Research Article

Two-Stage Chaos Optimization Search Application in Maximum Power Point Tracking of PV Array

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In order to deliver the maximum available power to the load under the condition of varying solar irradiation and environment temperature, maximum power point tracking (MPPT) technologies have been used widely in PV systems. Among all the MPPT schemes, the chaos method is one of the hot topics in recent years. In this paper, a novel two-stage chaos optimization method is presented which can make search faster and more effective. In the process of proposed chaos search, the improved logistic mapping with the better ergodic is used as the first carrier process. After finding the current optimal solution in a certain guarantee, the power function carrier as the secondary carrier process is used to reduce the search space of optimized variables and eventually find the maximum power point. Comparing with the traditional chaos search method, the proposed method can track the change quickly and accurately and also has better optimization results. The proposed method provides a new efficient way to track the maximum power point of PV array.

1. Introduction

It is well known that the output power of a photovoltaic (PV) cell or panel varies with the change of external environment and load; the output power can be maximized by operating at a specific point on its exponential voltage-current characteristic curve. Under the same external environment such as irradiation and temperature, PV system requires the PV cell to produce more power. In order to bring the efficiency of PV device into full play, maximum power point tracking (MPPT) techniques [1–3] are commonly used in PV system. The function of MPPT is to detect the real-time output of PV array and make the PV system run well under the optimum work state. However, the output characteristic of PV cell is complex and nonlinear. It is difficult to determine its mathematical model accurately. How to design the high-performance systems for extracting maximum energy from photovoltaic arrays has become a focus and hotspot in the research of PV system.

The characteristics of PV arrays are low conversion efficiency, nonlinear, and dependent on irradiation and environment temperature. All these characteristics showed that

MPPT control is a complex and comprehensive problem. Over the past decades, many papers have developed a variety of MPPT algorithms for PV arrays, including the voltage feedback method [4], perturbation and observation (P&O) method [5, 6], conductance increment method [7], optimal gradient method [8], intermittent control scanning method [9], and so forth. In recent years, with the development of the theory of intelligent control, PID/fuzzy control methods [10–12], evolutionary algorithm method [13], artificial neural network method [14], and so on are also applied in the area of MPPT. Every method has its own advantage and disadvantage. In this paper, in order to improve the performance of traditional chaos search, a new two-stage chaos optimization algorithm is proposed.

2. PV Cell Model and Characteristics

2.1. Basic Model of PV Cells. The equivalent circuit of the ideal PV cell [15] is shown in Figure 1.

PV cells are usually series or parallel connected to reach the desired voltage and power. Assuming that a PV array

FIGURE 1: Equivalent circuit of PV cell.

consists of N_s PV cells connected in series, N_p PV cells connected in parallel, and neglecting the influence of the shunt resistance R_{sh} , the V_{PV} - I_{PV} characteristic equation is given as follows [15–18]:

$$I_{PV} = N_p I_{ph} - N_p I_{sat} \left(\exp \left(\frac{q (V_{PV}/N_s + I_{PV} R_s / N_p)}{nkT} \right) - 1 \right), \quad (1)$$

where n is the diode ideality factor, k is Boltzmann's constant, T is the absolute temperature, q is the electron charge, I_{ph} is the light-generated current, I_{sat} is the reverse saturation current of the p - n diodes, R_s is the series resistance of the PV module, and their values can be referenced in [15, 17].

The PV array power can be described as follows:

$$P_{PV} = N_p I_{ph} V_{PV} - N_p I_{sat} V_{PV} \left(\exp \left(\frac{q (V_{PV}/N_s + I_{PV} R_s / N_p)}{nkT} \right) - 1 \right). \quad (2)$$

2.2. Output Characteristic of PV Cell. From (1) and (2) we can see that the output characteristics of PV array are highly nonlinear, which are effected by the change of internal parameters and external environmental factors. However, when the irradiation and temperature are certain, the P_{PV} - V_{PV} and I_{PV} - V_{PV} characteristics can be expressed; it indicates that the maximum power point (MPP) of PV array can also be extracted under certain irradiation and temperature. The purpose of MPPT is to search the optimal working state of PV array, that is, to seek the optimal operating point on the P_{PV} - V_{PV} curves.

