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Improved particle swarm optimization for maximum power point tracking in photovoltaic module arrays

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HIGHLIGHTS

- This study proposed an improved PSO algorithm for MPPT in PV module arrays.
- A MPPT that incorporated shading and failure conditions in PV array is developed.
- The proposed MPPT method was built using improved particle swarm optimization.
- The proposed PSO algorithm can perform MPPT for multi-peak *P–V* characteristic curves.
- The proposed PSO algorithm exhibited superior tracking speed, response, and accuracy.

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ABSTRACT

In this paper, a maximum power point tracking (MPPT) method that incorporated shading and failure conditions in photovoltaic (PV) module arrays is developed. This MPPT method was built using improved particle swarm optimization (PSO). The PSO algorithm enables PV module arrays to perform MPPT for multi-peak power–voltage (*P–V*) output characteristic curves when shading or failures occur. This facilitates the tracking of actual maximum power points in PV module arrays. The HIP 2717 PV module produced by SANYO Electric Co., Ltd. was used in this study to assemble various array configurations. The characteristic curves of these array configurations when partial module shading or failure occurred were investigated. Numerous working conditions were selected for dual-peak, three-peak, and four-peak characteristics. PIC microcontrollers were then used to apply both the traditional and the proposed PSO algorithms to enable MPPT. A comparison of the measurement results showed that the proposed PSO algorithm exhibited superior tracking speed, response, and accuracy, compared with those of the traditional PSO algorithm.

1. Introduction

Photovoltaic (PV) power generation systems are composed of PV module arrays, power conditioners, and power transmission and distribution systems. Irradiation and environmental temperature changes directly affect the output power of PV module arrays, resulting in significant variations. Therefore, maximum power point tracking (MPPT) technology must be used to control PV module arrays to maximize power output. The majority of early MPPT methods have emphasized the use of traditional techniques [1–5], such as voltage feedback [1] and the constant voltage [2], power feedback [3], perturb and observe [4], and the incremental conductance methods [5]. However, these traditional MPPT methods are inappropriate for working conditions in which partial module shading or failures can occur in PV module arrays. This is because the power–voltage (*P–V*) characteristics of PV module arrays display dual-peak or multi-peak characteristics when partial module shading or failures occur [6–8]. Traditional MPPT methods can only track local maximum power points, but not global maximum power points.

Recently, numerous scholars have proposed intelligent MPPT methods for PV module arrays [9–20] to track maximum power points accurately and improve dynamic and steady-state tracking performance. However, these methods are applicable to MPPT only in conditions where the modules in the PV module arrays are not shaded. Multi-peak output curves occur frequently when modules in PV module arrays are partially shaded. Therefore, the development of an algorithm capable of accurately tracking maximum power points on complex and nonlinear output curves is critical. Scholars have proposed various algorithm architectures that are capable of tracking global maximum power points when modules

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are shaded. Among these, a two-stage method for tracking global maximum power points was suggested in [21]. However, when the global maximum power points are located to the left of the load line, this method could not track the maximum power points. In addition, this method is applicable only to tracking dual-peak characteristics. Another two-stage method for tracking global maximum power points was proposed in [22]. This method involved using a scanning program to determine curve regions containing global maximum power points. The program then applied the variable step size perturb-and-observe method to track the global maximum power points. However, this method must compare the maximum power points in each region before the global maximum power point can be derived, thereby limiting the tracking speed.

An MPPT algorithm built on the sequential extremum-seeking method was presented in [23]. This algorithm was built using approximate models and analysis of PV modules under different shading conditions. Staged searches are performed within the entire tracking range. Thus, this method provides higher computing efficiency compared with that of the sweeping search method. However, because this method adopts approximate models of PV module array shading characteristics, steady-state errors occur in the model and module parameters. A novel MPPT algorithm using artificial neural networks (ANNs) and fuzzy logic controllers was proposed in [24]. These ANNs are trained based on shading data obtained from the PV module arrays that use three-layer feed-forward training to determine global maximum power point voltage. Thus, this algorithm is connected to system parameters and requires the use of sunlight and temperature data to determine global maximum power points. These data are difficult to obtain because sensors must first be installed to obtain information. Other experts and scholars have proposed replacing the single module array of maximum power point trackers that have been used traditionally with multiple-tracker architecture [25]. This architecture would avoid an excessive influence on the overall system power generation when only several modules are shaded or fail. Although this method effectively increases overall power generation efficiency, numerous direct current (DC)–DC converters must be used, which raises equipment costs. Several papers [26,27] have been proposed to improve the dynamic and steady state responses of MPPT by adaptively tuning tracking step size. Although these methods can successfully improve the dynamic and steady state tracking performance at a specific scaling factor, an optimal scaling factor is difficult to determine due to the scaling factor is not the same under different operation conditions. In [28], a monotonically decreased tracking step size was adopted to track the exact maximum power point, but the implementation of this technique is rather complex. Some soft computing methods [29–31] are developed for MPPT algorithm under fast changing environments. These methods can rapidly calculate current maximum power points, but highly complex calculations are required. Therefore, they are not suitable for practical application. In [32], chaos search method was proposed to accurately track the global maximum power point. However, experimental results did not verify the effectiveness of this method.

