Evaluation of optimization effect of distribution network frame with distributed power generation: Based on structural equation model

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Abstract. With the development of renewable energy, the integration of a large number of distributed power sources is an inevitable trend in the development of future power systems. In this paper, a comprehensive evaluation model is constructed based on structural equations to evaluate the optimization effect of the distribution network with distributed power sources.

1. Introduction

The high proportion renewable energy power systems is an important research content of China's power system development and planning: China's energy transition and development goal are to realize that non-fossil energy accounts for 15% and 20% of primary energy consumption in 2020 and 2030, respectively, and strive to achieve renewable energy accounts for 60% in 2050 [1-2]. With the gradual deepening of the power system reform, the power distribution network presents increasingly complex multi-source characteristics. The management model of the power distribution network has also undergone significant changes.

At present, much literature studied the core backbone network of the power system. For example, Dong F.F. et al. constructed a comprehensive index system for the survivability of the core backbone network from the aspects of resistance, recoverability and connectivity [3-4]. Wang H.L et al. used the electrical betweenness as the line importance's search weight and took the number of lines in the sub grid as the main factor and the sum of the sub grid search weight as the secondary factor to construct the core backbone optimization model [5]. From the above literature, we can see that the current core backbone network researches are based on the traditional intermittent energy source (IES) of the power system, without considering the role of distributed generation (DG) in the power system core backbone network and its impact on the power system.

With the rapid development of society and the increasing living standard of the people, society's demand for the power distribution network's capacity is gradually increasing. Under this background, the power distribution network develops rapidly. The introduction of DG in the traditional power distribution network makes the power distribution network increasingly powerful, which can be used as both the terminal and the starting point for the power system. Therefore, this report studied the optimization effect of the power distribution network frame with DG, which is essential for improving the system's disaster resilience and ensuring its power supply to important loads.
2. Comprehensive evaluation model for optimization effect of distribution network planning.

2.1. Model construction and identification
In this report, the comprehensive evaluation model for the optimization effect of regional power grid is constructed by Structural Equation Model (SEM). The model is shown in Figure 1.

A second-order confirmatory factor model can be determined by equations (1) and (2). In the equations, the distribution network optimization result is exogenous latent variables (ξ), reliability, safety, adaptability, economic benefits, and environmental benefits are endogenous latent variables (η), 13 indicators are observation variables (y), ε is the measurement residuals that cannot be fully explained by the latent variables, and ζ is the estimation error that cannot be fully explained by endogenous latent variables. Λ is the regression matrix explained by the endogenous latent variable (factor load from η to y), and Γ is the regression matrix explained by the endogenous latent variable (regression matrix form η to ξ).

\[ y = \Lambda \eta + \epsilon \]  
\[ \eta = \Gamma \xi + \zeta \]

2.2. Data collection and analysis
The data collected in this questionnaire is about the optimization effect of distribution network, so respondents who have a good understanding of the power industry is selected in this report. This
questionnaire survey lasted for nearly three months (From July 2019 to September 2019). A total of 300 questionnaires were issued, and 280 were recovered, with a recovery rate of 93%. Among them, 270 questionnaires were valid, with an effective rate of 90%.

In this study, SPSS 19.0 is used to carry out Cronbach's $\alpha$ test based on the data collected from the questionnaire survey. The test results are shown in Table 1. According to the research of Nunnally (1978), Cronbach's $\geq 0.7$ belongs to a credible range. Therefore, the overall reliability of the questionnaire belongs to high reliability, while the other five parts belong to medium reliability, which all meet the reliability requirements.

| Subscale category                      | Composition of subscales | Question number | Cronbach's $\alpha$ | Reliability level |
|----------------------------------------|--------------------------|-----------------|---------------------|------------------|
| Evaluation of optimization effect      |                          | 13              | 0.85                | High reliability |
| Reliability                            |                          | 2               | 0.618               | Credibility      |
| Security                               |                          | 2               | 0.606               | Credibility      |
| Adaptability                           |                          | 2               | 0.619               | Credibility      |
| Economic performance                   |                          | 6               | 0.604               | Credibility      |
| Environmental benefit                  |                          | 1               | 0.685               | Credibility      |

