Research Article

Qunmin Yan*, Ruiqing Ma, Juanjuan Zhu, Hang Zhang, and Yujiao Li

Analysis of the overvoltage cooperative control strategy for the small hydropower distribution network

<https://doi.org/10.1515/phys-2020-0107>
received March 30, 2020; accepted May 2, 2020

Keywords: small hydropower, voltage quality, particle swarm algorithm, coordinated control, renewable energy

Abstract: In general, the seasonal characteristics of small hydropower (SHP) especially the power transmission during the summer flood season would lead to the steady overvoltage of the distribution network. In order to suppress this steady overvoltage, a strategy for coordinated cooperation between generator phase-in operation and shunt reactors which can be called cooperative control is proposed. The distribution network of SHP stations connected to the 35 kV Bantao substation in southern Shaanxi is taken as an example to study the mechanism of overvoltage after the SHP is connected to the grid. A distribution network model with SHP units is established. Based on the model, the effect of separately installing shunt reactors on the node voltage is studied in the case of generator lag phase operation and the influence of the operation mode of SHP unit on the node voltage is also analyzed separately. Finally, the improvement measures of cooperative control between the generator phase-in operation and the parallel reactors are analyzed by simulation. Results are presented to verify the improvement measures that can effectively restrain the overvoltage of the distribution network in the SHP area.

1 Introduction

Nowadays, thousands of small dams have been built around the world. They were used to control floods, store water, and improve river navigation. At present, some of these dams have gained a new feature: they are ready to promote the revival of providing small-scale local hydropower. Flowing water will drive turbines to produce clean electricity. Although small hydropower (SHP) is unlikely to produce most of the world's renewable energy supply, it can make the grid more flexible and resilient [1–3]. China is a country with relatively abundant water resources in the world [4–6]. In response to resource shortages and increasingly serious environmental problems, SHP has been supported and developed by the state as a renewable and clean energy source. The SHP system is shown in Figure 1. On the run-of-river bed, the high-level water is guided to the low-position water turbine through the water inlet pipe, and the water flow drives the turbine's rotating wheel to rotate, so that the water kinetic energy is converted into rotating mechanical energy. The turbine drives the coaxial generator rotor to cut the magnetic lines of force and generates an induced electromotive force on the stator winding of the generator. When the stator winding is connected to the external circuit, the generator is powered out through the transmission line.

The 28 SHP stations in a certain area of southern Shaanxi are connected to the main power grid through 35 kV transmission lines. Figure 2 shows the voltage distribution of the 35 kV bus of 28 SHP stations during the summer flood season. The blue column shows the maximum voltage, which is small load of summer operation. The purple column shows the minimum voltage, which is heavy load of summer operation. From the data of Figure 2, it can be seen that in the case of small load in summer, the 35 kV bus voltage of all substations has a

* **Corresponding author: Qunmin Yan**, Department of Electrical Engineering, School of Automation, Northwestern Polytechnical University, Xi'an 710072, China; Shaanxi Key Laboratory of Industrial Automation, Shaanxi University of Technology, Hanzhong 723000, China, e-mail: yanqunm@163.com

Ruiqing Ma: Department of Electrical Engineering, School of Automation, Northwestern Polytechnical University, Xi'an 710072, China, e-mail: marq@nwpu.edu.cn

Juanjuan Zhu: Department of Electrical Engineering, School of Electrical Engineering, Shaanxi University of Technology, Hanzhong 723000, China, e-mail: Zhujuanjuan@snut.edu.cn

Hang Zhang: Department of Electrical Engineering, School of Electrical Engineering, Shaanxi University of Technology, Hanzhong 723000, China, e-mail: hangzai6290@163.com

Yujiao Li: Department of Electrical Engineering, School of Electrical Engineering, Shaanxi University of Technology, Hanzhong 723000, China, e-mail: aza006@126.com

Figure 1: Schematic diagram of an SHP system.

severe upper limit. In the summer heavy load operation, the 35 kV bus voltage also has the overvoltage problem.

The voltage quality problem in the SHP distribution network system has always been a part of the distribution network system. If the voltage is too high, it will affect the safe operation of the power equipment, and it will easily lead to the unreasonable distribution of the power flow, resulting in the decline of the economic level of the entire power grid [7]. At present, many scholars have proposed many voltage regulation measures for distribution networks for SHP access, especially for the problem that exceeds the limit of the distribution voltage when the SHP is in the full power state in summer. In ref. [8,9], measures such as changing line parameters, adjusting transformer ratio, changing generator terminal voltage, generator phase-in operation, and accessing parallel reactive power compensation device were pointed out. The three stages of voltage regulation of the generator's phase-in operation, the installation of shunt reactors and the modification of transformer taps were analyzed, and a comparative analysis of the effects of voltage regulation was carried out in ref. [10,11]. In ref. [11,12], the voltage is the constraint condition, the active loss is the objective function, and the original dual interior point method is used to optimize the voltage of the SHP distribution network. In ref. [13,14], a reactive power compensation scheme with comprehensive sensitivity and the reactive power compensation point selection method to maximize the voltage quality were proposed. A sensitivity method was adopted to analyze the configuration scheme of reactive power optimization, and the scheme was verified through economic evaluation indicators in ref. [15,16]. Yang [17] proposed a comprehensive control scheme of reactive power control, voltage control, decentralized control, and centralized control to improve the voltage quality of the distribution network connected to SHP. In ref. [18,19], the overvoltage of the SHP isolated network, the power supply, and the region entering the flood season were theoretically analyzed. Ma *et al.* [20] proposed the

