Research and application of voltage coordinated control method for distributed photovoltaic connected to low voltage distribution network

Hongxu Yin\textsuperscript{1}\textsuperscript{*}, Bing Zhang\textsuperscript{2}, Liang Song\textsuperscript{1}, Jie Liu\textsuperscript{2} and Yingjie Zhang\textsuperscript{1}

\textsuperscript{1} State Grid Dezhou Power Supply Company, Dezhou, Shandong Province, 253000, China
\textsuperscript{2} State Grid Shandong Power Supply Company, Jinnan, Shandong Province, 250000, China
\textsuperscript{*}Corresponding author’s e-mail: sddlzdzkj@163.com

Abstract. Distributed photovoltaic access is likely to cause the problem of voltage limit violations, which greatly affects the consumption of distributed photovoltaics. At present, the existing methods do not consider the coordinated control of multiple voltage levels. In response to this problem, this article firstly analyzes the multi-voltage coordinated control method of distribution network. On the basis of data analysis, this paper formulates a control method for regulating the low-voltage distribution network by using the medium-voltage network. In addition, optimized calculations were carried out on the voltage condition range of distributed photovoltaic access to the low-voltage distribution network. Finally, this paper analyzes the impact of distributed photovoltaic access on the voltage level of the distribution network, and provides a technical reference for the economic operation of the distribution network.

1. Introduction

In recent years, distributed photovoltaics have developed rapidly and installed capacity has continued to increase\cite{1-2}. Because distributed photovoltaic power generation has the characteristics of randomness, intermittence, and poor operation perception characteristics after being connected to the grid, this will bring new challenges to load forecasting, grid peak shaving, and safe and stable operation of equipment\cite{3-5}. Some researchers have also analyzed the problems and optimal scheduling strategies after the distributed photovoltaic grid connection\cite{6-7}.

Through research and data analysis, distributed photovoltaics have many characteristics such as large numbers, scattered distribution, and poor operational perception characteristics, which are the main reasons for the current adverse effects on the power grid. After distributed photovoltaics are connected to the distribution network, the original power flow distribution of the distribution network is changed. Under the condition of large photovoltaic output, the power grid will be reversed. In severe cases, it will cause the power distribution equipment to overload. At the same time, the volatility of distributed photovoltaic output also increases the volatility of the distribution network voltage. In severe cases, the local grid voltage will exceed the limit, and new requirements will be put forward for the protection configuration of the distribution network. At present, the grid-related performance of distributed photovoltaics is generally poor. Photovoltaic inverters are power electronic devices, and the inversion process will produce high-order harmonics, which will have a certain
impact on the power quality of the distribution network. After large-scale grid-connected distributed photovoltaics, if they do not have low-voltage and high-voltage ride-through capabilities, they are prone to collective disconnection when the grid is abnormal, which will have an impact on the reliable supply of electrical energy.

At present, there are many problems in the low-voltage distribution network, such as weak communication means, incomplete data collection [8-10], and imperfect voltage regulation measures for distributed power sources. As energy storage equipment, contact switches, and controllable loads will be connected in large numbers, the formation of medium-voltage distribution networks has a certain coordinated control capability. The existing research on the use of distributed power in the distribution network is mainly for the distribution network of a single voltage level, and does not consider the mutual influence between the distribution networks of multiple voltage levels.

Because distributed photovoltaics have the characteristics of randomness, intermittency, and poor operation perception characteristics, this brings new challenges to the load forecasting of power systems, grid peak regulation, and safe and stable operation of equipment. Although domestic and foreign research institutions have analyzed the problems and optimal scheduling strategies after distributed photovoltaics are connected to the grid, they have not involved a multi-voltage coordinated control strategy that comprehensively considers distributed photovoltaics from the perspective of production and operation. Under the existing distribution network structure, it is very necessary to increase the acceptance of distributed photovoltaics. Therefore, from the perspective of actual control operation, this paper makes full use of the coordinated control ability of the equipment, proposes a new voltage control method, and conducts a feasibility verification of the method combined with a practical case.

2. Operational management strategy

The traditional low-voltage distribution network structure is usually radial. Due to the access of distributed photovoltaic power, the radial power distribution method of the distribution network has changed, and the grid structure has shown a more complex trend. At the same time, distributed photovoltaics are affected by changes in the surrounding environment, and the power generation has the characteristics of randomness and volatility. Therefore, distributed photovoltaics pose new challenges to the management of voltage quality, and increase the burden of the distribution system on voltage control. The voltage and reactive power control of the distribution network will be greatly affected. At this time, the grid manager cannot only consider the reactive voltage optimization of the distribution network, because this method is neither economical nor comprehensive. Since the access of distributed photovoltaic power sources has a certain supporting effect on the voltage of the distribution network system, it is necessary to consider the coordinated control between distributed photovoltaic sources and the distribution network.

