International Core Journal of Engineering
Volume 6 Issue 4, 2020
ISSN: 2414-1895
DOI: 10.6919/ICJE.202004_6(4).0020

Optimization Research on the Voltage of Distribution Grid with HHPV Accessed Based on GA

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Abstract

The randomness and volatility of household photovoltaic (HHPV) have become the key factors restricting network consumption. The high proportion of HHPV grid-connected affects the static voltage stability of the regional network. The impact of HHPV access on the voltage fluctuations of the distribution network is studied in this paper by analyzing the HHPV system. A reactive power optimization method for distribution network with HHPV accessed based on genetic algorithm (GA) is proposed. Finally, the IEEE33 node distribution network model is used to simulate the HHPV access to the distribution network under different penetration rates. The feasibility and accuracy of the proposed reactive power optimization method for distribution network with HHPV accessed has been verified, which can effectively solve the problem of voltage fluctuations in distribution network.

Keywords

Household photovoltaic, Distribution network, Voltage fluctuation, Reactive power optimization.

1. Introduction

The solar energy has become a research hotspot due to its abundant resources and convenient access [1], among which photovoltaic power generation is becoming one of the main forms of solar energy in the future. However, because the photovoltaic power generation has the characteristics of intermittent and strong randomness, photovoltaic power generation changes the distribution of power flow in the distribution network, which easily leads to voltage overruns and increased network losses. On the other hand, the photovoltaic power generation is likely to cause severe light abandonment and low photovoltaic consumption, which will adversely affect the power quality and stable operation of the distribution network [2-4]. Therefore, the grid voltage fluctuations caused by changes in photovoltaic power output power are a key issue that cannot be ignored.

There have been some studies on the voltage fluctuations caused by HHPV access to the distribution network. Reference [5] used the short-term analysis method to calculate the island probability of the load point based on the principle of balance, and studied the reliability of the power supply of distributed photovoltaic power generation connected to the distribution network. Reference [6] analyzed the influencing factors of voltage fluctuations after photovoltaic power generation was connected to the distribution network, and the influence of the ring network structure on the voltage fluctuations was studied from the perspective of short-circuit capacity. Reference [7] proposed a voltage characteristic analysis method based on the superposition principle for the distribution network with photovoltaic power generation accessed, which decomposes the voltage drop at any point in the distribution network into the voltage drop caused by the distribution network bus and the photovoltaic power supply access. Reference [8] proposed a dynamic reactive power distribution

ISSN: 2414-1895 DOI: 10.6919/ICJE.202004_6(4).0020

method for severe local voltage problems caused by large-scale access of distributed photovoltaic power generation, established a reactive power optimization model for the distribution network, and transformed it into a second-order cone programming model for solving. Reference [9] analyzed the influence of the wind farm on the voltage of the nodes based on the power model of the wind farm, when it is connected to a simple power system, and generalize it to the complex power system, reveal the fluctuation rule of the node voltage, and summarize the distribution characteristics of the key nodes of the voltage fluctuation. In order to solve the problem of voltage overruns and fluctuations caused by a high proportion of HHPV connected to low-voltage distribution networks, a centralized-in-situ two-phase voltage/reactive power control method for photovoltaic inverters was proposed in [10]. Reference [11] studied the sequential two-level planning model of distributed power sources to improve the economic benefits of distributed power sources and reduce the active power loss of the distribution network. In order to ensure the safe and stable operation of the power system after large-scale wind power is connected, a study on the maximum access capacity of grid-connected wind farms based on particle swarm optimization is proposed in [12]. The above literatures have studied the impact of distributed power access on the distribution network voltage, but there is still a lack of research on the impact of voltage after HHPV connected to the distribution network.

In summary, the voltage fluctuations caused by HHPV access to the distribution network are analyzed and studied in this paper. Firstly, the impact of HHPV access on the voltage fluctuation of the distribution network is analyzed and analyzed through the HHPV system. Then, with the goal of reducing the voltage fluctuation of the distribution network, a reactive power optimization method for distribution network with HHPV accessed based on GA is proposed. Finally, in the Matlab/Simulink simulation platform, the IEEE33 node distribution network model is used to simulate the voltage fluctuations caused by HHPV access to the distribution network under different penetration rates. The feasibility and accuracy of the reactive power optimization method for HHPV distribution network proposed based on GA in this paper has been verified, and it can effectively solve the voltage fluctuation problem of distribution network.

