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Comprehensive Evaluation of Carrying Capacity in Distribution Network with Large-scale Electric Heating Equipment

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Abstract. In view of the power quality problems such as voltage fluctuation and transformer overload caused by large-scale access of electric heating equipment, the comprehensive evaluation index system and the evaluation method of the distribution network carrying capacity were proposed. Taking IEEE33 node system as an example, based on the tested node electricity load and thermal load demand, through the calculation of each evaluation index, influence of different electric heating modes on the distribution network carrying capacity was analysed and the rationality of the proposed evaluation method was verified. The results showed that using electric heat pump with thermal storage system for heating can reduce the peak voltage deviation, the network loss and further ensure the safe operation of power distribution network under the premise of satisfying the user's thermal load demand and the stability of the distribution network.

1 Introduction

With the rapid development of the economy and the continuous consumption of conventional energy, environmental pollution and energy crisis have become issues that cannot be ignored. Compared with the traditional coal-fired heating method, electric heating uses clean and efficient electric energy to provide heating protection for the majority of heating users, which can effectively reduce the emission of pollutants such as carbon dust, carbon dioxide, sulfur dioxide and nitrogen oxides, and alleviate air pollution in heating areas. Electric heating mainly includes forms of hot and cold air conditioners, electric boilers, heat pumps (ground source, air source), heating cables, electric metal film, electric heaters, etc. The typical characteristics of electric heating are high power, concentrated load, highly prone to peak load, large peak-to-valley difference, and greater impact on the distribution lines.

In this context, along with the rapid development of diversified loads such as decentralized electric heating, electric vehicles, and energy storage devices, the end-use loads gradually show a trend of high power, randomness, intermittency, and decentralization [1-2]. In order to adapt to the rapid development of new energy and diversified loads and accelerate the transformation and upgrading of the distribution network, it is necessary to actively sort out and analyse the power quality problems of the distribution network and take effective measures to reduce the impact of the access of diversified loads on the distribution network [3-4].

The Ref [5] gave the electric load and evaluation indexes for planning electric heating, considering the actual needs of low-voltage distribution network planning. Li et al. [6] analysed the evaluation requirements and indexes of low-temperature heat pump units in the application of "coal to electricity" and proposed improvement measures. Wang [7] studied the working principle and control mode of electric heating controller and designed the related software and hardware system. In Ref [8], low-voltage agriculture network voltage risk assessment method was proposed. In order to finely characterize the demand response of different users, a modelling method of regional electric heating load characteristics considering the dual variability of demand and response behaviour was proposed in Ref [9]. A transient heat balance relationship model for household electric heating was established, and a method for assessing the regulability of electric heating customer loads was investigated in Ref [10]. To promote the wind power consumption and reduce the coal consumption rate, Li [11] established a joint optimization model for the generation side and the electric heating side. The Ref [12] investigated the degree of impact of large-scale electric heating access on the voltage transient drop and harmonic content of the distribution network and the suppression measures. Li et al. [13] used Gumbel-Copula function to establish the joint distribution function of wind speed and electric heating load, and improved the accuracy of distribution network reliability assessment by accounting for the correlation between them.

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In general, the research works at this stage generally focus on meeting the power supply demand, optimizing the equipment, and controlling the operation, but lacks consideration for the power quality problems such as voltage fluctuation and transformer overload that will be brought by the large-scale access of electric heating equipment to the distribution network.

In this paper, the comprehensive evaluation index system and the evaluation method of the carrying capacity of the distribution network were proposed at first. And according to the IEEE 33 node system for arithmetic analysis, the impacts of different heating methods on the distribution network carrying capacity were analysed. The proposed evaluation method can provide safer and more effective guidance for the scale access to electric heating equipment.