application of series capacitor compensation technology to solve the problem of voltage failure by analyzing the series compensation principle. Shi [21] presented a method for calculating the optimal acceptance capacity of runoff SHP considering that the adaptive reactive power control is proposed for the problem of overvoltage limit of access point. The distribution network with SHP is prone to high load voltage during the flood period, and a comprehensive solution for increasing the cross-sectional area of the conductor and transforming some overhead conductors into a three-core overhead cable was proposed in ref. [22]. At present, there are two types of solutions for the study of the voltage limit of distribution networks with SHP. One is to limit the voltage limit by optimizing the access position of the SHP unit, accessing capacity, predicting the output of the SHP group, and the reactive power of the distribution network. The other type uses voltage regulation devices and employs different control strategies to regulate the system voltage to meet voltage limits. These measures and methods have a single adjustment feature, lack flexibility and real time, and require a large amount of communication resources. In addition, some SHP stations are characterized by poor mountain environment, frequent natural disasters, and variable climate, which may lead to communication failures and may cause the existing voltage regulation measures to lose their function. At the same time, a large number of voltage-regulating devices and reactive power compensation devices are used, which are characterized by complicated operation and poor economy.

This article mainly studies the long-term steady-state overvoltage of the SHP distribution network during the summer flood season. In order to suppress this steady-state overvoltage, this article proposes a cooperative control strategy for generator phase-in operation and shunt reactor. The strategy aims at minimizing the node voltage offset in the distribution network, which not only improves the operation performance of the SHP unit itself but also achieves local control, reduces the input capacity of the reactive power system of the distribution network system, and improves the economics of the power system. This article takes the five SHP stations distribution network system models connected to the 35 kV Bantao Substation in southern Shaanxi as an example for verification and analysis. The rest part of the article is organized as follows. In Section 2, the influence of SHP access on the distribution network voltage is analyzed. In Section 3, an overview of the distribution network system containing SHP groups in the study is given. In Section 4, a distribution network model with SHP groups is established. In Section 5, the overvoltage suppression method is analyzed, the coordinated control strategy is proposed, and the algorithm for solving the model is given. In Section 6, the

Figure 2: Distribution of 35 kV bus voltage in the 28 SHP stations during summer flood season.

simulation results of the overvoltage suppression method are given and compared. In Section 7, some conclusions are given.

2 Impact of SHP access to the distribution network on voltage

It can be seen from Figure 3 that the voltage of node 1 before the voltage is not connected to the SHP is as follows:

$$V_l = V_0 - \sum_{k=1}^l \frac{\sum_{n=k}^N P_n R_k + \sum_{n=k}^N Q_n X_k}{V_{k-1}}. \quad (1)$$

It can be seen from the above equation that the node voltage varies with the transmission power of the line. From the theory of power system tidal current distribution, load power is the main cause of changes in line transmission power. Assume that the access location of the SHP is node 1, and the access capacity is $PDG + jQDG$. The node voltage after the SHP access can be derived by equation (1):

$$V_l = V_0 - \sum_{k=1}^l \frac{(\sum_{n=k}^N P_n - P_{DG})R_k + (\sum_{n=k}^N Q_n - Q_{DG})X_k}{V_{k-1}}. \quad (2)$$

Figure 3: Distribution chain model.

It can be known from equation (2) that the node voltage and the line transmission power change after the SHP are connected. Before the SHP is connected, the voltage distribution is generally reduced according to the tidal current distribution on the feeder. After the SHP is connected, the transmission power on the original power line will decrease, which will cause the voltage of each node to increase to different degrees. The static model of the load has the following three types: constant power, constant current, and constant impedance. The nature of the load is inductive power and capacitive power. Excessive inductive power will cause a voltage drop, and excessive capacitive power will cause a high voltage. The load model studied in this article is the inductive power at constant power. When the access capacity is greater than the power of the load point, the load cannot be absorbed locally, and the excess power will flow to the head end V_0 of the distribution network, causing the voltage of each node along the line to increase. When the power is increased by a certain value, some or all of the node voltages will be severely exceeded.

3 Overview of the distribution network with SHP centralized access

The distribution network of SHP stations connected to the 35 kV Ban Tao substation in southern Shaanxi is taken as an example. PSASP software was used to establish a system simulation model shown in Figure 4. The rated power of Xinyaping Power Station is 2.5 MW,

Figure 4: Electrical connection diagram of the regional distribution network of Bantao substation.

the rated power of Wuxinqiao Power Station is 5 MW, the rated power of Niujiangxiang Power Station is 2 MW, the rated power of Bantao Power Station is 3.2 MW, and the rated power of Jieling Power Station is 3.5 MW. The 35 kV Bantao substation is connected to the large power grid through the 110 kV Jiangnan substation. The line parameter model from node 1 to node 7 and node 2 to node 3 is LGJ-95, and the line parameter model between the remaining nodes is LGJ-120. After each SHP generator is connected to the grid, each generator will not only be able to meet the load requirements of the appendix at the Bantao substation but will also send the remaining power to the Jiangnan substation. From the aforementioned reasons, it is known that this will cause the operating range of the voltage to exceed the voltage requirement for safe operation. The voltage of nodes 1, 2, 3, 4, 5, and 6 is taken as the research object, and node 2 is the split bus node of node 1.

The data of active, reactive, and impedance of each line in each power station are given in Tables 1 and 2. The active load of the Bantao Substation under the small load of summer mode operation of the hydropower station is 0.28 MW, and the reactive load is $0.09 M_{\text{var}}$. Table 3 shows the voltage statistics of major monitoring points in the distribution network during the summer flood season.

