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An Energy Efficiency Assessment Method for Distribution Network Containing DG

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Abstract

Energy efficiency assessment of distribution network containing distributed generation is one of the core contents of power grid construction. Aiming at the lack of a quantitative evaluation method for energy efficiency of distribution network containing distributed generation, a novel energy efficiency assessment method based on the super-efficiency model is proposed. Starting from the basic elements and operational requirements of the distribution network containing distributed generation, the energy efficiency assessment metric set is constructed. On this basis, the concept of generalized energy efficiency function is defined, and the super-efficiency model is used to assess the energy efficiency of the distribution network containing distributed generation. Finally, an example is given to evaluate and analyze energy efficiency. The results confirm the validity of the proposed method.

Keywords

Distributed Generation, Distribution Network, Super-Efficiency Model, Energy Efficiency Function, Energy Efficiency Evaluation

1. Introduction

The distribution network containing distributed generation (DG) is an important scene to absorb renewable energy and realize low-carbon development. Compared with the traditional distribution network, the distribution network containing DG has great changes in network structure, operation mode, functional position, and so on, which also puts forward higher requirements for maximizing the energy efficiency of the distribution network [1] [2] [3] [4] [5].

Energy efficiency evaluation is an efficiency evaluation of transforming input into output for the distribution network containing DG under the condition of meeting its basic elements and operation constraints. The energy efficiency of the distribution network is determined by the energy efficiency function relationship of input and output indexes in different scenarios. At present, the evaluation of energy efficiency of the distribution network is often from a single dimension, the evaluation method is often subjective, and the new characteristics of distribution network containing DG are not considered. The distribution network loss is not only related to the load rate, but also related to the access location, capacity, and power quality of DG [6].

The super efficiency model (SEM) is a planning model for solving the highest production technical efficiency, which can realize the full ranking of "relative advantages and disadvantages" among multiple objectives with multiple inputs and outputs. It has been widely used in the evaluation research of power systems. The model does not need to assume any initial value of weight in advance. The weight of each input and output index is obtained from the actual data of the evaluation object, which can effectively avoid subjective factors.

In this paper, the energy efficiency evaluation method of the distribution network containing DG based on SEM is established [7].

Firstly, starting from the basic elements and operation requirements of the distribution network, the index set of evaluation of energy efficiency in the distribution network containing DG is constructed. In order to distinguish the energy efficiency of the distribution network with and without DG, the DG permeability, power quality, and other indicators are introduced. Then, the concept of energy efficiency function is defined, the energy efficiency function is solved by SEM, and the appraisal value of energy efficiency of the evaluation object is determined. While comparing and evaluating the energy efficiency of the existing distribution network containing DG, the guiding planning and construction suggestions are put forward. Finally, a distribution network is taken as an example to verify the effectiveness of the proposed method.

2. Construction of Energy Efficiency Evaluation Index Set

1) Basic elements and operation requirements of distribution network containing DG

Distributed power grid, its energy efficiency is the efficiency of transforming the input into the output for the distribution network containing DG. In order to evaluate the energy efficiency of the distribution network containing DG, it is necessary to build the index set of the evaluation of energy efficiency in the distribution network containing DG first. The selection of the index of evaluation of energy efficiency should be based on the basic elements and operation requirements of distribution network containing DG.

The basic elements and operation requirements of the distribution network containing DG are shown in **Figure 1**. The basic elements include conventional generation, distributed generation, distribution network and load. The distribution network is generally a 35 kV or lower voltage grid, which is the link between the power supply and the load. In addition to the traditional electric load, the