2 Mathematical method

2.1 Comprehensive evaluation index system

As a new type of load, electric heating will have a certain degree of impact on the power grid when it is put into use in large quantities. In terms of system load carrying capacity, if the electricity is randomly connected to the grid in a disorderly manner, the rapid superposition of electric heating loads will increase the burden on the system, and may even aggravate the peak-to-valley difference of the distribution grid load curve, which limits the ability of the distribution grid to accept electric heating equipment. In terms of the distribution grid, the large-scale electric heating equipment access will also change the load structure and characteristics of the distribution grid. Moreover, the traditional distribution grid planning guidelines may not be applicable to the scenario of large-scale electric heating equipment access. In general, the impacts of electric heating access on the distribution network include power quality and operating economy.

The impact on the power quality of the distribution network: The large-scale electric heating equipment access will lead to a large increase in the power demand of the access node, which will increase the load of the line supplying the power, increase the line voltage landing, and eventually lead to the voltage of the access node not meeting the corresponding standard. The impact on the power quality will not be effectively controlled, and may even produce voltage instability.

The impact on the economics of distribution network operation: when large-scale electric heating equipment is connected to the grid, its power load has a greater impact on the network loss and transformer life of the distribution network. The centralized power consumption behaviour in a specific period and a specific area will lead to an increase in the power demand of some nodes, which makes the line loss increase and the network blockage deteriorate rapidly. For a single distribution transformer, the load distribution has changed significantly due to the addition of large-scale electric heating equipment. In some special hours, there may be a peak of power load caused by electric heating equipment turning on at the same time. If the power consumption behaviour of electric heating equipment is not guided or optimally dispatched, the centralized use of a large number of electric heating equipment will cause the overload operation of the local distribution transformer.

In conclusion, the evaluation indexes for the electric heating equipment acceptance capacity can be divided into two categories: decisive indexes and impact indexes. Decisive indexes refer to those indexes that will seriously endanger the safe and stable operation of the power system, and must be satisfied when electric heating equipment is connected to the distribution network; impact indexes refer to those indexes that will have an impact on the economic operation of the power system, and can be used as a qualitative reference analysis when electric heating equipment is connected to the distribution network.

(1) Nodal voltage deviation:

$$\Delta U = \frac{U_i - U_e}{U_e} \tag{1}$$

Where, U_i means the actual voltage at a node of the distribution network; U_e denotes rated system voltage. The change of node load and operation mode in the distribution network will lead to the change of voltage at each node, and when the node voltage shift is too large, it will cause the voltage crossing problem, which is not conducive to the safe and reliable operation of the power system, so this index is the decisive index.

(2) Maximum load capacity of the system

$$P_{load,\max} = S \times \mu \times \cos\varphi \tag{2}$$

Where, S means transformer capacity; μ represents transformer load ratio; $\cos\varphi$ denotes power factor. Transformer overload or long-term operation at higher load rates have a serious impact on the life of the transformer, which is not conducive to the safe power supply of the power system. Therefore, this index is the decisive index.

(3) Network loss

$$Loss = \sum \frac{(P_i^2 + Q_i^2)}{U_i^2} \times R_i \tag{3}$$

Where, P_i and Q_i represent the active and reactive power of line i, respectively; R_i denotes resistance of line i. Network loss is the sum of active power loss of each line in the distribution network, which reflects the economic operation of the power system and does not endanger the safety of the distribution network to a greater extent, therefore, this index can be used as an impact index.

2.2 Distribution network carrying capacity evaluation method

In the evaluation of the distribution network carrying capacity, the decisive index node voltage deviation and the maximum load capacity of the system are used as the basis, and the influence index is also referred to analyse the carrying capacity of the distribution network.