During the flood season in summer, the direction of the tide changes, and the power is inverted by the distribution network to the system. For the five SHP stations in the above system in southern Shaanxi, the 35 kV Bantao substation is connected nearby. Normally, as the load is low and scattered in the mountainous areas, the SHP units deliver power to the large grid. Considering the loss of voltage drop in the power grid, the voltage at the beginning of the 35 kV line is 5% higher than the rated voltage, which is 36.75 kV. This will keep the voltage at

the end of the 35 kV line near the rated voltage. In the actual operation of SHP units, the power factor is about 0.95, which is in excessively lag phase operation. The load is smaller than the power generation of the SHP group. The extra power will be fed to the large power grid, which will lead to a long line of power flow. According to the above formula, the longer the power flows through the line and the more the power transmitted, the more the voltage drop. At this time, to meet the power balance requirement, the 35 kV bus voltage will increase up to the voltage of the distribution line network point increases. This will affect the user's electrical appliances and it may also burn out the equipment, seriously affecting the voltage quality. It can be seen from Table 3 that the bus voltage of each node is above 40 kV during the heavy load of summer flood season, and the node voltage is above 39 kV in the small load of summer mode. The bus voltage of the Dengxinqiao Power Station even reached 43 kV during the summer heavy load mode operation, which seriously exceeded the national standard for power quality. In order to reduce the impact of overvoltage on the power supply equipment and electrical equipment, it is necessary to adopt the corresponding solutions to improve the voltage quality of the Bantao substation in southern Shaanxi.

4 Distribution network planning model with the SHP group

4.1 Objective function

The radial SHP unit is connected to the main line via a dedicated line or a dispersed “T”. During the summer

Table 1: Power plant output data

Power station name	Active contribution/ M_w	Reactive power/ $M_{var.}$
Niujingxiang Power Station	1.95	0.64
Dengxinqiao Power Station	3.33	1.09
Jieling Power Station	3.68	1.21
Bantao Power Station	3.89	0.95
Xinyaping Hydropower Station	2.23	0.78

flood season, the local load cannot absorb the generated power *in situ*, which leads to the change in the power flow to the substation bus and the access line node connected to the main network and the SHP cluster. At the same time, the SHP feed-in tariff is lower, and a large number of access points to SHP can reduce the operating cost of the distribution network. Therefore, the voltage offset and active power loss are selected as important indicators for the actual operation of the distribution network, and the minimum voltage offset index is used as the SHP connection. The minimum voltage offset index is also regarded as the measurement standards of voltage quality in the distribution network.

4.2 Minimum voltage offset

A large number of SHP stations are connected at the end of the trunk line and branch line of the distribution network, and then the power is transferred to the nearest substation bus. Due to the difference in the capacity and location of each SHP, the voltages at the busbar and the nodes along the line are also different. Therefore, whether the node voltage is qualified is one of the important indicators for testing the safety and power quality of the system. In this article, while reducing the bus voltage at the point of entry, we strive to keep the voltage of each node in the whole line at a reasonable level, so as to control the global voltage of the distribution network. The minimum voltage offset can be expressed as:

Table 2: Line impedance between two nodes

Line number between two nodes	Resistance/ Ω	Reactance/ Ω
67	2.0763	3.299
57	0.0891	0.1416
24	1.647	2.6169
23	1.1715	1.5265
17	2.7243	3.299

$$\min f_1 = \Delta U = \sum_{i=1}^N \left(\frac{u_i - u_{iN}}{u_{i \max} - u_{i \min}} \right), \quad (3)$$

where u_i is the actual voltage amplitude of the node, u_{iN} is the amplitude of the rated operating voltage of the node, $u_{i \max}$ and $u_{i \min}$ are the maximum allowable value and the minimum allowable value of each voltage at the node i , respectively, and N is the number of nodes of the distribution network system.

4.3 Minimum active power loss

A large number of access points to runoff SHP will inevitably affect the distribution of power flow in the distribution network. In addition, the lack of management of SHP will affect the network loss of the entire distribution network system. The minimum active power loss of the distribution network can be expressed as:

$$\min f_2 = P_{\text{loss}} = \sum_{i=1}^N R_i \frac{P_i^2 + Q_i^2}{|V_i|^2}, \quad (4)$$

where P_{loss} is the active power loss of the distribution network; N is the number of branches of the distribution network; R_i , P_i , Q_i , and V_i are the branch resistance, active power, reactive power, and node voltage amplitude, respectively.

Table 3: Main monitoring point voltage statistics during the summer flood season

35 kV SHP bus voltage monitoring point	Maximum voltage/kV	Minimum voltage/kV
Bantao Substation	40.92	39.14
Jieling Power Station	42.10	40.51
Xinyaping Hydropower Station	42.67	40.44
Bantao Power Station	42.43	40.77
Niujingxiang Power Station	42.25	40.31
Dengxinqiao Power Station	43.17	41.81

4.4 Constraints

4.4.1 Equality constraints

For distribution networks with SHP groups, the power constraints are as follows:

$$\begin{cases} P_S + \sum_{i=1}^n P_{Gi} = P_{\text{loss}} + P_{\text{load}} \\ Q_S + \sum_{i=1}^n Q_{Gi} = Q_{\text{loss}} + Q_{\text{load}}, \end{cases} \quad (5)$$

where P_S , Q_S are the injection power of the system balance node; P_{Gi} , Q_{Gi} are the power injected by the i th SHP unit in the system; P_{loss} , Q_{loss} are the total network loss of the system; and P_{load} , Q_{load} are the total load of the system.

