DOI 10.24425/aee.2021.136984

Coordinated control strategy for microgrid stability maintenance under isolated island operation

PAN WU[1], XIAOWEI XU[2]

[1]*Power Supply Co., Ltd.*
Luqiao District, Taizhou, Zhejiang Province, China
[2]*Power Supply Co., Ltd.*
Tonglu, Zhejiang Province, China
e-mail: p07154@yeah.net

(Received: 13.08.2020, revised: 10.11.2020)

Abstract: In this study, the inverter in a microgrid was adjusted by the particle swarm optimization (PSO) based coordinated control strategy to ensure the stability of the isolated island operation. The simulation results showed that the voltage at the inverter port reduced instantaneously, and the voltage unbalance degree of its port and the port of point of common coupling (PCC) exceeded the normal standard when the microgrid entered the isolated island mode. After using the coordinated control strategy, the voltage rapidly recovered, and the voltage unbalance degree rapidly reduced to the normal level. The coordinated control strategy is better than the normal control strategy.

Key words: coordinated control, isolated island operation, microgrid, particle swarm optimization

1. Introduction

The traditional centralized power supply system is relatively simple in the structure and relatively low in cost, but it is faced with the disadvantages of low reliability and large interference. Once a fault occurs at a point, it will easily spread to the whole power grid [1]. To make up for these defects, the distributed grid was proposed. The distributed power grid [2] is a large power grid composed of complex micro grids, and its power supply form is very suitable for existing new energy sources, such as photovoltaic power generation, wind power generation, etc. Although the microgrid composed of energy such as photovoltaic and wind cannot provide large-scale power supply, it can supplement the main grid, reduce the current feeder loss, and enhance the reliability, efficiency, and flexibility of power [3]. Zhang *et al*. [4] proposed an improved pre-synchronization controller for the isolated island operation mode of the microgrid with photovoltaic power generation to stabilize the microgrid. The experimental results showed the effectiveness of the strategy. Liang *et al*. [5] established the multi-master-slave control model of the three-source microgrid in the isolated island mode, then established the small-signal decoupling control model and its stability discriminant equation based on "virtual impedance", and verified the influence of converter parameter variation in the microgrid on stability by the simulation experiment. Zhang *et al*. [6] proposed a direct current bus control algorithm and found through the simulation that the algorithm could realize the stable operation of the microgrid. In this study, the particle swarm optimization (PSO) algorithm was applied to the coordinated control under the isolated island operation mode of the microgrid, and it was compared with the traditional power coordinated control strategy in the subsequent simulation experiments. In the related studies mentioned above, relevant control strategies are proposed for microgrid stability, which can realize the stability control of microgrid. The traditional microgrid coordinated control strategy under the isolated island mode is to add an energy storage battery which can supplement the power in the microgrid because of the mismatch between power supply and load power. Once the microgrid power mismatch is detected, the power will be supplemented immediately. Although the traditional coordinated control strategy is relatively simple, there are delays in the response to power mismatch among more than one energy storage battery in the microgrid, and the battery capacity is limited. To solve the above defects, this study used the unbalanced voltage compensation for the inverter to realize the coordinated control of the microgrid. Moreover, the optimal compensation voltage was calculated using the PSO algorithm to improve the control effect. The purpose of this paper is to ensure the power stability of the microgrid when it enters the isolated island mode due to sudden fault, so as to improve the security of the grid. The contribution of this paper is to provide an effective reference for the power stability regulation strategy of the microgrid under the operation mode of the isolated island.

2. Coordinated control of microgrid based on PSO algorithm

2.1. Traditional coordinated control

The isolated island operation mode of the microgrid caused by unplanned grid failure [7] will cause system instability due to the mismatch between the power supply and load power. Therefore, effective control strategies are needed to control the microgrid. The traditional control strategy starts with the power of the microgrid: since the instability is caused by the power mismatch between the power supply and load, the stability can be improved as long as the power of the unmatched part is compensated. The basic steps of the control strategy are as follows. When the microgrid control center detects the isolated island mode, it first calls the energy storage batteries [8] to inject active power into the microgrid or absorb active power to stabilize the frequency of the microgrid. Then the frequency affected by the energy storage battery is taken as a reference to control the frequency of other microgrid power sources. The calculation formula of the control power is as follows:

