPPT control, and various MPPT techniques have been proposed (Tafti et al., 2019; Dhimish, 2019). Publications on this topic now number tens of thousands (Eltamaly et al., 2018), therefore classifying and summarizing the current MPPT methods is very important for future research.

The output characteristics of a PV array are non-linear and are affected by the irradiance and ambient temperature. For an array of well-matched modules, under even irradiance, there is a unique peak point on the P–V characteristic curve. Some traditional MPPT techniques include CVT (Lasheen et al., 2017), OVT (Veerapen et al., 2017), SCT (Sher et al., 2017; Cui et al., 2019), P&O (Alik and Jusoh, 2018; Manickam et al., 2017; Ei et al., 2018; Ghamrawi et al., 2018; Abdel-Salam et al., 2018, 2019; Ahmed et al., 2018), IC (Yatimi et al., 2019; Motahhir et al., 2018; Kumar et al., 2019), etc., and artificial intelligence control methods, such as FLC (Li et al., 2019d,a,b,c; Yilmaz et al., 2018; Farajdadian and Hosseini, 2019a,b), NN (Hamdi et al., 2019; Messalti et al., 2017; Issaadi et al., 2019; Mohamed et al., 2019a,b), SM (Pahari and Subudhi, 2018; Kihal et al., 2019), etc. However, a PV installation can encounter many environmental factors such as dust, clouds, buildings, leaves, electric poles, bird droppings and so on, which can easily cast non-uniform shadows on the PV array surface. Under these PSCs, multiple peaks may occur in the P–V curve (Tafti et al., 2019; Dhimish, 2019), and the traditional MPPT control methods may not be able distinguish an LMPP and the GMPP. Hence, studying the MPPT control algorithms of PV power generation systems under PSCs is of great significance for their efficiency and reliability (Dhimish, 2019).

PV array reconfiguration has been proposed in 1990 as another method of performing MPPT under PSCs (Salameh and Liang, 1990). Subsequently, many more reconfiguration structures were proposed, such as SS (Pongratananukul and Kasparis, 2004), PS (Wang and Hsu, 2010), TCT (Dhana and Rajasekar, 2018; Vijayalekshmy et al., 2016; Matam and Barry, 2018a; Belhaouas et al., 2017; Mahmoud and El-Saadany, 2017; Matam and Barry, 2018b), SP (Manjunath et al., 2018; Iraji et al., 2018; Amer et al., 2015; Harrag and Messalti, 2016), BL (Belhachat and Larbes, 2015), HC (Bana and Saini, 2017), etc. More MPPT control techniques have been studied to better switch relays or switches quickly during reconfiguration (Sai and Moger, 2019). Artificial intelligence algorithms for MPPT have also been developed and can be classified as bionic and evolutionary algorithms. Compared to evolutionary algorithms, which includes GA (Holland, 1992; Huang et al., 2018; Shah and Singh, 2019), DE (Storn and Price, 1997; Kermadi and Berkouk, 2017; Tey et al., 2018), the bionic algorithms are more favored by investigators, which includes PSO (Kennedy and Eberhart, 1995; Ishaque et al., 2012a,b; Ishaque and Salam, 2013; Li et al., 2019d,a,b,c; Saad et al., 2018; Hu et al., 2019), ACO (Dorigo and Gambardella, 1997; Socha and Dorigo, 2008; Titri et al., 2017; Lekshmi and Umamaheswari, 2018), ABC

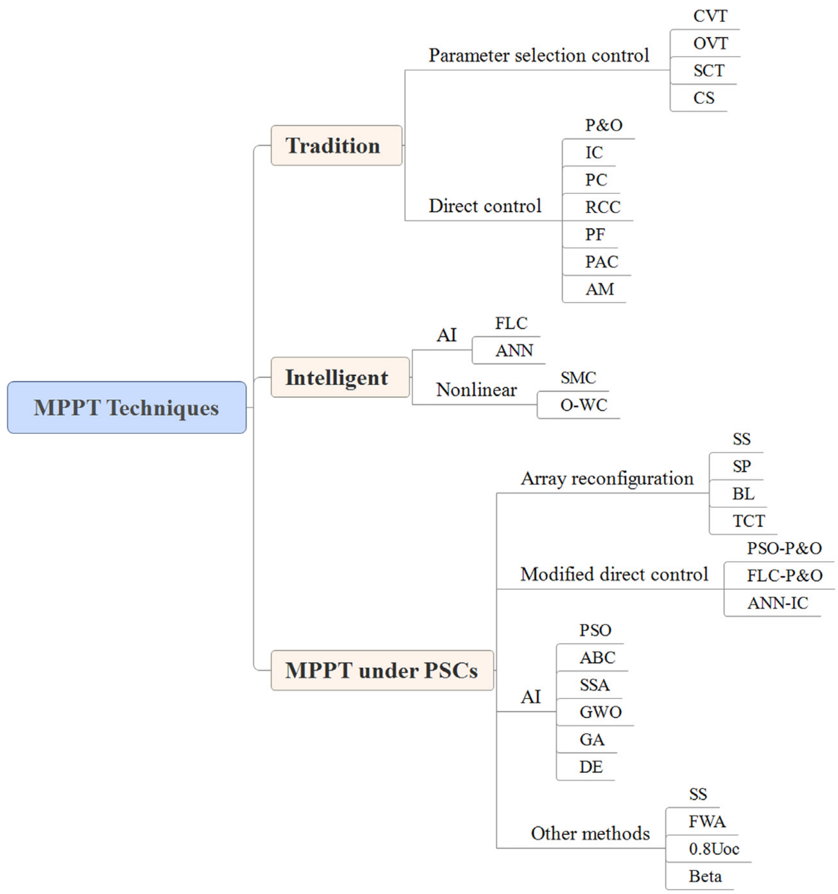

Fig. 1. Simplified classification of some common MPPT control methods.

(Karaboga, 2005; Padmanaban et al., 2019; Soufyane et al., 2015; Fathy, 2015), SSA (Mirjalili et al., 2017; Wan et al., 2019; Yang et al., 2019a,b; Ibrahim et al., 2018; Mohamed et al., 2019a,b) GWO (Mirjalili et al., 2014), etc. However, many authors prefer to combine AI algorithms with direct control methods (Kumar et al., 2019; Pilakkat and Kanthalakshmi, 2019; Sundareswaran et al., 2016; Kermadi et al., 2019; Al-Majidi et al., 2018; Danandeh and Mousavi, 2018a,b; Kihal et al., 2019; Furtado et al., 2018) or combine multiple intelligent algorithms (Wan et al., 2019) to perform MPPT under PSCs. Alternative algorithms proposed and successfully applied to MPPT of PV system under PSCs include SSM (Liu et al., 2014; Sundareswaran et al., 2014), FLS (Ramaprabha et al., 2012), $0.8U_{OC}$ method (Ahmed et al. 2015), FA (Manickam et al., 2017), BA (Li et al., 2019d,a,b,c; Jain and Agarwal, 2004), etc.

In this paper, the main MPPT methods are reviewed and classified in terms of their control theory and their implementation. Their merits are discussed and compared, especially under PSCs. Reviewed existing methods are grouped as in Fig. 1, where they are divided into three main types as follows:

i. Traditional MPPT methods;

ii. MPPT methods based on intelligent control;

iii. MPPT methods under PSCs.

The paper is organized as follows. Section 2 reviews the MPPT control methods under normal irradiation conditions, including the traditional and AI methods. Section 3 presents and compares four categories of MPPT control methods under PSCs. Finally, conclusions are drawn in Section 4.

2. MPPT control methods for PV system

2.1. Traditional MPPT methods

Commonly used traditional MPPT methods can be divided into the following two types: control methods based on parameter selection, and direct MPPT control algorithms based on sampled data.

