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Research Article

A new energy frequency adjustment model based on adaptive power control optimization algorithm for photovoltaic power generation systems

Han Zhou*, Congtong Zhang, Haoqin Yang

System Operation Department, Yunnan Power Grid Company Ltd., Kunming, 650217, China

Abstract. With the low-carbon transformation of the global energy structure, photovoltaic power generation, as one of the renewable energy sources, continues to expand its installed capacity and grid connection scale. However, traditional photovoltaic power generation systems mainly use constant power output algorithms, which make it difficult to effectively handle complex situations such as sudden load changes or power shortages during dynamic adjustment, and can easily cause frequency exceeding standards or even system instability. Therefore, this paper proposes a new energy frequency adjustment model based on Newton's quadratic interpolation method. Firstly, this study constructs a new energy frequency regulation model for the adaptive power control optimization algorithm of photovoltaic power generation systems and then conducts a detailed analysis of the model. The results showed that when load 2 was cut off, the highest frequency of the research model could reach 52.50 Hz, while the highest frequency value of the traditional frequency regulation model was only 48.46 Hz. This indicated that the research model had better frequency regulation performance when dealing with large load fluctuations. In the photovoltaic power generation system, when there was a power deficit, the output power of the new energy frequency regulation model based on the adaptive power control optimization algorithm was reduced by 0.032 MW. The output power of the traditional rated regulation model was reduced by 0.029 MW. Overall, the frequency regulation performance and stability of the system were improved. It is of great significance to solve the challenges faced by photovoltaic power generation systems.

Keywords: Photovoltaic power generation system; Adaptive; P&O power control algorithm; Newton's quadratic interpolation method; New energy

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1. Introduction

Against the backdrop of sustained growth in global energy demand, photovoltaic power generation, as a renewable energy source, is increasingly valued and occupies a vital position in the energy structure (Abbas *et al.,* 2024; Afkar *et al.,* 2022). Since the oil crisis in the 1970s, governments and research institutions around the world have increased their investment in research and development of renewable energy technologies, leading to the rapid development of photovoltaic power generation technology. Especially in the past decade, with the advancement of technology and the reduction of costs, the commercial application of photovoltaic power generation has been widely popularized worldwide (Endiz, 2024). Photovoltaic Power Generation Systems (PPGS) use solar panels to convert solar energy into electricity, solving the problem of traditional energy shortage and providing an effective way for the sustainable development of global energy (Mathi and Chinthamalla, 2024; Alia *et al.,* 2022). Therefore, numerous experts and scholars have conducted in-depth research in the field of PPGS. Senapati et al (2023) used the perturbation observation method to verify the Maximum Power Point Tracking (MPPT) problem of PPGS through simulation. Under simulated lighting conditions, the MPPT error of the disturbance observation method was only ±1%, and the response time was within milliseconds. Shen *et al* (2023) proposed a generalized discrete-time equivalent model for modeling the interface of Grid Connected Photovoltaic Systems (GCPS). Through comparative experiments, it has been shown that the model could effectively predict the output power and current of GCPS, providing a powerful tool for optimizing control of the system. Yang *et al* (2022) proposed an optimization algorithm based on elastic neural networks to address the issue of optimizing the allocation of energy storage capacity in high permeability PPGS. It indicated that the optimization algorithm could lift the energy utilization efficiency and stability of high permeability PPGS. Qi *et al* (2020) proposed a hybrid wind power PPGS based on a Foldable Umbrella Mechanism (FUM) to address the challenges of installation and operation of PPGS on highways. The system achieved photovoltaic power generation without affecting the normal use of highways through the design of ab FUM while utilizing hybrid wind technology to improve Power Generation Efficiency (PGE). Through on-site testing and simulation analysis, the application of this system on highways had high feasibility and practicality. To solve many problems in tracking the global maximum peak power of photovoltaic systems, Kishore *et al.* (2020) adopted a new meta-heuristic method, that is, an opposition-based balance optimization algorithm, to alleviate oscillations around the global maximum peak power. The simulation results showed that under dynamic PSC, the efficiency of this method was

* Corresponding author
Email: Zhouhan199210@outlook.com (H. Zhou)

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95.09% within 0.16 seconds, 96.17% under uniform PSC, and 86.25% under composite PSC. To solve the problem of low control efficiency of a photovoltaic system, Rashid and Swarup (2024) proposed a red-tailed eagle MPPT method based on a meta-heurism algorithm. The effectiveness of the Red-tailed Eagle algorithm in monitoring the output power of photovoltaic systems was evaluated through MATLAB simulation. This algorithm, as an effective MPPT technology for photovoltaic systems, had better performance.

Although photovoltaic power generation shows great potential and prospects, the system still faces many challenges in actual operation (Kahani *et al.,* 2022). Due to environmental factors such as light intensity, temperature, and shadows, the power generation of PPGS fluctuates greatly, which may lead to unstable grid frequency and pose a threat to the stability of the entire power system (Alabri and Jayaweera, 2022). In addition, the output power of PPGS is directly proportional to the intensity of light, so the power generation will significantly decrease under dark or cloudy conditions. This instability may lead to frequency fluctuations in the power grid and have an impact on the stability of the power system (Zhu *et al.,* 2022). In recent years, with the rapid development of artificial intelligence and big data technology, interpolation methods are constantly optimized and upgraded to adapt to more complex and changeable application scenarios. The interpolation method can infer unknown data points based on known data points, thereby more accurately analyzing the characteristics and trends of the data. Some domestic and foreign researchers have made outstanding achievements in the field of interpolation methods. For the vibration analysis of PPGS plate model, Hou *et al* (2022) proposed a strain gradient plate model based on meshless moving Kriging interpolation method. This model could effectively describe the strain distribution and evolution law of PPGS plates during vibration, providing a basis for vibration analysis and optimization design of the system. Ren *et al* (2021) proposed an improved algorithm based on interpolation to address the issue of chromaticity resampling in PPGS. The experiment showed that the improved algorithm could effectively solve the chromaticity resampling problem in PPGS and improve the PGE and stability of the system. Li *et al* (2021) proposed a high-quality geospatial interpolation method based on Double Inverse Distance Weighting (DIDW) for the problem of geospatial data interpolation in PPGS. Practical application cases have shown that the method based on DIDW had good applicability in PPGS. Yang *et al* (2023) proposed a centroid rational interpolation method to address numerical computational problems in PPGS, particularly in solving Helmholtz equations in irregular domains. Through theoretical analysis and numerical experiments, it has been found that this method could efficiently and accurately handle complex photovoltaic system models by constructing a centroid rational interpolation function, with high computational accuracy and stability.