The node power flow constraints in the SHP group distribution network are as follows:

$$\begin{cases} P_i = V_i \sum_{j=1}^N V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ Q_i = V_i \sum_{j=1}^N V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}), \end{cases} \quad (6)$$

where P_i and Q_i are the inject active power and the reactive power at node i ; G_{ij} is the conductance between nodes i and j ; B_{ij} is the susceptance between nodes i and j ; θ_{ij} is between nodes i and j voltage phase angle difference; and N is the number of nodes.

4.4.2 Inequality constraints

The transmission power of each branch line shall meet:

$$P_{p.b.} \leq P_{p.b. \max}, \quad (7)$$

where $P_{p.b. \max}$ is the active power and transmission power limit of the branch in the distribution network, which shall meet all SHP units in the distribution network system:

$$\begin{cases} P_{H,j \min} \leq P_{H,j} \leq P_{H,j \max} \\ Q_{H,j \min} \leq Q_{H,j} \leq Q_{H,j \max}, \end{cases} \quad (8)$$

where $P_{H,j}$ is the actual value of the active power of the i th SHP unit, and $Q_{H,j}$ is the actual value of the reactive power of the i th SHP unit.

The power factor for all SHP units and access substations should meet:

$$\begin{cases} \cos \phi_{G \min} \leq \cos \phi_G \\ \cos \theta_{S \min} \leq \cos \theta_S, \end{cases} \quad (9)$$

where $\cos \phi_G$ is the power factor of the SHP unit operating in various states, and $\cos \theta_S$ is the total station power factor of the substation operation.

For distribution networks with SHP groups, to give full play to the operational capabilities of SHP units, while considering economics, the reactive constraints of the entire distribution network are as follows:

$$Q_{Ci}^{\min} \leq Q_{Ci} \leq Q_{Ci}^{\max}, \quad i = 1, \dots, N_c, \quad (10)$$

where $Q_c^{\max}$ and $Q_c^{\min}$ are the upper and lower limits of the reactive capacity of the reactive reactor, and N_c is the number of reactive reactors.

5 Analysis of the control strategy

In order to improve the voltage quality of the distribution network, methods such as changing the voltage of the generator terminal, the transformer tap, the line parameters, and reactive power compensation are often used in the power system. This article focuses on the effect of SHP grid connected to bus voltage during the summer flood season in southern Shaanxi and takes into account that the remaining node voltage is at the qualified level. SHP feeds into the power grid, and the generator terminal voltage does not change when it is connected to the large power grid. For the purpose of this article, the voltage regulator is not used to change the transformer tap, mainly based on the following two reasons.

- (1) The reactive power consumed by the transformer is reduced before adjusting the tap changer, which further increases the grid voltage. In the case of insufficient reactive power, by changing the tap of the transformer to increase the voltage, the reactive power consumed by the transformer will increase, which expands the reactive power shortage in this area and causes the system voltage level to drop further.
- (2) The operation of SHP is independent. In the simulation study of this article, the voltage of the 35 kV bus can be reduced by changing the on-load voltage regulator at the overvoltage side of the 110 kV Jiangnan substation. However, the transformer of the 35 kV Bantao substation does not have a load adjustment function and cannot carry voltage adjustment with load. Therefore, the Bantao substation cannot use the adjusting transformer tap to adjust the pressure.

By equation (1), the formula for voltage drop is written as:

$$\Delta U = (Lr_0P + Lx_0Q)/U_N, \quad (11)$$

where L is the line length, r_0 is the line unit resistance, and x_0 is the line unit reactance. Changing the line parameters can achieve the effect of reducing the voltage drop. In this article, all line parameter models are changed to LGJ-120, but the effect of voltage drop is not very obvious. This is because the changed line is short and the impedance change is small. In particular, the reactive power of the power grid system is sufficient, resulting in the change in the line parameters to reduce the voltage and cannot achieve the desired results, and the replacement of a larger area of the wire means the material consumption and cost. With the increase, it is necessary to replace the wires after the power outage in the regional power grids, resulting in poor operability and economy. Therefore, this article uses the combination of reactive power compensation and phase-in operation of hydropower units to solve the problem of overvoltage. In Figure 5, different power factors have different effects on the voltage. The higher the power factor, the lower the node voltage. Conversely, the node is higher.

5.1 Generator phase-in operation analysis

In Figure 5, V_1 is the voltage of the large grid terminal, V_2 is the voltage of the load terminal, and the power generated by the generator is $P_2 + jQ_2$, which flows to the busbar V_2 . At this time, the operation mode of the generator is the lag phase operation. V_2 can be obtained as shown in the following equation:

$$V_2 = V_1 - \frac{(P_1 - P_2)R + (Q_1 - Q_2)X}{V_1}. \quad (12)$$

It can be seen from the aforementioned formula that the flow direction of the reactive power of the generator also directly affects the voltage of the node V_2 . In order to control the corresponding node voltage, the generator can be operated in the phase-in phase by changing the operation mode of the generator. At this time, the generator is a reactive load, and the reactive power Q_2 is opposite to the direction in which the generator is running in the lag phase. The generator absorbs the reactive power from the system and changes to $-Q_2$. Equation (12) becomes equation (13):

$$V_2 = V_1 - \frac{(P_1 - P_2)R + (Q_1 + Q_2)X}{V_1}. \quad (13)$$

It can be seen from equations (12) and (13) that the phase-in operation of the generator can reduce the voltage at the V_2 node. Therefore, the generator phase-in

Figure 5: Schematic diagram of the distribution network with generator.

operation can effectively suppress the grid voltage high problem. In addition, the phase adjustment of the generator does not require additional investment costs and saves costs.

