Capacity Optimization and Maintenance of Low Voltage Reactive Power Compensation Equipment in Distribution Netw

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Abstract. Low-voltage distribution network has the characteristics of large number of nodes and branches, radial network and three-phase asymmetry in normal operation, which directly affects the power quality of users. In this paper, the load variation, the three-phase asymmetry and the capacity attenuation of capacitors are considered, and the state evaluation and three-phase capacity planning of LV reactive power compensator are studied. Genetic algorithm is used to realize economical and efficient control effect of bus voltage stability through reasonable planning of finite compensation equipment in multi-node system. Experimental results show that the proposed method can effectively optimize the location and capacity of the compensation device, and can improve the overall voltage level of distribution network economically and reasonably.

1. Introduction

Distribution network has the characteristics of large scale, wide range of points, long power supply radius and three-phase asymmetry. It faces the problem of high power loss for a long time. Therefore, the loss reduction of distribution network needs to be solved urgently[1]. According to the voltage level, the distribution network can be divided into 110kV and above high-voltage distribution network, 110kV and below, 10kV and above medium-voltage distribution network, and 0.38kV low-voltage distribution network. Among them, low voltage distribution network is directly connected with users, its power supply reliability and power quality are directly related to the economic and social benefits of power enterprises. Reactive power compensation is one of the effective measures for reducing loss and increasing voltage in power network. At present, there are three kinds of reactive power compensation in low voltage distribution network: pole reactive power compensation, large load fixed reactive power compensation and distribution low voltage side reactive power compensation[2]. The low voltage reactive power compensation device has high cost-effective and is easy to realize automatic control. However, in the actual operation process, the phenomenon of insufficient compensation or excess often occurs, which is also the main reason for the problem of unqualified voltage/reactive power at the low voltage side of the distribution transformer[3]. How to monitor and effectively evaluate the operating state and compensation effect of LV reactive power compensation device on line, find out the cause of unqualified voltage/reactive power, adjust planning scheme and perfect control strategy has become a key problem to be solved urgently in the development of intelligent reactive power management in distribution network.
The existing assessment methods are mainly aimed at the quality and reliability of voltage and reactive power of distribution network and even the whole network, but not specifically for low-voltage reactive power compensation devices. However, the operating state of the low voltage reactive power compensation device directly affects the reactive power distribution, voltage level and loss reduction effect of the low voltage distribution network. Therefore, it is necessary to establish a comprehensive evaluation index system to reflect the operating state of low-voltage reactive power compensation device.

2. Evaluation of reactive power compensation device in distribution network

2.1. Condition monitoring of low voltage reactive power compensation device in distribution network

At present, there is no real-time communication network between the operation and maintenance center of the distribution network and the low-voltage reactive power compensation equipment of the distribution network[4], and the operators and maintenance personnel cannot know the real-time status of the reactive power compensation equipment installed on the low-voltage side of the distribution network's 10kV feeder, nor can they monitor and evaluate the status of the reactive power compensation equipment[5], let alone reform the reactive power compensation equipment of the distribution network to improve the power quality and line loss rate of the current 10kV feeder. So as to improve the economy and safety of power grid operation from the technical and management perspective, and comprehensively improve the management level and service quality of power supply enterprises. Centralized management function of reactive power compensation device: Uniformly set the field parameters of reactive power compensation device within the scope of system management.

Report generation: Can automatically generate all kinds of daily, monthly and yearly reports needed for daily management. DSM and service support functions: load analysis and forecasting, distribution and transformation information query services, implementation of orderly power consumption plans, and power quality online monitoring. Power marketing management technical support functions: remote meter reading, on-line monitoring of power meter operation status, load and energy data classification and statistical analysis, line loss analysis.

2.2. Evaluation index of operation status of low voltage reactive power compensation device in distribution network

The evaluation index system of the operating state of the low voltage reactive power compensator is shown in Table 1. The specific indicators include four types of first-class indicators, namely, the assessment indicators for the eligibility of three-phase voltage and reactive power, the assessment indicators for the symmetry of three-phase power[6], the assessment indicators for the cause of unqualified voltage/reactive power deficiency, and the assessment indicators for the capacity attenuation of capacitor banks and the balance of switching times.

| Performance Evaluation Index of Low Voltage Reactive Power Compensation Devices |
|--------------------------------------------------------------------------------|
| Evaluation Index of Qualified Degree of Three Phase Voltage and Reactive Power | Index of Qualified Degree of Three Phase Voltage | Low/High/Pass Rate of Three Voltages |
| Evaluation Index of Qualified Degree of Three Phase Reactive Power | Three-phase reactive power default/overcharge rate |
| Three Power Symmetry Evaluation Index | Symmetry of Active Load | Maximum/average asymmetry of three phase active load |
Evaluation Index of Reactive Power Load Symmetry
Traceability assessment index of nonconformance reason of voltage

Maximum/Average Asymmetry of Three Phase Reactive Power
Low three-phase/single-phase undervoltage ratio

Keywords var insufficiency causetraceevaluation index
Three-phase underdelivery/improper capacity/serious undercapacity rate
Single phase underdelivery/improper capacity/serious undercapacity rate

2.2.1. Three phase voltage and reactive power qualification evaluation index
In order to evaluate the effect of voltage and reactive power regulation of low voltage and reactive power compensator, not only the qualified ratio of three-phase voltage and reactive power is considered,[7], but also the index of unqualified nature and degree, that is, the degree of high or low voltage and overcompensation or undercompensation of reactive power is considered.