The specific evaluation process is shown in Figure 1. Firstly, the distribution network data, target values of indexes and the types of users included in the distribution network, i.e., commercial area, office area, and residential area, are input. Because the actual local distribution network is composed of multiple electricity loads, the electricity consumption patterns of different functional area electricity loads vary. The peak of electricity load in residential area occurs before users travel to work and after they go home from work, the peak of electricity load in commercial area mainly occurs during business hours, and the peak of electricity load in office area mainly occurs during normal working hours. In addition, the demand pattern of electric heating load varies in different functional areas, and users expect different values of electric heating load in different functional areas, so it is necessary to consider the distribution of electric load of point heating equipment in each node of the distribution network from the perspective of time and space, and analyse the acceptance capacity of different functional areas.

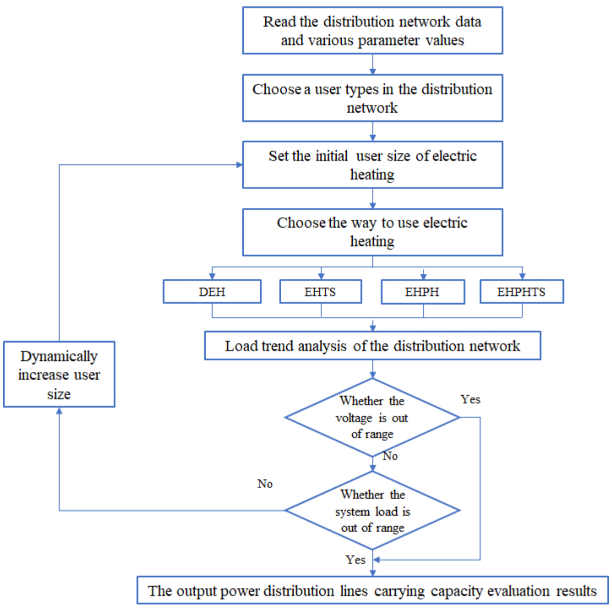

Figure 1. Flow chart of distribution network carrying capacity evaluation

Secondly, the initial size of an electric heating user is given, and different electric heating use modes are selected, including: direct electric heating (DEH), electric heating with thermal storage (EHTS), electric heat pump heating (EHPH) and electric heat pump heating with thermal storage (EHPHTS).

DEH mainly uses resistance wire, electric heating film and other electric heat conversion methods for users to heat, it usually does not have temperature control function, while the switch state decided by the users. Therefore, large-scale DEH will weaken the load peak regulation function of electric heating equipment, or even cause the phenomenon of "peak on peak".

EHTS can achieve "peak cutting and valley filling" for the overall electricity load according to the user's basic power load level, i.e., using higher power to heat the heat transfer medium during the low hours of electricity consumption, and using the heat stored in the heat transfer medium to maintain the heating throughout the day during the peak hours. According to the different heat medium, the main types include ordinary thermal storage electric heating device, solid thermal storage electric heating device and phase change thermal storage electric heating device.

EHPH uses low-grade heat energy obtained from nature's air, water or soil, and then provides the user with high-grade heat energy that can be utilized after power works. Generally, heat pumps have a COP of about 3 to 4. So, the electric heat pumps can use less electricity to meet the user's heat load demand, but the electric heat pump itself does not have the peak regulation function, which may cause the phenomenon of "peak on peak".

EHPHTS is based on the electric heat pump plus the thermal storage device, which can reduce the demand for heating electrical load and provide strong controllability and interruption for electric heating equipment through the thermal storage device, achieve “peak cutting and valley filling”, is more conducive to the flexible operation of the power grid and improve the operation stability of the distribution network.

Finally, the user load is connected to different load nodes of the distribution network and the power flow analysis is carried out. The obtained results are analysed to see whether the voltage exceeds the range. If the voltage exceeds the range, the set user scale is the maximum carrying capacity of the distribution network. If the system load does not exceed the range, it will be judged whether the system load exceeds the range; if the system load does not exceed the range, it will dynamically increase the user size and recalculate, until the system load exceeds the range, the set user scale is the maximum carrying capacity of the distribution network.