When the model fits well, KMO (Kaiser-Meyer-Olkin) test, and Bartlett sphere test are used in this paper to judge whether variables are suitable for factor analysis. The results are shown in Table 2. Table 3 shows that the overall KMO sample measure value of the questionnaire is 0.856, and the result of Bartlett sphere test is 0.000. It can be seen that the sample data collected in this questionnaire can meet the requirements of factor analysis.

| Inspection items                      | Overall Questionnaire   |
|---------------------------------------|-------------------------|
| Kaiser-Meyer-Olkin measurement         | 0.856                   |
| The approximate chi-square            | 1170.844                |
| Bartlett's sphericity test            |                         |
| Df                                    | 136                     |
| Sig.                                  | 0.000                   |

3. Comprehensive evaluation results and analysis

3.1. Model results and discussion
Modification of the model is divided into three steps: first perform parameter estimation test and then analyze the model fit. Secondly, check the standardized factor load and correction index of each variable. Finally, the model is revised based on the economic significance of each variable.

In the case of sample number 270, the absolute value of T value exceeding 1.96 can be regarded as significant. As shown in the Table 3, the non-standardized regression parameter of first-order factor market stability for second-order factor optimization effect is 0.89, standard error is 0.12, and t value is 7.60 (t-value is the original estimator divided by standard error). Since t-value is greater than 1.96, it reaches the significance level, indicating that this parameter is statistically significant. Other parameters also passed the significance test and were statistically significant.

For higher-order factor analysis, the most important coefficient is the path coefficient of higher-order factors. This parameter reflects the explanatory power of higher-order factors to primary factors and represents the relative importance of first-order factors to second-order factors. The results show that the standardized path coefficients of reliability, safety, adaptability, economic benefits and environmental benefits are 0.90, 0.96, 0.75, 0.88 and 0.73, respectively.
Table 3. Cronbach’s $\alpha$ reliability test results of the questionnaire

| Path | Nonstandard parameter estimation | Standard error | t-value | Parameter test $(t>1.96)$ |
|------|----------------------------------|----------------|---------|---------------------------|
| Reliability ← Optimization effect | 0.89 | 0.12 | 7.60 | Notable |
| Security ← Optimization effect | 1.04 | 0.13 | 8.35 | Notable |
| Adaptability ← Optimization effect | 0.76 | 0.08 | 9.19 | Notable |
| Economic benefit ← Optimization effect | 0.93 | 0.10 | 8.98 | Notable |
| Environmental benefit ← Optimization effect | 0.70 | 0.10 | 7.33 | Notable |

Table 4. Weight coefficient table of variables in distribution network optimization effect evaluation model

| First-level index | Weight $(\beta_i)$ | Second-level index $(\eta_j)$ | Weight $(\rho_{ij})$ | Third-level index |
|-------------------|--------------------|-------------------------------|---------------------|------------------|
| Evaluation on the optimization effect of distribution network $\xi_1$ | | | | |
| Reliability | 20.74% | 67.82% | y11 (Power supply Reliability rate) | |
| | | 32.18% | y12 (Cabling rate) | |
| Security | 24.88% | 61.06% | y21 (Comprehensive voltage qualification rate) | |
| | | 39.94% | y22 (N-1 pass rate) | |
| Adaptability | 17.28% | 50.66% | y31 (capacity load ratio) | |
| | | 49.34% | y32 (inter station contact rate) | |
| Economic benefit | 20.28% | 25.23% | y41 (Combined line loss ratio) | |
| | | 17.50% | y42 (Equipment utilization) | |
| | | 7.27% | y43 (Net present value) | |
| | | 17.27% | y44 (Payback period) | |
| | | 22.73% | y45 (Direct contribution rate of GDP) | |
| | | 10.00% | y46 (Employment rate) | |
| Social benefit | 16.82% | 100% | y51 (Degree of Environmental Improvement) | |

3.2. Model evaluation

By using the final model of the second order factor obtained above, the optimization effect of distribution network can be evaluated. This paper uses the correlation weight method to determine the weight of the index system.