$$\begin{cases} P_1 = \dfrac{f' - f}{k_p} \\ U = U' \end{cases}, \tag{1}$$

where: P_1 is the active output of the energy storage battery, f and f' are the actual operation frequency and reference operation frequency of the microgrid, respectively [9], and U, U' are the actual operating voltage and reference operating voltage of the microgrid, respectively. The above-mentioned coordinated control method based on power compensation is simple and straightforward in the principle and implementation. It can stabilize the microgrid only by absorbing excessive power or compensating insufficient power through an energy storage battery. However, in the process when the energy storage battery is used to make the balance regulation of the microgrid and other micro sources, refer to the new frequency given by the energy storage battery to adjust the output. Although the energy storage battery will make a timely response at the moment of "the isolated island" formation, the frequency follow-up of other micro-power sources will delay, which will eventually delay the coordinated control of the microgrid. Also, the energy storage batteries that can be installed in the microgrid have limited installation capacity and cost control [10].

2.2. Unbalanced voltage compensation control based on PSO algorithm

Since the traditional control strategy mentioned above has problems such as delay and the limited capacity of the energy storage battery, this study proposed a coordinated control strategy based on PSO by combining the unbalanced voltage compensation with the PSO algorithm [11] from the perspective of voltage compensation of the microgrid. The cause of the unbalanced voltage is the same as that mentioned above, i.e., when the microgrid enters the mode of isolated island operation, the power supply and load power are unbalanced, resulting in voltage imbalance. The unbalanced voltage compensation control framework is shown in Fig. 1. In Fig. 1, $i_{o,abc}$ and $u_{o,abc}$ are the current and voltage at the inverter port, and $i_{pcc,abc}$ and $u_{pcc,abc}$ are the current and voltage at the PCC terminal. In Fig. 1, after reference voltage u_{ref} is synthesized

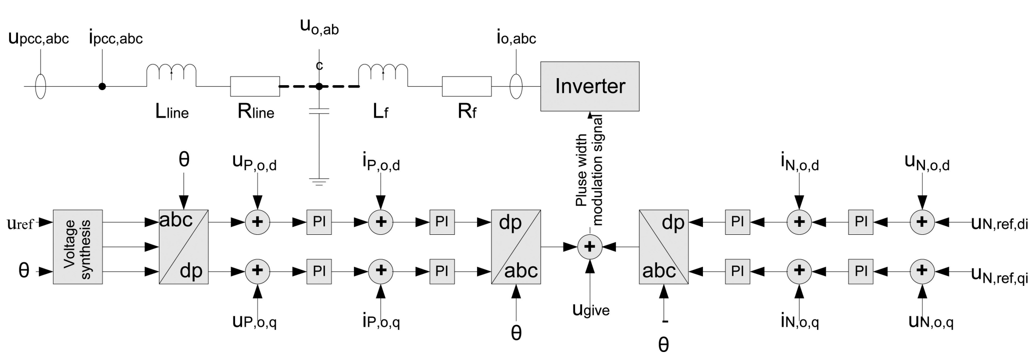

Fig. 1. The microgrid coordinated control framework based on unbalanced voltage compensation

with θ that is obtained by the integral calculation of angular frequency, it transforms from the three-phase axis to the dq axis. Then after the PI link processing based on the positive sequence current voltage $u_{P,o,d}$, $i_{P,o,d}$, $u_{P,o,q}$, $i_{P,o,q}$ of d and q axes, it transforms from the dq axis to the three-phase axis. Feedback voltage u_{give} and the reference voltage and negative sequence compensation instruction that are processed by PI constitute the pulse width modulation signal. The inverter adjusts the current according to the signal to stabilize the microgrid. In the process of voltage balance regulation, if the voltage at any part of the inverter port and PCC is fully compensated, the other part cannot be guaranteed to be fully compensated. Therefore, the PSO algorithm is adopted to realize the coordinated voltage balance at the inverter port and PCC, as shown in Fig. 2.

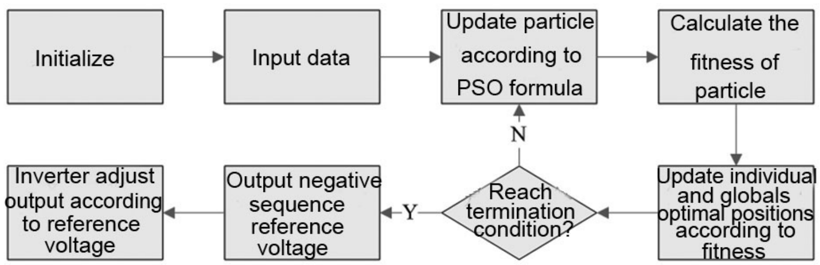

Fig. 2. The flow of the PSO algorithm

The detailed flow is as follows.