3. Chaos Optimization Search Method

Chaos is a universal complex nonlinear phenomenon which has many good properties such as ergodicity, regularity, and randomness. The ergodicity and regularity mean a chaos motion can go nonrepeatedly through every state in a certain domain. The randomness means that a chaos motion might be sensitive to the initial conditions. By using these properties, the chaos optimization method for solving complex problems was proposed [19–21], which is a stochastic search

algorithm that differs from any of the existing evolutionary algorithms. The usual way to accomplish the algorithm is to produce chaos variables by single carrier at first. Secondly, transform the variables from chaos space into the solution space. Finally, try to find out the optimal solution with the chaos characteristics of randomness, ergodicity, and regularity.

The traditional chaos optimization algorithm, which usually uses single carrier, has poor search ability. It may take a long time for traditional chaos search to reach some special state [22]. That means that it cannot provide enough speed to track the MPP of PV system. In order to overcome the shortcomings of chaos optimization algorithm, some new approaches are proposed [23, 24]. In this paper, a two-stage chaos optimization search method is first applied in the field of MPPT. The proposed method will improve the efficiency of chaos search and overcome the blindness of traditional chaos search.

3.1. Chaos Mapping and First Carrier. The chaos optimization search is achieved through the chaos variables. There are many methods to produce chaos variables, among them the logistic mapping method [25] is generally selected; the equation is expressed as follows:

$$x_{n+1} = \mu x_n (1 - x_n) \quad n = 1, 2, 3, \dots, \quad (3)$$

where μ is a control parameter, it is easy to prove that, when $\mu = 4$, (3) is completely in chaos condition [21]. x_n is ergodic within $[0, 1]$. The logistic mapping bifurcation diagram is shown in Figure 2(a). Take different initial values between 0 and 1 (except some fixed value such as 0, 0.25, 0.5, 0.75, and 1); we can get different chaos variables with different orbits by iteration. Go on iterating; any variable in the optimization space can be obtained, as shown in Figure 2(b).

In Figure 2, the chaos variables produced by the logistic mapping are ergodic, but the uneven distribution (denser on both ends and sparser in the centre) of orbital points will weaken its ergodicity.

In order to give full play to the ergodicity of chaos variables, the probability density of logistic mapping should be improved (namely, reducing the probability density on both ends, meanwhile, increasing the probability density in the centre). In this paper, a power function is adopted. The function can be written as follows:

$$x_n^j = \begin{cases} x_n^w, & x_n \in [0, \gamma]; \\ x_n^v, & x_n \in [\gamma, \lambda]; \\ x_n^r, & x_n \in [\lambda, 1], \end{cases} \quad (4)$$

where $0 < \gamma < \lambda < 1$, $0 < w < 1$, $0 < v < 1$, $r > 1$, x_n is the original chaos variables, and x_n^j is the new chaos variables. If $x_n \in [0, \gamma]$, $0 < w < 1$, then $x_n^j > x_n$; it will make the points at the bottom move up; if $x_n \in [\lambda, 1]$, $r > 1$, then $x_n^j < x_n$; it will make the points at the top move down. The smaller the size of w and the larger the size of r , the greater the size of moving distance. It is easy to prove that $x_n^j \in [0, 1]$, and x_n^j is still ergodic in the interval $[0, 1]$. When $\gamma = 0.7$,

FIGURE 2: Bifurcation diagram and iterative sequence of logistic mapping.

FIGURE 3: Iterative sequence of the modified logistic mapping.

$\lambda = 0.9$, $w = 0.4$, $\nu = 0.6$, and $r = 3.9$, the ergodicity of x_n^j is depicted in Figure 3. We can see that the probability density becomes more well-distributed: it is decreasing significantly than before near the ends and obviously increasing in the centre. The improved logistic mapping is used as the first carrier process of chaos optimization algorithm in this paper.

3.2. Search Space Mapping and Reducing

3.2.1. Search Space Mapping. The chaos variable $x_n^j \in [0, 1]$, which is produced by the first carrier, must be transformed into the solution space (namely, the output voltage range of PV array); the transform equation is given as below:

$$x'_n = c_l + d_l x_n^j, \quad (5)$$

where c_l and d_l are the parameters whose initial values are related to $[a, b]$ and a and b are the boundary value of output

FIGURE 4: Diagram of reducing the search space.

