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Optimal configuration of acquisition terminals in regional distribution grids considering dynamic observability

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Optimizing the configuration of acquisition terminals can maximize the observability and state estimation accuracy of the distribution grid achieving comprehensive perception of the distribution grid. However, the existing optimization configuration methods typically target a single topology structure. For regional distribution grids with dynamic topology changes, it cannot meet the observability requirements of all their topologies. In this regard, this paper proposes an optimal configuration scheme for regional distribution grid acquisition terminals considering dynamic observability. Firstly, the regional distribution grid considering the change of contact switch is modeled. Based on the observation redundancy and state estimation accuracy, the dynamic observability index of regional distribution grid is proposed. Then, a multi-objective optimal configuration model of acquisition terminal is constructed with the objective function of maximizing dynamic observability and minimizing configuration cost. Finally, the effectiveness of the proposed approach is validated with the simulation model.

KEYWORDS

regional distribution grid, acquisition terminal configuration, state estimation accuracy, observation redundancy, dynamic observability

1 Introduction

In order to achieve the dual-carbon goal and cope with the energy crisis, the traditional energy structure is changing to a clean energy structure, the proportion of distributed energy access in the distribution grid is increasing, but its volatility and randomness bring more uncertainty and dynamics to the distribution grid designed to meet the energy flow demand, which brings new requirements to the operation and control strategy of the distribution grid. (Xia et al., 2022; Olusola, 2020). In order to improve the power supply stability of the distribution grid and ensure the normal operation of the power supply in an emergency, multiple distribution areas of the same voltage level are connected by a contact switch to form a regional distribution grid (Rohit et al., 2020). Due to factors such as distributed energy access, changes in power load, and natural disasters, regional distribution grids adjust the status of contact switches according to actual situations in order to ensure the reliability and stability of power supply, and the topology structure of regional distribution grids also changes accordingly.

In order to ensure the safe and stable operation of the regional distribution grid, it is necessary to monitor and control the grid operation status in real time (Ramírez et al., 2019). The acquisition terminal is a device used to collect, transmit, and process power parameters such as voltage, current and phase angle (Seyed-Ehsan et al., 2019). It is usually installed on the key nodes of the distribution line to obtain real-time data of the grid operating status (Zhu et al., 2019).

If the measurement data of all nodes in the distribution grid can be obtained directly or indirectly by the acquisition terminal, the comprehensive perception of the distribution grid is realized, and its topology is considerable (Yang et al., 2019). In regional distribution grids, contact switches are used to control the flow of electricity to different parts of the grid. When the status of the contact switch changes, such as opening or closing, the connection method of the power grid will correspondingly change, leading to changes in the topology structure of the distribution grid. Therefore, the observability demand of regional distribution grids is dynamically changing.

Considering the high cost of acquisition terminal configuration and the large number of nodes and branches in the distribution grid, it is not in line with the actual economic situation to apply the acquisition terminal to the distribution grid on a large scale. (Manousakis and Korres, 2020). How to reasonably configure the acquisition terminal in the distribution grid has become a research hotspot (Almunif and Fan, 2020; Masoud et al., 2023). proposed a power management unit (PMU) configuration optimization method based on integer programming (Rupanjali and Abhinanda, 2023). studied incorporating unobservable depths into the system to achieve weak global observability (Sun et al., 2022). proposes a multi-objective optimization model, whose objectives include minimizing the number of D-PMUs, maximizing grid measurement redundancy (NMR), and maximizing the average number of observable buses (ANOBC) under N-1 contingencies.

Most of the above studies only take minimizing the number of configurations as the objective function, and do not consider the impact of optimal configuration results on observability. Reference (Riccardo et al., 2021) studied the PMU optimal configuration model with the goal of minimizing the state estimation error, and solved it by the immune discrete particle swarm optimization algorithm. In (Wei et al., 2023), based on the principle of error degree analysis, an improved genetic-simulated annealing algorithm is proposed and applied to the multi-objective optimal configuration problem of PMU. Reference (Xu et al., 2020) also proposed the state estimation accuracy and PMU configuration node weight value as the goal, and applied the genetic algorithm to solve the problem. However, the optimal configuration of the acquisition terminal of the regional distribution grid needs to consider its dynamic observability, which is not considered in most of the above studies.

Therefore, this paper proposes an optimal configuration method of regional distribution grid acquisition terminals considering dynamic observability. In this paper, firstly, the regional distribution grid is modeled, and the dynamic observability index of the regional distribution grid is proposed based on the observation redundancy and the state estimation accuracy. Then, a multi-objective optimization configuration model of the acquisition terminal with the objective function of maximizing the dynamic observability and minimizing the configuration cost is constructed. Finally, it is verified by the simulation model that the proposed method can meet the observability requirements of all topologies of the regional distribution grid. The main contributions of this article are as follows.

