Control strategy of grid-connected inverter droop based on GMPPT method

Xuyang Zhang¹,⁶, Jun Teng¹, Pengqiao Zhang¹, Minglei Jia¹, Cong Yu², Yifei Sun¹, Jia Sun¹, Pengran Ma¹, Bowen Zhou³, Nanjun Cao⁴, Hengyu Liu⁵ and Zhiwei Yu¹

¹ State Grid Yingkou Power Supply Company, China; ² Yingkou Huayi Power Construction Survey and Design Co., Ltd., China; ³ College of Information Science and Engineering, Northeastern University, China; ⁴ State Grid Liaoning Electric Power Company Limited Economic Research Institute, China; ⁵ Electric Power Research Institute of State Grid Liaoning Electric Power Co., Ltd., China

⁶ Email: zxy1083604729@126.com

Abstract. The conductance increment method (INC) can be quickly and accurately stabilized at the maximum power point (MPP) but easily falls into the local extreme point (LMPP) in the shadow environment. Considering the particle swarm optimization (PSO) can quickly achieve global optimal search but the number of iterations is too large when local convergence, leading to fluctuation and energy loss. Therefore, a global maximum power point tracking (GMPPT) is proposed, which combined the PSO and INC and improved them. In this paper, the research object is the single-phase two-stage PV grid-connected system. The GMPPT needs a stable DC voltage (U_{dc}) to track accurately and the grid-connected inverter needs a stable U_{dc} in order to ensure the quality of grid power. Therefore, the goal of the inverter control is to achieve the combination of GMPPT and grid-connected control. Based on the characteristics of PV power generation, a PV grid-connected droop control strategy based on GMPPT is proposed, which realizes the stability of U_{dc} and the output of MPP and meets grid-connected requirements. Finally, the simulation model of PV grid-connected system based on Matlab/Simulink software is used to verify the effectiveness of the proposed control strategy.

1. Introduction

MPPT technology has been a hot issue in research for several years [1-2]. The scholars came up with single peak MPPT algorithms at early stages [3] and later proposed various multi-peak MPPT algorithms in the shadow environment [4]. Although the above algorithms have a certain tracking effect, they still have the problem of low tracking efficiency and slow convergence. Therefore, how to implement MPPT is still under further study. In order to solve the multi-peak problem, domestic and foreign scholars have done a lot of research on the multi-peak problem under local shadow. Among them, the GMPPT method based on modern control theory has been widely studied in MPPT control of PV power generation, including fuzzy logic control algorithm (FLCA), neural network algorithm (ANN), ant colony algorithm (ACA) and PSO algorithm, etc. In [5], this paper introduces a polynomial fuzzy model-based MPPT control approach to increase the performance and efficiency of PV electricity generation. The proposed method relies on a polynomial fuzzy modeling, a polynomial parallel distributed compensation, and a sum-of-squares decomposition. In [6], the ANN algorithm is trained in the shadow environment to obtain the correlation function between the input and output.
values and the input value is used as the reference signal of the control unit. Finally, the global search is realized by using the control signal generated by the signal. In [7], the ACA algorithm is used to obtain global maximum and improve the efficiency of solar panels. PSO algorithm is widely used in MPPT technology [8], which can avoid falling into the LMPP. Compared with other intelligent algorithms, its control system is easy to set up and the running time is short, which can reduce energy loss. However, considering its initialization randomness and the immutability of its inertia weight coefficient, it is necessary to modify the basic PSO algorithm to make it suitable for PV GMPPT under local shadow, ensuring good convergence and accuracy.