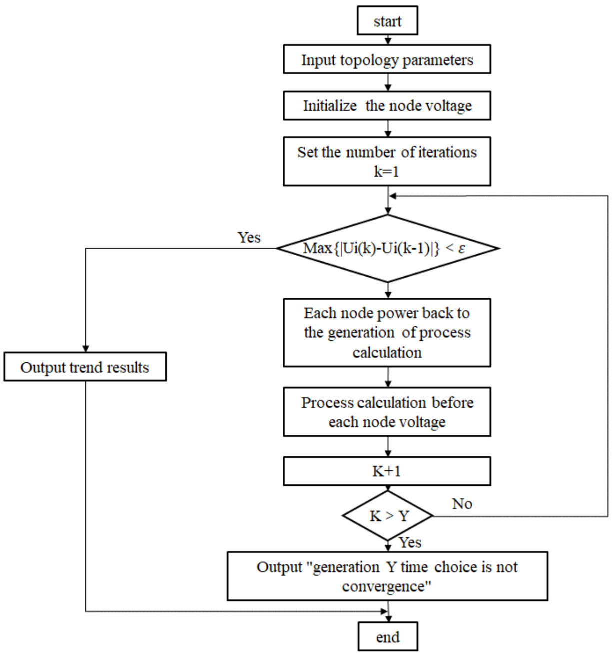

Figure 2. Flowchart of forward and backward substitution method

The power flow analysis is solved by the forward and backward substitution method. The method is widely

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used in power flow calculation of distribution network. The algorithm adopts the known network parameters directly and follows the breadth-first search strategy. Firstly, the distribution network is layered, and then the power flow distribution of the distribution network is obtained by pushing forward and backward according to the layers, without solving the Jacobian matrix. The advantages of this algorithm include: high computational efficiency, fast speed, simple programming, small memory occupation, easy to understand. The specific calculation process is shown in Figure 2.

3 Validation

This paper takes 33-node distribution system as an example to analyse the electric heating equipment carrying capacity of distribution network. The distribution network topology structure and tested node position are shown in figure 3. The distribution network has 32 branches, total load is (3715 + j2300) kVA, the rated voltage is 10 kV, rated capacity of transformer is 500 kVA, the selected test node is located in a residential area, the original test node load curve and heat load curve are respectively shown in figure 4 and figure 5.