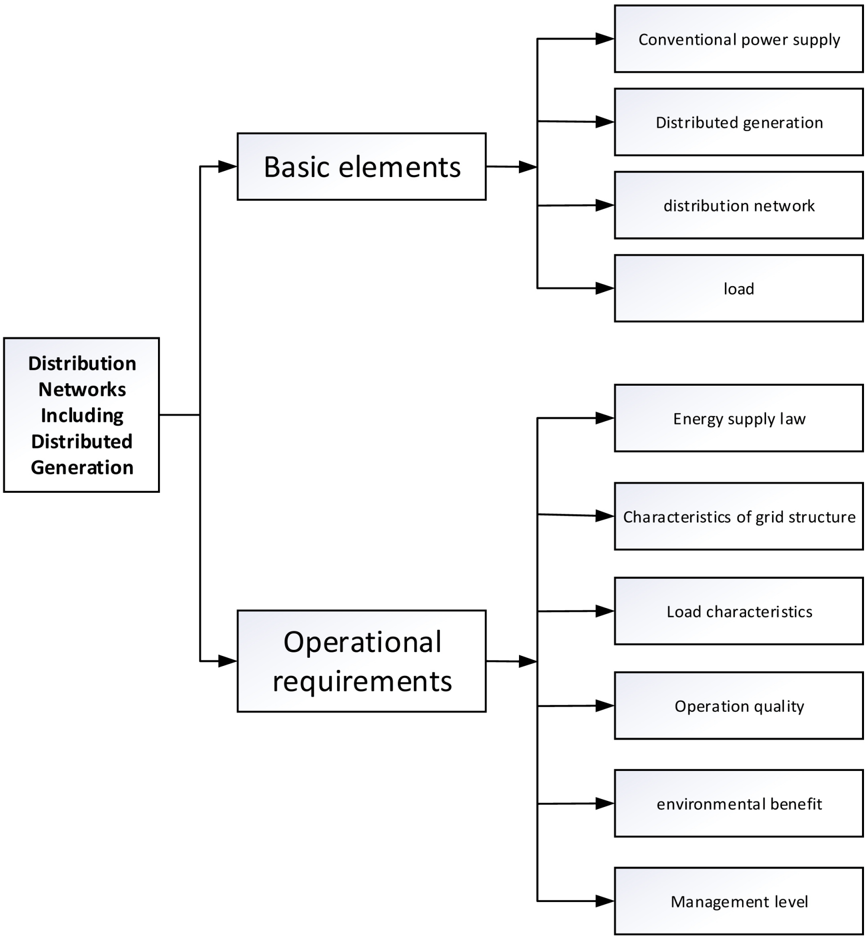

Figure 1. Basic elements and operation requirements of distribution network containing DG.

load also includes a variety of users who can actively respond to the needs of the grid, such as electric vehicle charging station.

In order to coordinate the basic elements of the distribution network containing DG, ensure the safe and stable operation of the distribution network, high-quality and reliable power supply, and maximize the operation efficiency of the distribution network containing DG, the distribution network containing DG must meet the operation requirements of energy supply law, network structure characteristics, load characteristics, operation quality, environmental benefits and management level.

2) Energy efficiency evaluation index set

Based on the basic elements and operation demand of distribution network containing DG, the index set of evaluation of energy efficiency is constructed. The index set follows the following principles: a) the selected indexes should be representative and can represent the basic elements of the distribution network containing DG and reflect many aspects of its operation demand; b) the selected indexes should be able to reflect one aspect of the input or output of the distribution network containing DG and should be as easy to obtain as possible.

According to the above principles, seven indexes including DG permeability, equivalent resistance, operation load, power quality, emission reduction, comprehensive cost and network loss are selected to form the index set of evaluation of energy efficiency in distribution network containing DG. Among them, DG permeability, power quality and emission reduction are only considered in the evaluation of evaluation of energy efficiency in distribution network containing DG.

a) DG permeability: It refers to the proportion of total power supply of DG in the total power demand of distribution network in the evaluation period. The high DG permeability indicates that renewable distributed power supply is the main energy supply mode.

b) Equivalent resistance: represents the elements of the distribution network and reflects the characteristics of the grid frame for distribution network operation, which refers to the total equivalent resistance of various basic equipments such as distribution network lines and transformers. The equivalent resistance of distribution network with different scales and grid structures is different.