The control effect of the grid-connected inverter not only determines the power quality delivered to the grid, but also affects the control effect of GMPPT. Therefore, the goal of the inverter control is to achieve the combination of GMPPT and grid-connected inverter control. In [9], by using the proposed voltage loop controller, it is possible to reduce the oscillation of the bus voltage and the current surge to the large grid when switching between the grid-connected and island modes; and use software lock-in to ensure the same frequency and phase of the grid-connected voltage. In [10], in order to solve the problem of insufficient control performance of various traditional control strategies in the complex environment of grid-connected inverters, the active disturbance rejection control (ADRC) strategy based on the virtual synchronous generator (VSG) is proposed. The mathematical model of a grid-connected photovoltaic inverter based on the VSG is built. The proposed control strategy provides the inverter with more disturbance attenuation and provides rotational inertia. The control strategy estimates and compensates the total disturbance and generates the reference active power and reactive power by ADRC. The control strategy converts the three-phase voltage and current outputs into positive and negative sequences on the dq reference frame. The VSG control module generates a reference voltage command and outputs it to the dual closed loop PI feedforward decoupling control. In [11], an improved V/δ control algorithm is used to solve the problem of low control accuracy and large frequency fluctuation in the island mode. In [12], the influence of distributed PV generation on the grid voltage profile is analysed first, and then, the sensitivity of the grid voltage to the PV inverter output power is deduced. Aiming at overhead line distribution network, the local voltage regulation strategy based on the power control of the grid-connected PV inverter is proposed. In [13], this study presents the development of a strategy that enables a push-pull converter controlled by MPPT and a low-power plug and play grid-connected inverter governed by droop control to operate stably even under variations in solar radiation. The goal is achieved based on the following two approaches: designing the dc-link capacitor properly and using a control loop in order to adapt the droop curves in accordance with the available input power.

Controlling the grid inverter well is not only related to the quality of the grid connection of the PV power generation system, but also has a direct impact on the MPPT. In this paper, with a single-phase two-stage PV grid-connected system as the research object, an improved PV grid-connected droop control strategy based on GMPPT are proposed. The model is established by MATLAB/SIMULINK to simulate and verify the control effect of GMPPT algorithm and grid-connected control strategy.

2. Improved GMPPT control method

2.1. Improved PSO method

PSO algorithm is a swarm intelligence optimization algorithm, which is widely used in the application of PV MPPT, and the iterative formula is provided by Eq. (1) – (2)[14].

\[
V_{i+1}^k = \omega V_i^k + a_1 r_1 (P_i^k - X_i^k) + a_2 r_2 (P_g^k - X_i^k)
\]

\[
X_i^{k+1} = X_i^k + V_i^{k+1}
\]

\(i = 1, 2, ..., n\). \(V_{i+1}^k\) is the step of the ith particle at the k+1th iteration. \(P_i^k\) is the best position of the ith particle after the kth iteration. \(P_g^k\) is the best position after the kth iteration globally. \(X_{i+1}^k\) is the position
of the ith particle at the k+1th iteration. \( \omega \) is the inertia weight. k is the current iteration number. a1 and a2 are acceleration coefficients. \( r_1 \) and \( r_2 \) are random numbers distributed in the interval \([0,1]\).

In Eq. (1), the step \( V_{k+1}^i \) is random because of the randomness of \( r_1 \) and \( r_2 \), which will lead to cost too much time and low precision. Thus it is necessary to remove parameters \( r_1 \) and \( r_2 \).

The \( \omega \) can be regarded as the similarity between current speed of the particle and the quondam. The larger \( \omega \) is, it is beneficial to the global optimization. The smaller the \( \omega \) is, the better the local optimization is. Therefore, the linear inertia weighting method can be used to realize the real-time variation of \( \omega \), meeting the requirements of the speed and accuracy of the entire search process[14]. The real-time \( \omega(k) \) is shown by Eq. (3).

\[
\omega(k) = \omega_1 (\omega_1 - \omega_2) (T_{\text{max}} - k) / T_{\text{max}}
\]  

(3)

\( \omega_1 \) and \( \omega_2 \) are the initial value and the final value of \( \omega \), respectively. k is the number of iterations and \( T_{\text{max}} \) is its maximum value. In general, when \( \omega_1 \) is 0.8 and \( \omega_2 \) is 0.3, the algorithm performs best.

In this paper, take 4 x 1 PV array as the study object. The flow chart of the improved GMPPT algorithm is shown in Figure 1. Firstly, the particle number and the position are initialised. According to the literature [15], the first particle position \( U_1 \) is 0.78\( U_{OC} \). The kth particle position \( U_k \) is \( U_1 + (k - 1)U_{\text{ref}} \). The particle number N is 4. The improved PSO algorithm is adopted to realize global searching for the optimal local location, ending with retaining \( G_{\text{best}} \) and its corresponding voltage \( U_{\text{best}} \). Finally, after searching the optimal local location the variable step INC method [15] is adopted to track the MPP in the optimal local location. \( U_{\text{best}} \) is used as the initial voltage for the INC method.