1. This article models the topology model of regional distribution grids, considering the dynamic changes in their topology structure, that is, the topology structure changes with changes in switch states.
2. A dynamic observability index was proposed as a criterion for judging the quality of the acquisition terminal configuration scheme, and based on this, a multi-objective optimization configuration model for acquisition terminals was constructed. The dynamic observability index consists of state estimation accuracy and observation redundancy.
3. Verify the effectiveness of the proposed method through simulation experiments, which can meet the observability requirements of all topology structures and achieve global optimization. From the configuration results, it not only meets the requirement of the lowest configuration cost for the acquisition terminal, but also maximizes the overall dynamic observability index of the system.

The contributions of this paper are as follows. The section II constructed a regional distribution grid model that considers dynamic changes in topology structure; The section III constructing dynamic observability indicators based on state estimation accuracy and observation redundancy; The section IV proposes a multi-objective optimization model for acquisition terminals; The section V proves the feasibility of this method through case verification.

2 Modeling of regional distribution grid considering the change of contact switch

2.1 Regional distribution grid topology model

The regional distribution grid is formed by connecting multiple distribution areas with the same voltage level through the contact switch. There is a correlation between the topology of the regional distribution grid and the state of the contact switch. The topology structure $\boldsymbol{D}$ of regional distribution grid is described based on adjacency matrix.

$$D = \left(d_{ij}\right)_{n\times n} \in \{0,1\}^{n\times n},\quad d_{ij} = \begin{cases} 1, \text{node i is connected to j} \\ 0, \text{other} \end{cases} \tag{1}$$

where i, j are node numbers, $i, j \in \{1, 2, \ldots, n\}$; d_{ij} are adjacency matrix coefficient; n is the total number of distribution grid nodes.

Considering the influence of the change of the state of the contact switch on the topology of the regional distribution grid, a judgment coefficient a_{ij} is added to the adjacency matrix coefficient d_{ij}. Therefore, the regional distribution grid topology $\boldsymbol{D}'$ considering the change of the contact switch is:

$$a_{ij} = \begin{cases} 0, \text{the switch between node i and j is off} \\ 1, \text{other} \end{cases} \tag{2}$$

$$D' = \left(a_{ij}d_{ij}\right)_{n\times n} \in \{0,1\}^{n\times n} \tag{3}$$

2.2 Acquisition terminal configuration cost model

Considering that the cost of installing acquisition terminals at different nodes is different, the cost $C(B)$ of configuring acquisition terminals in regional distribution grid can be expressed as:

$$C(B) = \sum_{i=1}^{N} C_i b_i \tag{4}$$

where, $\boldsymbol{B}$ is an N-dimensional column vector composed of b_i; b_i is a 0-1 variable that characterizes whether the node i installs the acquisition terminal. When the node i is equipped with the acquisition terminal, $b_i = 1$, otherwise it is 0; C_i is the cost of installing the acquisition terminal at node i.

3 Dynamic observability index

When evaluating the impact of the acquisition terminal configuration results on the dynamic observability of the regional distribution grid, this paper considers two aspects: state estimation accuracy and observation redundancy.

3.1 State estimation accuracy

In this paper, the state estimation accuracy[1] is represented by the average node voltage amplitude estimation error and the average node voltage phase angle estimation error.

The estimation error of the average node voltage amplitude of the regional distribution grid is expressed as:

$$e_{mag} = \frac{1}{N}\sum_{n_k=1}^{2^k}\sum_{i=1}^{N}\tau_{n_k}\left|\left|V_{i,true}\right| - \left|V_{i,est}\right|\right| \tag{5}$$

The average node voltage phase angle estimation error of the regional distribution grid is expressed as:

$$e_{ang} = \frac{1}{N}\sum_{n_k=1}^{2^k}\sum_{i=1}^{N}\tau_{n_k}\left|\varphi_{i,true} - \varphi_{i,est}\right| \tag{6}$$

where, N represents the number of nodes; n_k represents the state number of the contact switch; τ_{nk} denotes the proportion of the n_k-th contact switch state, where $\sum_{n_k=1}^{2^k}\tau_{n_k} = 1$; $|V_{i,true}|$ represents the true value of the voltage amplitude of the ith node; $|V_{i,est}|$ represents the estimated value of the voltage amplitude of the ith node;$\varphi_{\mathrm{i,true}}$ represents the true value of the voltage phase angle of the ith node; $\varphi_{\mathrm{i,est}}$ represents the estimated value of the voltage phase angle of the ith node.