c) Operation load: it represents the load elements, and reflects the load characteristic demand of distribution network operation, which refers to the total load size of DG distribution network within the evaluation and statistics time. The size of the operation load reflects the scale and management level of the distribution network to a certain extent.

d) Power quality: represents the elements of distribution network, and reflects the operation quality and management level requirements of distribution network. The power quality is determined by multi-dimensional indexes, such as voltage deviation, frequency deviation, voltage flicker, three-phase imbalance, harmonic, voltage sag and interruption, etc. The quantitative evaluation value of power quality is shown in **Table 1**.

e) Emission reduction: it represents the power supply elements and reflects the environmental benefit demand of distribution network operation. It refers to the reduction of pollutant emission when new energy or clean energy replaces traditional energy for power generation.

Table 1. Quantitative evaluation value of power quality.

category	Quantitative evaluation value range	Quality description
I	[0.9, 1.0]	High quality, good overall quality
II	[0.8, 0.9)	Good, 1 - 2 indicators have problems
III	[0.7, 0.8)	Good, there may be several indicators behind
IV	[0.6, 0.7)	Average performance, possible problems
V	[0, 0.6)	The problem is relatively prominent and may need to be dealt with

f) Comprehensive cost: it represents the elements of distribution network, mainly reflects the network structure characteristics and management level requirements of distribution network operation, and refers to the total input cost of DG distribution network operation in the evaluation period.

g) Network loss: it represents the elements of distribution network, reflects the network structure characteristics, operation quality and management level requirements of distribution network operation, and refers to the energy loss of network. This index is related to the structure of distribution network, reflects whether the power flow of distribution network is optimized, and also reflects the management level of distribution network operation.

Considering the input and output of distribution network, the index set of evaluation of energy efficiency in distribution network containing DG is decomposed into input index set and output index set, as shown in **Figure 2**.

3. Energy Efficiency Evaluation Method of Distribution Network with DG Based on Super Efficiency Model

1) Energy efficiency function of distribution network containing DG

In this paper, based on the index set of energy efficiency evaluation in distribution network with DG, the index set of input and the index set of output are obtained; then the energy efficiency function of distribution network with DG is given; finally, the energy efficiency evaluation value is solved by SEM to realize the energy efficiency evaluation of distribution network with multi-input and multi output.

There are Z distribution networks with DG to be evaluated, and the set of distribution networks with DG to be evaluated is $D = \{D_1, D_2, \cdots, D_Z\}$. Let the kth distribution network with DG to be evaluated be D_k, its index set of input be

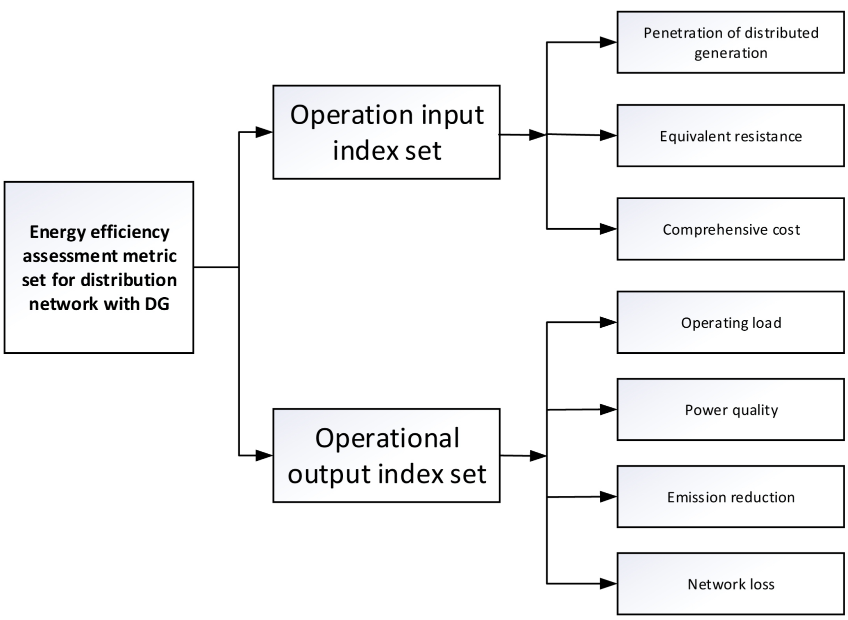

Figure 2. Energy efficiency assessment metric set for distribution network with DG.