1. The parameters of the algorithm are initialized [12].
2. The current and voltage data of the inverter and PCC port collected by the sensor are input into the algorithm.
3. According to Equation (2), the position and velocity of particles are calculated iteratively:

$$\begin{cases} v_i(t+1) = v_i(t) + c_1(p_i - x_i(t)) + c_2(g_i - x_i(t)) \\ x_i(t+1) = x_i(t) + v_i(t+1) \end{cases}, \tag{2}$$

where: $x_i(t)$ and $x_i(t+1)$ are the particle position of the current time of iteration and the next time of iteration (the coordinates of the particle position is the negative sequence voltage reference command), $v_i(t)$ and $v_i(t+1)$ are the particle speed of the current time of iteration and the next time of iteration respectively, c_1 and c_2 are learning factors, p_i stands for the best position of the particle that is reached in multiple times of iterations, and g_i is the best position that is reached in the population at the current time of iteration. In the iterative searching process of the particle, to ensure the effectiveness of the corresponding results of the particle, it is necessary to limit the search space by constraint conditions. The conditions are: the voltage imbalance degree of the inverter and PCC port does not exceed the corresponding maximum allowable range, and the compensation voltage of negative sequence ports of inverters is equal.

4. After the particle swarm is updated, the fitness of each particle in the population is calculated:

$$\begin{cases} f = k_1 \left| u_{N,o1} - u_{N,o2} \right| + k_2 g_{DG} + k_3 g_{PCC} \\ g_{DG} = r_{DG} \max(0, \xi_{DG} - \xi_{DG,\max}) \\ g_{PCC} = r_{PCC} \max(0, \xi_{PCC} - \xi_{PCC,\max}) \\ \xi_{DG} = \dfrac{\sqrt{u_{N,\mathrm{ref},d}^2 + u_{N,\mathrm{ref},q}^2}}{\sqrt{u_{P,o,d}^2 + u_{P,o,q}^2}} \\ \xi_{PCC} = \dfrac{\sqrt{u_{N,prepcc}^2 + u_{N,prepcc,q}^2}}{\sqrt{u_{P,pcc,d}^2 + u_{P,pcc,q}^2}} \\ u_{N,prepcc,dq} = \left(u_{N,\mathrm{ref,dq}} - z_f i_{N,o,dq}\right) - z_{\mathrm{line}} i_{N,o,dq} \end{cases}, \tag{3}$$

where: f is the objective function, i.e., fitness, k_1, k_2 and k_3 are the proportion of the corresponding penalty function, g_{DG} and g_{PCC} are the penalty functions of voltage unbalance between the inverter and PCC [13], r_{DG} and r_{PCC} are the penalty factors of the corresponding unbalance degree, ξ_{DG} and ξ_{PCC} are the degree of voltage unbalance between the inverter and PCC, $u_{N,prepcc,dq}$ is the predictive value of PCC terminal's negative sequence voltage predicted according to the negative sequence compensation voltage at the dq axis, z_f and z_{line} are the filter impedance and line impedance of the inverter respectively, and $i_{N,o,dq}$ is the actual inverter negative sequence current.

5. According to the fitness of particles, the individual optimal particle and the globally optimal particle are selected.
6. If the algorithm is not terminated, it returns to step 3. If the algorithm is terminated, the negative sequence reference voltage corresponding to the optimal particle is output.
7. Taking the calculated negative sequence reference voltage as the negative sequence compensation instruction, the inverter is adjusted according to the frame shown in Fig. 2 to realize the coordinated control.

Through the above flow of the PSO algorithm, the optimal negative sequence reference voltage is gradually iterated out as the negative sequence compensation instruction of the inverter. After that, the inverter is controlled by PI according to the control theory in Fig. 2. The direct current power supply can adjust the output alternating current voltage and current after being regulated by the inverter.

3. Simulation analysis

3.1. Experimental environment

In this study, the stable and coordinated control strategy of the isolated island operation of the microgrid was simulated using MATLAB software [14]. The experiment was carried out in a laboratory server. The server configurations were based on a Windows7 system, I7 processor, and 16 G memory.