5.2 Analysis of operation method of the shunt reactor

The shunt reactor absorbs capacity charging power in the power grid, which can improve the problem of overvoltage in the power grid system and improve the voltage stability. The shunt reactor installation location studied in this article is the primary side bus of the substation, which is the bus side of node 1. The compensation capacity is controlled by the number of shunt reactors to further adjust the voltage. The compensation capacity of the shunt reactor can be calculated by using Figure 6 to determine the compensation capacity. A simple power system is shown in Figure 6.

From Figure 6, there is the voltage after setting the compensation device:

$$U_i^2 = \left[U_{jc} + \frac{P_i r_{ij} + (Q_j - Q_c) x_{ij}}{U_{jc}} \right]^2 + \left[\frac{P_i x_{ij} - (Q_j - Q_c) r_{ij}}{U_{jc}} \right]^2. \quad (14)$$

In equation (14), after setting the compensation device, the voltage on the low voltage side bus of the substation to the overvoltage side is U_{jc} . From the above formula, the following equation can be obtained:

Figure 6: Simple system with parallel compensation devices.

$$\frac{Z_{ij}^2}{U_{jc}^2} Q_c^2 - 2 \left(\frac{Z_{ij}^2}{U_{jc}^2} + x_{ij} \right) + \left[U_{jc}^2 - U_i^2 + 2(P_j r_{ij} + Q_j x_{ij}) + \frac{Z_{ij}^2}{U_{jc}^2} (P_j^2 + Q_j^2) \right] = 0. \quad (15)$$

If the supply voltage U_i is known and the required U_{jc} is given, then all parameters and variables except those in equation (15) Q_c are known and can be solved. If the solved Q_c is positive, it means that the compensation device should supply inductive reactive power; otherwise, it should draw inductive reactive power.

Although the aforementioned formula is accurate, it is rarely used in practice. Instead, another simplified calculation is commonly used. The derivation process is as follows: when calculating the voltage drop of the power transmission system shown in Figure 6, the lateral component may be omitted, before setting the compensation equipment:

$$U_i = U_j + \frac{P_i r_{ij} + Q_i x_{ij}}{U_j}, \quad (16)$$

where U_j is the substation low voltage bus voltage that is calculated to the overvoltage side before setting compensation equipment. After setting the compensation device:

$$U_i = U_{jc} + \frac{P_j r_{ij} + (Q_i - Q_c) x_{ij}}{U_{jc}}. \quad (17)$$

In both (16) and (17), U_i will remain unchanged. By the above two equations, the following equation can be obtained:

$$U_j + \frac{P_i r_{ij} + Q_i x_{ij}}{U_j} = U_{jc} + \frac{P_j r_{ij} + (Q_i - Q_c) x_{ij}}{U_{jc}}. \quad (18)$$

From above, Q_c can be solved:

$$Q_c = \frac{U_{jc}}{x_{ij}} \left[(U_{jc} - U_j) + \left(\frac{P_j r_{ij} + Q_j x_{ij}}{U_{jc}} - \frac{P_j r_{ij} + Q_j x_{ij}}{U_j} \right) \right]. \quad (19)$$

The second part of square brackets in the formula is generally small and can be omitted. Thus, the aforementioned formula can be changed to:

$$Q_c = \frac{U_{jc}}{x_{ij}} (U_{jc} - U_j). \quad (20)$$

For more complex networks, $Z_{ij} = r_{ij} + jx_{ij}$ in the aforementioned equation is the equivalent impedance between the power supply and the node of the installation compensation device.

5.3 Cooperative control method and model solving

It can be seen from the above analysis that the generator can inhibit the voltage limit of the distribution network node under both the phase-in operation and the independent parallel reactor. Therefore, this study proposes a strategy for coordinated operation of generator phase-in operation and shunt reactor. The overall idea of the strategy is that when the key node of the distribution network or the substation bus voltage of the substation exceeds the limit, the generator farther from the busbar or trunk will run in the phase-in to control the voltage reduction of the busbar in the range. At this time, if part of the node voltage or the bus voltage is still limited, the shunt reactor that inputs the corresponding capacity is started. The input of the shunt reactor is also put into operation from the far side of the busbar or the trunk line and finally reaches the voltage requirement set by the objective function. The model solving process uses particle swarm optimization algorithm (PSO), which is inspired by Kennedy and Eberhart's results from artificial life research. A global random search algorithm based on swarm intelligence is proposed by simulating migration and clustering behavior during the foraging of birds. The main idea of the PSO algorithm is to initialize a group of random particles (random solutions) and then find the optimal solution through iteration. In each iteration, the particle updates itself by tracking two extremums; the first is the optimal solution found by the particle itself, this solution is called the individual extremum; the other extremum is the optimal currently found for the entire population [23–27]. Solution to this extreme value is the global extremum.

In this article, the phase depth X ($X_1, X_2, X_3, \dots$) of each generator included in the system and the dispersive access capacity Y ($Y_1, Y_2, Y_3, \dots$) of the shunt reactor in the system are selected as the main variables. The algorithm flow is as follows.

- (1) Input the original distribution network data information, set the initialization parameters of the X and Y populations such as population size N , inertia weight ω , learning factor c , iteration number $t_{\max}$, particle maximum velocity $V_{\max}$, and the maximum iteration number $T_{\max}$, thus random particles X, Y are generated under constraints.
- (2) Initialize particle swarm X , call the power flow calculation program to calculate the fitness value of each particle X , and update the particle's speed and position. If no better particle X is found for

successive $t_{\max}$ iterations, the PSO algorithm considers the current particle X to be the global optimal solution. Otherwise, the particles are updated and a new iteration is performed until the maximum number of iterations $t_{\max}$ is met.