When shadow occurs or solar intensity changes, the output power of the PV array also follows the change. Thus, it is necessary to restart the PSO algorithm, making the system working in a new MPP stably. Variation of power \( \Delta P \) can be represented as shown by Eq. (4).

\[
\Delta P = \frac{|P - P_n|}{P_n}
\]

(4)

When the performance period exceeds 1 minute or \( \Delta P \geq 0.1 \), PSO algorithm will restart.

2.2. Control effect of the proposed GMPPT

The parameters of the PV array are listed in Table 1. To analyze the multi-peak characteristic curves of PV cells in series connection, the solar intensities in different time periods are set in Table 2. The temperature is 25°C. The P-U characteristic curves of the PV array in different time periods are shown in Figure 2.
Table 1. Simulation parameters of the PV array.

| Simulation Parameters | Value  | Simulation Parameters | Value  |
|-----------------------|--------|-----------------------|--------|
| Open-circuit voltage $U_{oc}$ | 42.48V | Current in MPP $I_m$ | 4.048A |
| Short-circuit current $I_{sc}$ | 4.58A | Reference temperature $T_{ref}$ | 25℃ |
| Voltage in MPP $U_m$ | 35V | Reference solar intensity $R_{ref}$ | 1000W/m² |

Table 2. The solar intensities in different time periods.

| Time(s) | PV1(W/m²) | PV2(W/m²) | PV3(W/m²) | PV4(W/m²) |
|---------|-----------|-----------|-----------|-----------|
| t1:0-0.25 | 1000 | 1000 | 1000 | 1000 |
| t2:0.25-0.5 | 1000 | 1000 | 1000 | 800 |
| t3:0.5-0.75 | 1000 | 1000 | 800 | 600 |
| t4:0.75-1.0 | 1000 | 800 | 600 | 400 |

Simulations are taken by using the improved INC method and the proposed GMPPT algorithm respectively and P-t curves are shown in figure 3. In figure 3, it can be obtained that both algorithms can track the MPP during t1 due to the uniform solar condition. The solar intensity of PV4 changed to 800 W/m² when t is 0.25 s. The INC algorithm found the LMPP in 0.2575 s. It is approximately 438W with a power oscillation difference about 10.8 W. However, the theoretical GMPP is about 511 W, thus the INC method caused a large amount of power loss. The proposed GMPPT found the MPP in 0.2525 s, which is much closer to the theoretical value and the power oscillation difference is about 1.5 W. Obviously, the energy loss is reduced. Similarly, during the t3 and t4 period, the INC algorithm only found a LMPP, but the proposed GMPPT found the true MPP. Therefore, it can be concluded that the proposed method shows great advantages in convergence speed, tracking precision, power oscillation mitigation and energy loss reduction.

3. Improved grid-connected droop control strategy

3.1. Algorithm improvement

Droop control is a kind control technology of grid-connected inverter. It decomposes the active and reactive power of the inverter, so that it realizes the independent operation control of the parallel inverter. The droop control formula is shown by Eq. (5).
Where P and Q are the real-time active and reactive power of the inverter output, U and f are the output voltage and frequency of the inverter, and Q0 and P0 are the references of the P and Q. U0 and f0 are the rated grid voltage and frequency. kP and kQ are the active and reactive droop coefficients.

When the PV power generation system is connected to the grid, it should ensure that the first stage achieves the MPPT in order to send the maximum active power Pmax to the grid. And at the same time, the output power of the latter inverter is controlled in real time to keep with the power of the first stage. So according to the formula (5), P0 should be the maximum power of PV power generation, that is, P0 = Pmax and Q0 = 0.