3.2 Observability redundancy

In the distribution grid, the ratio of the number of independent measurements to the number of state variables is called redundancy. For a grid with N nodes, the number of state phasors is N. The observation redundancy R_i for node i is shown as follows.

$$R_i = b_i + \sum_{j=1, j\neq i}^{N} a_{ij}d_{ij}b_j \tag{7}$$

Therefore, $R(B) = \sum_{n_k=1}^{2^k}\sum_{i=1}^{N}R_i$ is the total observed redundancy of the regional distribution grid under all switching conditions.

In summary, the dynamic observability index $O(B)$ for evaluating the configuration results of the acquisition terminal can be expressed as:

$$O(B) = \lambda_e\left(\alpha e_{mag} + \beta e_{ang}\right) + \lambda_r R(B) \tag{8}$$

where, α and β are the weights of amplitude error and phase angle error, this paper assumes that both are 0.5; λ_e and λ_r are the weight coefficients of the state estimation accuracy index and the total observation redundancy index, respectively.

4 Multi-objective optimization configuration model for acquisition terminals

Based on the content of the first two chapters, an optimal configuration model for acquisition terminals is proposed with the objective function of minimizing the cost of acquisition terminal configuration and maximizing dynamic observability. The objective function is represented as:

$$\begin{aligned} &\mathrm{argmin}\left(C(B) - O(B)\right) \\ &\quad s.t.\ R_i \geq 1 \\ &\quad C(B) \leq C_{\max} \\ &\quad e_{mag} \leq e_{\max.mag} \\ &\quad e_{ang} \leq e_{\max.ang} \end{aligned} \tag{9}$$

Where, C_{max} represents the upper limit of the total cost of the acquisition terminal configuration; $e_{max,mag}$ and $e_{max,ang}$ represent the allowable upper limits of voltage amplitude and phase angle error, respectively.

5 Case studies and analysis

The acquisition terminal optimization configuration model proposed in this paper uses 'Cplex', and the dual gap is set to 0 to ensure that all solutions are global optimal solutions.

1 State estimation accuracy is represented by the average node voltage amplitude estimation error and the average node voltage phase angle estimation error, obtained through a two-step mixed measurement method (Yuan et al., 2023).