2. Analysis of HHPV

At present, the commonly used HHPV systems include off-grid systems and grid-connected systems. Off-grid HHPV systems are mainly composed of photovoltaic modules, photovoltaic controllers, batteries, and off-grid inverters. Photovoltaic modules convert solar radiant energy into DC electrical energy, and charge and discharge the battery through a photovoltaic controller. On the one hand, the photovoltaic controller can directly output DC power to power the DC load, and on the other hand, it can convert DC power to AC power through an off-grid inverter to power the AC load.

Compared with the off-grid type, the grid-connected HHPV system eliminates the need for photovoltaic controllers and batteries. After the photovoltaic module converts solar energy into DC power, the DC power is converted into AC power by the grid-connected inverter to supply power to the local load. If there is a shortage, it will be supplemented by the public grid, and if there is a surplus, it will be fed back into the public grid.

In a HHPV system, photovoltaic cells directly convert light energy into electricity through photovoltaic or actinic effects. The equivalent circuit of a photovoltaic cell is shown in Figure 1.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202004_6(4).0020

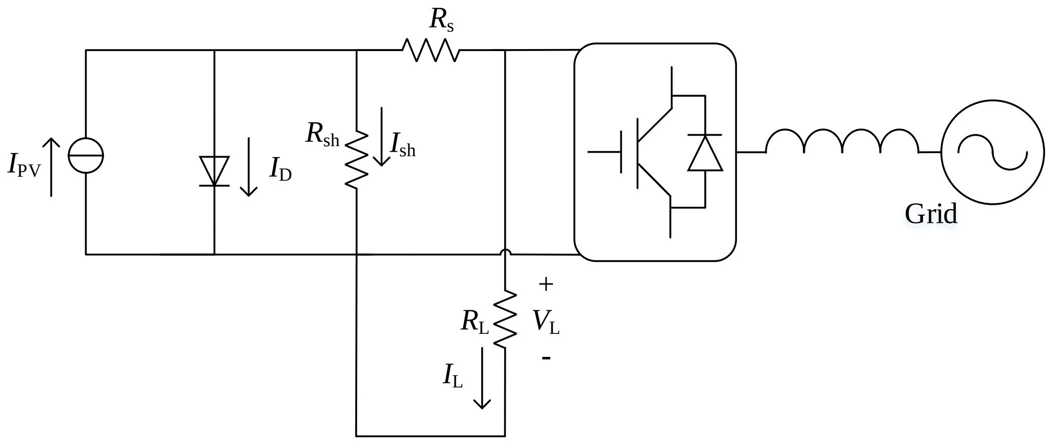

Figure 1. Photovoltaic cell equivalent circuit

This circuit is mainly composed of a series resistor R_S, a shunt resistor R_{sh} and an optical drive current source. At the same time, in order to meet the accuracy requirements of the engineering analysis, the parallel resistance R_{sh} and the series resistance R_{sh} are increased. R_{sh} is used to simulate the leakage current caused by surface contamination or crystal defects. R_{sh} is used to represent the surface resistance at the top of the diffusion zone, the battery body resistance, the resistance between the upper and lower electrodes and the photovoltaic cell, and the resistance of the metal conductor [13].

R_L is the load resistance, I_L is the load current, and I_L is the load voltage. Under light conditions, the photovoltaic cell PN will generate a photocurrent I_{pv}, and the current on the diode is I_D, which can be expressed as:

$$I_{\mathrm{L}} = I_{\mathrm{pv}} - I_{\mathrm{D}} - I_{\mathrm{sh}} \tag{1}$$

Where the photocurrent I_{pv} is:

$$I_{\mathrm{pv}} = [I_{\mathrm{pv.STC}} + K_{\mathrm{temp}}(T - T_{\mathrm{STC}})] \cdot \frac{S}{S_{\mathrm{STC}}} \tag{2}$$