The normalization formula is as follows:

$$\rho_{ij} = \lambda_{ij} / \sum_{j=1}^{n} \lambda_{ij}$$

(3)

Where, $\rho_{ij}$ is the corresponding weight of the j-th measurement index of first-order factor $\eta_i$, and the same method is applied to determine the weight of first-order factor.

The specific measurement method of the optimization effect of second-order factor distribution network is as follows:

$$\xi_{1(OF)} = \sum_{i=1}^{H} \beta_i \sum_{j=1}^{K} \rho_{ij} y_{ij}$$

(4)
Among them, \( \xi_j \) represents the optimization effect of distribution network grid, \( \beta_i \) represents the weight of first-order factor, \( \rho_{ij} \) is the weight of the \( j \) measurement index of first-order factor, \( y_{ij} \) represents the index value of the \( \eta_i \) measurement index of the first order factor. \( H \) represents the number of first-order factors, and \( K \) represents the corresponding number of indicators corresponding to first-order factors. The weight distribution of the evaluation index system for the optimization effect of distribution network grid is shown in Table 4.

4. Conclusion and countermeasures

In combination with the high IES penetration rate of the high-proportion renewable energy power system, this paper analyzes the core grid characteristics of the distributed power system and builds a related evaluation index system. Based on the structural equation model, this paper constructs a comprehensive evaluation model, which provides an important reference for the planning of the distribution network.

In a distribution network with distributed power sources, through real-time integration and planning of distributed power generation, better power quality, improved power supply safety, reliability, and loss savings can be obtained. Therefore, this article proposes the following countermeasures:

1) Improve the power grid's ability to gather and deliver new energy. First of all, the dispatching agency should give full play to the frequency and peak regulation capabilities of the coal power generating units at the sending and receiving ends. Secondly, the dispatching agency should make full use of the short-term and ultra-short-term power prediction results of renewable energy to revise the transmission curve on a rolling basis.

2) Increase the proportion of renewable energy transmission across provinces and regions. To give full play to the frequency and peak shaving capabilities of the coal-fired power generating units at the sending and receiving ends, the dispatching agency must make full use of the short-term and ultra-short-term power prediction results of renewable energy, and roll the power transmission curve.

3) Implement urban and rural distribution network construction and intelligent upgrade. On the one hand, power grid companies should continue to carry out the transformation and construction of distribution network, promote the construction of smart grid, and improve the coverage of distribution automation. On the other hand, the power grid company should enhance the acceptance ability of distributed energy and the guarantee ability of new terminal electricity such as clean heating.

References

[1] Yang W.H., Bi T.S., Huang S.F. (2011) An approach for critical lines identification based on the survivability of power grid. J. Proceedings of the CSEE., 31(7): 29-35.
[2] Pan X.D., Wu J, Liu D.C. (2014) A method for constructing core backbone grid in differential planning based on importance degrees of components. J. Automation of Electric Power Systems, 38(19): 40-46.
[3] Dong F.F., Liu D.C., Wu J. (2014) A method of constructing core backbone grid based on improved BBO optimization algorithm and survivability of power grid. Proceedings of the CSE, 34(16): 2659-2667.
[4] Zhao Y.J., Liu D.C, Wu J. (2014) Survivability evaluation of backbone network based on linear discriminant analysis and principal component analysis. Power System Technology, 38(2): 388-394.
[5] Wang H.L., Liu D.C., Wu J. (2014) Core backbone network searching based on improved quantum binary particle swarm optimization. Proceedings of the CSEE 34(34): 6127-6133.