Energy Efficiency Evaluation of Distribution Network Considering Power Quality Conditions

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Abstract. There are three-phase imbalance, voltage deviation, frequency fluctuation and other power quality problems in the traditional AC distribution network, which are difficult to meet the demand of power users for high power quality. The AC-DC hybrid distribution network is superior to the AC distribution system in terms of reducing power loss and improving power supply quality. Based on the research status of energy-saving indexes of distribution network, considering the characteristics of AC-DC hybrid distribution network, this paper analyzes the factors that affect the energy efficiency level of AC-DC hybrid distribution system, constructs the evaluation index system, determines the classification evaluation standards of different indexes according to the relevant standards, and puts forward the quantitative evaluation method of the energy efficiency level of AC-DC hybrid distribution network.

Keywords. Power quality; energy efficiency index; comprehensive evaluation; national standard.

1. Introduction

The traditional AC power distribution system faces a series of problems, such as large line loss, three-phase imbalance, and shortage of power supply corridors, which are difficult to satisfy the growing demand of power users. With the implementation of national new energy utilization strategy, more and more attention has been paid to distributed generation for its advantages of low transmission loss and high reliability. Renewable energy sources must undergo multiple electrical energy conversions before they can be converted into qualified alternating current before they can be connected to the AC distribution network. The increase of alternating current and direct current transformation links not only increases the investment cost of the system, but also affects the reliability of the system [1-3].

Compared with AC distribution network, DC power supply has obvious advantages in the power supply system with distributed power access and a large number of switching power loads. But at present, the research of DC distribution network is still in its infancy. and there are a lot of problems to be studied, which can not replace AC distribution network in a short while. Therefore, AC-DC hybrid power distribution system is more likely to become a mode of distribution network in the future [4].

As a major energy consumer, power grid enterprises should pay attention to the work of energy-saving and loss-reducing. The transmission network has high voltage level, high reliability and small loss. At present, the average line loss rate of UHV, UHV and high-voltage power grid in China is between 1% and 2%; while the line loss rate of medium and low voltage power grid with 35kV and below is between 2% and 7%, which is significantly higher than that of 66kV and above, and accounts for about 70% of the line loss, indicating that the key point of energy conservation and consumption...
At home and abroad, energy efficiency of distribution network has been investigated and analyzed to varying degrees. Foreign countries have focused on how to reduce line loss. In China, the loss analysis and related experimental research on equipment, such as harmonic and three-phase imbalance, have been mainly carried out. In addition, some relevant literature has put forward some valuable evaluation indexes and methods for energy efficiency evaluation of power distribution network, but there is still lack of systematic research. The established index system focuses on one aspect, or the evaluation method fails to reflect the energy efficiency level of the power distribution network on the whole. Ref. [5] only evaluates the use ratio of power distribution network equipment, considering the establishment of index system from the different operation states of lines and distribution transformers, and lacks the static index reflecting the equipment parameters; Ref. [6] establishes index system for different voltage levels of distribution network, and does not consider the influence of distribution network structure difference and load density in different regions on the evaluation results. Ref. [7] is only limited to the system loss, and the energy utilization efficiency should be improved on the premise of ensuring certain performance indexes such as safety and reliability.

With regard to the AC-DC hybrid power distribution network, there have been relevant demonstration projects in the world, but most of them focus on the research of operation control technology, protection technology, etc. [8], and the research about the energy efficiency of the AC-DC hybrid power distribution network is less. According to the principle of differentiation, a technical and economic evaluation index system of AC/DC distribution power network is established in Ref. [9], but the evaluation index does not consider the influence of structure and equipment of AC / DC hybrid power distribution network on energy efficiency. In Ref. [10], the energy efficiency evaluation system of DC power distribution network with super capacitor hybrid energy storage device is proposed, which is not comprehensive in the selection of energy efficiency indexes, such as the charging and discharging efficiency is not considered into the energy storage.

Therefore, this paper divides the AC-DC hybrid power distribution network into four parts: medium-voltage distribution power network, distribution transformer, low-voltage DC distribution power network and low-voltage AC distribution power network, set up energy efficiency index system from the whole perspective, considers the depth of energy efficiency indexes at all levels, the correlation between the indexes, etc., and makes a more reasonable and comprehensive evaluation of energy efficiency level of the AC-DC hybrid power distribution network.

2. AC/DC Hybrid Distribution System
In this paper, the chain structure of AC-DC hybrid distribution network is proposed for modeling. The main components of the network structure are energy storage device, distributed power supply, DC load, rectifier inverter device, etc., which can effectively improve the permeability of renewable energy and raise the energy efficiency of distribution network. The simplified AC/DC hybrid power distribution system topology is shown in figure 1.