The current ID flowing through the diode is:

$$I_{\mathrm{D}} = I_0[e^{\frac{q(V_{\mathrm{L}}+I_{\mathrm{L}})}{K \cdot A \cdot T}} - 1] \tag{3}$$

The current I_{sh} flowing through the parallel resistor R_{sh} is:

$$I_{\mathrm{sh}} = \frac{V_{\mathrm{L}} + I_{\mathrm{L}} \cdot R_{\mathrm{S}}}{R_{\mathrm{sh}}} \tag{4}$$

Where I_0 is the reverse saturation current of the photovoltaic cell, the amount of charge is q=1.6×10^{-19}C, the Bozeman constant K=1.38×10^{-23}J/K, and T_{STC} is the operating temperature of the photovoltaic cell under standard conditions. The absolute temperature T=t+272K [14], A is the ideal factor of the PN junction, S is the light intensity at the operating point, and S_{STC} is the light intensity under standard conditions.

3. Reactive Power Optimization Method of Distribution Network with HHPV Accessed Based on GA

In view of the impact of HHPV power supply on the distribution network to the voltage, it is necessary to reasonably express and evaluate the impact degree. A comprehensive and reasonable evaluation system is very important for improving the stability of system operation.

When a large number of nodes are connected to the photovoltaic power supply for households, in order to visually identify the system voltage fluctuations in different access states, this article will introduce the average voltage fluctuation rate H to quantify the system voltage fluctuations in different states. The larger the H value, the larger the current voltage fluctuation of the system and the worse the running stability.

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The specific quantification method is to take the standard voltage of each node as the standard threshold value "1", subtract the standard voltage from the current node voltage of the system, and sum it up to obtain the current voltage fluctuation level of the system. To further make this indicator universally applicable to different systems, divide the total number of system nodes to obtain the *H* of the system. The calculation formula is as follows:

$$H = \frac{\sum_{i=1}^{n} |U_i - 1|}{n} \cdot 100\% \tag{5}$$

Where n is the number of system nodes, i is the node number, and U_i is the current node voltage value.

GA is an optimized search method based on the principles of natural selection and genetic genetics which can choose the best individual through the law of survival of the fittest. A reactive power optimization method for power distribution network based on GA is proposed in this paper. In order to ensure the safe and stable operation of the power distribution network with HHPV accessed, the reactive power compensation in a power distribution network with HHPV accessed is reasonably configured.

In order to reduce the impact of HHPV access on the voltage of the distribution network, the minimum H of the system and the active network loss P_l are selected as the objective function, and the distribution with HHPV accessed including the constraints of the power flow equation and inequality constraints is established. The reactive power Q_{Si} input from the reactive compensation node is selected as the control variable, and the voltage of the distribution network node is used as the state variable.

The mathematical model for reactive power optimization of the distribution network with HHPV accessed is as follows:

$$\min F = \min H + \min P_l + \min \sum_{i=1}^{n} Q_{Si} \tag{6}$$

Where n is the number of system nodes, and i is the node number.

In the above mathematical model, the inequality constraint of the control variables is:

$$Q_{Si\min} \leqslant Q_{Si} \leqslant Q_{Si\max} \tag{7}$$

Where $Q_{Si\min}$ and $Q_{Si\max}$ are the upper and lower limits of the reactive power input to the reactive power compensation node, respectively. And i is the node number.

The state variable inequality constraint is as follows:

$$U_{i\min} \leqslant U_i \leqslant U_{i\max} \tag{8}$$

Where $U_{i\min}$ and $U_{i\max}$ are the upper and lower limits of the node voltage respectively. And i is the node number.

The equation constraint condition to be satisfied by the mathematical model for reactive power optimization of the distribution network with HHPV accessed is the power constraint power flow equation. The specific mathematical expression is as follows:

$$\begin{cases} U_i \sum_{j=1}^{j=n} U_j (G_{ij} \cos\delta_{ij} + jB_{ij} \sin\delta_{ij}) = P_i \\ U_i \sum_{j=1}^{j=n} U_j (G_{ij} \sin\delta_{ij} - jB_{ij} \cos\delta_{ij}) = Q_i \end{cases} \tag{9}$$

Where s of nodes i and j. G_{ij}, B_{ij} and δ_{ij} are the conductance, susceptance, and voltage phase angles between nodes i and j. n is the total number of system nodes.