2.1.1. Control methods based on parameter selection

The control algorithms based on parameter selection attempt to achieve the tracking control of the maximum power point by using knowledge of the defining parameters of a PV panel and measured parameters of its operating conditions. The intrinsic physical parameters of a PV panel, together with measurements of the irradiation and operating temperature, permit the establishment of an optimized mathematical model. Such models enable the prediction of P–V and I–V characteristic curves of the panel under given operating conditions, and hence determine also the maximum power point. An equivalent circuit model of the PV cell is commonly used, and the accuracy of several parameters in this model is important for the performance of this method. The control methods in this category mainly include CVT, OVT, SCT, LT, CS, CF, etc., and representative examples are summarized below.

CVT (Lasheen et al., 2017; Pilakkat and Kanthalakshmi, 2019) is the simplest parameter selection MPPT method, based on the assumption that there is a linear relation between the module voltage at MPP and the open circuit voltage. This method regulates the module terminal voltage based on its open circuit value. However, the method cannot effectively achieve perfect MPPT, particularly under large temperature variations.

OVT (Veerapen et al., 2017) is similar in principle to CVT, except that the CVT method tracks a constant voltage, but this method starts from open circuit, reduces the module voltage in variable voltage steps and tracks the varying voltage. It can also be seen from the output characteristics of the PV array that when the open circuit voltage U_{OC} changes under different irradiation and temperature, the maximum power point voltage U_M will change approximately proportionally. An approximate linear relationship between U_{M} and U_{OC} can be calculated by using

$$U_{\mathrm{M}} = K_{\mathrm{U}} U_{\mathrm{OC}} \tag{1}$$

where K_{U} is a constant of proportionality and less than 1, and U_{OC} can be measured by disconnecting the PV array from the load. In (Veerapen et al. 2017), OVT was used in low light irradiation ($G \leqslant 350$ W/m^2), and the relationship was further extended by linear fitting. The empirical coefficient was determined by a least squares method.

The principle of SCT (Sher et al., 2017; Cui et al., 2019) is similar to VCT. The output characteristics of the PV array indicate that, when the short-circuit current I_{SC} of the PV array changes with the environment, mainly due to irradiance, the maximum power point current I_{M} of the PV array also varies approximately linearly with I_{SC}. An approximate linear relationship between I_{M} and I_{SC} of the PV array under this irradiation can be calculated by using the following equations:

$$I_{\mathrm{M}} = K_{\mathrm{I}} I_{\mathrm{SC}} \tag{2}$$

where K_{I} is a proportional constant and less than 1, which is very little affected by temperature, and the values of K_{I} for different PV arrays are different. For example, the K_{I} values in the literatures (Sher et al., 2017; Cui et al., 2019) are 0.94 and 0.92 respectively.

CS (Noguchi et al., 2002a,b) obtains the I-V characteristic curve of the PV array directly by sweeping the array current over a sufficient range and observing the voltage at the peak power point. Compared with other methods, the main disadvantage of the current scanning method is that the tracking speed is slow.

2.1.2. Direct control methods based on sampled data

The methods in this category track the maximum power point by taking sampled data, such as voltage, current and power, from a PV array. These direct methods do not rely on any model of the PV and are simple to implement in practice, and hence are widely used. These methods include P&O, IC, PC, RCC, PAC, AM, VF, PF, etc., and are often combined with intelligent search algorithms to further improve tracking accuracy and speed. Some of these methods are summarized as follows

P&O (Alik and Jusoh, 2018), also known as the hill climbing method, is one of the most commonly used techniques implementing MPPT in a PV system. The principle of P&O is to increase or decrease the voltage, or the duty cycle of the PV array terminal converted, at regular intervals, and observe the direction of power change there after to determine the next control signal. P&O is simple and reliable, and easy to implement. However, the algorithm tracks the MPP by constantly changing the terminal voltage of the PV array, which can easily cause output power oscillation. Furthermore with the change of the environmental conditions the method can result in power loss of the PV system. To overcome this issue, many modification of this method (Manickam et al., 2017; Ei et al., 2018; Ghamrawi et al., 2018; Abdel-Salam et al., 2018, 2019; Ahmed et al., 2018) have been proposed.

IC (Yatimi et al., 2019; Motahhir et al., 2018; Kumar et al., 2019) is another commonly used algorithms for MPPT control, and operates by comparing the instantaneous conductance I/V with the negative of the slope conductance -dI/dV, these becoming equal at the MPP. When the environmental conditions changes, the method can smoothly track the change in MPP, regardless of the characteristics and parameters of the PV module. However, the control process of IC is relatively complex, and the measurement accuracy and speed will affect the performance of the tracking to a certain extent. At the same time, the step size of the voltage increment is also proportional to the tracking error. An improved IC method has been proposed (Motahhir et al., 2018), in which the allowable error is taken within a certain accuracy range that satisfies the MPPT. Compared with the conventional technique, the modified method can quickly detect an increase or decrease in irradiation and make the right decision, the steady state oscillation is ignored and the loss of power is reduced.

PC (Wu et al., 2016) is a method similar to IC. The method take account the parasitic capacitance of the PN junctions in the cell, and stray inductance between the PV cells. The introduction of parasitic capacitance can reduce the error signal when not at the MPP, and also enhances the anti-interference ability of the PV system. Therefore, the accuracy of PC in practical applications is higher, but the method is difficult to implement.

PCC method is similar to P&O, and utilizes the continuous switching with in the converter to perturb the voltage and current of the PV array, thereby enabling MPPT. The perturbation is naturally occurring in the PV system, and there is no need to intentionally perturb the voltage and current. In addition, the method makes it unnecessary to obtain the parameters of the PV array in advance. Therefore, some simple and inexpensive circuits can be used to implement relevant functions. However, using this method requires the converter to work in CCM (Esram et al., 2006; Costabeber et al., 2015).

PAC (Salameh and Dagher, 1990; Nguyen and Lehman, 2008) is an earlier method which adjusts the number of series and parallel connection of PV arrays according to different loads, so that the PV array can meet different load requirements and operate at the MPP. However, this method has the fatal shortcoming that its real-time performance is very poor, as it cannot change the working point of the PV array quickly enough as the external environment changes.

AM (Rabinovici and Frechter, 2010; Hart et al., 1984) uses a dummy PV array module to establish a reference model of the working PV array at the same instantaneous irradiation and temperature. This method can avoid the loss of accuracy due to the aging of the PV cell, but it is too expensive for a small power system; the problem of multiple maximum values also needs to be considered for a high-power system.

PF (Hua et al., 1998) calculates the present output power, either in hardware or software, by collecting the output voltage and current values of the PV array. It adjusts the output voltage value according to the power difference between the current and previous cycle. The output voltage may not be unique at the same output power, so the PC controller should be designed as a single-value control mode, that is, only one side of the P–V curve is used. Taking the left side as an example, the output power becomes larger when the output voltage is increased, and vice versa (Li et al., 2019d,a,b,c). This method is practical and convenient, but it is not very reliable and stable, and it is rarely used in practice.

2.2. Intelligent MPPT control methods

The P–V characteristic curve of a PV module is non-linear and will change with the temperature and irradiation, and it may exhibit multiple peaks, hence, the conventional MPPT control method may fail.To deal with this, MPPT control methods based on intelligent algorithms have been widely proposed and successfully applied; these methods include FLC, NN, SMC, etc. Some common intelligent MPPT control methods are analyzed as follows.

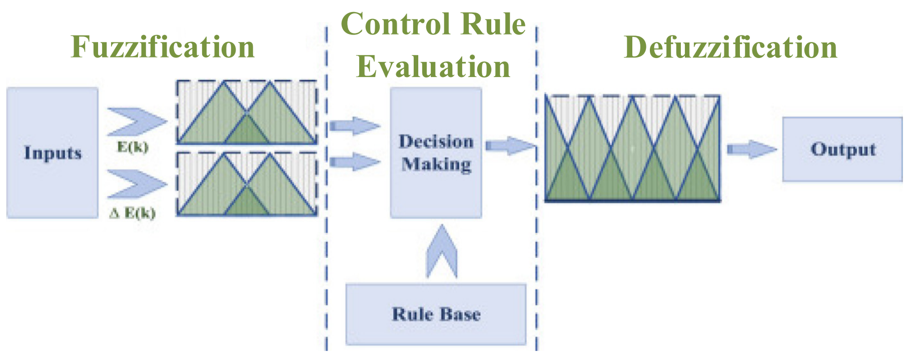

Fig. 2. FLC block diagram.