$X_k = [x_{1k}, x_{2k}, x_{3k}]^T$, and its index set of output be $Y_k = [y_{1k}, y_{2k}, y_{3k}, y_{4k}]^T$. Let the weights of the rth input index and output index of D_k be w_{rk} and u_{rk} respectively, then its vector of weight of input index be $W_k = [w_{1k}, w_{2k}, w_{3k}]^T$ and the vector of weight of output index be $U_k = [u_{1k}, u_{2k}, u_{3k}, u_{4k}]^T$.

The energy efficiency function of distribution network with DG is as follows:

$$E_k(X_k, W_k, Y_k, U_k) = \frac{\sum_{q=1}^{4} u_{qk} y_{qk}}{\sum_{r=1}^{3} w_{rk} x_{rk}}, k = 1, 2, \cdots, Z \tag{1}$$

The weight vector in Equation (1) is a variable. It is necessary to select an appropriate algorithm to determine the reasonable weight vectors W_k and U_k to evaluate the energy efficiency of distribution network with DG.

2) Super efficiency energy efficiency evaluation model

Super efficiency model (SEM) is an improvement of data envelopment analysis (DEA), which can sort the energy efficiency of distribution network with DG with multi-input and multi-output. The SEM method can be used to solve the problem that the objective function value of multiple evaluation objects in DEA is limited to 1, and cannot be further sorted. All evaluation units can be fully sorted according to the evaluation value of energy efficiency from high to low. The specific steps of solving the above energy efficiency function by SEM are as follows.

a) With the help of DEA mechanism, taking W_k and U_k as optimization variables, taking the maximum function value E_k of DEA energy efficiency of the kth distribution network with DG as the objective, and taking the energy efficiency function value E_j of all evaluation objects as the constraint, the optimization model is constructed as follows:

$$\max E_k = \frac{\sum_{q=1}^{4} u_{qk} y_{qk}}{\sum_{r=1}^{3} w_{rk} x_{rk}} \tag{2}$$

$$s.t. \begin{cases} E_j \le 1, & j = 1, 2, \cdots, Z \\ w_{rk} \ge 0, & r = 1, 2, 3 \\ u_{qk} \ge 0, & q = 1, 2, 3, 4 \end{cases} \tag{3}$$

By using the Charnes-copper variant Equation (2), it can be transformed into a linear programming form:

$$g = \frac{1}{W_k^T X_k} \tag{4}$$

$$\alpha = g W_k \tag{5}$$

$$\beta = g U_k \tag{6}$$

where g is a numerical value, a and b are vectors. Then the linear programming model shown in Equations (7) and (8) can be obtained:

$$\max E_k = \beta^T Y_k \tag{7}$$

$$s.t.\begin{cases} \alpha X_j - \beta Y_j \ge 0, & j = 1,2,\cdots,Z \\ \alpha X_k = 1 \\ gw_{rk} \ge 0, & r = 1,2,3 \\ gu_{qk} \ge 0, & q = 1,2,3,4 \end{cases} \tag{8}$$

According to DEA algorithm, when W_k is the maximum, The solutions α and β of linear programming are called the optimal weight vector of D_k.