The total active network loss of the system is:

$$P_l = \sum_{j=1}^{j=n} G_{ij} (U_i^2 + U_j^2 - 2U_i U_j \cos\delta_{ij}) \tag{10}$$

ISSN: 2414-1895
DOI: 10.6919/ICJE.202004_6(4).0020

The reactive power optimization process of the distribution network with HHPV accessed based on GA is shown in Figure 2.

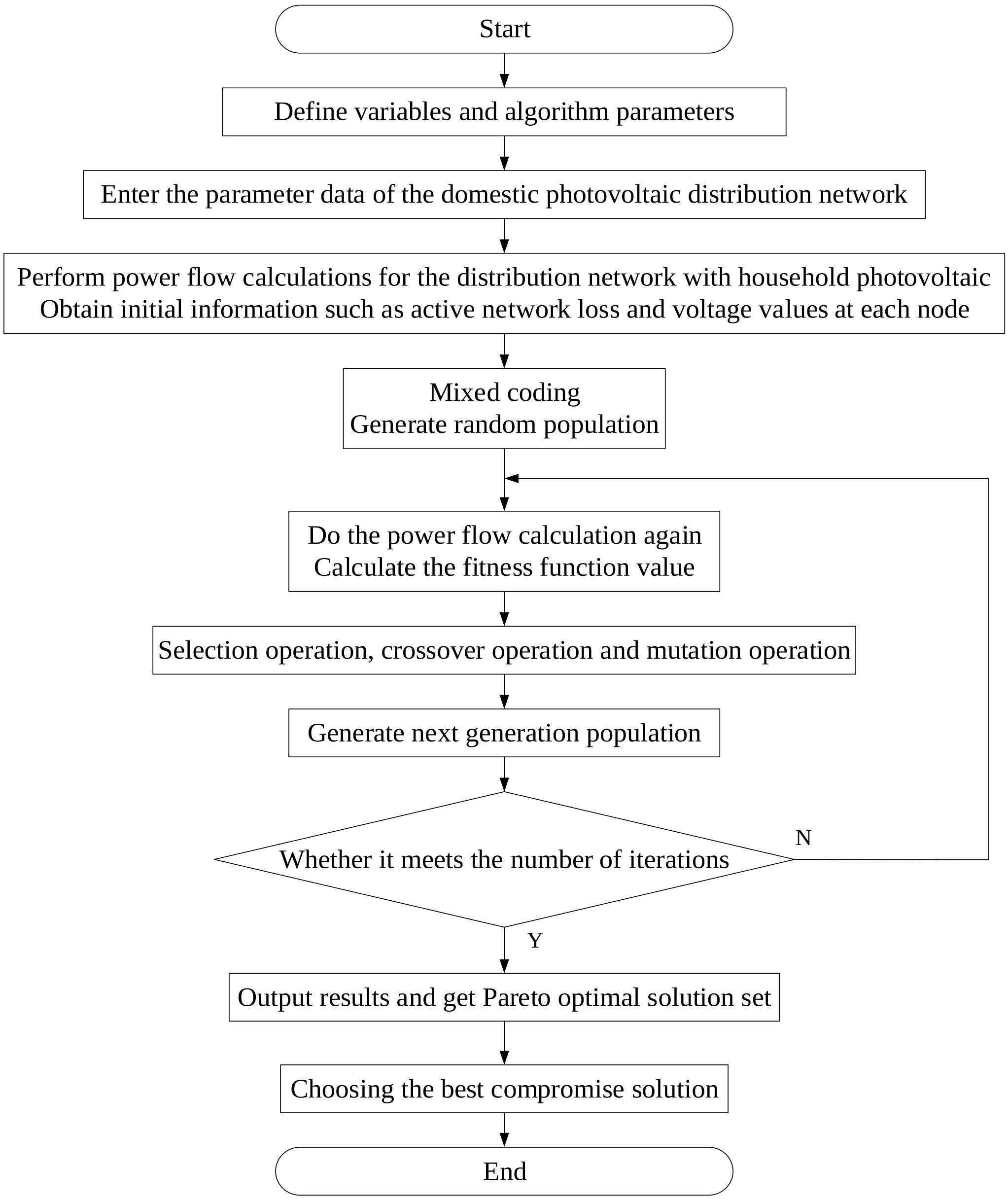

Figure 2. Reactive power optimization of the distribution network with HHPV accessed based on GA