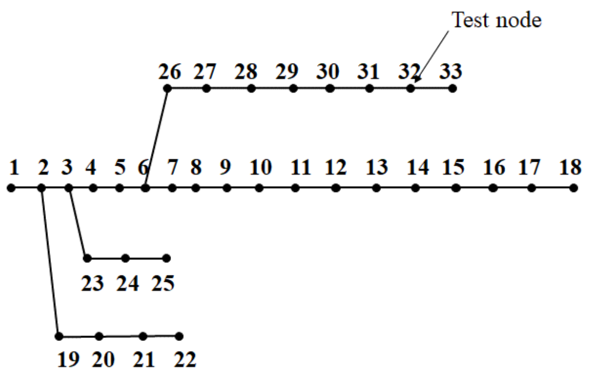

Figure 3. Distribution network topology diagram

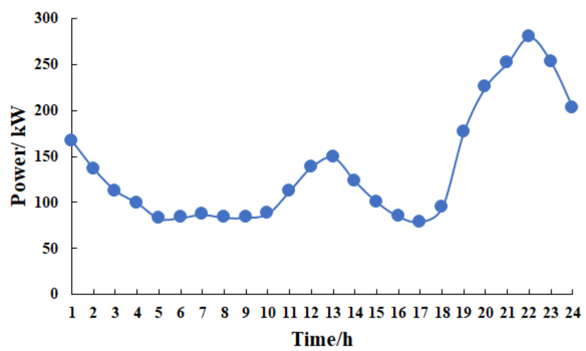

Figure 4. Original power load curve of the tested node

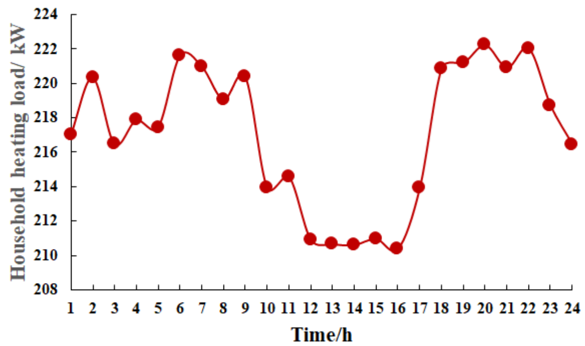

Figure 5. heat load curve of the tested node

For the 10kV distribution system, the allowable voltage deviation range is ±7%, and the voltage deviation of any node in the system shall not exceed this range. If the voltage deviation is greater than 1.07 or less than 0.93, the system cannot be considered to operate safely and stably. Therefore, when the voltage of the node with the largest voltage deviation is greater than 1.07 or less than 0.93 and the transformer does not overload, the number of electric heating users connected at this time is the electric heating equipment carrying capacity of the distribution network. Or the voltage deviation is within the allowable range, while the node load exceeds the maximum load capacity of the transformer, the number of electric heating users connected to the distribution network is the carrying capacity of electric heating equipment.

The electric heating load under different electric heating modes will be connected to the test nodes, and the power flow calculation will be carried out. The number of electric heating users will continue to increase until the node voltage exceeds the limit, the system load is overloaded or the upper limit of the number of node users is reached, so as to analyse the impact of large-scale access of electric heating equipment on the distribution network.

Figure 6 is the load curve graph of the tested nodes under different electric heating modes. It can be seen from the graph that the system load is close to the maximum load capacity when the number of users on the nodes reaches the upper limit. The main reason for this phenomenon is that the peak period of direct electric heating load and the peak period of the original electric load of the tested node basically coincide, and the superposition produces "peak on peak". Although the phenomenon of "peak on peak" also occurs when using EHPH, because the electric heat pump equipment itself consumes less power than the direct electric heating equipment which does not reach the upper limit of the transformer load. After the use of heat storage equipment, system total load is evenly distributed throughout the day to each time to maintain the stable operation. When using the EHPHTS, it directly reduces the peak of the original electric load usage.

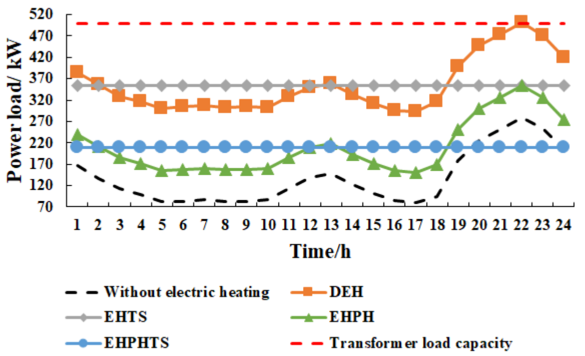

Figure 6. tested node load curves of different electric heating modes

As can be seen from Figure 7, the voltage deviation of the tested node in each mode is the largest at 22:00 in a 24-hour day, because the electrical load of the whole system is higher at this time. Figure 8 shows the voltage deviation of each system node at 22:00. Because this 33-node distribution network is a radial distribution network, the voltage deviation at the end node of the branch is the largest under the original load, i.e., node 18. But large-scale access of electric heating equipment to the tested node 32, the voltage deviation at node 32 is larger than node 18. So, if the electric heating equipment carrying capacity of different nodes of the distribution network is not considered when planning for electric heating equipment, it will aggravate the node voltage deviation and transformer overload.