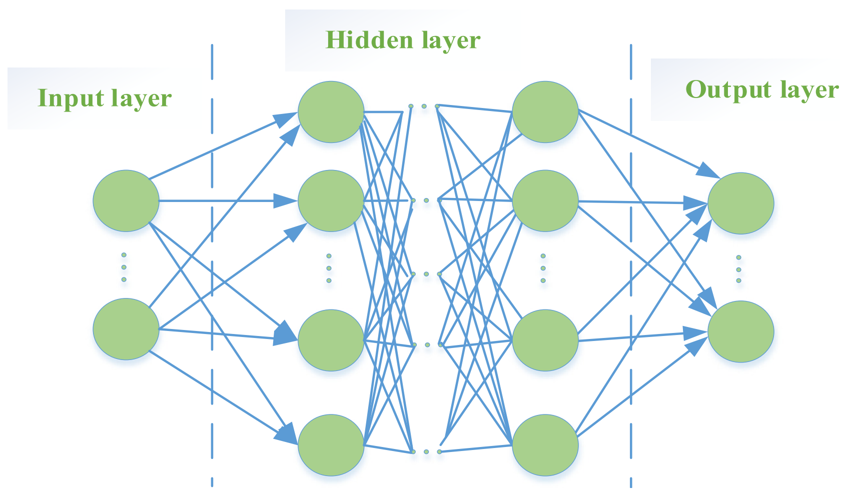

Fig. 3. Schematic diagram of neural network.

FLC (Li et al., 2019d,a,b,c; Yilmaz et al., 2018; Farajdadian and Hosseini, 2019b,a) is a common type of artificial intelligence algorithm, based on a set of fuzzy rules. As shown in the block diagram (Fig. 2), its implementation can be divided into the three steps of fuzzification, control rule evaluation and defuzzification. The key feature of FLC is incorporating expert experience and knowledge into language rules to control the system. Moreover, FLC can track the MPP quickly, and in steady conditions there is no fluctuation after reaching the MPP, that is, it has better dynamic and steady-state performance. However, the main disadvantages of FLC are that variation of irradiance can cause drift and the implementation is complex. Defining fuzzy sets, determining the shape of membership functions and the development of rule tables require more intuition and experience from designers, which directly affects the tracking speed and accuracy. Some researchers have tried to combine the traditional MPPT algorithm with FLC to improve the convergence speed, and reduce steady-state oscillation and implementation complexity. In Li et al. (2019d,a,b,c), the intermediate variable Beta was introduced as the third channel, which simplifies the membership function and reduces the dependence on the designer's experience. Yilmaz et al. (2018) proposed a PV panel sourced boost converter, with FLC, under variable temperature (25–60 °C) and irradiance (700–1000 W/m^2). This system was connected to a buck converter with PI control to function as a battery charging controller. In addition, FLC has also been proposed for an MPPT scheme in which four optimization algorithms are presented for optimizing fuzzy membership functions (MFs) and generating the proper duty cycle (Farajdadian and Hosseini, 2019a,b).

NN (Hamdi et al., 2019; Messalti et al., 2017; Issaadi et al., 2019; Mohamed et al., 2019a,b) is a new type of information processing technology. The most commonly used neural network structure has three layers: input layer, hidden layer and output layer, as is shown in Fig. 3. When applied in a PV system, many samples of input and output data are used to train variables such as weights and deviations of the network, thereby creating a mathematical model of the unknown function for the system. The input parameters may be U_{OC}, I_{SC}, illumination, etc., and the output parameters may be duty ratio, voltage, and the like.The training may be time consuming and the number of neurons in the hidden layer has a great influence on the training time of the network and the accuracy of the results. At present, many researchers combine NN with other intelligent algorithms to obtain better results. One example proposed is the combined PSO-RBFNN algorithm (Hamdi et al., 2019). In order to reduce training time, the PSO is used to optimize the number of RBFNN parameters, adjust the weight parameters and introduce the phase velocity to achieve the effect of implementing regulation. In Mohamed et al. (2019a,b), The controller parameters are optimized and adaptively tuned using a predictive neural network controller. It predicts the control parameters by tracking the mean square errors of grid currents and dc-bus voltage and eliminating these errors in a very short finite time.

SMC (Pahari and Subudhi, 2018; Kihal et al., 2019) is proposed by using the discontinuity of the control, relying on its high frequency conversion to force the closed loop system to reach and remain on the designed sliding surface. This method can significantly improve the tracking speed of the PV system, but the choice of the step size of the modulation depth of the switching device will affect the dynamic and steady-state characteristics of the system tracking. When the ΔU increases, the tracking speed

Table 1
The summarization of dynamic PV array reconfiguration methods.

Structure	Strategy	Required switches	Acquired parameters	Remarks	
				Advantage	Disadvantage
SS	Series (Pongratananukul and Kasparis, 2004)	Zero	Zero	High applicability	Low efficiency and high power losses
Parallel	Parallel (Wang and Hsu, 2010)	Zero	Zero	High applicability and high output current	Low efficiency and low output voltage
TCT	DS (Dhana and Rajasekar, 2018)	NS	Irradiance	High efficiency and high reliability	High complexity
	Z-Z (Vijayalekshmy et al., 2016)	NS	Irradiance	High applicability and high efficiency	Limited to 3 × 3 array
	IE (Matam and Barry, 2018a,b)	24-DPST	Current, voltage and irradiance	Short calculation and processing time	High complexity and acquired three parameters
SP	IE (Mahmoud and El-Saadany, 2017)	NS	Irradiance	Short computational time	Complexity and low reliability
	Dynamic PV array (Matam and Barry, 2018a,b)	15-SPST, 5-DPDT	Voltage and irradiance	High reliability	Poor versatility
	RPV (Manjunath et al., 2018)	6-SPDT, 5-DPST, 4-DPDT	Voltage, irradiance	High applicability	Only two transition modes of connection
	SWS (Iraji et al., 2018)	6-switches for each SWS	Current and irradiance	High convergence	Low reliability and high randomness
	Adaptive (Amer et al., 2015)	$6N_{FST} + 3N_{FMIM} + (N_{FST} - 1) + (N_{FMIM} - 1)$	Current and irradiance	High compatibility	Complexity and many switches
	IE (Harrag and Messalti, 2016)	NS	Irradiance	High convergence	High randomness
BL	(Belhachat and Larbes, 2015)	NS	Irradiance	High applicability and low cost	High complexity and not widely used
HC	(Bana and Saini, 2017)	NS	Irradiance	High stability	High complexity and not widely used

can be accelerated, but the fluctuations in the output power and voltage of the PV array will also increase. In order to improve the steady state performance of the control, Pahari and Subudhi (2018) proposed Integral sliding mode control. In Kihal et al. (2019), the external voltage control combined with P&O and adaptive integral differential slip film is used to design a new sliding surface, in which the derivative and integral terms are chosen to eliminate the overshoot during fast changes in solar irradiation and to minimize the steady-state fluctuation.

2.3. Classification and summarization for MPPT control methods

Summarizing the above discussion, Table 1 shows the performance of the MPPT control methods. In Table 1, some MPPT control methods are evaluated from the point of view of complexity level, tracking speed, efficiency, and accuracy, etc. Each performance indicator is divided into three to five degrees, including low, medium, medium–low, medium–high and high. From Table 1, it can be seen that the various MPPT control methods have their own advantages and inevitable shortcomings. These MPPT control methods are not perfect, and have broad research prospects and development space, especially in the case of PSCs (see Table 2).