b) By using dual theory and SEM method, the linear programming model is improved and the super efficiency model of energy efficiency evaluation is obtained:

$$\min \theta_k \tag{9}$$

$$s.t.\begin{cases} \sum_{j=1, j\ne k}^{Z} \lambda_j x_{rj} + p_r = \theta_k x_{rk}, & r = 1,2,3 \\ \sum_{j=1, j\ne k}^{Z} \lambda_j y_{qj} - p_q = y_{qk}, & q = 1,2,3,4 \\ \lambda \ge 0, & j = 1,2,\cdots,Z \\ p_r \ge 0, p_q \ge 0 \end{cases} \tag{10}$$

where θ_k is the energy efficiency evaluation value of SEM of D_k, that is, the effective utilization degree of input relative to output; λ_j is the combination coefficient of the jth evaluation object; p_r and p_q are the relaxation variables of input index and output index respectively.

According to the above basic elements and operation requirements of distribution network with DG, more indicators meeting the selection principle can be added to the index set of energy efficiency evaluation in distribution network with DG, and the super efficiency model of evaluation is extended based on the constructed index set of energy efficiency evaluation in distribution network with DG to improve the accuracy and comprehensiveness of energy efficiency evaluation.

4. Example Analysis

1) Energy efficiency assessment

Taking the statistical data of 24 low voltage stations in Zhejiang distribution network with DG as an example, the basic index data and energy efficiency evaluation values of input index set and output index set of each evaluation object are shown in **Table 2**. The network loss rates of 24 typical low-voltage stations with DG in the above research object are statistically analyzed. The statistical results of the network loss rates are shown in **Table 3**.

2) Result analysis

Through the analysis of the results of the above examples, the following conclusions are drawn.

a) The traditional network loss rate and the generalized index of energy efficiency defined in this paper are used to evaluate the distribution network with

Table 2. Index data and energy efficiency of the evaluation object.

Station Area No	Equivalent resistance/Ω	DG permeability/%	Comprehensive cost/Ten million yuan	running load/MWh	Power quality	Emission reduction/t	Network loss/MWh	DEA Energy efficiency assessment value	SEM Energy efficiency assessment value	Network loss rate/%
1	17.30	25.39	7.13	42772.88	0.55	1.55	4875.936	0.942	0.942	10.233
2	19.58	26.85	7.23	37862.19	0.89	1.70	2627.411	1.000	1.112	6.489
3	18.85	29.19	6.58	52193.51	0.90	2.09	3517.618	1.000	1.096	6.314
4	17.60	31.00	5.31	50522.56	1.00	2.16	3776.923	1.000	1.145	6.956
5	21.40	31.16	8.18	37730.94	0.94	1.69	4542.223	0.917	0.917	10.745
6	17.68	31.66	4.66	34287.27	0.90	1.48	2040.124	1.000	1.409	5.616
7	22.80	32.64	9.96	42139.80	0.43	1.96	4498.326	0.837	0.837	9.645
8	22.47	35.19	7.88	48210.25	0.72	2.39	4623.460	0.951	0.951	8.751
9	16.28	35.61	6.69	40867.80	0.92	1.97	2247.269	1.000	1.131	5.212
10	22.03	36.93	6.12	47595.96	1.00	1.37	4963.199	0.860	0.860	9.443
11	22.10	37.22	8.03	36264.47	0.74	1.90	3460.966	0.754	0.754	8.712
12	19.75	38.38	4.83	46009.91	1.00	2.44	3431.816	1.000	1.002	6.941
13	24.57	40.69	7.15	44378.04	0.43	2.52	3719.246	0.884	0.884	7.733
14	17.91	40.77	7.18	29455.45	0.50	1.72	3433.821	0.698	0.698	10.441
15	20.05	41.92	6.43	44041.98	0.83	2.58	3799.487	0.909	0.909	7.942
16	19.95	45.84	4.38	49119.84	1.00	3.05	2691.595	1.000	1.225	5.195
17	23.16	46.65	5.84	41305.86	0.83	1.64	4749.342	0.687	0.687	10.312
18	25.34	48.54	6.36	39858.79	0.84	2.77	4544.691	0.838	0.838	10.235
19	24.26	49.32	9.60	35699.07	0.90	2.45	3005.718	0.747	0.747	7.766
20	17.82	50.99	5.15	28282.09	0.95	1.99	2113.645	1.000	1.020	6.954
21	20.27	52.36	8.45	33088.15	0.63	2.44	3183.187	0.752	0.752	8.776
22	25.40	56.63	8.33	33051.89	0.51	2.63	3122.386	0.695	0.695	8.632
23	16.31	56.90	4.63	42522.95	0.87	3.34	3097.810	1.000	1.337	6.790
24	26.31	62.96	8.91	37042.78	0.42	3.34	4215.221	0.808	0.808	10.217