(1) In order to evaluate the effect of voltage and reactive power regulation of low voltage and reactive power compensator, not only the qualified ratio of three-phase voltage and reactive power is considered, but also the index of unqualified nature and degree, that is, the degree of high or low voltage and overcompensation or undercompensation of reactive power is considered.

(2) Low/High/Pass Rate of Three Phase Voltage
The percentage of qualified points of daily three-phase voltage amplitude in the total points is the pass rate, which is expressed by percentage. Similarly, the ratio of the non-conforming points beyond the lower limit or the upper limit to the total points is the low or high rate. Among them, the qualified range of voltage amplitude is determined by the reference guideline of local power company and actual system.

(3) Three-phase reactive power default/overcharge rate
The time when the power factor of a certain phase is lower than the power factor limit is the time of the phase undercompensation, and the time when the difference between the reactive power load and the compensation is negative is the time of the phase overcompensation[8].

In order to evaluate the asymmetry degree of three-phase reactive load and provide reference basis for capacity allocation, the following indexes are put forward: maximum asymmetry degree of three-phase active load (B)/average asymmetry degree (O), maximum asymmetry degree of three-phase reactive power load (D)/average asymmetry degree (F). If the maximum deviation of three-phase active load is $P_{\text{imax}}$ at midday I time and the maximum deviation of three-phase reactive load is $Q_{\text{imax}}$, the formula is as follows:

$$\epsilon_{P_{\text{imax}}} = \frac{\max(P_{\text{imax}})}{S_n} \cdot 100\% , i = 1, 2, \cdots N \quad (1)$$

$$\epsilon_{P_{\text{avg}}} = \frac{\sum_{i=1}^{N} P_{\text{imax}} / N}{S_n} \cdot 100\% \quad (2)$$

In formula (1) ~ (2): $S_n$ is the rated capacity of the transformer to which the device belongs.
2.2.2. Traceability evaluation index for causes of unqualified voltage / insufficient reactive power

Insufficient/excess reactive power compensation in the low voltage side of distribution transformer is an important cause of unqualified voltage. In the case of adequate and not excessive compensation, if the voltage is still not qualified due to the lower/higher upper voltage caused[8]. Therefore, the assessment of the causes of voltage nonconformance mainly consider the above two aspects. The time of three-phase voltage amplitude is low and all uncompensated is Nvol, and the time of three-phase voltage amplitude is high and all compensated is NVoh. Lvol and LVoh calculate using the following formula.

\[
L_{\text{vol}} = \frac{N_{\text{vol}}}{N} \cdot 100\% \quad (3)
\]

\[
L_{\text{voh}} = \frac{N_{\text{voh}}}{N} \cdot 100\% \quad (4)
\]

The voltage amplitude of single phase in one day is low, the power factor is qualified and the time of total complement is NVla and NVlb respectively, while the voltage amplitude is high, the power factor is qualified and the time of total complement and total tangent is NVla and NVlb respectively. In the case of phase A, LVla and LVha are calculated as follows, respectively:

\[
L_{\text{vla}} = \frac{N_{\text{vla}} - N_{\text{vl}}}{N} \cdot 100\% \quad (5)
\]

\[
L_{\text{vha}} = \frac{N_{\text{vha}} - N_{\text{vh}}}{N} \cdot 100\% \quad (6)
\]

Insufficient reactive power distribution low voltage side undercompensation.

3. Capacity calculation of reactive power compensation in distribution network based on genetic algorithm

3.1. Design of distribution network genetic algorithm model

In the process of reactive power compensation adaptability modeling, fitness function is used as the standard and basis to optimize the direction and result of iteration. Through power flow calculation, the voltage data of each node is obtained, and then the voltage of each node is different from its expected value[10]. The solution of the least square of voltage deviation is reserved. The aim of the fitness function is to make each node run stably in the optimal voltage range. The fitness function of the distribution network model designed is as follows:

\[
\min f = \omega_1 \sum_{i=1}^{N} (u_i - \bar{u}_i)^2 + \omega_2 N \quad (7)
\]

In the equation (7), N is the number of compensation points of the distribution network; omega \(\omega_1\) and \(\omega_2\) are the penalty coefficients of their respective polynomials. From the expression (7), it can be seen that the value of the function is the minimum to satisfy the objective of optimal control. Using the MATLAB random number mechanism to generate a random number in [0, 1], we can get a higher function value with a higher probability of being selected. The fitness function is required to have the minimum value of the function, so the fitness function needs to be converted to the reciprocal for design and processing to meet the optimal goal of reactive power optimization.

\[
f = \frac{1}{1+N} \quad (8)
\]