- (3) Optimize particle Y . Based on the determination of the position variable X , the variable Y is optimized using the PSO algorithm, and the process is similar to step (2).
- (4) Update the iteration counter T . It is judged whether or not the current (X, Y) is optimal according to the adaptive value of particle Y at the end of step (3). Otherwise, the particles are updated and a new iteration is performed until the maximum number of iterations $t_{\max}$ is met.
- (5) Output optimal solution. That is, (X, Y) at the end of the iteration.

6 Simulation results

6.1 Simulation of operation mode of SHP unit

When the SHP unit is operating in practice, to improve their own economic benefits, SHP units usually have a power factor of 0.95. Therefore, this study simulates the influence of power factors of all SHP units on the voltage quality of distribution network in the 35 kV Bantao Substation area when they are in lead and lag under seven different power factors and in unit power factor.

- (1) All hydropower units of the five power stations are in a lag-phase operation, and the distribution of node

Figure 7: Node voltage distribution when different power factors are delayed.

voltages in the case of seven different power factors is shown in Figure 7.

It is known from Figure 7 that when all hydropower units are in the lag phase operation state, all node voltages are almost maintained above 40 kV under seven different power factors. As the power factor decreases, the bus voltage will be higher due to the supporting effect of reactive power on the voltage. From node 1 to node 5, the voltage change in the node is relatively flat. However, node 6 varies greatly. Node 6 is far away from the bus line of the 35 kV Bantao substation, and the impedance is large, so the voltage drop is large.

- (2) Adjust the excitation system of the generator, change the operation mode of the generator, and make the hydropower units of Niujiangxiang and Xinyaping power stations in the phase-in operation state. The power factor is also from seven operating modes from 0.8 to 0.98. The remaining power factor of the hydropower station is 0.95, and the voltage distribution curve of the node is shown in Figure 8.

It is known from Figure 8 that when the Niujiangxiang and Xinyaping hydropower units are in the phase-in operation state, the node voltage is lower than that of the lagging power factor. As the depth of the phase-in, the node voltage becomes lower and lower. Voltage change at node 6 is inconsistent with the rest of the nodes. First, the line long node voltage deviation is large. Second, since the bus of node 6 is powered by the Niujiangxiang power station, the voltage of node 6 is greatly affected when the power factor is advanced. When the power factor is higher than 0.92, the voltage of node 6 is higher than that of node 5. When it is lower than 0.92, the voltage of node 6 is lower than the voltage

Figure 8: Node voltage distribution during phase-in operation of two power stations.

Figure 9: Node voltage distribution curve with power factor 1.

of node 5, and the voltage drop formula is known. The voltage is related to the change in power. As the depth of phase-in increases, the more reactive power is absorbed by the generator, the greater the voltage drop.

- (3) The generator power factor is equal to 1, that is, the excitation system of the generator is adjusted so that the voltage distribution curve is obtained when the reactive power output is 0, as shown in Figure 9.

As can be seen from Figure 9, the 35 kV bus voltage in the Ban Tao substation area has dropped, and the node voltage level has dropped from 41 kV to about 38 kV, but it still cannot meet the voltage quality stipulated by national standards. This is because the excess reactive power of the large power grid causes the voltage of the spot peach substation to increase, and the SHP will transmit power to the grid during the summer wet season, which will cause an increase in the bus voltage of the SHP unit group that is connected to the Bantao Substation.

6.2 Parallel reactor suppresses overvoltage simulation

Through simulation analysis and calculation, when the shunt reactor compensation is performed, the node voltage can be effectively suppressed. The compensation capacity and the node operating voltage are shown in Figure 10.

It can be seen from Figure 10 that the 35 kV bus voltage drops after the shunt reactor is put into operation. As the compensation capacity increases, the node voltage also drops. Therefore, the compensation capacity of the shunt reactor can effectively reduce the over voltage caused by the excess power in the power

Figure 10: Node voltage distribution after compensation by the shunt reactor.

grid. The larger the compensation capacity, the more obvious the voltage drop.

6.3 Simulation analysis under collaborative control

6.3.1 Simulation under coordinated control

In order to verify the collaborative control strategy proposed in this article, the distribution network of Figure 4 is still taken as an example. Node 1 is the substation bus voltage, and the remaining nodes are the SHP step-up transformer bus voltage. Since there are fewer nodes in this example, the shunt reactors are connected in parallel to the 35 kV bus of the substation in the form of centralized compensation. Assuming that the bus voltage of the substation is 35 kV rated voltage, the PSASP simulation software is used to verify the traditional voltage regulation mode and the coordinated operation mode of the shunt reactor. The results are shown in Tables 4 and 5. In the case where the power factor is positive, the generator is in the late-phase operation, and the negative value indicates that the generator is in the phase-in operation.