3. PV system MPPT control methods under PSCs

To overcome the problem of the output power drop due to the multi-peak property of the characteristic curve of the PV system under PSCs, some researchers have proposed methods which have shown increased accuracy of the MPPT and hence increased the output power of the PV array under PSCs. However, these methods have the problems such as requiring real-time data measurement (Noguchi et al., 2002a,b), special circuit configurations (Mishima and Ohnishi, 2002) or lengthy calculation (Solodovnik et al., 2004), etc. As modern control theory and artificial intelligence develop, some more practical and reliable methods for global optimum tracking have become available. These emerging intelligent control methods provide more options for MPPT control of PV systems under PSCs.

Following a review of current literatures (Eltamaly et al., 2018; Belhachat and Larbes, 2019; Kumari and Geethanjali, 2019; Venkateswari and Sreejith, 2019; Jiang et al., 2018; Batarseh and Zater, 2018; Belhachat and Larbes, 2018a,b, 2019; Danandeh and Mousavi, 2018a,b; Pathy et al., 2019; Rezk et al., 2019; Fernandez-Guillamon et al., 2019; Podder et al., 2019; Ahmad et al., 2019; Sitbon et al., 2018; Nihanth et al., 2019; Li et al., 2019d,a,b,c, 2018a,b), the existing representative GMPPT methods under PSCs can be summarized and grouped into the following four categories:

i. Hardware control methods based on array reconfiguration;
ii. Control methods based on artificial intelligence algorithms;
iii. Improved direct control methods based on perturbation self-optimization;
iv. Some MPPT methods based on other principles.

3.1. Hardware control method based on array reconfiguration

The hardware control methods based on PV array reconfiguration refer to the use of switches, sensors and controllers to dynamically change the PV array connection structure to increase the immunity of the system to PSCs. The concept of PV array reconfiguration was first proposed by Salameh and Dagher (1990), and was then widely developed and applied (Nguyen and Lehman, 2008; Velasco-Quesada et al., 2009).

As shown in Fig. 4, the PV array interconnection structures (Sai and Moger, 2019) include SS, SP, BL, TCT, HC, etc. The output characteristics of all these connections have been analyzed through simulation and experiment (Bastidas-Rodriguez et al., 2013; Liu et al., 2011). Moreover, the performance of common PV array joint structures under PSCs have been evaluated (Woyte et al., 2003; Karatepe et al., 2007; Wang and Hsu, 2011). It can be seen that changing the array connection structure appropriately can

Table 2
Performance comparison of some MPPT methods for PV system.

Category		MPPT	MPPT performance indicators						
			Complexity	Tracking speed	Cost	Efficiency	Accuracy	Preference with PSC	Hardware implementation
Traditional MPPT technology	Control methods based on parameter selection	CVT	Low	Medium	Low	<90%	Low	Unable	Easy
		OVT	Low	Medium	Low	<90%	Low	Unable	Easy
		SCT	Low	Medium	Low	<90%	Low	Unable	Easy
		CS	Low	Slow	Medium	<90%	Low	Unable	Easy
	Direct control methods based on sampled data	P&O	Medium–low	Medium	Medium	>95%	Medium	Unable	Easy
		IC	Medium	Medium	Medium	>97%	Medium–high	Unable	Easy
		PC	Medium–high	Medium	High	>97%	Medium–high	Unable	Difficult
		RCC	Medium	Medium	Medium	>97%	Medium	Unable	Easy
		PAC	High	Slow	High	<90%	Medium–low	Unable	Difficult
		AM	Medium	Slow	High	<90%	Medium	Unable	Difficult
		PF	Medium–low	Slow	Medium	>90%	Medium–low	Unable	Easy
The MPPT method based on intelligent control	AI control methods	FLC	Medium–high	Fast	High	>98%	Medium–high	Able	Medium
		NN	High	Fast	High	>98%	Medium–high	Able	Difficult
	Nonlinear control methods	SMC	Medium	Fast	High	>98%	Medium–high	Able	Medium

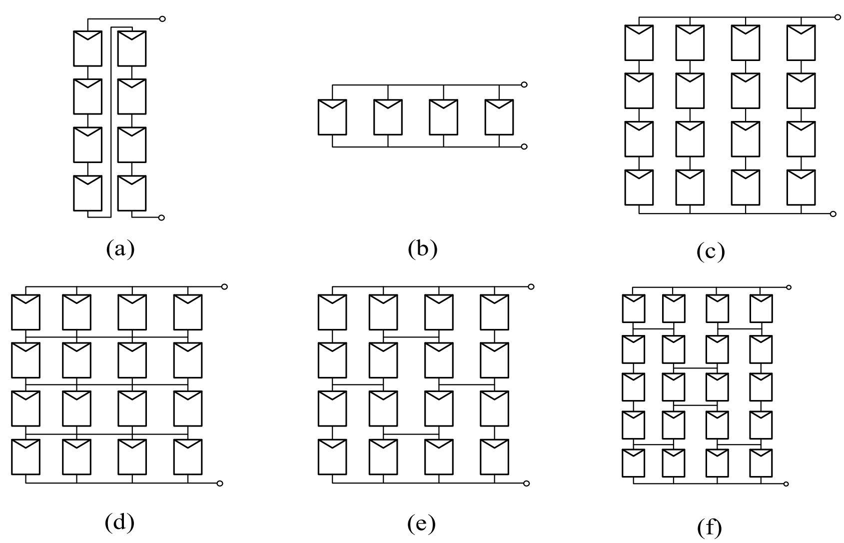

Fig. 4. PV array configuration structures: (a) SS, (b) Parallel, (c) SP, (d) TCT, (e) BL and (f) Honey-Comb.

reduce the shading effect and enhance the power output to some extent.

In addition, in recent years, some methods of combining intelligent control with hardware array reconfiguration have been proposed (Sai and Moger, 2019) to enhance the immunity of PV systems under PSCs. These methods are all aimed at MPPT under PSCs. In Dhana and Rajasekar (2018), the PV array uses the TCT connection structure, and a new puzzle-based physical reconfiguration scheme is proposed. This is termed the dominant square (DS) method and leads to physical relocation of the modules within the conventional TCT interconnection. This helps to attain uniform total current in each row of the array. difference with the method. A new and different Zig-Zag method was proposed by Vijayalekshmy et al. (2016), Nevertheless, the method has demonstrated its effectiveness only for a simple 3 $\times$ 3 PV array. Matam and Barry (2018a,b) applied a dynamic reconfiguration method to a Building Integrated PV System (BIPV). A new physical arrangement scheme for the PV array has been presented (Belhaouas et al., 2017), and is mainly based on maximizing the geometric distance between modules that are topologically adjacent within the PV array. Manjunath et al. (2018) proposed a new re-configurable PV array (RPV) based water-pumping system. In addition, an optimized switching set (SWS) topology for PV modules is developed in Iraji et al. (2018).

Many suitable PV array configurations have been reported so far, and the most often used solutions rely on the TCT and SP configurations. The SS, Parallel, BL, and HC configurations are rarely used due to low efficiency, complicated wiring, etc. For the TCT configuration, the most challenging part is to connect PV modules with similar irradiance levels in each row, which is known as irradiance equalization (IE). For SP connection, the aim of reconfiguration is to build strings of series connected modules with similar irradiance levels, then connect all the strings in parallel (Sai and Moger, 2019). A summary of dynamic PV array reconfiguration methods reported in the literature is presented in Table 1. These methods are summarized in term of strategy, required switches and other distinguishing parameters. A simple evaluation of the advantages and shortcomings of these methods is given. In the table, DPST, SPDT and SPST denote double-pole single-throw, single-pole dual-throw and single-pole, single-throw types of switches respectively. N_{FST} is the number of flexible strings and N_{FMIM} is the number of flexible micro-inverter modules in the PV system.