Considering the change of Pmax in real time, assume that the inverter starts to run stably at point A, Pmax = PA, as shown in figure 4. When the environment changes, Pmax changes and Pmax=PB. But the large power grid is so strong that the frequency of the grid-connected inverter will keep invariant. And the inverter will continue to output the frequency f0, so the inverter output power remains P A. PA ≠ Pmax=PB causes the U dc to rise or fall. The instability of the U dc will cause the control accuracy of the MPPT, so it is necessary to control the stability of the U dc. The inverter can be operated at point B by moving the P-f curve down. From equation (5) and the above analysis, it is possible to solve the power imbalance problem of the front and rear stages by adjustment of the rated frequency f0 of the power grid in real time.

![Figure 4. Droop characteristic curve when the MPP fluctuates.](image)
Among them, $k_{Qp1}$ and $k_{Qp2}$ are proportional coefficients. $k_{Qi2}$ is an integral coefficient. Q is real-time reactive output and $Q_0=0$. The simplification formula (8) is available as (9) as follows.

$$U = (k_{Qp} + k_{Qi} / s)(-Q) + U_0$$  

(9)

For the two-stage PV power generation system, the difference between the front and rear stages caused the DC bus voltage $U_{dc}$ to fluctuate back and forth. When $P<P_{max}$, $U_{dc}$ will increase. Similarly, when $P>P_{max}$, $U_{dc}$ will decrease. The MPPT algorithm tracks the MPP by controlling the PV output voltage $U_{PV}$. In the boost circuit, the relationship between $U_{PV}$ and $U_{dc}$ is as shown in equation (10).

$$U_{PV} = (1-d)U_{dc}$$  

(10)

From equation (10), it can be seen that $U_{dc}$ should be kept stable in order to accurately implement MPPT algorithm. The MPPT algorithm needs to be implemented by the boost circuit and the stable DC bus voltage needs to be implemented by the inverter. Therefore, it can be realized by adding a bus voltage stabilization loop in the frequency control section. The specific formula is as shown in equation (11).

$$f = (k_{Pp} + k_{Pv} / s)*(P - P_{max}) + f_0 + (k_{Pp3} + k_{Pv3} / s)*(U_{dc} - U_{dc ref})$$  

(11)

Among them, $U_{dc}$ is the real-time measurement voltage and $U_{dc ref}$ is the reference voltage. $k_{Pp3}$ and $k_{Pv3}$ are respectively the proportional and integral coefficients.

Finally, the calculation formula for the PV grid-connected droop control strategy is as shown in equation (12).

$$\begin{align*}
\Delta U_0 &= \left(k_{Qp2} + k_{Qv2} / s\right)(0 - Q) \\
U &= k_{Qp} * (Q - 0) + U_0 + \left(k_{Qp2} + k_{Qv2} / s\right)(0 - Q)
\end{align*}$$

(8)

$$\begin{align*}
\Delta U_0 &= \left(k_{Qp2} + k_{Qv2} / s\right)(0 - Q) \\
U &= k_{Qp} * (Q - 0) + U_0 + \left(k_{Qp2} + k_{Qv2} / s\right)(0 - Q)
\end{align*}$$

(12)

In this paper, a single-phase two-stage PV grid-connected inverter is used as the discussion object. The boost circuit is used to complete the pre-stage MPPT control, and then the improved droop control strategy is used to control the post-stage inverter to realize the output power of the inverter consistent with the output power of the front-stage in real time, achieve MPPT and meet the grid-connected conditions. The frequency is at 50 ± (0.2-0.5) Hz and the output voltage and current of the inverter are output in phase. Figure 5 is the overall control structure of the grid-connected PV system.

Figure 5. The overall control structure of the grid-connected PV system.
3.2. Control effect of improved grid-connected control strategy

The solar intensities in different time periods are set in Table 3. The temperature is 25°C. Figure 6-9 show the simulation results of PV grid-connected control.

Table 3. The solar intensities in different time periods.

| Time(s) | PV4(W/m²) | PV3(W/m²) | PV2(W/m²) | PV1(W/m²) |
|---------|-----------|-----------|-----------|-----------|
| t1:0-0.25 | 1000     | 1000      | 1000      | 1000      |
| t2:0.25-0.5 | 1000     | 1000      | 1000      | 800       |
| t3:0.5-1  | 1000     | 1000      | 800       | 600       |

In Figure 6, the MPP of the PV array in different intensities is basically the same as the corresponding MPP in the above figure 2. The inverter output power is basically equal to the actual PV output power during stable operation, with a no more than 1% difference.