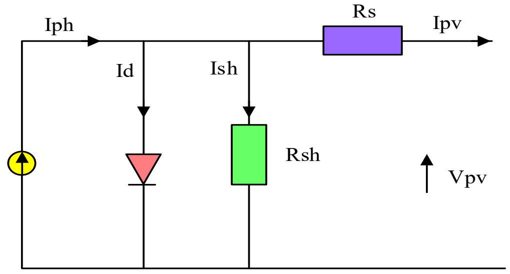

Fig 1 Schematic diagram of the simplified equivalent circuit of a photovoltaic cell

To further improve the stability and efficiency of PPGS, a New Energy Frequency Regulation Model (NEFRM) based on Perturb and Observe Power Control Algorithm (P&O-PCA) is proposed by optimizing the interpolation method. Compared with Senapati *et al.* 's disturbance observation method used in MPPT and Shen *et al.*' s grid-connected photovoltaic system interface modeling, the research model not only focuses on the output power optimization of PPGSs but also extends to the frequency regulation of new energy power grids, providing a new solution for the stable operation of new energy power systems. Compared to the balance optimization algorithm based on pairwise difference adopted by Kishore *et al.,* the P&O algorithm may have faster response speed and higher adjustment accuracy in frequency regulation, as the P&O algorithm itself is designed to quickly track the maximum power point. The NEFRM based on P&O algorithm can adaptively adjust the output power of PPGS according to different lighting conditions, load changes and other factors, thereby achieving the goal of stabilizing the grid frequency. Compared to the FUM-based hybrid wind PPGS proposed by Qi *et al.,* the application of P&O algorithm in frequency regulation may be more extensive and flexible, as it does not require additional hardware facilities, only software upgrades or adjustments to the control strategy of existing PPGS. Compared with the elastic neural network-based optimization algorithm proposed by Yang *et al.,* the adaptability of the P&O algorithm in frequency regulation may be more direct and efficient because it adjusts the output power directly through perturbation observation without the need for a complex neural network model. Overall, compared with existing NEFRMs, the research model breaks through the limitations of the two being independent in traditional research and achieves collaborative optimization control of PPGS from the power generation end to the grid end. The research model has significant advantages in response speed, regulation accuracy, flexibility, and robustness, providing new technological means for improving the stability and efficiency of PPGS, and is of great significance for promoting the stable operation of new energy power systems.

2. Method

To solve the problem of power control and frequency regulation of PPGS, Newton's quadratic interpolation method is introduced in this paper, and the fast and accurate prediction of photovoltaic power output is realized by constructing quadratic interpolation polynomial. In the aspect of algorithm design, a three-layer control architecture is proposed. The bottom layer adopts improved P&O algorithm to realize fast dynamic quantity control. The dual-loop control strategy of Grid-Connected Inverter (GCI) is designed in the middle layer. The PI controller of the outer-ring realizes the stable power regulation, and the proportional controller of the inner-ring realizes the fast current tracking. Active power scheduling mechanism is established on the top layer. For frequency regulation, a dual-mode frequency regulation strategy combining sagging control and emergency control is proposed to monitor the frequency deviation of the power grid in real-time and dynamically adjust the photovoltaic output power.

2.1 PPGS adaptive power control optimization algorithm

Photovoltaic cells are devices that can directly convert solar energy into electrical energy (Sugiura *et al.,* 2023). It utilizes the principle of photoelectric effect to convert the energy of photons in sunlight into electronic energy, ultimately generating electric current. Photovoltaic cells are typically composed of multiple thin sheets or film layers, which contain semiconductor materials such as silicon (Cheriet *et al.,* 2022). Each photovoltaic module is an independent system, and in some cases, multiple modules are considered as one system solely for determining installed capacity. The simplified equivalent circuit diagram of photovoltaic cells is shown in Figure 1.

Short Circuit Current (SCC) is the current flowing during the operation of the power system due to abnormal connections between phases or between phases and ground. Open Circuit Voltage (OCV) denotes the voltage difference between the positive and negative terminals of a power supply when its output port is disconnected in a circuit (Li *et al.,* 2023). The actual Maximum Power Output (MPO) value is the product of the SCC and OCV corresponding to the maximum power point, and its expression is shown in equation (1).

$$p_m = I_m * V_m \tag{1}$$

In equation (1), p_m represents maximum power, I_m represents SCC, and V_m represents OCV. The expression for the output current I_{pv} of the photovoltaic panel is shown in equation (2).

$$I_{pv} = I_l - I_d \tag{2}$$

In equation (2), I_d represents the saturation current of the voltage plate and I_l represents the photogenerated current. Photovoltaic cell OCV method is a very simple method in which the cell voltage V_{pv} is compared with the given voltage corresponding to the optimal voltage V_{opt}, and the voltage error obtained is used to adjust the duty cycle of the converter (Zerzouri *et al.,* 2023). The expression for V_{opt} is shown in equation (3).

$$V_{opt} = k_1 - V_{co} \tag{3}$$

In equation (3), k_1 represents the proportional constant (0.71<1k<0.78), and V_{co} represents the OCV of the battery. Power Control Algorithm (PCA) is a type of algorithm used to manage the transmission power in wireless communication systems, which controls the transmission power on the wireless path by changing the transmission power of mobile or base station transceiver stations within a certain range (Hassan *et al.,* 2023). The conventional algorithms for power control technology include bisection and Newton's interpolation (Kennedy *et al.,* 2023). Among them, binary search is a search algorithm that searches for a specific element in an ordered array. In power control, the binary method is used to determine the optimal transmission power to achieve optimal communication performance. The framework of the binary algorithm is shown in Figure 2.

In Figure 2, U2 represents the port voltage of the first iteration PV array, P1 represents the output power of the first iteration PV array, U3 represents the port voltage of the second iteration PV array, and P3 represents the output power of the second iteration PV array (Lu *et al.,* 2020). In the binary system, each iteration requires determining the next action based on the judgment criteria. The judgment condition is usually to compare the function value at the midpoint of the current interval with the function value at the endpoint of the interval. If the product of the function value at the midpoint and the function value at the endpoint is less than 0, it indicates that the solution of the equation is located on one side of the current interval, and the next iteration needs to continue searching on that side. The iterative process in the standard dichotomy is shown in equation (4).