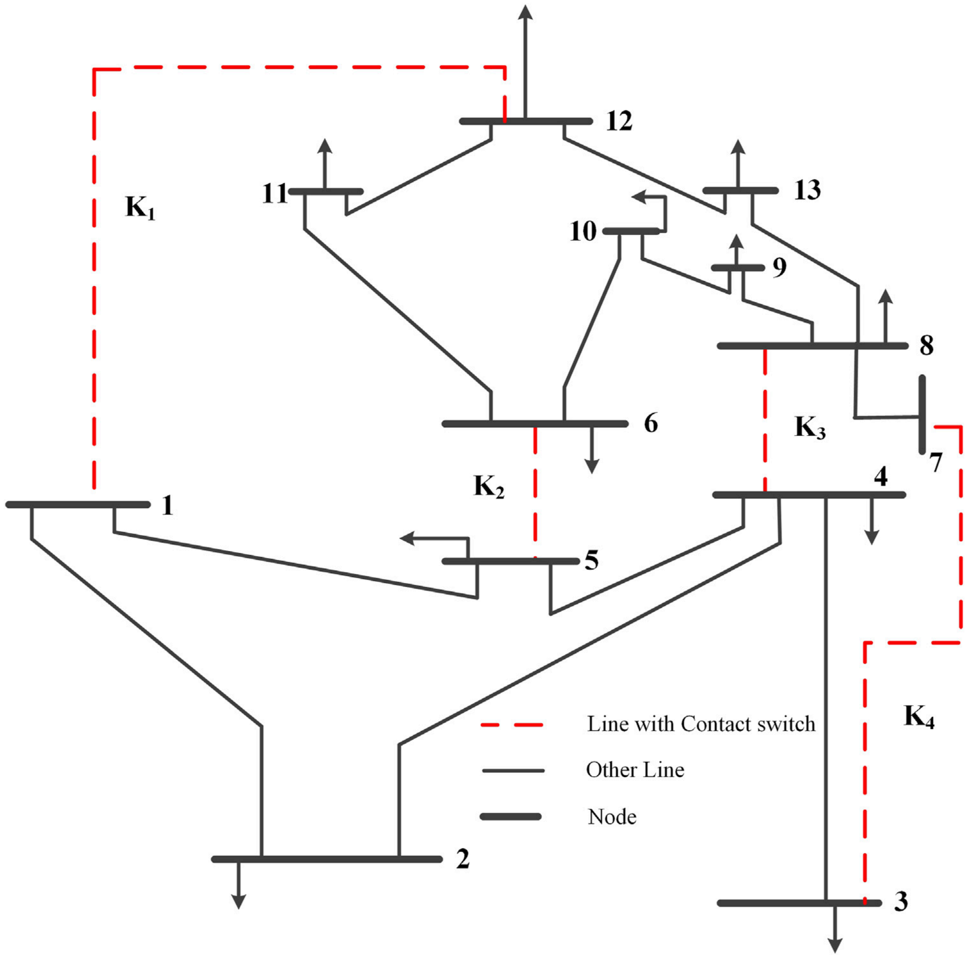

FIGURE 1
Simulation model topology.

5.1 Example description

This paper takes Figure 1 as the simulation model. In this model, there are 13 nodes, 16 branches and 4 contact switches. The node load data is taken from the first 13 nodes of the “IEEE 33” model.

5.2 Analysis of simulation results

The model assumes that the proportion of the main contact switch states is 0.6, while the proportion of other states is 0.4. $e_{max,mag}$ and $e_{max,ang}$ are 0.025 and 0.02 respectively.

Firstly, the simulation model is solved without considering the constraints of state estimation accuracy. Figure 2 shows the minimum number of acquisition terminals required and the maximum achievable system redundancy under all topology structures. From the Figure 2, different topology structures will directly affect the number of acquisition terminal configurations and the maximum redundancy of the system.

In order to further analyze the impact of terminal configuration position on dynamic observability, the proposed model algorithm was compared with the node voltage estimation error ranking method based on traditional measurement state estimation. As shown in Figure 3; Table 1, according to the optimal configuration results of the acquisition terminals obtained from the model proposed in this article, the average node voltage amplitude and phase angle error of all topology structures have basically decreased, proving that the method proposed in this article can effectively improve the accuracy of distribution grid state estimation. According to the method described in this article, when configuring the acquisition terminals at node {4, 5, 6, 8, 12}, the average state estimation error index for all topologies is 0.02325, and the total observable redundancy is 1.8594. In traditional methods, when configuring acquisition terminals at node {2, 3, 6, 8, 12}, the total state estimation error index for all topologies is 0.02763, and the average observable redundancy is 1.6756. From this, the method proposed in this paper is superior to traditional methods, proving the effectiveness of the proposed method.

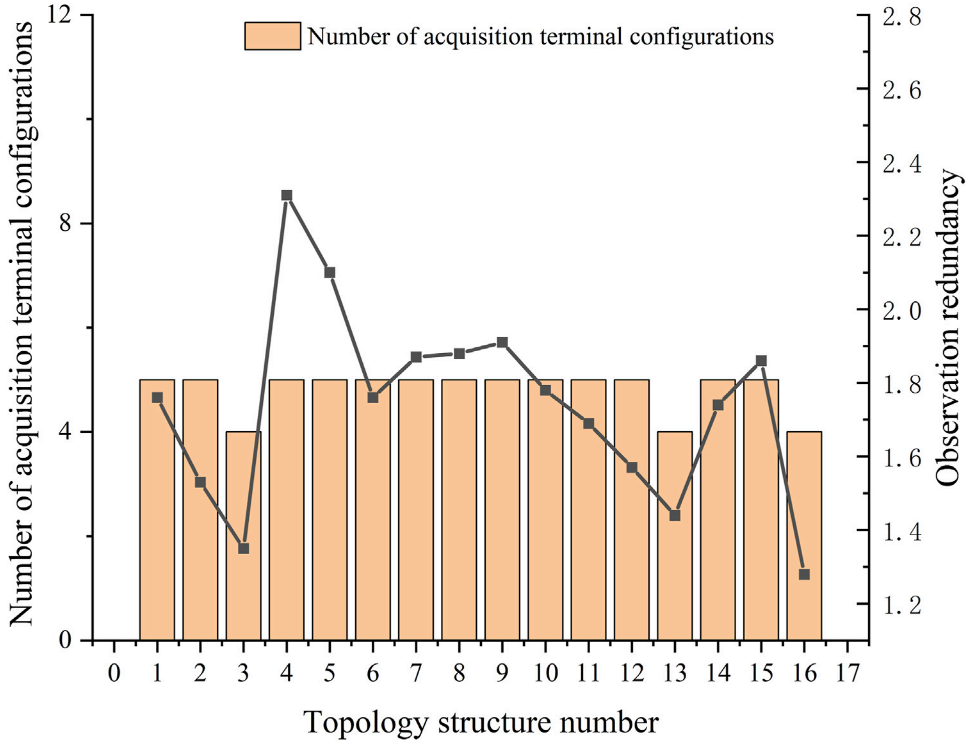

FIGURE 2
The impact of acquisition terminal configuration on redundancy.