When the solar intensity enters t2 from t1, it is quickly adjusted to a new balance after 0.04s. When the solar intensity enters t3 from t2, the system quickly adjusts to a new balance after 0.05s. And the power on both sides of the inverter is basically the same, making the system work smoothly.

In Figure 7, the DC bus voltage on the input side of the inverter can also be stabilized at around 500V in the event of a sudden change in the environment, thus providing a stable input voltage for the inverter and ensuring the accuracy of the GMPPT control.
In figure 8, at the start of the system the grid-connected current keeps up with the grid-connected voltage after 0.09s. When the environment changes suddenly at 0.25s, it can quickly adjust and keep in sync with the grid voltage through 0.04s. When the environment changes suddenly at 0.5s, grid-connected current can also keep in sync with the grid voltage and operate stably after 0.05s.

In figure 9, the system frequency is abruptly changed at 0.25s, and it oscillates briefly between 49.8-50.2Hz. After rapid adjustment, it can operate stably at 50Hz. The environment changes suddenly at 0.5s, it oscillates briefly between 49.97-50.05Hz. But after rapid adjustment, it is still able to run stably at 50Hz.

4. Conclusions
An improved GMPPT method combined with INC method and PSO algorithm is proposed in order to solve the problem that traditional MPPT algorithm is easily trapped in LMPPs under PSC, and to improve the convergence speed and tracking precision. An improved PV grid-connected droop control strategy based on GMPPT is proposed to keep DC bus voltage stability and make sure the maximum power output in grid-connected mode, and meet grid-connection requirements. Through experiment simulation and analysis, conclusions are as follows.

Compared with the INC method, the improved GMPPT can effectively avoid to be trapped in LMPPs, find the real MPP and improve the convergence speed and tracking precision. Obviously, the oscillations and energy loss are reduced.

The improved PV grid-connected droop control strategy based on GMPPT can realize DC bus voltage stability and maximum power output in grid-connected mode, and meet grid-connection requirements.

References
[1] Li H, Yang D, Su WZ, et al. 2019 IEEE Transactions on Industrial Electronics 66(1) 265-275
[2] Mahmoud Nour Ali 2018 Twentieth International Middle East Power Systems Conference (MEPCON) 97-102
[3] Zhang MR, Jiang LM, Sun H, Zhou C 2016 Proceedings of the CSEE 36(01) 104-111
[4] Alireza Ramyar, Hossein Imameini, Shahrokh Farhangi 2017 IEEE Transactions on Industrial Electronics 64(4) 2855-2864
[5] Mohsen Rakhshan, Navid Vafamand, Mohammad-Hassan Khooban, Frede Blaabjerg 2018 Automation & Instrumentation 6(1) 292-299
[6] Wei C, Zhang Z, Qiao W, Qu LY 2016 IEEE Transactions on Power Electronics 31(11) 7837-7848
[7] Sarat Kumar Sahoo, M Balamurugan, Sai Anurag, et al. 2017 Innovations in Power and Advanced Computing Technologies (i-PACT) 1-4
[8] Ramadan B A Koad, Ahmed Faheem Zoba, Adel El-Shahat 2017 IEEE Transactions on Power Electronics 8(2) 468-476
[9] Deng Y, Tao Y, Chen GP, et al. 2017 IEEE Transactions on Industrial Electronics 64(7) 5919-5929
[10] Li J, Wen BY, Wang HY 2019 IEEE Access 7 39509-39514
[11] Yang G, Yang QX, Zhang T 2016 Automation of Electric Power Systems 40(05) 96-101
[12] Tong XQ, Zhong MH, Zhang XQ, et al 2019 The Journal of Engineering 2019(16) 2525-2528
[13] Ruben Barros Godoy, Douglas Buytendorp Bizarro, Elvey Tessaro de Andrade, et al. 2017 IEEE Transactions on Industry Applications 53(3) 2358-2368
[14] Yu L, Shi F, Wang H, Hu F 2015 Intelligent Algorithm [M] Beijing University of Aeronautics and Astronautics Press
[15] Zhang XY, Zhang HG, et al. 2016 IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC) 1503-1506