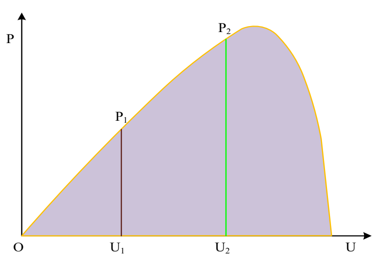

Fig 2 Diagram of binary algorithm

$$x(n+1) = \frac{x(n) - f(x(n))}{f'(x(n))} \tag{4}$$

In equation (4), $x(n)$ represents the approximate solution of the n-th iteration, and $f(x)$ is the function to be solved. Although dichotomy has the advantages of simplicity and easy implementation, the convergence speed of dichotomy is relatively slow, especially in the region close to the solution, each iteration can only halve the search interval, resulting in low computational efficiency (Suh *et al.,* 2022). At the same time, the output power of the photovoltaic system is affected by many factors such as light intensity and temperature, which is complicated and difficult to model accurately. Newton's quadratic interpolation method can quickly build an approximate model of the system through a small number of sampling points, so that the output power of the system can be accurately predicted and adjusted. Therefore, Newton's quadratic interpolation method is used to adjust the energy frequency of photovoltaic system. In Newton's interpolation method, interpolation polynomials can be obtained by recursively calculating the difference quotient. The recursive formula for differential quotient is shown in equation (5).

$$d = \frac{\delta}{D} \tag{5}$$

In equation (5), δ represents the difference in function values between two points, and D represents the distance between two points. Interpolation polynomials are mathematical expressions constructed based on differences to approximate a given function. After knowing the function values of several points, interpolation polynomials can be constructed through the difference quotient (Zhang *et al.,* 2023). The expression for the interpolation polynomial is shown in equation (6).

$$\begin{aligned} P(x) &= \frac{f(xi) + f(xi+1) - f(xi) \times f(xi+1)}{f(xi+2)} + \ldots \\ &+ (-1)^{(n-1)} f(xi) \ldots \frac{f(xi+n-1)}{(f(xi+n) \ldots * f(xi+n-1))} \end{aligned} \tag{6}$$

The remainder is the error between the interpolation polynomial and the original function. In Newton's interpolation method, the remainder is expressed as equation (7).

$$Rn(x) = f(x) - Pn(x) \tag{7}$$

In equation (7), $Rn(x)$ represents a n-order polynomial interpolation. For n interpolation nodes, the difference quotient of order (n-1) needs to be calculated, and every calculation of the difference quotient of order higher requires n-1 operations, so the computational complexity of the difference quotient is $O(n^2)$. The interpolation polynomials are constructed by

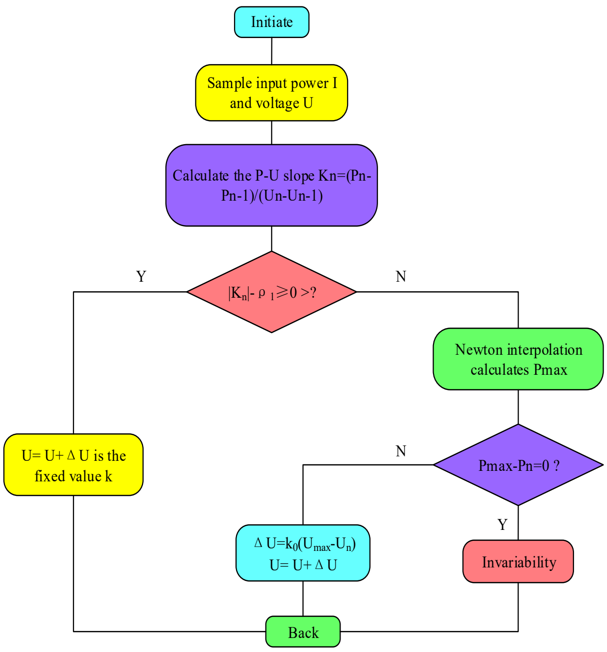

Fig 3 PPGS based on Newton's interpolation method

different quotients, each of which corresponds to a term in the polynomial, so the construction complexity of the interpolation polynomial is also O(n), and the overall computational complexity of Newton's interpolation method is O(n^2). The size of the remainder reflects the approximation accuracy of the interpolation polynomial to the original function. The power function of Newton's interpolation fitting curve is expressed as equation (8).

$$P(x) = y_0 + d_0 * (x - x_0) + d_1 * (x - x_0)(x - x_1) + \dots + d_n (x - x_0)(x - x_1) \dots * (x - x_n) \quad (8)$$

In equation (8), x is the power output value corresponding to the input value for a known data point. The flowchart of PPGS based on Newton's interpolation method is shown in Figure 3.

In Figure 3, it is necessary to first collect power data of photovoltaic cells under different light intensities and temperatures (Endiz, 2023). Then, Newton's quadratic interpolation method is used to construct a quadratic polynomial approximating the behavior of the original function in a given interval by constructing and solving a set of linear equations based on the known data points and their derivative information. Then the quadratic polynomial is used to establish the mathematical model of photovoltaic power according to the collected photovoltaic power data, thereby reflecting the power output characteristics of photovoltaic cells under different conditions. Then, based on the predicted photovoltaic power, corresponding power control is carried out. If the predicted power surpasses or lower than the actual demand, the output power of PPGS can be reduced or increased.

2.2 Construction of NEFRM for P&O-PCA

Due to the lack of rotating components in PPGS, when it replaces synchronous generators to provide electrical energy to the system, the equivalent inertia time constant of the system will decrease. Meanwhile, if PPGS is unable to provide effective frequency support and the frequency modulation voltage is fully applied to the synchronous generator, load changes will cause more significant frequency fluctuations. In an AC power system, the dynamic calculation of system frequency is shown in equation (9).

$$2H \frac{d\Delta f_{sys}}{dt} = \Delta P_G - \Delta P_L - kdf \Delta f_{sys} \quad (9)$$

In equation (9), Δf_{sys} is the frequency deviation of the system frequency. ΔP_G represents the power change of the generator primary energy side. ΔP_L represents the power change of the generator primary energy load. H represents the equivalent inertial time constant of the system. kdf represents the equivalent damping coefficient of the system. The frequency regulation mode based on photovoltaic power generation mainly includes frequency droop control mode and emergency control mode. The former mode utilizes an inverter to control the Output Power of the Photovoltaic Array (PAOP), making it vary with the frequency of the grid (Anssari *et al.,* 2024). Among them, the active power frequency droop coefficient formula is shown in equation (10).

$$m = \frac{\Delta\omega 2\pi N}{100} \quad (10)$$

In equation (10), $\Delta\omega$ represents the change in frequency. 2π is the coefficient required to convert the frequency from Hz to radians per second. N is the rated frequency of the power system. The calculation formula for reactive power voltage sag coefficient is shown in equation (11).

$$n = \frac{\Delta QM}{\sigma} \quad (11)$$

In equation (11), ΔQ represents the reactive power change, M represents the rated voltage, and σ is the unit conversion factor. When the grid frequency grows or lowers down, the PAOP decreases or increases (Senthilkumar *et al.,* 2023). The purpose of this control strategy is to enable PPGS to have a certain degree of adaptive ability to the frequency changes of the power grid, thereby maintaining its stable operation. This study adopts a single-stage Photovoltaic Grid-connected Power Generation System (P-GPGS) and corresponding control modules, as shown in Figure 4.