The operation steps of the proposed reactive power optimization method are:

1) Define the variables in the mathematical model of reactive power optimization and determine the parameters of the genetic algorithm.

2) Enter the initial data including the total number of nodes in the distribution network system with HHPV accessed and the location of the HHPV access nodes.

3) Calculate the initial power flow of the photovoltaic distribution network with households, and obtain the initial information such as the active network loss and the voltage values of each node.

4) Perform mixed coding operations on control variables to randomly generate initial populations.

5) Perform power flow calculation again, and calculate fitness function for each individual in the population.

6) Perform selection, crossover, and mutation operations to generate next-generation populations.

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7) Check whether the number of iterations is satisfied. If it is satisfied, the calculation is terminated. If not, return to 4).

8) Output optimal results, algorithm calculation ends.

4. Case Study

In order to explain the impact of HHPV access on the distribution network voltage specifically, the IEEE 33-node system is used for simulation experiments in this paper. According to the results of load flow calculation, the degree of change of the node voltage before and after the HHPV access is described. With a village as an example, the initial voltage of the HHPV access node is 220V, the total capacity of the station area is 275kVA, the total active power is 247.5kW, and the total reactive power is 120kVar.

The increase in the penetration rate of photovoltaic power will cause the end voltage value to be higher than the voltage value of the initial node where the PV is connected to the house. Figure 3 shows the network structure of an IEEE33 node with HHPV accessed.

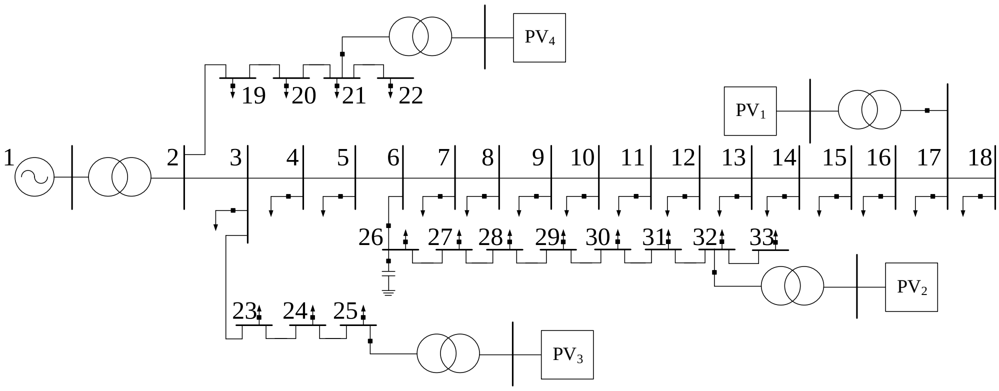

Figure 3. IEEE 33 node network with HHPV accessed

It is assumed that all nodes of the IEEE33 node system are connected to HHPV power, and the capacity of each node connected to HHPV power is equal. Several experiments were conducted to change the penetration rate of HHPV. In order to ensure the comprehensiveness and rationality of the test, the access capacity is accessed according to 5% ~ 30% of the total load capacity of the IEEE33 node system.

The specific capacities of HHPV power supplies with different penetration rates are shown in Table 1:

Table 1. Access capacity of HHPV power supply with different permeability

Numble	Power penetration rate	Input active power/kW	Input reactive power/kVar
1	5%	12.375	6
2	10%	24.75	12
3	15%	37.125	18
4	20%	49.5	24
5	25%	61.875	30
6	30%	74.25	36

Figure 4 shows the simulation results of the voltage distribution of the system nodes under different HHPV access penetration rates.