voltage. The initial values of c_l and d_l can be described as follows:

$$c_l = a; \quad d_l = b - a. \quad (6)$$

3.2.2. Search Space Reducing. The diagram of reducing the search space is shown in Figure 4. The process is described as below: assuming x_i^* is the current optimal solution, the distances $L_{xa} = x_i^* - a$ and $L_{xb} = b - x_i^*$ are not equal. In the next search, the new search space is $[a', b']$, the center is x_i^* , and the radius is $\min(L_{xa}, L_{xb})/r_1$. From Figure 4, we can see

$$\begin{aligned} a' &= x_i^* - \frac{\min(|a - x_i^*|, |b - x_i^*|)}{r_1} \\ b' &= x_i^* + \frac{\min(|a - x_i^*|, |b - x_i^*|)}{r_1}, \end{aligned} \quad (7)$$

where r_1 is a constant, $r_1 \geq 1$. According to (5), the new values of c'_l and d'_l can be written as follows:

$$c'_l = a'; \quad d'_l = b' - a'. \quad (8)$$

Then,

$$\begin{aligned} c'_l &= x_i^* - \frac{\min(|a - x_i^*|, |b - x_i^*|)}{r_1}, \\ d'_l &= 2 \times \left(\frac{\min(|a - x_i^*|, |b - x_i^*|)}{r_1} \right). \end{aligned} \quad (9)$$

Consider the following:

$$a = c_l; \quad b = c_l + d_l. \quad (10)$$

FIGURE 5: The ergodicity of x''_n .

The equation of search space reducing can be given by

$$\begin{aligned} c'_l &= x_i^* - \frac{\min(|c_l - x_i^*|, |d_l + c_l - x_i^*|)}{r_1}, \\ d'_l &= 2 \times \left(\frac{\min(|c_l - x_i^*|, |d_l + c_l - x_i^*|)}{r_1} \right). \end{aligned} \quad (11)$$

3.3. The Secondary Carrier. The secondary carrier of chaos optimization algorithm for refine search is as shown in

$$x''_n = \begin{cases} x^* \times x_{1t}^\alpha & \text{when } n \text{ is odd;} \\ x^* + (1 - x^*) \times x_{2t}^\beta & \text{when } n \text{ is even,} \end{cases} \quad (12)$$

where x^* is a given point (i.e., a current optimal solution), x_{1t} and x_{2t} are chaos variables produced by (3), respectively, $0 < \alpha < 1$, and $\beta > 1$. From (12), it is easy to see that when n is odd, $x''_n \in [0, x^*]$ is ergodic; when n is even, $x''_n \in [x^*, 1]$ is also ergodic. Therefore, $x''_n \in [0, 1]$ is ergodic in the area $[0, 1]$.

If α is set to a small value and β is set to a big one, then we can acquire the distribution of chaos sequence x''_n , as shown in Figure 5. The figure shows that x''_n has higher density and better ergodicity near the given point of x^* .

3.4. Chaos Optimization Search Strategy for MPPT of PV Array. The output characteristic of PV array is highly nonlinear, as previously mentioned, and chaos optimization is mainly to solve the optimization problem for nonlinear multimodal function with boundary constraints. The question can be described as follows:

$$f = f(x_i^*) = \max f(x_i) \quad x_i \in [a, b] \quad i = 1, 2, 3, \dots, N, \quad (13)$$

where x_i is the optimization variable; it is a vector that its dimension equals to the parameter number of optimization problem. In this paper, it means output voltage of PV array. N is the number of optimization variable; $f(x_i)$ is the mathematical model for optimization problems; here, it

means the output power of PV array. If the output power of PV array depends on the continuous objective function, $f(x_i^*)$ is the maximum output power of PV array, and x_i^* is the output voltage of maximum power point.

The traditional chaos search is blindness; that is, it is difficult to determine the search times which are related to the complexity of objective function and the size of optimization space. So, it cannot guarantee the quality of search [26, 27]. In order to improve MPPT precision and speed in PV system, in this paper, the process of chaos optimization search was divided into two stages: the rough search based on the first carrier process and the refine search based on the secondary carrier. The proposed method is easy to realize and has high efficiency in search process.

In normal conditions, the proposed two-stage search algorithm can be described as follows.

Step 1 (initialization). Initialize $k = 0$, $k' = 0$, $p^* = 0$, $a = 0$, $b = 50$, $L_1 = 6$, $L_2 = 100$, $L_3 = 3$, $\alpha = 0.5$, and $\beta = 3$. k and k' are iterative signs of chaos variables in first and secondary carrier, respectively, k and $k' = 0, 1, 2, \dots, n$. Put initial values which have very small differences into $x_i(0)$, $0 < x_i(0) < 1$, $i = 0, 1, 2, \dots, m$; then it can produce m trajectories of different chaos variables. p^* is the objective function; here, it is the maximum output power of PV array. a and b are the boundary value of the output voltage of PV array. L_1 is the number of iterations while p^* keeping constant. L_2 is the number of rough or refine searches. L_3 is the number of global searches.