It can be seen from Table 4 that the SHP units all operate with a power factor of 0.95. If the voltage of all nodes is to be controlled at a reasonable level, the reactive capacity of the shunt reactor needs to be $9.93 M_{var}$. Table 5 shows the simulation results of the three coordinated modes of operation. Mode 1 is that two SHP units farthest from the bus run at their maximum in-phase depth, and the remaining SHP units are in a delayed phase. At this time, to control the voltage of

Table 4: Simulation results in the traditional operation mode

Power station name	$\cos \varphi$	Node number	Node voltage/kV	Shunt reactor compensation capacity/ M_{var}
Niujingxiang Power Station	0.95	2	35	9.93
Dengxinqiao Power Station	0.95	3	35.12	
Xinpingya Power Station	0.95	4	35.36	
Jieling Power Station	0.95	5	35.44	
Bantao Power Station	0.95	6	35.99	

each node to a certain level, the reactive capacity of the shunt reactor to be input is $8.77 M_{\text{var}}$. Mode 2 is based on mode 1, according to the principle of far and near from the bus, and then add an SHP unit to run at the maximum phase-in depth. In order to control the voltage of the bus and each node, the reactive capacity of the shunt reactor is $4.06 M_{\text{var}}$. Mode 3 is that five SHP units of the power station operate in the phase depth range, and all the node voltages of the shunt reactors are not required to be qualified. In summary, it can be seen that both the traditional operation mode and the coordinated operation mode can suppress the node overvoltage. However, the coordinated operation can control not only the bus voltage well but also the voltage of all nodes to be qualified. At the same time, it reduces the input capacity of the shunt reactor and the complexity of control and improves the economic efficiency of the grid. The trend from the simulated curve can reflect that the capacity of the shunt reactor gradually decreases as the coordinated operation control mode increases. Especially in this example, because the distribution network has a simple structure and fewer nodes, when the SHP

units are all in phase operation, the purpose of suppressing overvoltage can be achieved without installing a shunt reactor.

6.3.2 Application extension of cooperative control results

As SHP is located in the mountainous area, the location of the substation is remote. It is relatively difficult to install a certain number of shunt reactors, and switching or maintenance is not very convenient. When shunt reactors are installed in substations, the greater the reactive power flowing in the grid, the greater the line loss. If the main transformer of the substation fails, the operation of the shunt reactor connected to it will be limited and it will not be able to achieve the effect of regulating the voltage, which will also seriously threaten the quality of the bus voltage affecting the system. Based on the above analysis, the cooperation of the shunt reactor and the phase-in operation of the generator can effectively solve the above situation. In the actual

Table 5: Simulation results under coordinated operation mode

Operation mode	Power station name	Node number	Shunt reactor compensation capacity/ M_{var}	$\cos \phi$	Node voltage/kV
Coordinated operation mode 1	Niujingxiang	2	8.77	-0.97	35
	Dengxinqiao	3		-0.95	35.11
	Xinpingya	4		0.95	35.15
	Jieling	5		0.95	35.22
	Bantao	6		0.95	35.2
Coordinated operation mode 2	Niujingxiang	2	4.06	-0.97	35
	Dengxinqiao	3		-0.95	35
	Xinpingya	4		0.95	35.16
	Jieling	5		0.95	35
	Bantao	6		-0.95	34.97
Coordinated operation mode 3	Niujingxiang	2	0	-0.97	35.08
	Dengxinqiao	3		-0.95	35.08
	Xinpingya	4		-0.96	35.05
	Jieling	5		-0.95	35.07
	Bantao	6		-0.95	35.05

Figure 11: Node voltage distribution after different compensation capacity and generator phase-in operations.

distribution network operation process, due to the difference in the phase-in capability of SHP units, the power system generally pays more attention to the variation in the bus voltage. Therefore, taking the actual power grid structure of Figure 4 as an example, when simulating the continuous control of the distribution bus voltage of the distribution network containing SHP groups in a range, moderately control the phase range of the unit and obtain the compensation capacity value of the continuous shunt reactor. In the simulation, the Niujiangxiang power station and the Xipingya power station are set to phase-in operation, and the lead power factor is 0.8–0.95. When the other power stations are running in phase, the power factor is 0.95; the compensation capacity of the shunt reactor is from 1 to 4 M_{var} . Get the node operating voltage as shown in Figure 11.

It can be seen from Figure 11 that after the generator phase-in operation and the shunt reactor compensation work together, the node voltage of the bus decreases. Compared with Figure 10, the compensation capacity of the shunt reactor is reduced and the effect of the voltage drop is more pronounced. Therefore, when the actual system is running, the phase depth of the suitable SHP unit can be determined according to the voltage required by the busbar, and the capacity of the shunt reactor to be input is finally determined. With the depth of the phase-in, the node voltage is getting lower and lower. Due to the small compensation capacity of the shunt reactor, the number of shunt reactors to be installed will also be reduced. At the same time, the generator does not require additional investment costs for phase-in operation, and the overall economic benefits will also increase significantly.

7 Conclusion

This article analyzes the overvoltage mechanism of a distribution network containing SHP groups under reverse power conditions. Several different methods of overvoltage suppression are studied by simulation. The control strategy of coordinated operation of shunt reactor and hydropower unit is proposed. The distribution network of an SHP group in southern Shaanxi is taken as an example for experimental analysis. Upon comparing the traditional method of using a shunt reactor alone with the coordinated operation control method, it can be seen from the simulation results that when the substation bus voltage is 35 kV, the coordinated operation mode 1 can reduce the reactive power capacity of the system by 11.68% and the voltage of node 6 has an inhibition rate of 2.2% within the acceptable range. The coordinated operation mode 2 can reduce the reactive power capacity of the system by 59.1%, and the voltage of node 6 can reach 2.8% within the qualified range. Due to the small-scale capacity of the system, coordinated operation mode 3 system does not need to input reactive power, all node voltages are qualified. It can be seen from the above analysis that the coordinated operation control strategy can control not only the voltage quality of substation bus with SHP centralized access but also the voltage quality of all hydropower unit step-up transformers. The node voltage plays a global control role and also reduces the input capacity of the reactive power equipment of the power system. The simulation results show the effectiveness of the coordinated operation control strategy.

Acknowledgments: The authors admit to using the PSASP program developed by the China Academy of Electric Power Sciences.