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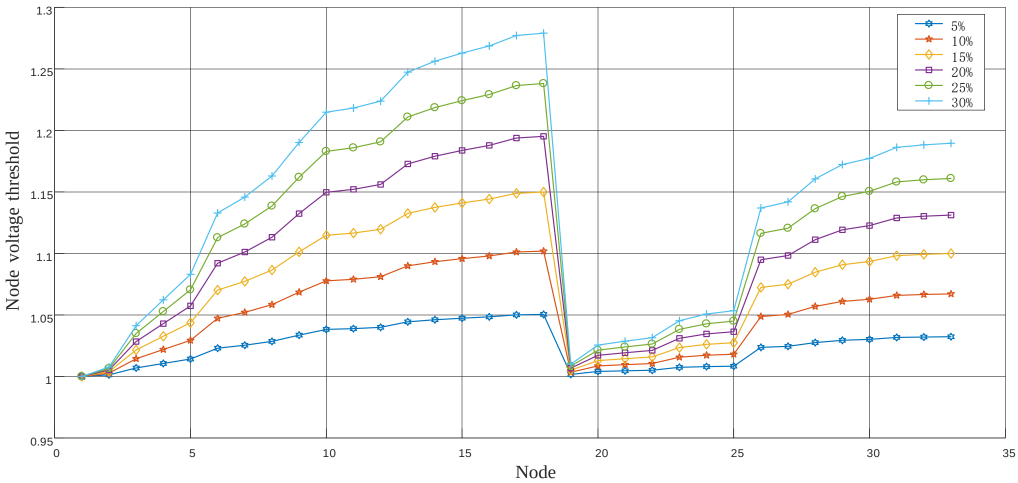

Figure 4. System node voltage distribution

Considering the voltage drop on the line, node 18 in the main line is the farthest from the transformer access point, so the voltage at this node is the highest. According to the simulation results, it can be known that the higher the penetration rate of HHPV at each node of the distribution network, the larger the standard voltage value and the larger the voltage fluctuation. With the increase of the penetration rate of photovoltaic power, the end voltage value is higher than the voltage value of the initial node where the HHPV is connected.

Aiming at the system node voltage distribution with a penetration rate of 30% for HHPV power, the reactive power optimization method for distribution networks with HHPV accessed based on GA was used to participate in the optimization and adjustment. At this time, the amount of active power input is 74.25kW. The amount of reactive power input Q is to be optimized, and the constraint condition is: $0 \le Q \le 0.006$. The voltage U_i of each node is used as a state variable, and the constraint condition is: $0.9 \le U_i \le 1.1$. The main parameters of GA in the example are set as: the cross probability is 0.8, the mutation probability is 0.01, the number of iterations is 90, the population size is 50, and the number of binary coding bits is 8 bits.

Figure 5 shows the node voltage distribution before and after reactive power optimization under the condition that the penetration rate of HHPV power is 30%.