In single-stage P-GPGS, the relationship between the output current of the photovoltaic array I and the Port Voltage of the Photovoltaic Array (PAPV) is shown in equation (12).

$$I = C * \frac{dV}{dt} \quad (12)$$

In equation (12), C is the capacitance of the photovoltaic cell, and $\frac{dV}{dt}$ is the rate of change of the port voltage. The PAOP

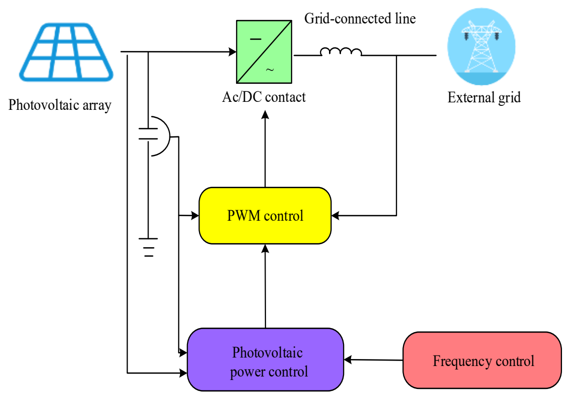

Fig 4 Single-stage P-GPGS and its control module

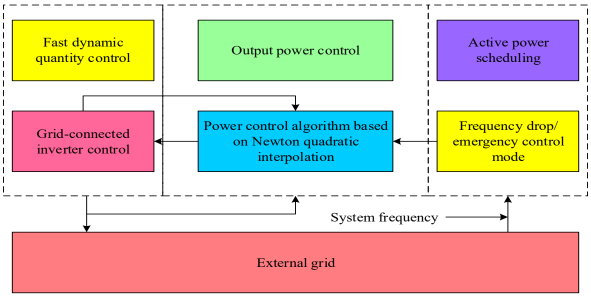

Fig 5 Schematic diagram of the overall control system of P-GPGS

function is usually a nonlinear function, and its output power is related to factors like light intensity and temperature (Jafar *et al.*, 2024). In an ideal scenario, the PAOP is shown in equation (13).

$$P = I * V \quad (13)$$

In equation (13), V is the PAPV. The overall control system for photovoltaic power generation proposed this time is divided into three layers, and decoupling is achieved between each layer through different time scales. The overall control system diagram of the P-GPGS is shown in Figure 5.

In Figure 5, the first layer is fast dynamic quantity control, which mainly monitors the voltage, current, temperature, and other parameters of the photovoltaic array in real-time, as well as the frequency, voltage, and power of the power grid. In the second layer of output power control, a Dual Loop Control (DLC) strategy of GCI is adopted. The main focus of this layer is to control the PAOP based on its output power curve. This layer also needs to limit the PAOP and current of the photovoltaic array to ensure the safe operation. Among them, the DLC diagram of the GCI is shown in Figure 6.

In Figure 6, the DLC includes two control loops: the outer loop and the inner loop. The former is responsible for stabilizing and adjusting the output power, while the latter is responsible for achieving fast tracking of voltage and current. The outer loop control usually uses a PI controller, which calculates a reference current value based on the deviation between the PAOP and the set power. This reference current value will serve as the input for the inner loop control. The formula for PI controller is shown in equation (14).

$$(u = K_p \times e + K_i \times \int e\, dt) \quad (14)$$

In equation (14), K_p is the proportional gain, e is the error signal, K_i is the integral gain, and $\int e\, dt$ is the integral of the error signal. The inner loop control usually uses a proportional controller PI controller or an integral controller, whose function is to quickly track the actual output current of the GCI based on the reference current value output by the outer loop controller. The output formula of the proportional controller is shown in equation (15).

$$(O = K_p \times e) \quad (15)$$

The inner loop control can also control the voltage of the GCI to ensure that the inverter can stably output current (Gali *et*