Conflict of interest: The authors declare no conflict of interest.

Funding: This research was funded by the Shaanxi Provincial Education Department (program no. 20JS018).

Author contributions: Conceptualization, Y. M.; methodology, M. Q.; software, Z. H. and L. J.; and validation, Z. J.

References

- [1] Smalley E. Water power to the people. *Nat Energy*. 2016;92:1–4.
- [2] Zhang J, Luo CY, Curtis Z, Deng SH, Wu Y, Li YW. Carbon dioxide emission accounting for small hydropower plants – a case study in

- southwest China. *Renewable Sustainable Energy Rev.* 2015;47:755–61.
- [3] Lopes VS, Borges CLT. Impact of the combined integration of wind generation and small hydropower plants on the system reliability. *IEEE Trans Sustainable Energy.* 2015;6(3):1169–77.
 - [4] Borkowski D, Węgiel T. Small hydropower plant with integrated turbine-generators working at variable speed. *IEEE Trans Energy Convers.* 2013;28(2):452–9.
 - [5] Kong Y, Wang J, Kong Z, Song F, Liu Z, Wei C. Small hydropower in China: the survey and sustainable future. *Renewable Sustainable Energy Rev.* 2015;48:425–33.
 - [6] Liu X, Ming Z, Xu H, Peng LL, Deng JR. Small hydropower financing in China: external environment analyses, financing modes and problems with solutions. *Renewable Sustainable Energy Rev.* 2015;48:813–24.
 - [7] Xu ZD, Sun GC, Pan BR, Xu N, Li CQ, Ma HZ. An equivalent modeling for synthesis load of distributed network with small hydropower. *Appl Mech Mater.* 2014;666:119–24.
 - [8] He Z, Huang D, Zhang C, Wang B, Ma Z. Evaluation research of the influence of small hydropower station for fuel project on social development impact. *Computer and Computing Technologies in Agriculture VIII.* Springer International Publishing; 2014.
 - [9] Kowalczykjuško A, Mazur A, Grzywna A, Listosz A, Rybicki R, Pytko A, et al. Evaluation of the possibilities of using water-damming devices on the Tyśmienica River to build small hydropower plants. *J Water Land Dev.* 2017;35(1):113–9.
 - [10] Zhou S, Zhang X, Liu J. The trend of small hydropower development in China. *Renewable Energy.* 2009;34(4):1078–83.
 - [11] Gogoșe DE, Lonescu CS, Brașoveanu L, Armas L, Opris L, Costinas S. Modeling hydrodynamic changes induced by run-of-river hydropower plants along the Prahova River in Romania. *J Energy Eng.* 2018;144(2):04017078–11.
 - [12] Zhang LX, Pang MY, Wang CB. Energy analysis of a small hydropower plant in southwestern China. *Ecol Indic.* 2014;38(3):81–88.
 - [13] Liu ZY. *Global Energy Internet.* Beijing: China Electric Power Press; 2015.
 - [14] Pei W, Sheng K, Kong L, Qi ZP. Impact and improvement of distributed generation on distribution network voltage quality. *Proc CSEE.* 2008;28(13):152–7.
 - [15] Li J, Tang J, Zhang YJ, Wei B. Mechanism analysis on the effect of small hydropower plant group on the reactive voltage of distribution network. *South Power Syst Technol.* 2012;6(5):39–42.
 - [16] Meng TR, Zou GB, Xu CH, Sun WJ, Ma YW. A voltage regulation method based on district-dividing coordinated control for active distribution network. *Proc CSEE.* 2017;37(10):2852–60.
 - [17] Yang J. *Research on impact of small hydropower connected distribution power grid.* Beijing: North China Electric Power University; 2013.
 - [18] Niu X. *Optimum power supply schemes and its evaluation method for county-level power grid with abundant hydropower stations.* Beijing: North China Electric Power University; 2011.
 - [19] Peng BY. *Study on the impact of system operation grid-accessed small hydropower.* Beijing: Beijing Jiao Tong University; 2010.
 - [20] Ma HL, Ren ZM, Lu WX, Han YX, Wang ZJ, Chen LJ. Optimal reactive power compensation configuration in distribution power system integrated with small hydro power plant. *Adv Mater Res.* 2014;960–1:1162–7.
 - [21] Shi XT. *Voltage optimal control research on distribution network with abundant small hydropower stations.* Guangzhou: South China University of Technology; 2012.
 - [22] Zhang YS. *The effects on stable running of power grid of the distributed network with small hydropower.* Changsha: Hunan University; 2012.
 - [23] Zhang JZ, Ai X. A particle swarm optimization based comprehensive optimization algorithm for grid-connected positions and operation parameters of multi-type distribution generations. *Power Syst Technol.* 2014;38(12):3372–7.
 - [24] Yu DM, Zhu HM, Han WQ, Holburn D. Dynamic multi agent-based management and load frequency control of PV/fuel cell/wind turbine/CHP in autonomous microgrid system. *Energy.* 2019;173:554–68.
 - [25] Zhao N, Xia MJ, Mi WJ. Modeling and solution for inbound container storage assignment problem in dual cycling mode. *Discret Contin Dynamical Syst – S;* 2020.
 - [26] Smirnov V, Volchenkov D. Five years of phase space dynamics of the standard poor's 500. *Appl Math Nonlinear Sci.* 2019;4(1):209–22.
 - [27] Qin Y, Lou Y, Zhao YQ, Zhang J. Research on relationship between tourism income and economic growth based on meta-analysis. *Appl Math Nonlinear Sci.* 2018;3:105–14.