Recently, various scholars have presented MPPT techniques for PV module arrays based on PSO algorithms [33–38] to improve dynamic response speed. However, the characteristics of modules under partial shading were not considered in [33]. Thus, the method by [33] is applicable for MPPT only when all modules are under identical sunlight conditions. Although the method in [34] tracks global maximum power points effectively under conditions of varying amounts of shade, this method can be applied only to systems containing multiple converters. In addition, although the method in [35] can track global maximum power points with multi-peak characteristic curves, the learning factors and weight values in the algorithm are fixed. Thus, tracking performance lacks robustness, causing low success rates in the tracking of global maximum power points with limited iteration numbers. When maximum power points are tracked successfully, the dynamic response speed is slow. Improved PSO algorithms were presented in [36–38]. The method proposed by [36] lacks system design criteria and practical design considerations. Reference [37,38] improved the traditional PSO algorithm for application to shaded PV module arrays. However, the linear decreasing method was used for parameter selection in this PSO algorithm. This parameter selection is not optimized for PV module arrays with nonlinear characteristics, particularly characteristics that occur under shaded conditions.

Therefore, in this study, the parameters of a retentive PSO algorithm [39] were adjusted using nonlinear methods to shorten tracking time and develop an MPPT method that is superior to the traditional MPPT methods used in PV module arrays under conditions of partial module shading or failure. The proposed method showed increased effectiveness in MPPT when multi-peak *P–V* characteristic curves appeared in the PV module arrays.

2. Shading and failure characteristics in PV module arrays

Arrays composed of HIP 2717 PV modules [40] that are produced by SANYO Electric Co., Ltd. were the test objects in this study. Table 1 shows the electrical specifications of these modules under standard testing conditions (AM1.5, sunlight intensity of 1000 W/m^2 and PV module temperature of 25 °C).

2.1. PV module simulator circuitry

To facilitate experimentation on PV module array shading and failure characteristics, an HIP 2717 PV module simulator containing adjustable partial shadow and failure circuitry was used, as shown in Fig. 1 [41]. The circuit architecture comprised a Darlington pair amplification circuit, an output current limiter, and a voltage stabilization circuit to enable implementation of PV modules containing various shading characteristics. Variable resistors VR_{Isc} and VR_{Voc} were adjusted to possess both open-circuit voltage and short-circuit current output characteristics at various shade ratios. The R_B and VR_{Voc} divider circuits were used to adjust shade ratios. When a V_{PV} power supply is not provided, the PV module simulator does not contain output power; this is equivalent to setting the PV module to failure conditions.

The BJT transistor 2N3055, with ratings of I_C = 15 A, V_{CEO} = 60 V, P_{tot} = 115 W, and h_{FE} = 20, was chosen for the output transistor Q_2. Then, the 2N2219, with ratings of I_C = 0.8 A, P_{tot} = 3 W, V_{CEO} = 30 V, and h_{FE} = 20, was chosen for Q_1 to form a Darlington amplifier with Q_2. Accordingly, the 2N1815, with ratings of I_C = 150 mA, P_{tot} = 400 mW, V_{CEO} = 50 V, and I_B = 50 mA, was chosen for Q_3 and Q_4 to serve as the base current driver of Q_1.

In the PV module simulator circuit, the resistance values of R_A, R_B, R_C and R_D are given 2 kΩ, 2 kΩ, 2 Ω, and 510 Ω, respectively. According to the shadow ratios of a PV module, the open-circuit voltage, V_{oc}, and short-circuit current, I_{sc}, can be determined according to their *I–V* characteristic curves, using either a

Table 1
Electrical specifications of the SANYO HIP 2717 PV modules.

Maximum output power (P_{mp})	27.8 W
Maximum power point current (I_{mp})	1.63 A
Maximum power point voltage (V_{mp})	17.1 V
Short-circuit current (I_{sc})	1.82 A
Open-circuit voltage (V_{oc})	21.6 V
Module length and width specifications	496 mm × 524 mm