3.2. Experimental setup

The basic structure of the experiment in this study is shown in Fig. 3. For the convenience of calculation, only two inverters and distributed generation were used to form the microgrid. Each inverter was responsible for one load, and the relevant parameters are shown below. Two inverters and distributed generation were connected in a line, which was connected with the transformer through a static switch, and the other side of the transformer was connected with the distribution network. The corresponding voltage and current sensors were set at the port and PCC of the two inverters, and the collected current and voltage information was sent to the microgrid control center. The microgrid control center has a corresponding coordinated control strategy. According to the current and voltage collected by the sensor, after the judgment by the coordinated control strategy, the inverter was regulated by the pulse width modulation signal to realize the stability of the isolated island operation of the microgrid. Table 1 shows relevant parameters in the simulation experiment, and relevant parameters needed by the PSO algorithm were determined by the orthogonal experiment.

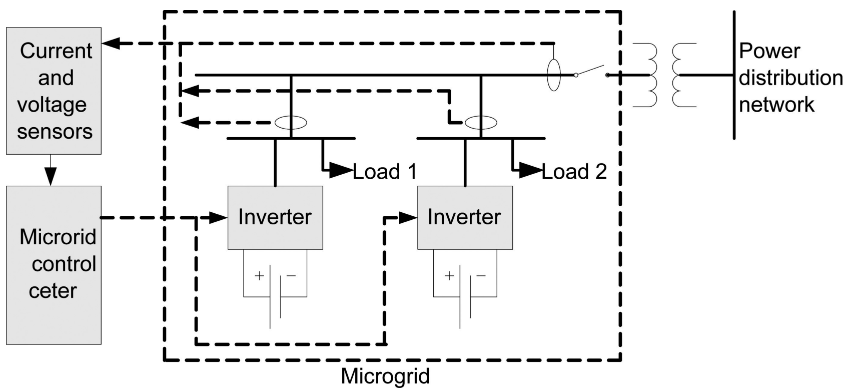

Fig. 3. The setting of relevant parameters of microgrid

Table 1. The basic structure of the microgrid under the coordinated control

Parameter	Value	Parameter	Value
Distributed supply voltage	900 V	Active droop coefficient	5×10^{-6}
Microgrid voltage frequency	50 Hz	Reactive droop coefficient	10^{-4}
Inverter filter capacitance	20 µF	Load 1 and 2	250 Ω
Inverter filter inductance	5 mH	Penalty coefficient $g_{DG} g_{PCC}$	1
Inverter filter resistance	0.1 Ω	Weight k_1	20
Line inductance	0.5 mH	Weight $k_2 k_3$	5
Line resistance	0.5 Ω	Maximum voltage imbalance	0.02

3.3. Experimental methods

Firstly, the simulation model was built according to the basic structure shown in Fig. 3 in MATLAB software, and the PSO algorithm in the microgrid control center module is initialized, and then the simulation experiment is started. The steps are as follows. Two inverters were turned on at the same time and connected to the public bus in the microgrid to form PCC, and pre-synchronization was carried out for some time. At the moment, the microgrid was connected to the distribution network through the substation. After the pre-synchronization, the fault condition of the distribution network was simulated. The static switch between the microgrid and distribution network was used to disconnect them, and the disconnection time was taken as the initial time. Within 0.2 s after disconnection, the microgrid control center did implement the coordinated control strategy and adjusted the unbalanced voltage by relying on the regulation performance of the inverter. After 0.2 s, the PSO algorithm based coordinated control strategy was used until the microgrid was stable again. In the above process, the changes in voltage and voltage imbalance in the microgrid were collected by the sensor and recorded.

Moreover, to further verify the effectiveness of the proposed coordinated control strategy based on the PSO algorithm, it was compared with the traditional power-based coordinated control strategy mentioned above. The basic structure of the microgrid simulation model used in the traditional coordinated control strategy was consistent with that in Fig. 3. The difference only lies in the coordinated control strategy adopted in the control center module and the energy storage battery for each inverter in the microgrid, in which the load power provided by the energy storage battery was 4 kW. The steps were consistent with those of the coordinated control strategy.