3.2. Control methods based on artificial intelligence algorithms

AI control algorithms are among the most popular at present, the main methods including PSO (Kennedy and Eberhart, 1995), ABC (Karaboga, 2005), ACO (Dorigo and Gambardella, 1997), SSA

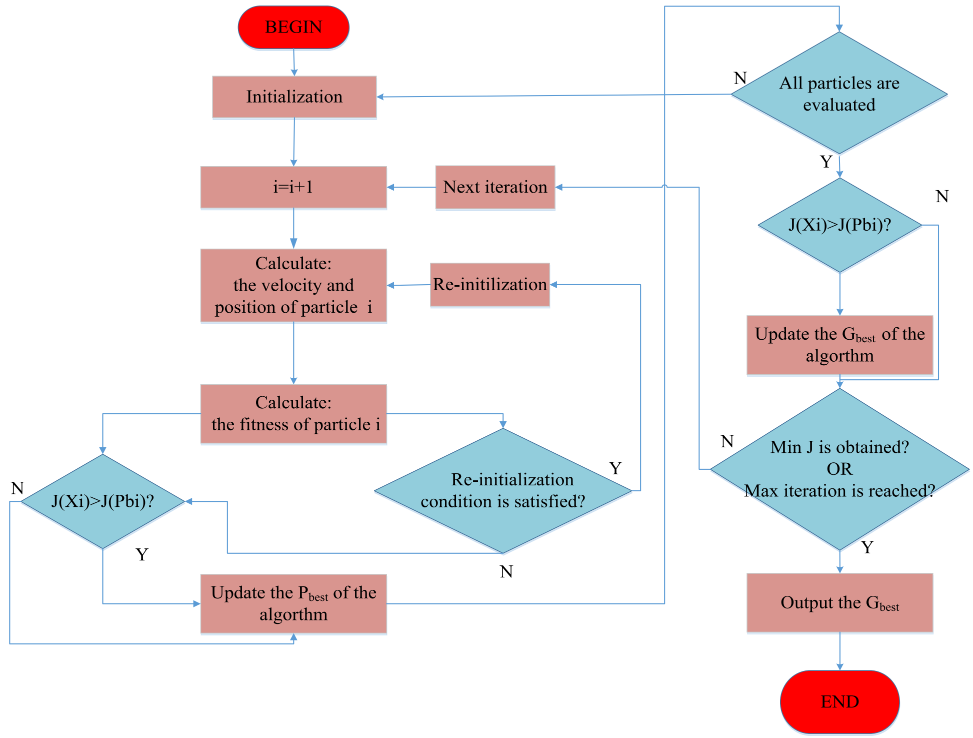

Fig. 5. Flowchart of PSO method.

(Mirjalili et al., 2017), GWO (Mirjalili et al., 2014), GA (Holland, 1992), DE (Storn and Price, 1997), etc. Many applications to PV arrays have been proposed and have shown their effectiveness for MPPT in PV system under PSCs.

PSO algorithm is a multi-extreme function global optimization method developed by simulating birds' foraging behavior (Kennedy and Eberhart, 1995). Its excellent performance for solving multi-peak problems in multi-variable system has been widely acknowledged by researchers in many different fields. Fig. 5 shows flowchart of PSO in multi-peak MPPT. The objective of the PSO is to find the best particle which represents the global optimal solution, that is, the GMPP of the PV array. The particle can be the output voltage or the output current, and the objective function can be the output power. Assuming a converter is fitted, duty ratio can be the control variable. However, the group initialization and changing environment have a great impact on its performance.

Therefore, in recent years, PSO algorithms have been improved and applied to PSCs by many researchers. Ishaque et al. (2012a,b) used three strategies to implement the PSO algorithm under non-uniform illumination, which effectively improved the tracking performance. Hamdi et al. (2019) combined PSO with ANN and RBF to further improve the tracking performance of the algorithm. In Li et al. (2019d,a,b,c), a new overall distribution PSO (OD-PSO) algorithm is proposed, which sets the possible peak point voltage to the initial position of the particle by OD-MPPT, thus ensuring that the PSO algorithm only needs to find MPP quickly and efficiently in a very small search area. Saad et al. (2018) proposed a novel hybrid centralized and distributed control of a hybrid renewable energy system. An improved PSO which acts as a master controller is used to control the power of the sources based on Interlinking Converter control. Another improved PSO (IPSO) algorithm, which adopts both global and local modes to locate the maximum power point, has been proposed in Hu et al. (2019). Compared to the standard PSO algorithm, many random and interfering variables are removed, and the structure is optimized significantly.

The search principle of the ACO algorithm is similar to that of PSO. The major difference is that the ACO algorithm only memorizes position information. The algorithm was first introduced by Dorigo and Gambardella based on the foraging behavior of real-life ants when finding the best path toward food (Dorigo and Gambardella, 1997). The main advantage is that it can adapt to real-time changes and run continuously (Sundareswaran et al., 2016; Socha and Dorigo, 2008; Titri et al., 2017; Lekshmi and Umamaheswari, 2018). Socha and Dorigo (2008) presented an extension of ACO to continuous domains. A new bio-inspired MPPT controller is based on the ant colony optimization algorithm with a new pheromone updating strategy (ACO_NPU MPPT). This saves computation time and has an excellent tracking capability with high accuracy, zero oscillations and high robustness (Titri et al., 2017). Although the ACO algorithm shows excellent performance in dealing with maximum power point tracking control problems, there are few papers on MPPT directly using the ACO algorithm, and instead it is mainly used indirectly to optimize other controllers to improve MPPT performance. Lekshmi and Umamaheswari (2018) focused on the realization of an efficient solar power fed DC–DC single ended primary inductor converter (SEPIC) using a second order ACO tuned PI controller. Statistical analysis shows that ACO yields better results when compared to GA.

ABC algorithm is a relatively new application of swarm intelligence algorithms. It was proposed by Karaboga (2005) based on the bee's foraging behavior, learning, memory and information sharing characteristics. In other words, it simulates the leader, scouter and follower to look for the honey source, while a process of continuous iteration is used to find the optimal honey source; this is suitable for the optimal value of dynamic parameters. Compared with other conventional or intelligent algorithms, ABC algorithm has better positive and negative feedback mechanism and randomness in the group cooperation process, and these give it faster convergence and better robustness. There is also low computational complexity and high accuracy, and stability does not depend on the initial conditions and the ability to