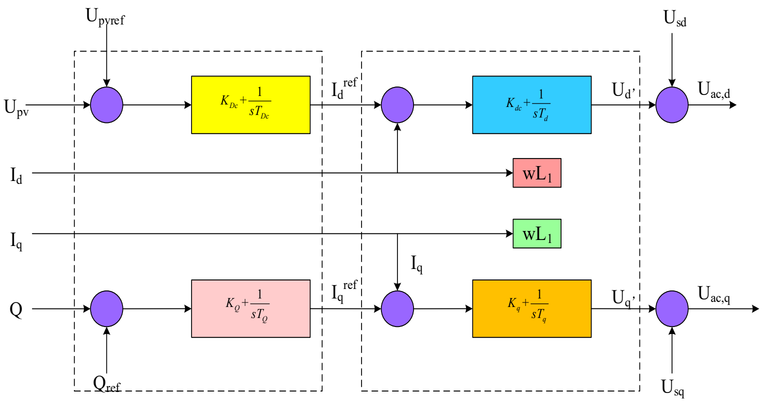

Fig 6 DLC diagram of grid-connected inverter

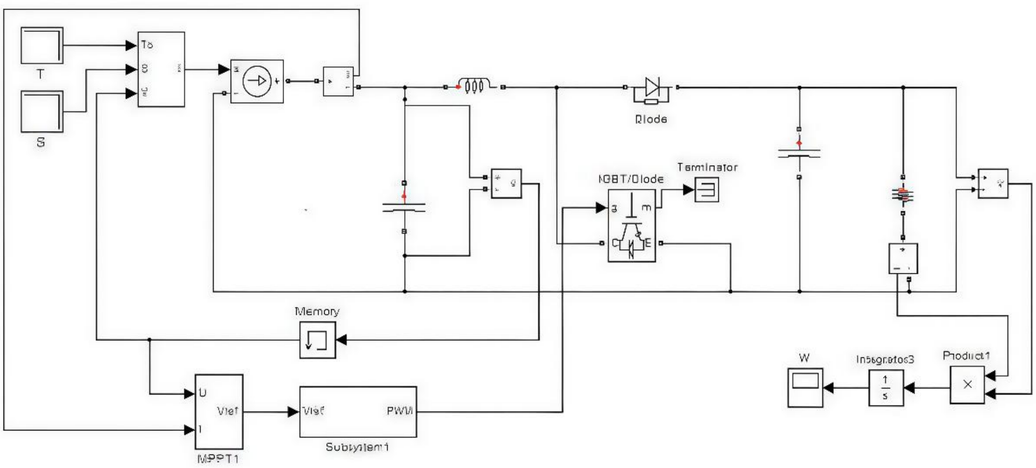

Fig 7 MPPT control diagram of P&O-PCA model

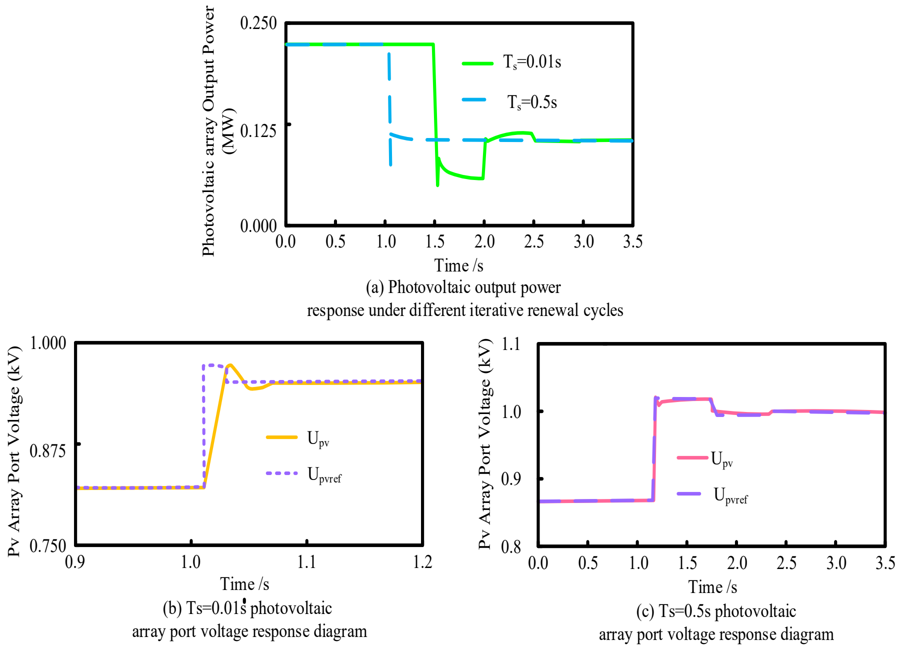

Fig 8 The output power response of PV under different iterative renewal cycles based on P&O-PCA

al., 2023). The third layer of this research system is active power scheduling, which is mainly used to schedule the active power of PPGS based on the demand and operation. By reasonably scheduling and controlling the active power of PPGS, the stable operation of the power grid can be ensured. At the same time, this layer also needs to consider the priority scheduling of renewable energy to improve the utilization ratio in the power grid. MPPT control requires sampling the current and voltage signals at the output of the photovoltaic cell, outputting a curve through different algorithms, and superimposing this curve with a triangular wave to generate the required pulse signal. When the MPPT control module is built in Simulink, the MPPT control diagram of the P&O-PCA model is studied, as shown in Figure 7.

3. Result and Discussion

3.1 Result

This study analyzes the results of NEFRM based on the PPGS optimization algorithm. The P&O-PCA has shown good performance in PPGS, which can quickly and accurately respond to and track the reference voltage and maintain stability and accuracy under different iteration update cycles. This provided strong support for the application of the algorithm in practical PPGS.

3.1 Performance analysis of P&O-PCA

To comprehensively verify the P&O-PCA performance, this paper performs experiments on its transient response under different iteration update cycles. The response of photovoltaic output power under different iteration update cycles based on P&O-PCA is shown in Figure 8. Figure 8 (a) shows the irradiance change diagram. In Figure 8 (a), with the increase of time, when the iteration update period is 0.5 s, the PV output power diagram based on P&O-PCA hovers around 0.075-0.25 MW. When the iteration update period is 0.01 s, the PV output power graph based on P&O-PCA hovers around 0.050-0.25 MW. This is because within 0.5 s, the research algorithm cannot respond to changes in the external environment in a timely manner, while within 0.01 s, the algorithm can quickly adjust its working state and closely track the maximum power point. Figure 8 (b) shows the voltage response of the photovoltaic array port at Ts=0.01 s. When the iteration update cycle is 0.01 s, the difference in the fluctuation path between the PAPV and U_{PVref} voltage is small. Figure 8 (c) shows the voltage response of the photovoltaic array port at Ts=0.5 s. The fluctuation path of the PAPV and U_{PVref} voltage is basically consistent, the algorithm can still maintain stability and accuracy and effectively track the reference voltage even in long iteration update cycles. To verify the applicability of the research algorithm, experiment on the transient response of P&O-PCA in real operating scenarios is carried out. Figure 8 shows the transient response of P&O-PCA in real operating