Step 2 (the first chaos optimization search (rough search)). Producing chaos variables $x_i(k)$ according to (3) and then putting $x_i(k)$ into (4), new chaos variables $x_i^j(k)$ can be obtained easily. Then, map $x_i^j(k)$ to the optimal variables $x_i^j(k)$ (namely, the output voltage of PV array) according to (5).

Calculating $p(k)$, if $p(k) > p^*$, then $p^* = p(k)$, $x_i^* = x_i^j(k)$, else, abandon $x_i^j(k)$, $k = k + 1$. Loop until p^* remain unchanged after L_1 times or the iterations k is greater than L_2 .

Step 3 (the 2nd chaos optimization search (refine search)). Producing chaos variables $x_{1t}(k')$ and $x_{2t}(k')$ according to (3) and substituting them into (14), then get a new chaos variables $x_i''(k')$, where x_i^* is the current optimal solution from the first chaos optimization search.

Calculating $p(k')$, if $p(k') > p^*$, then $p^* = p(k')$, $x_i^* = x_i''(k')$, else, abandon $x_i''(k')$, $k' = k' + 1$. Loop until p^* remain unchanged L_1 times or the iterations k' are greater than L_2 .

Step 4 (reduce the search space and improve the convergence speed). Take the current optimal solution x_i^* as the center, adjusting c_l and d_l to reconstruct the domain range of optimal variables, according to (11). Meanwhile, adjusting α and β to speed up the convergence speed of the algorithm, according to

$$\alpha = \frac{\alpha}{r_2}, \quad \beta = \beta \times r_2, \quad (14)$$

where r_2 is a constant, $r_2 \geq 1$, and then return to Step 2.

FIGURE 6: Block flow diagram of MPPT process.

Step 5 (output). As soon as the number of whole loop is greater than L_3 , the whole loop terminates; output the maximum power p^* and the optimal output voltage x_i^* .

In Figure 6, it is the block flow diagram of MPPT process (including partial shading condition).

4. Simulation Experiment

4.1. Tracking Simulation for Step Response. By comparing the proposed two-stage method to the traditional chaos search and perturbation and observation (P&O) search which are commonly used, we can get the step response tracking results as shown in Figure 7. According to the simulation results, the P&O search tracked rapidly; it took less than 0.02 s to reach the operating point, but it had inherent voltage ripple

on the output of a PV system; the single carrier chaos search tracked steadily but slowly, more than 0.07 s to keep stable; the proposed method just needs about less than 0.03 s to reach the tracking object and make the system output steadily.

4.2. Simulation Model and Circuit Structure. According to the mathematical model of PV array as mentioned in Section 2, the simulation model of PV cell was built by MATLAB/Simulink, as shown in Figure 8. This paper takes the single-crystal silicon (whose type is JSM120W, made in JESOLAR) as the simulation prototype. Its parameters under standard test condition (STC: irradiation 1000 W/m^2 , temperature 298 K) are as below: open circuit voltage $U_{oc} = 52.1 \text{ V}$; MPP voltage $U_{mpp} = 44.9 \text{ V}$; short circuit current $I_{sc} = 2.82 \text{ A}$; MPP current $I_{mp} = 2.589 \text{ A}$; short circuit current variation coefficient with change of temperature

FIGURE 7: Tracking results of step response by three methods. (a) P&O, (b) single chaos, and (c) two-stage chaos.

FIGURE 8: The simulation model of photovoltaic array.

FIGURE 9: Main circuit structure based on proposed chaos search control.

FIGURE 10: Simulation results of PV array under the rapid irradiation change. (a) Irradiation decrease. (b) Irradiation increase.

FIGURE 11: Simulation result of PV array under the rapid temperature change. (a) Temperature rise. (b) Temperature drop.

$\lambda_I = 0.12\%/^{\circ}\text{C} = 0.003504 \text{ A}/^{\circ}\text{C}$; open circuit voltage change of temperature $\lambda_v = -126.79 \text{ mV}/^{\circ}\text{C}$. The main circuit structure based on proposed two-stage chaos search control has been given in Figure 9.