3.4. Experimental results

The coordinated control strategy based on PSO algorithm needs to calculate the negative sequence command current that was used for controlling the inverter in the micro grid with the PSO algorithm, so as to obtain the most appropriate inverter regulation parameters and maintain the imbalance of the microgrid under the isolated island operation mode within the safe range. When calculating the optimal negative sequence command current, the iterative curve of the PSO algorithm is shown in Fig. 4. It was seen from Fig. 4 that the imbalance degree in the microgrid decreased rapidly with the increase of the iteration times of the PSO algorithm, and it decreased to less than 0.02 after 20 times of iterations and then remained stable.

In the simulation experiment, the change of the inverter port voltage of the two coordinated control strategies with time is shown in Fig. 5 (the negative time of the time axis in Fig. 5 indicates the pre-synchronization time, 0 s indicates the starting of the control strategy at the disconnection moment; the data before 0 s were also recorded, and the display of the data is to present the sudden change of voltage when the grid was disconnected). It was seen from Fig. 5 that the voltage at the inverter port was stable at 340 V before the disconnection between the microgrid and distribution network at 0 s. The voltage at the inverter port dropped to 320 V at a very high speed at the moment of disconnection, i.e., 0 s. The voltage recovered to some extent due to the regulating function of the inverter itself at 0~0.2 s, but the recovery degree gradually reduced. Up to 0.2 s, the coordinated control strategy was not used in the two simulation models, and the structure was similar, thus the voltage changes were nearly coincident. After 0.2 s, the coordinated control

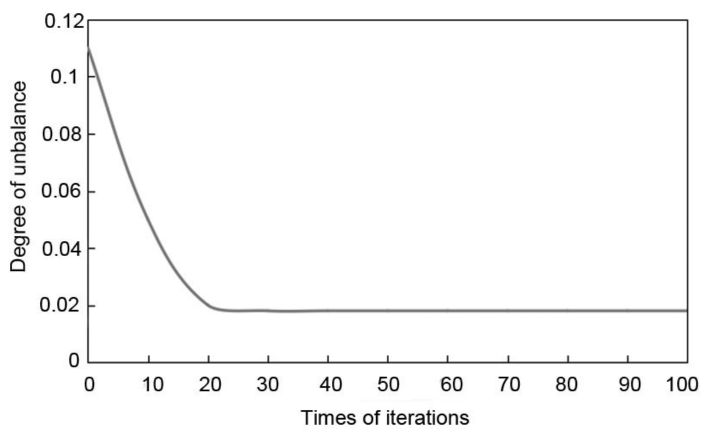

Fig. 4. Convergence curve of the coordinated control strategy based on PSO algorithm

strategy was used respectively. It was seen from the curve change in Fig. 3 that the two strategies could ultimately restore the voltage to the original level, but the coordinated control strategy proposed in this study recovered to the original level faster.

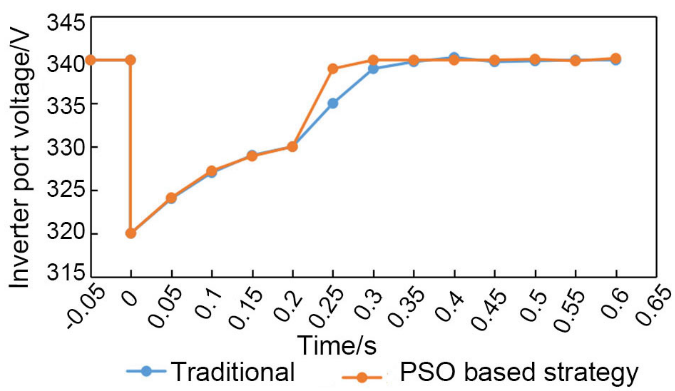

Fig. 5. Voltage variation of inverter port under two coordinated control strategies

It was seen from Fig. 6 that the voltage unbalance of the inverter and PCC port reached 8.5% and 9%, respectively, due to the disconnection at 0 s, which was far beyond the specified standard of IEEE (IEEE stipulates that the three-phase power supply unbalance degree of the electrical power system should be smaller than 2%). Within 0.2 s, the unbalance degree decreased under the regulation of the inverter, but the effect was not obvious. After 0.2 s, the coordinated control strategy was used, and the imbalance degree significantly reduced, and under the two coordinated control strategies, the imbalance degree reduced to less than 2%. The unbalanced voltage-based strategy adopted in this study could reduce the imbalance to a lower level more quickly.