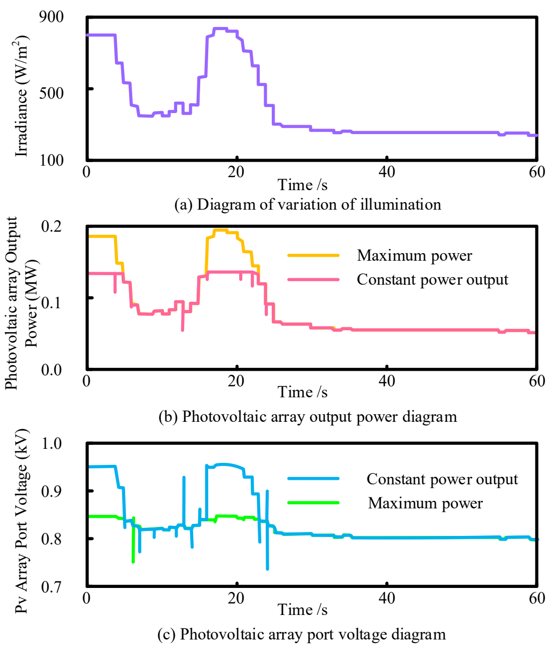

Fig 9 Transient response diagram of P&O-PCA in real operation scenario

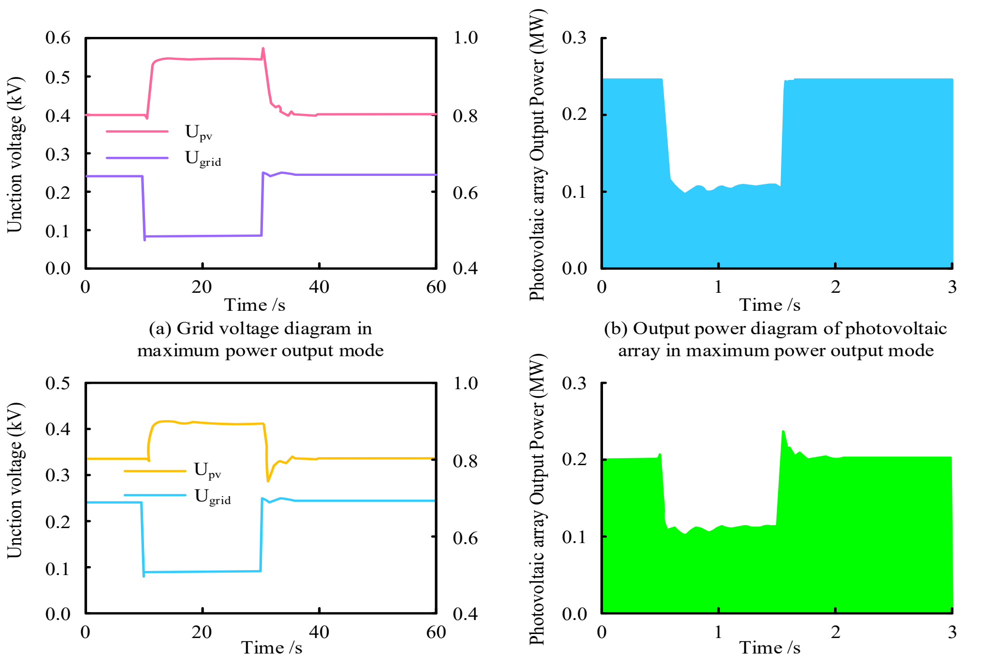

Fig 10 Transient response of P&O-PCA to short circuit fault

scenarios.

Figure 9 (a) shows the variation of irradiance. There are significant fluctuations in irradiance, which may be caused by the shading of buildings. Figures 9 (b) and (c) show the PAOP and PAPV. The research algorithm has good performance in constant power output and maximum power tracking. This further confirms the effectiveness and superiority of the algorithm, which can cope with various environmental conditions and maintain a stable operating state. To further verify the response capability of P&O-PCA under short-circuit fault conditions, this study applies P&O-PCA to MPO mode and constant power output mode respectively, to comprehensively evaluate its performance under different operating modes. The transient response of P&O-PCA to short-circuit faults is shown in Figure 10.

Figures 10 (a) and (b) show the voltage at the grid connection point and the PAOP under MPO mode. In Figure 10 (a), when a short circuit fault occurs, the P&O-PCA controls the maximum power voltage in the range of 0.4-0.55 kV, and it takes 20 seconds from the occurrence of the short circuit fault to the start of the algorithm to adjust the voltage and stabilize it within this range. Figure 10 (b) shows the output power diagram of the photovoltaic array in the MPO mode. In Figure 10 (b), when a short circuit fault occurs, the short-circuit startup time of the algorithm is 1 s, which is relatively short. Figures 10 (c) shows the voltage diagram of parallel nodes in constant power output mode. In Figures 10 (c), when a short circuit fault occurs, the P&O-PCA controls the maximum power voltage within the range of 0.25-0.4 kV, and the short-circuit startup time of the algorithm is 20 s, which is consistent with the performance in the MPO mode. Figure 10 (d) shows the output power diagram of photovoltaic array in constant power output mode. In Figure 10 (d), when a short circuit fault occurs, the short-circuit startup time of the algorithm is 1 s, indicating that the algorithm can quickly adjust the output power after detecting a short circuit fault.

To verify the applicability of the research model, this study applies the model to diesel generators and PPGS, and compares its power with the constant frequency model in the above two situations. The comparison of output power of different models is shown in Figure 11. Figure 11 (a) shows the power comparison of diesel generators. Over time, the research model only reduces the control of diesel generator power by 0.02 MW. The constant frequency model reduces the power control of diesel generators by 0.08 MW. Figure 11 (b) is a comparison chart of the output power of the photovoltaic power generation system. It can be seen from Figure 11 (b) that with the increase of time, the power control of the diesel generator by the constant frequency model does not decrease and always

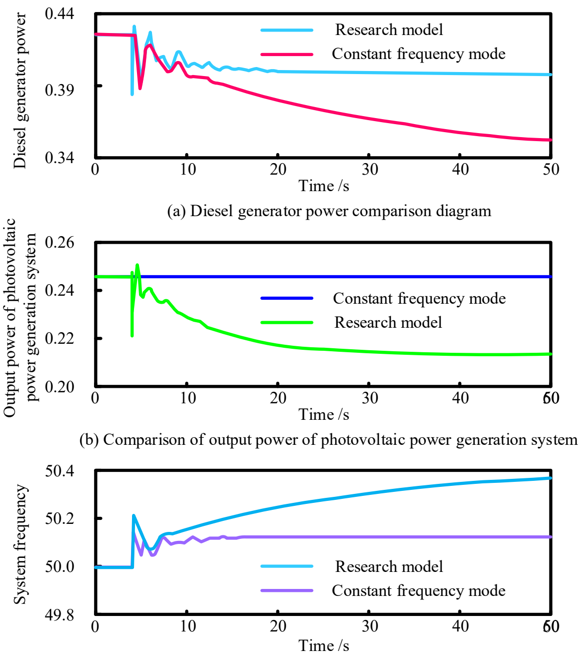

Fig 11 Comparison of the output power of different models

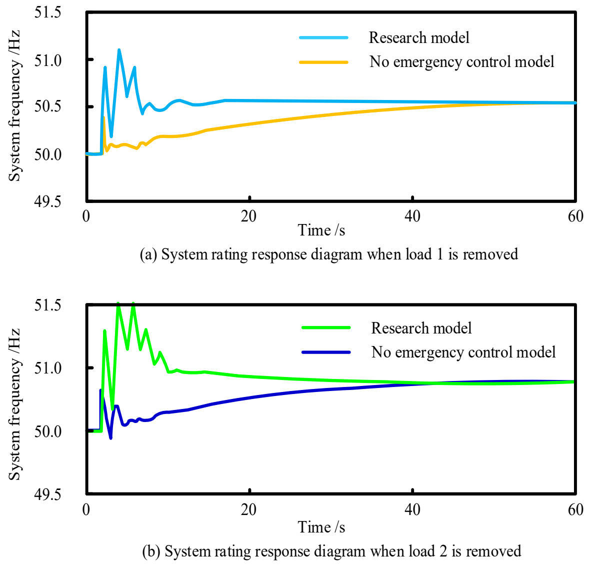

Fig 12 Transient response curves of micro-grid systems under different emergency control schemes