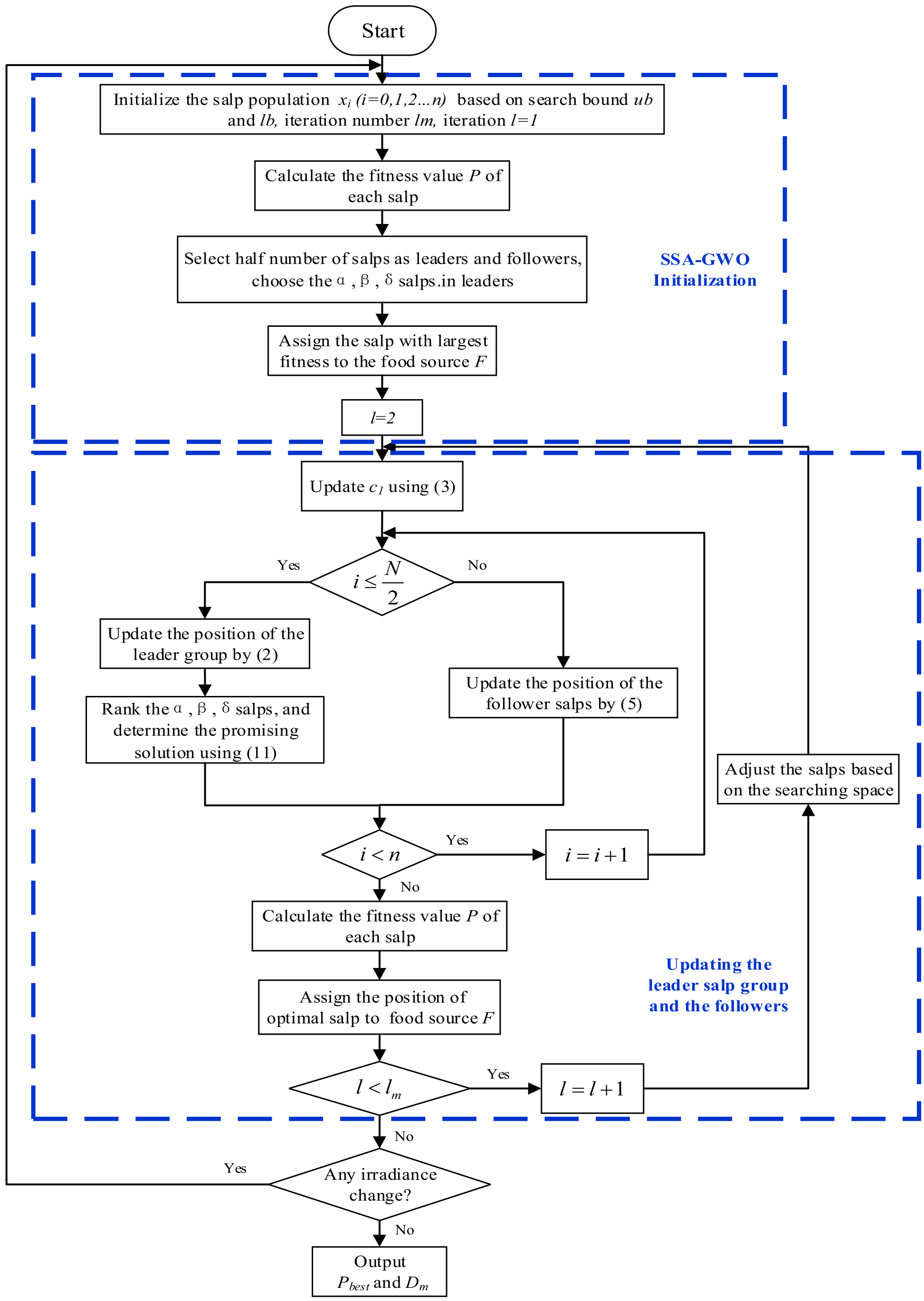

Fig. 6. The flowchart of SSA-GWO method.

handle local extrema. In Belhaouas et al. (2017), ABC is combined with P&O to improve the stability of the algorithm. Padmanaban et al. (2019) introduced a novel control system with MPPT for a grid-connected PV system. A hybrid adaptive neuro-fuzzy inference system and ABC algorithm were employed to optimize the membership function. Soufyane et al. (2015) applied the ABC algorithm to the MPPT control of a non-uniformly illuminated PV system, and compared it with the tracking performance of the PSO algorithm. This proved the excellent performance of the ABC algorithm in the MPP tracking control. An improved ABC optimization algorithm has been proposed to optimize the constraint equations of the PV modules and so to reduce the impact of uneven illumination (Fathy et al. 2016).

FA is used for MPPT in some literature(Shi et al., 2016; Teshome et al., 2016; Chaurasia et al., 2017). Shi et al. (2016) described a modified firefly algorithm that can rapidly and accurately extract the GMPP under PSCs. The algorithm introduces the concepts of the global and local firefly densities during each iteration, and includes two elimination mechanisms to adaptively adjust the firefly population. Teshome et al. (2016) proposed an improved firefly algorithm to make up for the shortcomings of a conventional one. In addition, the controller gains are simultaneously optimized by a powerful meta-heuristic firefly algorithm (Chaurasia et al., 2017).

Recently, a novel bio-inspired algorithm called SSA has been developed (Mirjalili et al., 2017), which has a simple search mechanism and a high optimization efficiency. Compared to the

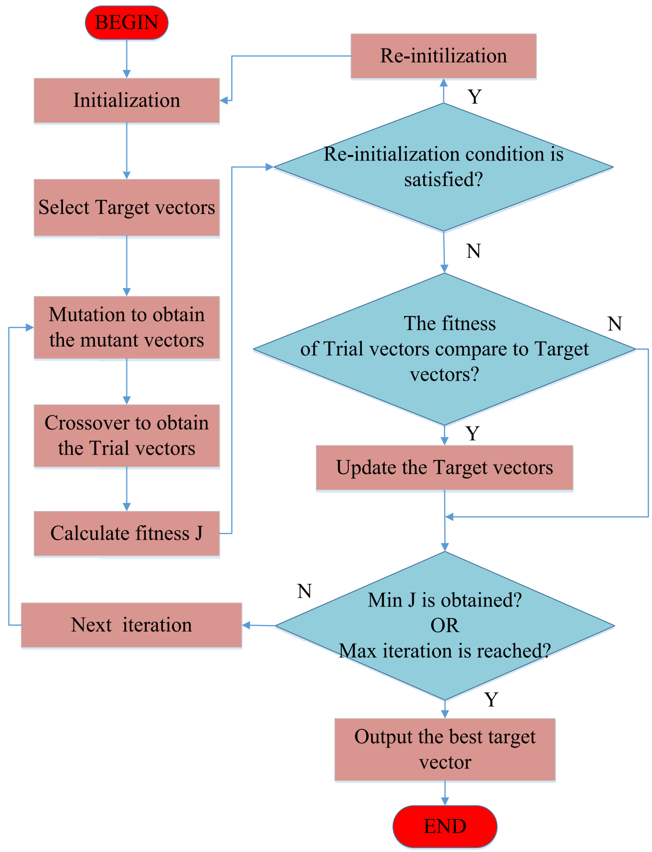

Fig. 7. The flowchart of GA method.

above bio-inspired algorithms, the SSA has only one parameter to update. However, it suffers from the same limitations that face the other metaheuristic (MH) algorithms, such as slow convergence, since its capability is not fully exploited. Wan et al. (2019) proposed an MPPT controller that combines SSA with GWO (namely, SSA-GWO). Its flowchart is shown in Fig. 6. The leader structure of the GWO algorithm is introduced into the basic SSA to enhance the global search capability. In addition, Yang et al. (2019a,b) proposed a novel bio-inspired optimization method named memetic salp swarm algorithm (MSSA). It is developed by extending the original SSA with multiple independent salp chains, thus it can implement a wider exploration and a deeper exploitation under the memetic computing framework. In Ibrahim et al. (2018), it is used to update the current solution through switching between the SSA and the PSO and this leads to a balance between the exploration and the exploitation of the SSA. The performance of SSA, GWO and other algorithms was analyzed (Mohamed et al., 2019a,b).

GA is a random search algorithm that simulates the natural selection of the biological world (Holland, 1992). The flow chart of GA is shown in Fig. 7, and the optimal solution of the problem is evolved through genetics, variation, intersection, and replication. Especially for real-time nonlinear and multi-modal objective function problems, it has high robustness and wide applicability; however, GA is not very stable and sometimes still finds the local optimal solution. In Huang et al. (2018), the proposed algorithm combines GA with the FA and its calculation process is further improved using a DE algorithm. Among them, the mutation process of DE and the absorption process of FA combine to simplify the calculation results of the genetic algorithm. The real coded improved genetic algorithm (RCGA)-based metaheuristic approach is proposed to regulate dc-link voltage according to a reference adaptive dc-link voltage, which improves the dynamic behavior of the system under variation of the CCP voltage (Shah and Singh, 2019).

DE algorithm is an evolutionary algorithm used for global optimization (Storn and Price, 1997). The flow chart of DE is shown in Fig. 8. This algorithm is used for solving these problems that are non-differentiable, non-continuous, nonlinear, noisy, flat, or multidimensional, or have many local minima, constraints, and stochasticity. Unlike PSO, there are only two parameters that are required to be set in DE, thereby reducing the complexity in tuning the required parameters to achieve accurate MPPT. In terms of the search principle, DE is more dependent on the initial generated random population than GE. In these groups, it uses selection, mutation, and crossover to refine and improve the next candidate solution (Kermadi and Berkouk, 2017). The standard DE algorithm is used to perform global maximum power point tracking under PSCs. Although a good tracking effect is achieved, it is based on a static objective function to obtain a predetermined P–V characteristic curve, and the actual P–V characteristics of the array always vary with temperature and solar irradiance. MPPT is also a nonlinear time-varying problem with certain limitations. Addressing this limitation, Tey et al. (2018) improved the conventional DE algorithm. As the tracking time is important for the MPPT controller, convergence is introduced in the improved DE algorithm to converge the searching toward the best particle in each iteration. To further reduce the tracking time, the donor and trial vectors are compared before the tracking process starts. Moreover, the improved algorithm can respond to load variation rapidly which ultimately reduces undesirable fluctuations at the output of PV array.