The access and application of the energy storage device and the distributed power supply can not only locally compensate the randomness of output power of distributed power supply, but also cut the peak and fill the valley of the load, so as to keep the load fluctuation relatively stable in each period [11-14]. Therefore, the distributed power supply and energy storage device will have a direct impact on the energy efficiency of AC-DC hybrid power distribution network.

3. Energy Efficiency Index System
The index system of power grid energy efficiency is an organic combination of system operation status and energy efficiency management level. To fully reflect the actual energy efficiency levels of the whole and each part of the AC-DC hybrid power distribution network, in this paper, analyzes the factors affecting the energy efficiency of the AC-DC hybrid power distribution network, and
establishes the index system of energy efficiency based on the relevant standards and specifications formulated by the state or industry.

Figure 1. The simplified diagram of AC/DC hybrid power distribution network.

3.1. Principles of Index System Construction

Compared with the safety, stability and stability of the high-voltage transmission network, the distribution network has put forward higher requirements for the reliability and economic index of power supply. Therefore, the objective function of energy efficiency evaluation of AC-DC hybrid power distribution network is to improve the energy utilization efficiency and minimize the loss of distribution network under the constraints of ensuring power quality and certain power supply reliability.

On the one hand, distribution network loss is usually composed of load loss and no-load loss. Load loss are copper losses in distribution equipment and are proportional to the square of the flow current. No-load loss refers to core loss, corona loss, insulation medium loss, etc. in the substation equipment, which is related to the operating voltage. Therefore, the comprehensive line loss rate index can not fully reflect the loss of distribution network. On the other hand, the energy efficiency evaluation focuses on that the power supply load of distribution network can be within the economic load range of distribution lines and transformers. Therefore, it is not only based on the level of line loss rate and distribution network construction standards to infer the local distribution network energy efficiency level.

China’s AC/DC hybrid distribution network is under construction, most of which use flexible, direct technology to upgrade the existing distribution network. Because of the differences of distribution networks in different regions in China, such as regional differences, development level differences, as well as the influence of urbanization process and other factors, the structure and load characteristics of AC-DC hybrid distribution networks are also different. Moreover, due to the existence of non-destructive electricity in the power supply system, the caliber of statistical line loss is not completely unified, which brings great difficulty to energy efficiency evaluation.

Based on this, in this paper, the energy efficiency index of AC-DC hybrid distribution network is divided from three aspects: static index, operation index and loss index.

3.2. Index System Construction

In the AC/DC hybrid power distribution network, the factors that affect system energy efficiency are:

1) Conductor resistance. The resistance of the wire is proportional to the radius of the power supply and inversely proportional to the size of the cross section of the wire. When the current is constant, reducing the line resistance can effectively reduce the power loss.

2) Power factor. For the AC/DC hybrid power distribution system, a lot of power electronic devices are used to generate harmonic pollution, but also raise the power loss of the AC system and AC load, reduce the power factor and system energy efficiency level of the AC side. By installing the
reactive power compensation device for distribution network, the power factor can be improved and the loss can be reduced.

3) Bus voltage. The system loss is divided into variable loss and fixed loss in DL/T 686-1999. The size of bus voltage will have a direct impact on the system loss. Too low, the variable loss will increase, too high, the fixed loss will increase. Therefore, it is necessary to reasonably regulate the bus voltage range and reduce the system loss.

4) Three phase load imbalance. In the AC/DC hybrid power distribution system, the instability of single-phase connected distributed power and load will easily lead to the three-phase imbalance of the system, reduce the transmission capacity of the distribution line and increase the line loss.

5) Converter efficiency. The type of converter should be low loss and high efficiency. The converter efficiency standard is formulated according to the relevant specifications of “full inverter efficiency of grid connected photovoltaic inverter” (en50530-2010).

6) Harmonic distortion rate. Power harmonics are mainly generated by nonlinear loads. For the power system, the power harmonic will reduce equipment utilization and increase the additional power loss of the power supply equipment.

7) Distributed power supply. The distribution network loss will change after the distributed generation is connected to the grid. Appropriate access location and capacity can reduce the power loss. At the same time, due to the emergence of multi power supply, there will be two-way power flow, which will change part of the grid voltage.

8) Energy storage device. The access of the energy storage device improves the daily load rate of the system, realizes load peak shaving and valley filling, keeps the balance between the input power and output power, and reduces the power loss. But meanwhile, the energy storage device will also produce energy storage loss, which will raise the energy consumption of the distribution network, so the charge discharge efficiency of energy storage system is included in the index system.