According to relevant standard requirements, if distributed photovoltaics are connected to the grid with 35kV and 10kV, distributed photovoltaics should have the ability to regulate active power. Under this requirement, the output power deviation and power change rate of distributed photovoltaic should not exceed the given value of the grid control agency, and the active power output can be adjusted according to the grid frequency, grid control agency commands and other signals. If distributed photovoltaics are connected to the grid through 380V, when distributed photovoltaics transmit electricity to the public grid, they should have the ability to accept the instructions of the grid regulation agency for active power control.

The connection topology of the medium and low-voltage distribution network is shown in Figure 1. Among them, $V_H$ and $V_L$ are the voltage amplitudes on both sides of the transformer, respectively. Transformer taps are an effective method of voltage control. By choosing different taps, the transformation ratio of the transformer can be changed, and the size of the low-voltage side can be changed by changing the size of the high-voltage side. This method affects the overall voltage level of the low-voltage distribution network by directly adjusting the transformer taps, and can realize the voltage regulation of the low-voltage distribution network. After adopting this measure, it is necessary
to perform a power flow calculation on the low-voltage distribution network to determine whether the voltage of the node where the voltage exceeds the limit meets the requirements, and finally determine an index that can be directly judged. When the low voltage distribution network does not exceed the voltage limit, the voltage range of the low voltage side can be adjusted by adjusting the high voltage side of the transformer.

The load characteristics in the distribution network are inconsistent with the photovoltaic power characteristics. At the same time, load peaks and photovoltaic power peaks occur in different time periods. These factors will cause the node voltage in the low-voltage distribution network to change significantly at different times. In the daytime state, the node voltage will increase during the period of excess photovoltaic power generation, and the node voltage will decrease during the heavy load period at night. Therefore, in order to ensure the safe operation of the distribution network after the distributed photovoltaics are connected, it is necessary to ensure that the voltage of the distribution network does not exceed the limit at any time. When the distributed photovoltaic is connected with 380V, the load in the low-voltage distribution network is single-phase power supply, so the distributed photovoltaic is also single-phase connected. Based on the above analysis, the maximum capacity of distributed photovoltaic and the minimum increase in voltage of the low-voltage distribution network are the optimal goals after the distributed photovoltaic is connected to the low-voltage distribution network.

The maximum objective function of connected distributed photovoltaic capacity is calculated according to the following formula.

$$P_{max} = \max \sum_{i} P_{i}^{PV}$$  \hspace{1cm} (1)

In the above formula, $P_{max}$ is the largest distributed photovoltaic capacity connected to all nodes at the same time, $P_{i}^{PV}$ is the distributed photovoltaic capacity at node $i$.

The minimum objective function of the voltage increase of the distribution network is calculated according to the following formula.

$$\Delta U_{min} = \min(\max(P_{i}^{a}, P_{i}^{b}, P_{i}^{c}) - U_{n})$$  \hspace{1cm} (2)

In the above formula, $\Delta U_{min}$ is the minimum value of the voltage rise of the low-voltage distribution network, $P_{i}^{a}$, $P_{i}^{b}$, $P_{i}^{c}$ are the voltages of the three phases a, b, and c at time $t$ at node $i$. $U_{n}$ is the reference voltage.

After determining the objective function, it is necessary to perform optimization calculations based on the constraints of the distribution network. The main constraints need to consider power flow constraints, line transmission power constraints, and node voltage constraints.

3. Example analysis

With reference to the topology of the IEEE 22-node system[6-7], a 33-node radial low-voltage distribution network was constructed with a voltage reference value of 380 V. The load types in the low-voltage distribution network are all residential loads. This article assumes that the load of each
node in the low-voltage distribution network is roughly the same. The load of each node is randomly generated between 3~4kVA, and the power factor of each node load is 0.95. The total load generated is 60.26+j36.76 kVA. All nodes in the low-voltage distribution network can be connected to distributed photovoltaics, and the accessible capacities are 7kW, 7kW, 8kW, 9kW, and 10kW respectively.

Multi-objective evolutionary algorithm is used to solve the distributed photovoltaic location and capacity model. At the same time, through data analysis, this paper obtains the relationship between the distributed photovoltaic access capacity and the voltage increase of the low-voltage distribution network. As shown in Figure 2, with the increase of distributed photovoltaic access capacity, the voltage rise of the low-voltage distribution network becomes more obvious.