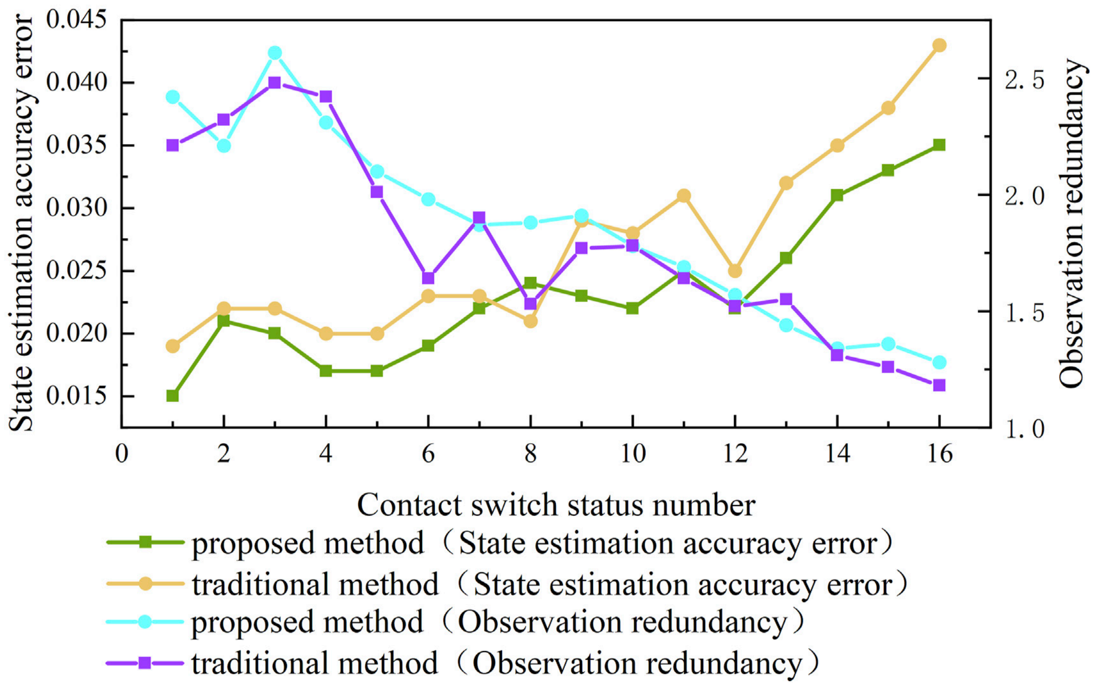

FIGURE 3
Influence of acquisition terminal configuration on state estimation accuracy error.

TABLE 1 Configuration results.

	Configuration results	Total observation redundancy	Average state estimation accuracy error
This method	Node 4、5、6、8、12	1.8594	0.02325
Traditional method	Node 2、3、6、8、12	1.6756	0.02763

6 Conclusion

This article proposes an optimized configuration model for data acquisition terminals that considers the dynamic observability of regional distribution grids. By analyzing the mapping relationship between the topology structure of regional distribution grids and the status of interconnection switches, a dynamic observability index is proposed based on observation redundancy and state estimation accuracy. Build a multi-objective configuration optimization model by combining the economic cost of collecting terminal configurations. The configuration results obtained by solving this model can meet the observability requirements of all topological structures in the regional distribution grid.

The next research direction can be combined with the development of the power Internet of Things. Based on the application scope and acquisition objects of different acquisition terminals, collaborative optimization of their deployment can be carried out to further improve the overall perception level of the distribution grid.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

YX: Conceptualization, Investigation, Writing–original draft. JH: Conceptualization, Writing–original draft. ZS: Data curation, Writing–original draft. TZ: Conceptualization, Writing–original draft. YuL: Software, Writing–original draft. TD: Formal Analysis, Writing–review and editing. WL: Supervision, Writing–review and editing. JL: Project administration, Supervision, Writing–review and editing. YH: Supervision, Writing–review and editing. LF: Visualization, Writing–review and editing. YiL: Validation, Writing–review and editing.

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Conflict of interest

Authors YX, ZS, WL, JL, LF, and YiL were employed by State Grid Zhejiang Electric Power Company. Authors JH and TD were employed by State Grid Zhejiang Electric Power Company. Authors YuL and YH were employed by State Grid Corporation of China.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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