According to the above descriptions of the algorithms, control methods based on artificial intelligence algorithm can be classified, as shown in Fig. 9.

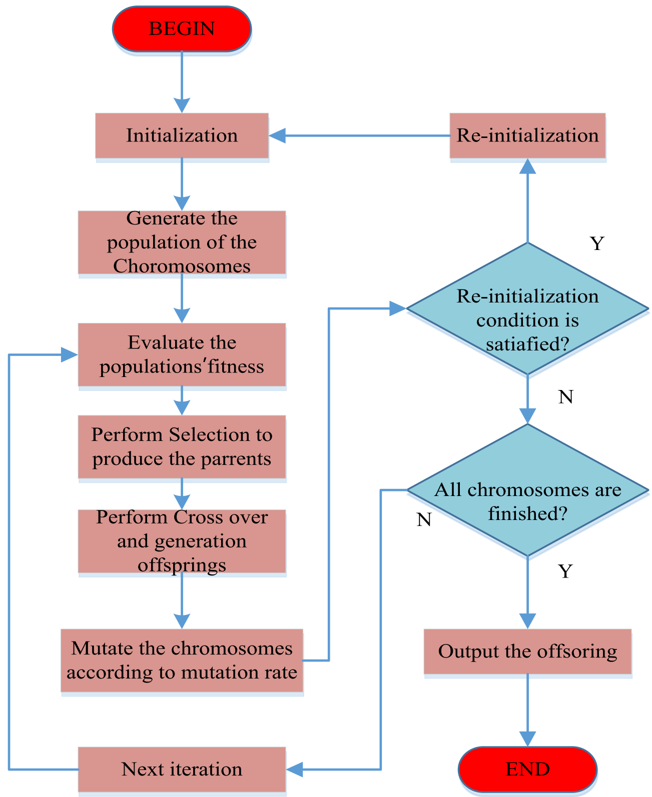

Fig. 8. The flowchart of DE method.

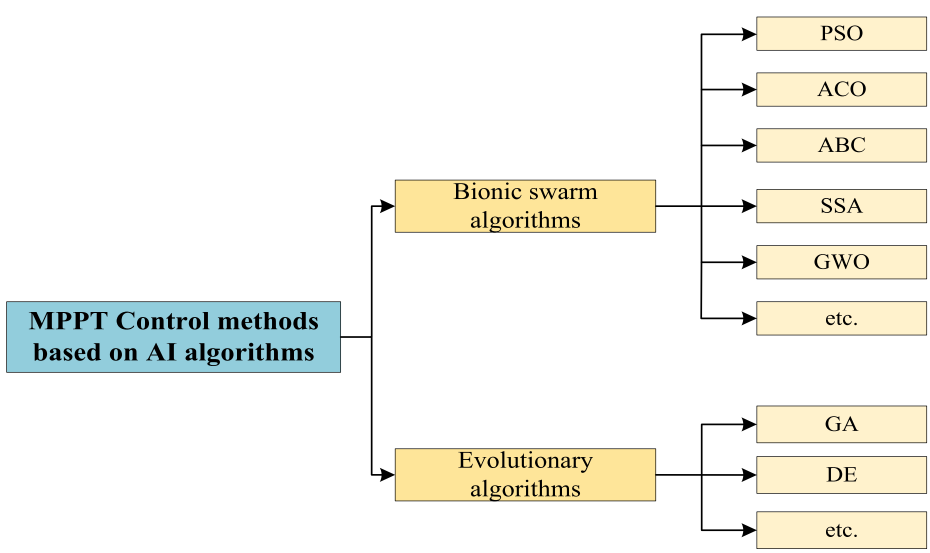

Fig. 9. Classification diagram of the MPPT control methods based on AI algorithms.

3.3. Improved direct control methods based on disturbance self-optimization

The concept of disturbance self-optimization refers to a direct control method using sampled data, which is improved to a certain extent according to the needs of the tracking control of the PV system. Traditional direct control algorithms based on sampled data are prone to fall into an LMPP under non-uniform illumination and fail. In order to overcome this limitation, many ways of improving the traditional direct control algorithm have been presented. The specific analysis is as follows

A hybrid approach that combines a phased search algorithm with a traditional direct control algorithm that divides the entire search process into two phases:

i. Narrow the search by moving the work point;

ii. Search the global maximum power point using a conventional algorithm in a small range.

In Kumar et al. (2019), a modified IC using a P–V curve region shifting based MPPT algorithm is developed to track the global power peak under partial shading conditions. The proposed algorithm determines the P–V curve as a combination of regions, and tracks the global peak by shifting the operating point from

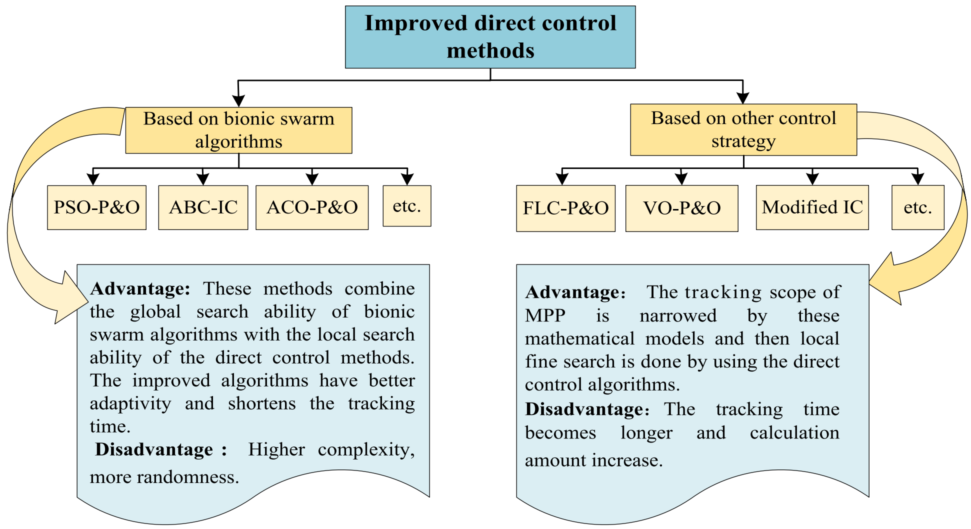

Fig. 10. Classification diagram of the improved direct control methods.

one region to another without using any nature-inspired techniques. In Pilakkat and Kanthalakshmi (2019), Sundareswaran et al. (2016) and Kermadi et al. (2019), three new algorithms are proposed respectively by combining ABC, ACO, PSO algorithm with the P&O method. These combine the global search ability of intelligent algorithms with the local search ability of P&O method, and are used for MPPT control under PSCs. In Al-Majidi et al. (2018), the proposed method is designed to incorporate the advantages of the FLC and P&O algorithms, whilst eliminating their drawbacks. The irradiance is classified into two types: fast changing and slow changing, and the FLC and P&O algorithms are used in the fast change and slow change stages respectively. Danandeh and Mousavi (2018a,b) combined the INC method and FLC in a new architecture in order to reduce the number of fuzzy rules and costs without missing the accuracy. This architecture has the advantages of a pure fuzzy system, like high speed and accuracy, while being less costly and simpler to implement. Kihal et al. (2019) presented a novel voltage-oriented MPPT (VO-MPPT) method, where the conventional P&O algorithm is combined with the proposed external voltage control based on an adaptive integral-derivative sliding mode. In Furtado et al. (2018), a trapezoidal region is proposed to reduce the global search range, thus improving the tracking speed of the P&O algorithm.

A summary of improved direct control methods based on disturbance self-optimization, as reported in the various literature, is presented in Fig. 10.