remains at 0.248MW. This study reduced the power control of the photovoltaic power generation system by 0.029MW. Figure 11 (c) shows the comparison of system frequencies. The control of the system frequency by the research model is stable at 50.1 Hz. To test the emergency control performance, the power control comparative experiments on micro-grid systems are performed using P&O-PCA-based NEFRM and models without emergency control under the conditions of cutting off load 1 and load 2. The result is shown in Figure 12.

Figures 12 (a) and (b) show the frequency response of the system when loads 1 and 2 are cut off. In Figure 12 (a), when load 1 is cut off, the model without emergency control shows significant power fluctuations within 10 seconds. The research model accurately controls the power of the microgrid system within 10 seconds and keeps the maximum power of the microgrid system at 50.6 Hz. In Figure 12 (b), when load 2 is cut off, the research model exhibits excellent fast response ability. Within 5 seconds, the system frequency rapidly increases and reaches its highest value, which is 52.50 Hz, while the non-emergency control model experiences significant frequency fluctuations in the first 5 seconds. To verify the superiority of the research model, a comparison is made between the P&O-PCA-based NEFRM and linear interpolation models, quadratic interpolation models, spline interpolation models, and constant frequency models. Table 1 shows the power control effects of different models.

In Table 1, different interpolation models and constant frequency models have differences in the power control effect of diesel generators, the output power control effect of PPGSs, and the system frequency control effect. In terms of the power control effect of diesel generators, when the load condition is 1, the power control effect of the research model is the best, reaching 2.02 MW. The power control effect of constant frequency model is the worst, only 1.90 MW. The power control effects of linear interpolation model, quadratic interpolation model, and spline interpolation model are 1.92 MW, 1.89 MW, and 1.95 MW, respectively. In summary, the research model not only performs well in the power control of diesel generators but also shows excellent ability in the overall power control of microgrid systems. The model can quickly and accurately respond to the change of system power demand, which provides a strong guarantee for the stable operation of microgrid system. However, the performance optimization of other interpolation models and constant frequency models under specific conditions remains to be further discussed and studied. To verify the stability of the research model, a NEFRM based on P&O-PCA is simulated. In this study, linear interpolation model and quadratic interpolation model are used as models for experiments, and the stability results of the three models are shown in Figure 13.

In Figures 13, when the time is 0.06 s, the output power curve of the NEFRM based on P&O-PCA tends to be stable. At this time, the output power of the model is 174.8 w, indicating

Table 1
Power control effect tables for different models

Model	Diesel generator Power control effect (MW)		Output power control effect of PPGS (MW)		System frequency control effect (Hz)		Time (h)	
	Load condition 1	Load condition 2	Load condition 1	Load condition 2	Load condition 1	Load condition 2	Load condition 1	Load condition 2
The research model	2.02	1.84	0.248	0.237	50.10	49.12	24	26
Linear interpolation model	1.92	1.88	0.219	0.208	48.75	47.63	24	28
Quadratic interpolation model	1.89	1.72	0.241	0.236	49.05	48.79	24	28
Spline interpolation model	1.95	1.88	0.235	0.224	49.02	48.55	24	29
Constant frequency model	1.90	1.86	0.225	0.215	48.50	47.48	24	29

Table 2
Comparison between simulation results and experimental results

Light intensity/(W·m²)	Theoretical power value/W		Experimental result		Simulation result	
			Power/W	Error/%	Power/W	Error/%
1000	200.49	1.84	199.73	0.38	198.95	1.02
500	95.16	1.88	95.09	0.07	94.82	0.08

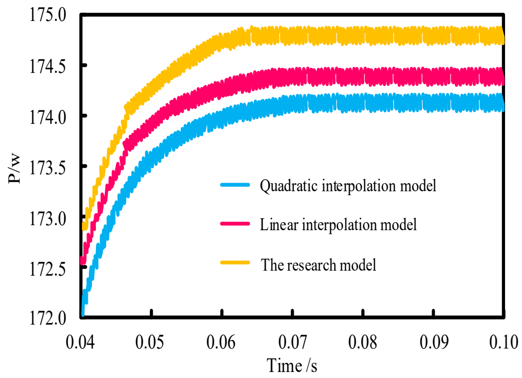

Fig 13 Simulation analysis of output power of different models

that the P&O-PCA has high response speed and stability in the frequency regulation process and can effectively and quickly adjust the output power of the new energy system. When the time is 0.07 s, the output power curve of the linear interpolation model tends to be stable, and the output power of the linear interpolation model is 174.4w. Although the linear interpolation model can also reach a stable state, its response time is slightly later than that of the P&O-PCA model, and the output power is slightly lower when it is stable. This may be due to the limited approximation ability and adaptability of linear interpolation method when dealing with new energy systems with nonlinear or complex changes. When the time is 0.08 s, the output power curve of the quadratic interpolation model tends to be stable, and the output power of the model is 173.8 w. This indicates that the response speed and stability of the quadratic interpolation model are relatively poor when dealing with the frequency regulation of new energy sources, and may not be suitable for time-sensitive or high-precision control scenarios. To verify the validity of this study, the maximum power and error of simulation results and experimental results are compared, as shown in Table 2.

In Table 2, when the light intensity is 1000 W/m^2 and 500 W/m^2 respectively, the maximum output power through the experimental results is 199.73 W and 95.09 W respectively, approaching the theoretical value. According to the simulation results, when the illumination intensity is 1000 W/m^2 and 500 W/m^2 respectively, the maximum output power of the simulation results is 198.95 W and 94.82 W respectively, which is also close to the theoretical value. The results show that both experimental results and simulation results are within the error range, indicating that this study is effective and feasible.