The access of distributed photovoltaics will increase the node voltage in the power distribution system, especially when the power is reversed, the voltage will exceed the limit. Through the on-load voltage regulating transformer, it can be adjusted to avoid the voltage exceeding the upper limit. However, when the photovoltaics are out of operation, some nodes will have serious low voltage problems.

![Figure 2. The relationship between the photovoltaic access capacity and the voltage increase](image1)

The tap on the high-voltage side of the transformer is selected to be 2.5%, and the timing curve of the maximum and minimum voltage of the low-voltage distribution network is calculated according to the results of site selection and capacity determination. The allowable range of voltage deviation of the low-voltage distribution network is -10% to 7%. On the basis of calculation, this article judges whether the voltage of each scene is within this range, and finally determines the scene where the voltage exceeds the limit. This article lists a certain scene that is the result of a sunny spring day, as shown in Figure 3.

![Figure 3. Voltage limit violation in the case of sunny summer](image2)
It can be seen from Figure 4 that VH exceeds the upper limit of the allowable value at time 12, 13, and 14. In these several scenarios, the voltage limit of the low-voltage distribution network has occurred. Without considering voltage regulation, the distribution network cannot accommodate distributed photovoltaics under this operating condition.

Using the voltage regulation strategy proposed in this article, the voltage is regulated by changing the transformer tap. According to this calculation method, this paper establishes the optimal operation model of the distribution network, and the objective function is the minimum voltage fluctuation. Since the load and the output of distributed photovoltaics are related to the seasons, different taps are selected for voltage regulation in different seasons, so the transformer taps can be adjusted up to 4 times a year. In accordance with the operating conditions on sunny days in summer, this article again adjusted the transformer tap from 2.5% to 5% to obtain the new allowable voltage range. The adjusted result is shown in Figure 5.

Comparing Figure 4 and Figure 3, it can be seen that changing the transformer tap to 5%, the upper and lower limits of the voltage will increase, but the voltage of the low-voltage distribution network will not exceed the limit, and ultimately improve the low-voltage distribution network.

Figure 4. Allowable voltage value after voltage regulation

4. Conclusion
Based on the reasonable selection of the optimal transformer tap, this paper adopts the controllable equipment of the medium-voltage active distribution network to adjust the voltage. Through the calculation and analysis of the actual power grid, it can be concluded the method proposed in this paper can maximize the low-voltage distribution network's ability to accept distributed photovoltaics. At the same time, this adjustment method can ensure the economical operation of the distribution network. With the continuous development of new energy power generation technology, more new energy power generation will be connected to the power grid in the future. In this context, it is necessary to combine advanced communication technology to improve the voltage control capability of the power system. In future research, this paper will pay more attention to the application of 5G communication technology in control signals.

Acknowledgments
This work was supported by science and technology project of state grid shandong electric power company(Research and application of high-proportion new energy multi-level coordinated regulation and absorption capacity improvement technology-2020A-041).

References
[1] Wang Ningbo., Ma Ming., et al. (2018) High-penetration new energy power system development: challenges, opportunities and countermeasures. Electric Power, 51:29-35.
[2] Yang Zilong., Song Zhenhao., et al. (2019) Multi-mode coordinated control strategy of distributed PV and energy storage system. Proceedings of the CSEE, 39:2213-2220.
[3] Wang Shouxiang., Liu Qi., et al. (2021) Connotation analysis and prospect of distribution
network elasticity. Automation of Electric Power Systems, 45:1-9.

[4] Chai Yuanyuan., Guo Li., et al. (2018) Distributed voltage control in distribution networks with high penetration of PV. Power System Technology, 42:738-746.

[5] Wang Chengshan., Song Guanyu., et al. (2017) Optimal configuration of soft open point for active distribution network considering the characteristics of distributed generation. Proceedings of the CSEE, 37:1889-1896.

[6] Zhao Bo., Xiao Chuanliang., et al. (2017) Penetration based accommodation capacity analysis on distributed photovoltaic connection in regional distribution network. Automation of Electric Power Systems, 41:105-111.

[7] Qian Pingfan. (2019) Vigorously develop distributed photovoltaic economy to create and enhance high-quality development momentum. Development Research, 10:49-58.

[8] Pei Zheyi., Ding Jie., et al. (2018) Analysis and suggestion for distributed photovoltaic generation. Electric Power, 51:80-87.

[9] Liang Weihao., Zhou Chao., et al. (2020) Fast evaluation method of the impact of distributed photovoltaic access on the reliability of distribution network. Distribution & Utilization, 37:60-66.

[10] Zhao Yi., Liu Li., et al. (2012) Study on the impact of photovoltaic power network-connected on voltage and power loss of distribution networks. Electric Switchgear, 50:17-20.