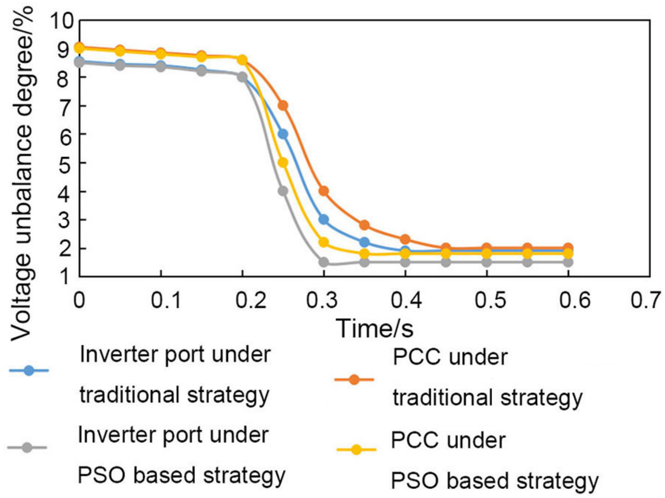

Fig. 6. The voltage unbalance between the inverter and PCC port under two coordinated control strategies

3.5. Discussion

In today's increasingly expanding power grid, the existence of the microgrid can be a good supplement to the large power grid and provide convenient power for the remote areas in the large power grid that are hard to reach. The grid and microgrid assist each other. However, once the power grid fails, in order to ensure the normal power consumption in other areas, the fault area will be disconnected from the normal area, and the microgrid will enter the isolated island operation mode. In the mode switching, the load power in the microgrid area that is previously shared by the grid and microgrid is only provided by the microgrid after entering the isolated island mode, which will lead to the mismatch of power and the power fluctuation. To reduce the impact of power fluctuations on the stability of microgrid, it is necessary to adjust the microgrid through the coordinated control strategy. The traditional coordinated control strategy mentioned in this paper that is aimed at the mismatch between the power of the microgrid and the load power, compensates the mismatched power with the energy storage battery. On the one hand, the response of complex energy storage batteries to power mismatch in the microgrid has different degrees of delay. On the other hand, the capacity of the storage battery is limited, and the installation cost of the complex battery is high. A coordinated control strategy based on unbalanced voltage was proposed in this study. The strategy did not need an additional energy storage battery to assist in power regulation, but uses the adjustment of inverter output to compensate for the unbalanced voltage in the microgrid. The regulation principle of the inverter in the strategy was that the control signal of the inverter was obtained after processing the electric power in the microgrid circuit collected by the sensor with PI based on the set negative sequence command voltage and the inverter adjusted the output. The control effect of the coordinated strategy based on unbalanced voltage on the stability of the microgrid largely depended on the negative sequence command voltage. In order to ensure the optimal negative sequence command voltage, this study used the PSO algorithm to optimize the negative sequence command voltage.

Then, to verify the effectiveness of the proposed control strategy based on unbalanced voltage, simulation experiments were carried out. The final experimental results were shown above. It was seen from the above results that the optimal negative sequence command voltage could be quickly iterated by the unbalanced voltage-based and PSO algorithm-based optimized coordination strategy. Moreover, the proposed strategy was compared with the traditional coordinated control strategy. The comparison results showed that the port voltage decreased rapidly when the microgrid entered the isolated island mode, and it recovered slowly when the control strategy was not used; once the control strategy was used, the voltage could be restored to the original level faster by the control strategy proposed in this study than the traditional strategy, as well as the degree of unbalance in the microgrid. The control strategy proposed in this study was better than the traditional control strategy, and the reason was that the capacity of the energy storage battery in the traditional strategy was limited, and the response delay of complex batteries to the isolated island mode was different, which made the control effect on the stability of the microgrid poor. The control strategy based on unbalanced voltage was to adjust the inverter according to the detection of a power signal by the sensor, which was more timely in response, and also adopted the PSO algorithm to optimize the command signal to the inverter, which made the response to the isolated island mode more timely and the voltage and unbalance degree recover more quickly.