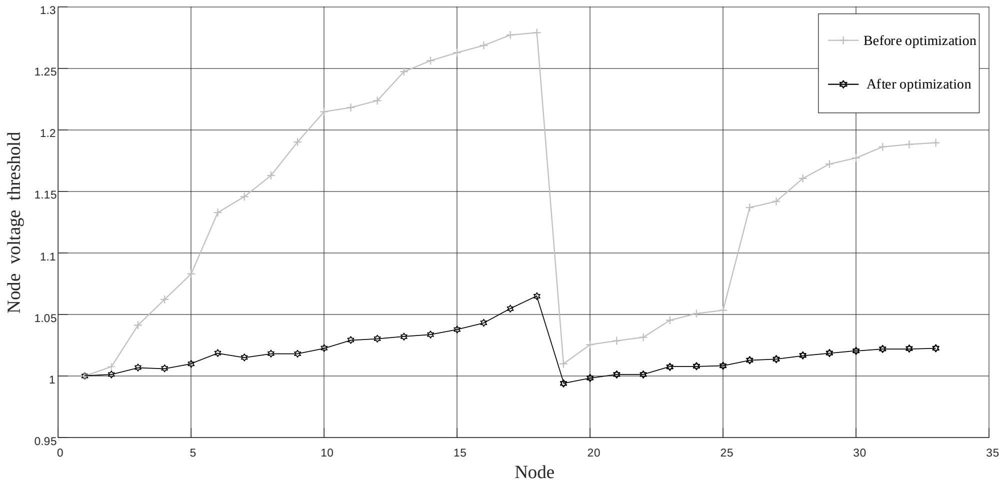

Figure 5. Reactive power optimization comparison

Comparing the two curves in Figure 4, it can be seen that the reactive power optimization method proposed in this paper adjusted the node voltage of the example system effectively, and reduced the active network loss of the system significantly. The total reactive power required by each node calculated from the simulation results is 23.5kVar, which can reduce the investment of reactive power devices and save their operating costs.

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In order to verify the adjustment effect of the reactive power optimization method proposed in this paper on H of the system, a random array is used to simulate a fluctuating HHPV power supply in the example. Node 19 is selected for a 15-second test, the voltage value curve before and after reactive power optimization is shown in Figure 6.

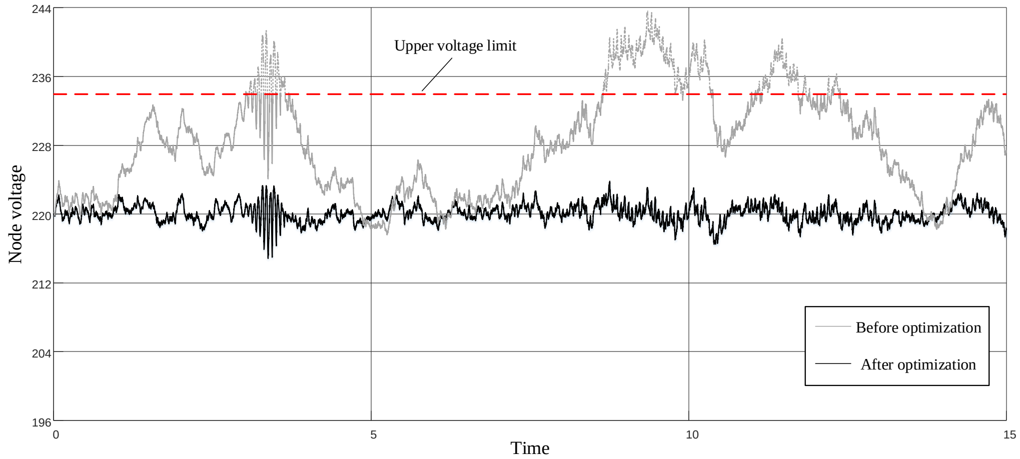

Figure 6. Comparison chart of voltage fluctuation

It can be seen from the results that the voltage before reactive power optimization often exceeds the limit. The optimization method proposed in this paper configures the reactive power compensation amount reasonably in the distribution network with HHPV accessed. It reduces the phenomenon of reactive over-compensation effectively, which can ensure that the network loss is reduced without the voltage exceeding the limit, and the node voltage stability level is improved significantly.

The H of the distribution network after reactive power optimization is 1.9275%, which is a great improvement compared with 4.9597% before the optimization. It can be seen that the voltage fluctuation of the system is reduced significantly, so the safety and stability of the system operation is also improved greatly.

5. Conclusion

The voltage fluctuation caused by HHPV access to the distribution network is analyzed and studied in this paper. HHPV system is analyzed and the different ways for HHPV to access the distribution network and their power generation principles are explained in this paper. The average voltage fluctuation rate H is introduced to quantify the system voltage fluctuation, and then analyze the impact of HHPV access on the distribution network voltage.

Taking the average voltage fluctuation rate, the total reactive power compensation and the minimum active network loss as the optimization goals, a reactive power optimization method for the distribution network with HHPV accessed based on GA was proposed, to solve the voltage fluctuation problem of the distribution network.

Based on Matlab/Simulink simulation platform, simulation tests are performed for voltage fluctuations caused by HHPV access to the distribution network under different penetration rates in the IEEE33 node model. The feasibility and effectiveness of the reactive power optimization method has been verified.

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