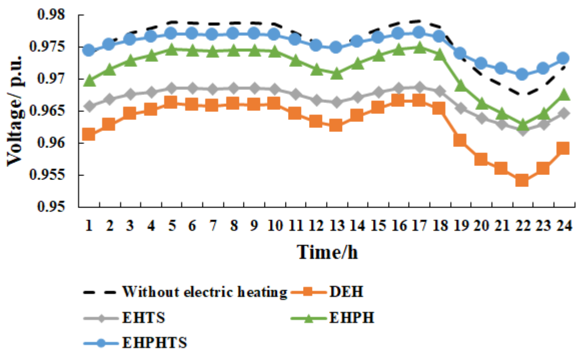

Figure 7. Node voltage deviation curve

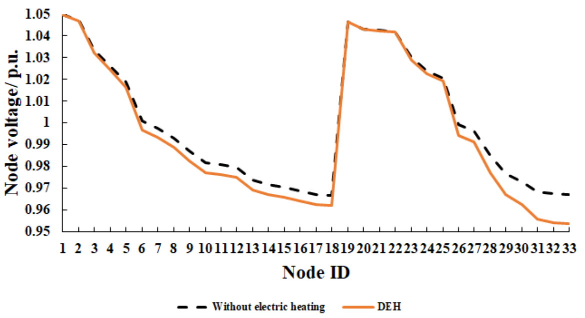

Figure 8. Voltage deviation of each system node

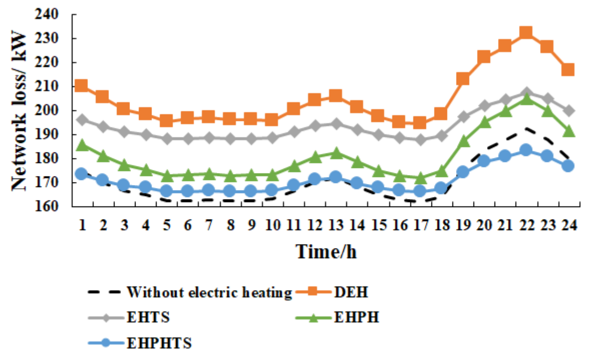

Figure 9. Voltage deviation of each system node

Figure 9 shows the variation of the system network losses. The network loss can reflect the operating economy of the distribution network and serve as a reference index to assess the carrying capacity. After different types of electric heating equipment are accessed, the system network loss increases the most when DEH is connected, and the power loss is the largest around 22:00. This is also due to the total system load is the largest at this time. By controlling the output characteristics of the electric heat pump, the EHPHTS carries out "peak cutting and valley filling" on the basic electric load of the users. The average load of the whole day is lower than the peak of the original power load, so the peak of the network loss is lower than the peak of the network loss generated by the original power load. Total network losses throughout the day are comparable.

4 Conclusions

Aiming at the power quality problems such as voltage fluctuation and transformer overload caused by large-scale access of electric heating equipment, the comprehensive evaluation index system and the evaluation method of distribution network carrying capacity are put forward at first. In addition, IEEE 33 node system is taken as an example to analyse the impact of different electric heating modes on the carrying capacity of the distribution network, which can provide safer and more effective guidance for large-scale access to electric heating equipment. The specific conclusions are as follows:

1)The nodal voltage deviation, maximum load capacity and network loss are proposed as evaluation index, and the evaluation method of the distribution network carrying capacity under the connection of large-scale electric heating equipment is set to analyse safety, reliability, power quality, operation economy and other aspects of distribution network quantitatively;

2)Through the comparison of different electric heating methods, it is found that direct electric heating is more likely to reach the maximum load capacity of the system due to the phenomenon of "peak on peak" for the original electric load, resulting in increased voltage deviation of the system nodes and increased network losses;

3)Under the premise of meeting the user's heat load demand and security and stability of the distribution network, EHPHTS can reduce voltage deviation and peak network loss, and further guarantee the safety of the distribution network. Therefore, the actual situation of the heating area can be combined with the local situation to choose the appropriate type of electric heat pump with thermal storage system for heating.

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