4. Conclusion

In this study, the PSO algorithm was applied to the coordinated control of the microgrid island operation mode and compared with the traditional power coordinated control strategy in subsequent simulation experiments. The results are as follows. When the microgrid was disconnected from the distribution network, the voltage at the inverter port decreased obviously, from 340 V to 320 V; when the control strategy was not enabled between 0 and 0.2 s, the voltage rose slowly; the control strategy was used in 0.2 s, the voltage rose rapidly, and the voltage recovery under the control strategy proposed in this study was faster. When the microgrid was disconnected from the distribution network, the voltage unbalance of the inverter and PCC port significantly exceeded the specified standard, 9.0% and 8.5%, respectively; when the control strategy was not enabled, the unbalance degree decreased slowly. After the coordinated control strategy was enabled, the unbalance degree rapidly reduced to the standard range, and moreover, the reduction speed was higher and the unbalance degree after stability was lower under the control strategy proposed in this study (inverter: 1.5%; PCC port: 1.8%). In conclusion, the unbalanced voltage-based and PSO algorithm-based optimized control strategy can effectively control the stability of the microgrid under the operation mode of the isolated island.

References

[1] Mohamed A., Lamhamdi T., Moussaoui H.E., Markhi H.E., *Intelligent energy management system of a smart microgrid using multiagent systems*, Archives of Electrical Engineering, vol. 69, no. 1, pp. 23–38 (2020).

[2] Selakov A., Bekut D., Sari A.T., *A novel agent-based microgrid optimal control for grid-connected, planned island and emergency island operations*, International Transactions on Electrical Energy Systems, vol. 26, no. 9, pp. 1999–2022 (2016).

[3] Obara S., Sato K., Utsugi Y., *Study on the operation optimization of an isolated island microgrid with renewable energy layout planning*, Energy, vol. 161, no. OCT.15, pp. 1211–1225 (2018).

[4] Zhang T.F., Li X.X., *A Control Strategy for Smooth Switching Between Island Operation Mode and Grid-Connection Operation Mode of Microgrid Containing Photovoltaic Generations*, Power System Technology, vol. 39, pp. 904–910 (2015).

[5] Liang H., Dong Y., Huang Y., Zheng C., Li P., *Modeling of Multiple Master–Slave Control under Island Microgrid and Stability Analysis Based on Control Parameter Configuration*, Energies, vol. 11, no. 9 (2018).

[6] Zhang L., Chen K., Lyu L., Cai G., *Research on the Operation Control Strategy of a Low-Voltage Direct Current Microgrid Based on a Disturbance Observer and Neural Network Adaptive Control Algorithm*, Energies, vol. 12, no. 6 (2019).

[7] Ma Y., Yang P., Guo H., Wang Y., *Dynamic Economic Dispatch and Control of a Stand-alone Microgrid in DongAo Island*, Journal of Electrical Engineering & Technology, vol. 10, no. 4, pp. 1433–1441 (2015).

[8] Worku M., Hassan M., Abido M., *Real Time Energy Management and Control of Renewable Energy based Microgrid in Grid Connected and Island Modes*, Energies, vol. 12, no. 2 (2019).

[9] Xu X., Zhou X., *Control Strategy for Smooth Transfer Between Grid-connected and Island Operation for Micro Grid*, High Voltage Engineering, vol. 44, no. 8, pp. 2754–2760 (2018).

[10] Roque J.A.M., Gonzalez R.O., Rivas J.J.R., Castillo O.C., Caporal R.M., *Design of a New Controller for an Inverter Operation in Transitional Regime Within a Microgrid*, IEEE Latin America Transactions, vol. 14, no. 12, pp. 4724–4732 (2017).

[11] Ma Y., Yang P., Zhao Z., Wang Y., *Optimal Economic Operation of Islanded Microgrid by Using a Modified PSO Algorithm*, Mathematical Problems in Engineering, vol. 2015, pp. 1–10 (2015).

[12] Li P., Xu D., Zhou Z., Lee W., Zhao B., *Stochastic Optimal Operation of Microgrid Based on Chaotic Binary Particle Swarm Optimization*, IEEE Transactions on Smart Grid, vol. 7, no. 1, pp. 66–73 (2016).

[13] Tan Y., Cao Y., Li C., Li Y., Yu L., Zhang Z., Tang S., *Microgrid stochastic economic load dispatch based on two-point estimate method and improved particle swarm optimization*, International Transactions on Electrical Energy Systems, vol. 25, no. 10, pp. 2144–2164 (2015).

[14] Radosavljević J., Jevtić M., Klimenta D., *Energy and operation management of a microgrid using particle swarm optimization*, Engineering Optimization, vol. 48, no. 5, pp. 1–20 (2015).

[15] Maulik A., Das D., *Optimal operation of microgrid using four different optimization techniques*, Sustainable Energy Technologies and Assessments, vol. 21, pp. 100–120 (2017), DOI: 10.1016/j.seta.2017.04.005.