Table 3. Partition statistics of network loss rate.

Range of network loss rate	Station Area No
[5%, 6%)	16, 9, 6
[6%, 7%)	3, 2, 23, 12, 20, 4
[7%, 8%)	13, 19, 15
[8%, 9%)	22, 11, 8, 21
[9%, 10%)	10, 7
[10%, 11%)	24, 1, 18, 17, 14, 5

DG, and the results are consistent on the whole. The low voltage substation area with higher energy efficiency evaluation value has lower network loss rate. Therefore, the energy efficiency evaluation method proposed in this paper is effective, and can give objective and comprehensive evaluation results combined with more dimensional evaluation indexes.

b) Take No. 1, No. 5 and No. 22 stations as examples to analyze. Although the network loss rate of No. 1 and No. 5 substation is higher than that of No. 22 substation, but the final evaluation results show that the evaluation values of energy efficiency of No. 1 and No. 5 substation are higher than that of No. 22 substation, which indicates that the energy efficiency evaluation of distribution network with DG cannot be determined only by the network loss rate or other single index. The index set of energy efficiency evaluation of distribution network with DG should involve as many indexes as possible, and the energy effect is determined by the relationship between input and output.

c) From the data analysis of DG permeability and network loss rate, it can be seen that the network loss rate and DG permeability of distribution network show a certain proportional law, that is, the higher the DG permeability is, the lower the network loss rate is. However, according to **Table 2**, there is a complex relationship between network loss rate and permeability, equivalent resistance, power quality, and other indicators. The network loss rate is relatively low in the station area with small equivalent resistance, good power quality, and high operation load. This relationship can be well reflected by the index of SEM.

d) By comparing the evaluation values of energy efficiency of the research objects [2] [3] [4] [8] [9] [10] by DEA and SEM, we can see that the DEA method has limitations. The evaluation value of energy efficiency of some research objects by DEA is limited to the highest point 1. When the evaluation value of energy efficiency of multiple research objects by DEA is 1, the energy efficiency of these research objects cannot be further compared. SEM method can effectively improve the limitations of the DEA method. The evaluation value of energy efficiency obtained by the SEM method is limited to 1, which improves the granularity of energy efficiency evaluation and effectively solves the problem of sorting all stations according to the evaluation value of energy efficiency.

5. Conclusion

This paper presents a research idea of efficiency utilization relationship between input and output of distribution network with DG, and designs evaluation method of energy efficiency based on SEM. The evaluation method of energy efficiency of distribution network with DG based on the super efficiency model is proposed in this paper. The evaluation set of energy efficiency composed of multiple indexes is effectively used. According to the relationship between input and output of distribution network, the objective and scientific evaluation of energy efficiency of distribution network with DG is realized. The experimental results show that the traditional narrow evaluation method of energy efficiency under a single index is difficult to meet the requirements of energy efficiency assessment of distribution networks with DG, which cannot consider the operational requirements of the distribution network, but also ignore the influence of input factors on energy efficiency assessment. SEM method is used to solve the evaluation value of energy efficiency of distribution network with DG, and the energy efficiency of distribution network with multi-input and multi-output is sorted. It is of great value to promote the staff of power supply companies, investment enterprises, government, and other relevant departments in the investment and construction, system planning, and operation and maintenance of the distribution network including DG.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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