Crossover operators can only rearrange and combine the results of existing calculations, easily fall into the local optimal solution, and the mutation operator must be designed to generate the value of new variables. When pop.mr is small and pop.cr is large, fewer new variables are generated, and the overall optimization iteration process is slower. When pop.mr is large and pop.cr is small, the current optimal solution is likely to be lost and the data prone to oscillation.
4. Examples and analysis
The loop-type distribution network structure is shown in Figure 2, showing the location of line impedance and reactive power to be compensated, with bus 1 as the power bus and the rest as the load bus. The power bus inputs power from a large power grid, and the voltage drop and power loss occur in the lines of the distribution network. In the circuit system structure shown in FIG. 1, the reference capacity \( S \) is 1MVA, the rated voltage \( U = 10kV \), and 1-4 indicates the node number of the distribution system.

![Fig. 1 Loop distribution network structure](image)

When the voltage of each node is the most stable, that is, the deviation between the voltage of each node and the expected value is the smallest, the model is validated. This is shown in Figure 2.

![Fig. 2 Comparison of node voltage before and after reactive power compensation in loop-type distribution network](image)

Figure 2 shows the comparison of node voltages before and after reactive power compensation in loop-type distribution network. Thus, for loop-type distribution network, only compensating reactive power of several nodes can reduce the voltage deviation of distribution network and increase the qualified rate of system voltage. The comparison of the compensation methods of loop-type distribution network before compensation, comprehensive compensation and traditional compensation is shown in Table 2.

| Compensation quantity/number | Voltage qualification rate \(/\%\) | Active power loss \(/MW\) | Reactive power loss \(/Mvar\) |
|------------------------------|-----------------------------------|--------------------------|-------------------------------|
| Before compensation          | -                                 | 51                       | 0.118                         | 0.61                          |
| Traditional compensation method | 4                                 | 76                       | 0.130                         | 0.72                          |
| Integrated compensation method | 3                                 | 98                       | 0.114                         | 0.59                          |
Thus, whether the traditional single point compensation or integrated compensation can improve the voltage level of loop-type distribution network as a whole. Compared with the traditional compensation method, the comprehensive compensation method is better in the number of compensation devices, in the active power loss and reactive power loss is better.

5. Conclusion
The existing assessment methods are mainly aimed at the quality and reliability of voltage and reactive power of distribution network and even the whole network, but not specifically for low-voltage reactive power compensation devices. However, the operating state of the low voltage reactive power compensation device directly affects the reactive power distribution, voltage level and loss reduction effect of the low voltage distribution network. Therefore, it is necessary to establish a comprehensive evaluation index system to reflect the operating state of low-voltage reactive power compensation device.

References
[1] Zeraati M, Golshan M E H, Guerrero J M. (2018) Voltage quality improvement in low voltage distribution networks using reactive power capability of single-phase PV inverters[J]. IEEE transactions on smart grid, 10(5): 5057-5065.
[2] Zimann F J, Batschauer A L, Mezaroba M, et al. (2019) Energy storage system control algorithm for voltage regulation with active and reactive power injection in low-voltage distribution network[J]. Electric Power Systems Research, 174: 105825.
[3] Pires V F, Pombo A V, Lourencio J M. (2019) Multi-objective optimization with post-pareto optimality analysis for the integration of storage systems with reactive-power compensation in distribution networks[J]. Journal of Energy Storage, 24: 100769.
[4] Alam M M, Ahmed M F, Jang Y M, et al. (2020) Automatic Control Approach of Reactive Power Compensation of Smart Grid[C]/2020 International Conference on Artificial Intelligence in Information and Communication (ICAIIIC). IEEE, 2020: 716-719.
[5] Sarkar M N I, Meegahapola L G, Datta M. (2018) Reactive power management in renewable rich power grids: A review of grid-codes, renewable generators, support devices, control strategies and optimization algorithms[J]. IEEE Access, 6: 41458-41489.
[6] Téllez A Á, López G, Isaac I, et al. (2018) Optimal reactive power compensation in electrical distribution systems with distributed resources. Review[J]. Heliyon, 4(8): e00746.
[7] Wang Q, Liao J, Su Y, et al. (2018) An optimal reactive power control method for distribution network with soft normally-open points and controlled air-conditioning loads[J]. International Journal of Electrical Power & Energy Systems, 103: 421-430.
[8] Feng S, Licheng Y, Zhitong G, et al. (2018) Reactive power optimization compensation of line losses calculation in rural areas[C]/2018 Chinese Control And Decision Conference (CCDC). IEEE, 2018: 6458-6463.
[9] Rahman M M, Arefi A, Shafullah G M, et al. (2018) A new approach to voltage management in unbalanced low voltage networks using demand response and OLTC considering consumer preference[J]. International journal of electrical power & energy systems, 99: 11-27.
[10] Lin B, Lin Q, Lai W, et al. (2021) Edge Computing Regulation Optimization Technology Based on Power Internet of Things[C]/IOP Conference Series: Earth and Environmental Science. IOP Publishing, 714(4): 042068.