3.2 Discussion

In the performance test, the power control of the constant frequency model decreased by 0.08 MW over time, while the research model decreased by only 0.02 MW. In terms of the output power of PPGS, the research model always maintained at 0.248 MW, and the constant frequency model decreased by 0.029 MW. This is because the P&O algorithm periodically changes the operating point of the photovoltaic system and observes the direction of power changes to determine the next control action and achieve precise control of the PPGS. This is similar to the results obtained by Ali *et al.* (2023) in studying the application of an enhanced P&O MPPT algorithm with a concise search area in grid-connected photovoltaic systems. The empirical study by Yusoof *et al.* (2023) shows that in solar cell charging systems, the P&O algorithm can improve charging efficiency and reduce voltage fluctuations compared to traditional methods. This finding supports the superior performance of the P&O model in terms of power stability in this study. Research by Kumar Nayak *et al.* (2023) shows that efficient MPPT algorithms can reduce the number of sensors while improving the overall performance of photovoltaic systems. These studies further confirm the effectiveness and adaptability of P&O algorithm in PPGS, especially in the face of complex environmental conditions, P&O algorithm can achieve optimal power output through dynamic adjustment.

By comparing and studying the performance of the model and the constant frequency model in diesel generators and photovoltaic systems, the superiority of the proposed model in power control was confirmed. The reduction in the power of the diesel generator by the research model was 0.02 MW, which was significantly lower than that of the constant frequency model, and the power reduction was completely avoided in the photovoltaic system. The research model adopted the adaptive power control optimization algorithm. This algorithm could adjust the control strategy according to real-time data and system status to cope with the constantly changing operating conditions. Therefore, with the increase of time, the power control of diesel generators in this study has not decreased. This result is consistent with the conclusion of Abbas *et al.* (2024) that the optimal control strategy for hybrid energy systems can reduce reliance on traditional generators and enhance the stability of renewable energy. Abbas *et al.*'s research further supports this finding. By optimizing the control of the photovoltaic/wind/battery/diesel hybrid power system, the operating time of the diesel generator has been reduced and the system efficiency has been improved. The research model stabilizes the system frequency at 50.1 Hz. The research by Abbas et al. also emphasizes the importance of frequency stability in independent microgrids. Their control strategy minimizes the frequency deviation by dynamically allocating the power output of different energy sources.

When load 1 is cut off, the model without emergency control had a violent power fluctuation within 10 seconds, but the research model could accurately control the power of the microgrid system and stabilize its maximum power at 50.6 Hz. When load 2 was removed, the research model responded quickly in just 5 seconds, and the system frequency increased rapidly and reached the highest value of 52.50 Hz. The P&O algorithm optimized the search speed by variable step size method. When the system is far away from the maximum power point, the disturbance amplitude is large, so that the MPP can be approached quickly. When approaching MPP, the step size is reduced to reduce oscillations, thereby improving frequency stability and accuracy. Cakmak *et al.* (2024) demonstrated through theoretical analysis and experimental comparison that under dynamic conditions, traditional P&O algorithms may experience power loss due to fixed step sizes, while a hybrid strategy combining voltage open-loop detection can shorten convergence time. The study further verified the effectiveness of adaptive step size adjustment, and its conclusion was consistent with the study of Yuksek *et al* (2023). In addition, the study of Dennai *et al.* (2024) also shows that although PSO sliding mode control and PSO-ANFIS controller perform well in some complex scenarios, P&O algorithm is still one of the most widely used MPPT algorithms in microgrid dynamic control due to its simplicity and high efficiency. These studies further confirm the advantages of P&O algorithm in terms of fast response and stability, especially in the face of dynamic scenarios such as sudden load changes.

Compared with various interpolation models and constant frequency models, the output power curve of the model based on P&O-PCA became stable at 0.06 s, and the output power was

174.8W. The linear interpolation model was stable at only 0.07 s, and the power was 174.4 W. The quadratic interpolation model was stable at 0.08 s and had a power of 173.8 W. The P&O-PCA model had the fastest response speed and the best stability. The latter two models had low stability power and lag response, so they were not suitable for scenarios requiring high response speed and stability. This result is consistent with the conclusions of existing studies. Abdul Khani *et al.* (2024) verified the fast convergence of P&O algorithm under standard illumination conditions through experiments, and its steady-state power error is larger, which is significantly better than the traditional open-loop method. The advantage of P&O algorithm lies in real-time tracking of dynamic characteristics through continuous system state disturbances, forming a closed-loop optimization process. Fappi and Tchakounte (2022) confirmed this in their research on the fuzzy logic based enhanced operation and maintenance MPPT algorithm for photovoltaic systems. However, the interpolation method is limited by model accuracy and calculation delay, which is difficult to adapt to the strong nonlinear and time-varying characteristics of photovoltaic systems, especially in dynamic scenarios such as fast moving clouds. However, under complex conditions such as local shading, P&O algorithms may fall into local optimal due to the fixed disturbance step size. A comparative study by Ravi et al. (2023) shows that the new meta-heuristic algorithm has better global search capability than P&O in dynamic lighting scenes, but has higher computational complexity. This also explains the poor performance of interpolation methods: they rely on preset model accuracy and are difficult to adapt to the strong nonlinear and time-varying characteristics of photovoltaic systems, especially in the case of rapid cloud movement, where model mismatch can lead to significant power fluctuations. Therefore, for high dynamic environments, it is necessary to balance the complexity and real-time performance of algorithms. The P&O algorithm is still an efficient and reliable choice under normal circumstances, but in extreme cases, it may need to be combined with intelligent optimization strategies.

In summary, the research model has excellent performance in power control, frequency control, and emergency control performance. P&O algorithm can effectively reduce power fluctuation and frequency deviation by dynamically adjusting power output, ensuring stable operation of the system, and providing a strong guarantee for the stable operation of the microgrid system.

4. Conclusion

This study proposed a P&O-PCA-based NEFRM to address the instability of photovoltaic power generation. In the result analysis, in the MPO mode, when a short circuit fault occurred, P&O-PCA could control the maximum power voltage within the range of 0.4-0.55 kV. Under constant power output mode, this algorithm could control the maximum power voltage within a reasonable range of 0.25-0.4 kV. This indicated that the algorithm could achieve effective voltage control in different modes, ensuring the normal operation of the system. In addition, when load 1 was cut off, the power fluctuation of the non-emergency control model was significant. However, within 10 seconds, the research model accurately controlled the power of the micro-grid system, stabilizing the maximum power at 50.6 Hz. This result indicated that the model could quickly respond to unexpected situations and ensure the micro-grid system operating stably. In summary, research algorithms have significant advantages in improving the stability of photovoltaic power generation. The limitation of this study is that the research model may not be compatible with some existing PPGS or devices. To better promote and apply this model in practical applications, future research can consider how to integrate it with existing systems and address interoperability issues.

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