4.3. Simulation Results

4.3.1. Simulation with Unimodal Power Output. Figure 10 shows the output performance of PV array using two-stage

chaos search method under the irradiation step change conditions, while the circumstance temperature is 298 K. Figure 10(a) shows the simulation with irradiation decrease: at the beginning, the irradiation is $1000 \text{ W}/\text{m}^2$, and the output of PV array is gradually controlled at 44.75 V and 2.595 A, which is nearly steady at STC MPP (44.90 V, 2.589 A). Meanwhile, the output power of the PV array is about 116.13 W, and the error is 0.103% (compared with the STC

FIGURE 12: Simulation results of PV array under partial shading condition. (a) Two-stage chaos. (b) P&O.

MPP 116.25 W). At $t = 1.28$ s, a step change is added to the irradiation from 1000 W/m^2 to 900 W/m^2 , and then the output power of the PV array is quickly turning into 103.45 W (43.72 V, 2.366 A). At $t = 2.56$ s, the irradiation is suddenly

changing from 900 W/m^2 to 800 W/m^2 , then the output power is promptly going down to 89.79 W (41.91 V, 2.143 A). At $t = 3.84$ s, the output power is changing from 800 W/m^2 to 700 W/m^2 , the output power is rapidly dropping into

75.88 W (40.03 V, 1.895 A). Figure 10(b) shows the simulation under the irradiation increase condition; the changing trend is opposite to Figure 10(a).

Figure 11 shows the output performance of PV array under the temperature step change conditions while the irradiation is 1000 W/m^2 . In Figure 11(a), there is a temperature rising: a step change from 273 K to 283 K at $t = 1 \text{ s}$, from 283 K to 293 K at $t = 2 \text{ s}$, from 293 K to 303 K at $t = 3 \text{ s}$, and then continue to change from 303 K to 313 K at $t = 4 \text{ s}$; in Figure 11(b), there is a temperature dropping, and the simulation shows that the tendency of output change of PV array is opposite to Figure 11(a).

From Figures 10 and 11, we can see that, while the circumstance conditions change, the voltage and current of PV array will respond quickly and overshoot less; the work state of PV system will be stabilized rapidly around the next MPP.

4.3.2. Simulation with Multimodal Power Output. To simulate the partial shading condition, the unshaded blocks (70 percent of the area) in the PV array are exposed to 1000 W/m^2 of solar irradiation, the shaded blocks (30 percent of the area) are exposed to 400 W/m^2 of solar insolation, and the circumstance temperature is 298 K. Because of the natural behavior of the bypass diode which are connected inside the PV array, the P_{PV} - V_{PV} curve of PV array under the partial shading condition must have two peaks: one is the global maximum power point (GMPP) and the other is the local maximum power point (LMPP). Under these conditions, traditional algorithms such as P&O method can only track either of the two MPPs; they cannot distinguish between them. If the LMPP was finally obtained, the output power of PV system will be significantly lower.

The simulation results are shown in Figure 12. Initially, the PV array receives a uniform irradiation of 1000 W/m^2 . It is observed that until $t = 0.5 \text{ s}$, the output voltage and current are retained, respectively. At that time, in Figure 12(a), the operating point is stabilized at 44.75 V, 2.595 A; in Figure 12(b), the operating point is stabilized around 44.69 V, 2.598 A. At $t = 0.5 \text{ s}$, the shading occurs; in Figure 12(a), the operating point is shifted to a new MPP at 81.17 W (GMPP). While the new operating point of P&O is shifted to LMPP (53.51 W), we can see that the tracking ability of the proposed method is superior than P&O method under the multimodal power output condition.

5. Conclusion

A novel two-stage chaos search method, which is first applied in the MPPT control for PV system has been proposed. In this method, an improved logistic mapping is used as the first carrier to produce chaos variables, and a power function carrier is used as the secondary carrier to reduce the search space. The proposed algorithm can overcome the blindness of the traditional chaos search and improve chaos search efficiency. The PV system simulation model has been built in MATLAB/Simulink with the mathematical model. Comparing the result of MPPT with the traditional single chaos and the P&O search, the proposed method has fast

tracking response and superior performance. According to the PV system simulation under different circumstances, the error of maximum output power with the proposed method is about 0.103%. The simulation shows that the proposed method is effective and valuable in MPPT.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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