3.4. MPPT methods based on other methods

A few tracking control methods that are not clearly in the above groups have also been researched. These include SSM, FA, $0.8U_{OC}$ method and FLS, etc. Since there are relatively few references to these, a brief introduction is made here.

In Liu et al. (2014) and Sundareswaran et al. (2014), the segmentation search method and the random search method are respectively used, which has fast tracking speed and can effectively perform GMPPT in most cases. However, these two methods are computationally intensive and not very accurate. Ramaprabha et al. (2012) applied the improved Fibonacci linear search algorithm to maximum power point tracking control, which has a fast response speed to adapt to dynamic changes during initialization or when environmental conditions change. At the same time, the power oscillation at steady state is reduced, and the tracking performance and the fast response speed are obtained under PSCs. The defects of the traditional $0.8U_{OC}$ method are pointed out (Ahmed and Salam, 2015), and the optimization is improved on this basis. Manickam et al. (2017) used a hybrid algorithm based on firework algorithm and P&O method to further optimize tracking performance.

Jain and Agarwal (2004) first proposed the BA and proved the effectiveness of this algorithm. It was further optimized and improved and applied to MPPT under PSCs (Li et al., 2019d,a,b,c, 2018a,b). Li et al. (2018a,b) adopted a new mathematical model under PSCs, in other words, PV method with partial shading is equivalent to a key module, linear independent source and constant voltage source, as shown in Fig. 11(a–c), and the tracking process of this algorithm is shown in Fig. 11(d). Therefore, the P–V curve is divided into several regions, and the improved Bate algorithm is used to find the local best of each region. It is considered that the maximum value of all the found points is the GMPP, and then the P&O algorithm further optimizes this point. At the same time, the BA is used to calculate the MPPT reference according to the PV voltage and current at GMPP.

3.5. Classification and summarization for MPPT control methods under PSCs

The performance of some MPPT control methods under PSCs is shown in Table 3, which is evaluated from six aspects of complexity, tracking speed, cost, etc. Each performance indicator is divided into three to five degrees, including low, medium, medium–low, medium–high and high. It is clear from Table 3 that array reconfiguration methods and improved direct control methods have high complexity, high cost and are difficult to implement. In addition, although artificial intelligence methods have high complexity, these methods have the advantages of fast tracking speed, high efficiency and accuracy. Other methods can be classed as more specific, and are most suitable for some particular class of PV system.

4. Conclusions

According to the above classification and summary of MPPT techniques, it is seen that research on MPPT methods for PV system has been an active topic for a long time, but further research is needed on the balance of rapidity, accuracy and stability of MPPT, especially under complex fast-changing irradiation conditions. Based on this, possible future research directions in MPPT methods in the future are as follows

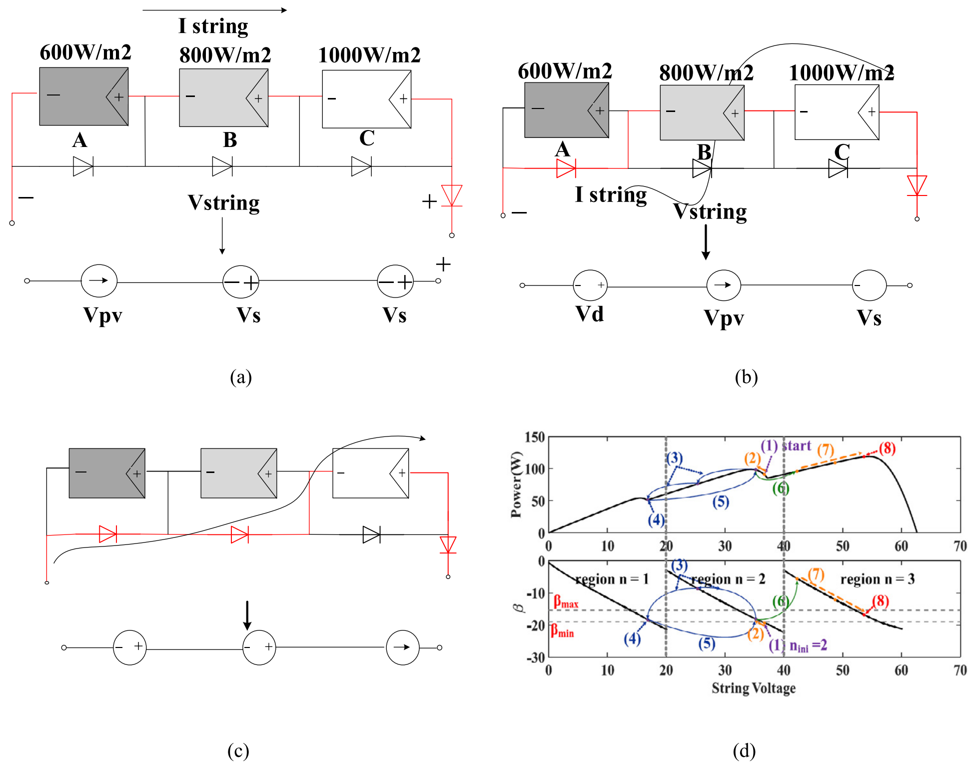

Fig. 11. Operation stages of a PV string under partial shading. (a) Stage I two bypass diodes conducted. (b) Stage II: one bypass diode conducted. (c) Stage III: no bypass diode conducted. (d) Tracking process under PSCs.

Table 3
Performance comparison of some MPPT methods under PSCs.

Category		MPPT	MPPT performance indicator					
			Complexity	Tracking speed	Cost	Efficiency	Accuracy	Hardware implementation
MPPT methods under PSCs	Array reconfiguration methods	SS, SP, BL, TCT, etc.	High	Slow	High	<90%	Medium–low	Difficult
	Improve direct control methods	ABC-P&O, ACO-P&O, PSO-CI, etc.	High	Fast	High	>99%	High	Difficult
	Artificial intelligence methods	PSO	Medium–high	Fast	High	>98%	High	Medium
		ACO	Medium–high	Fast	High	>98.5%	High	Medium
		ABC	Medium–high	Fast	High	>99%	High	Medium
		FA	Medium–high	Fast	High	>98.5%	High	Medium
		SSA	Medium	Fast	High	>99%	High	Medium
		GA	Medium–high	Fast	High	>98%	Medium–high	Easy
		DE	Medium	Fast	High	>98%	Medium–high	Easy
	Other methods	SS, RS, FLS, FWA, etc.	Medium–high	Fast	High	>98%	Medium–high	Medium
		Bate method	Medium	Fast	High	>98%	High	Easy
		0.8Uoc	Medium–low	Medium	Medium	<90%	Medium–low	Easy

i. The further combination of intelligent control methods and traditional control methods. In recent years, the MPPT control methods based on intelligent control have been favored by many researchers because of their superior global optimization ability and tracking control performance. However, there are also disadvantages or limitations of the poor real-time performance, low practicality, and high computational complexity. Nevertheless, the traditional tracking control methods can just compensate for the shortcomings in some aspects. Therefore, the MPPT control for a PV system, especially under the complex environments such as PSCs, should make full use of the existing various control methods to give full play to their respective advantages, developing strengths and avoiding weaknesses.

ii. One area of modeling that still appears to be lacking concerns the statistical properties of partial shading, which can vary from static (e.g. building shadow) to slow varying (e.g.bird droppings) or fast varying (e.g clouds.) Arrays and their MPPT schemes, and module relocation techniques, must be affected by the degree and structure of spatial correlations between the shading at different modules in an array. It would be useful to have more information on this. For example theoretical modeling of cloud shadows would be difficult, while gathering empirical data on shading would require a significant measurement campaign.

iii. Standardization of MPPT performance evaluation indicators. The existing methods for evaluating the MPPT performance are to judge whether the algorithm can accurately track the maximum power point, but a more informative the energy utilization index, that is, the ratio between the output power by the MPPT control method and the theoretical maximum output capability in a period of time. However, this indicator is closely related to the actual application environment of the PV system. In a complex application environment, the output MPP of PV array or PV system has randomness, uncertainty and instability which are hard to quantify.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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