9) Distribution transformer energy efficiency value. In the distribution network, the power consumption of distribution transformer is very large, and its loss accounts for more than 30% of the total loss of the distribution network. The energy efficiency of power grid is affected by the energy efficiency value of equipment itself.

Refer to [6-7, 15-16] and relevant national or industrial standards [17-22], the energy efficiency index of AC-DC hybrid power distribution network constructed by combining above analysis is shown in figure 2.

3.3. Index System Description

This paper considers the overall energy efficiency level of AC / DC hybrid distribution network from four aspects: medium voltage distribution network, distribution transformer, low-voltage DC distribution network and low-voltage AC distribution network. The indicators are further refined, including static indicators, operation indicators and loss indicators. The static indicators are the impact of static parameters such as the structure and equipment of the distribution network on energy efficiency, such as line parameters, reactive compensation capacity, distributed power capacity, etc.; the operation indicators reflex the energy efficiency level of the distribution power network equipment in operation, such as voltage qualification rate, power factor, etc.; the loss indicators are the main ones. There should be line loss and distribution transformer loss to directly reflect the power grid energy efficiency.

Because the power supply radius of the line is affected by the load density and terminal voltage drop, the standards in different regions are different. Therefore, the benchmark values of power supply radius and various losses (see table 1) will be considered in classification to make the evaluation results more reasonable. The operation life of the line has a non-linear relationship with energy efficiency, so the treatment of the operation life index of the line is shown in table 2. The positive index refers to the index value positively correlated with energy efficiency level, such as average cross section of conductor, voltage qualification rate, etc.; the reverse index refers to the index value negatively correlated with energy efficiency level, such as line life, average power supply radius and
so on., and the proportion of distributed power capacity within the limited scope is considered as the positive index.

![Energy efficiency indices system of AC-DC hybrid power distribution network.](image-url)

**Figure 2.** Energy efficiency indices system of AC-DC hybrid power distribution network.
Table 1. The baseline values of energy efficiency index for different regions.

| Power supply area          | Medium-voltage distribution network | Distribution transformer | Low voltage distribution network | Power supply area          | Medium-voltage distribution network |
|---------------------------|-------------------------------------|--------------------------|----------------------------------|---------------------------|-------------------------------------|
|                           | Supply radius                       | Line loss rate           | Transformer loss rate            | Supply radius             | Line loss rate                      |
| Urban area                | 3 km                                | 3.0%                     | 2.0%                             | 150 m                     | 6.0%                               |
| Suburb                    | 5 km                                | 4.0%                     | 2.5%                             | 250 m                     | 8.0%                               |
| Countryside               | 10 km                               | 5.0%                     | 3.0%                             | 400 m                     | 10.0%                              |

Table 2. The scalar corresponding to lines operating years.

| Service life | scalar |
|--------------|--------|
| <5           | 100    |
| 5-10         | 90     |
| 10-15        | 80     |
| 15-20        | 70     |
| >20          | 60     |

4. Evaluation Method and Case Analysis

In this paper, AHP is used for evaluation. The basic steps are as follows:

1. In order to deeply analyze the practical problems, the hierarchy is established to analyze the structure of the model. Here, the relevant factors are layered from top to bottom. The lower layer affects the upper layer, and the factors within the layer are basically independent.

2. The pairwise comparison matrix was constructed by using pairwise comparison method and 1-9 scale.

3. For each pair of comparison matrices, eigenvectors and maximum eigenvalues are calculated, and consistency tests are performed. If they pass, the eigenvector is the weight vector.

4. The combination weight vector can be selected as a quantitative basis for decision-making.

Due to the lack of actual engineering data of low-voltage DC distribution network, combined with the simulation data, based on the operation data between distribution networks in the same region, it is the original index data for the energy efficiency evaluation of AC-DC hybrid distribution network, see tables A1 and A2 in appendix A for the original parameters, reference values and normalized scalars of each index. See tables A3 and A4 in appendix A for the weight of layer index and table A5 in appendix A for the comparison of index scores of two regions. The energy efficiency level of power grid can be divided into five levels according to the comprehensive score, and the specific division method is shown in table 3. See tables 4-7 for index weight of medium-voltage distribution network, distribution transformer, low-voltage DC distribution network and low-voltage AC distribution network.

From tables 8 and 9, it can be concluded that the regional energy efficiency level is slightly lower. Comparing the index scores of each layer, it is found that the operation index and loss index scores are relatively low in the regional medium-voltage distribution network, specifically, index scores of the average total capacity of distribution and transformation equipment and the line loss qualification rate of a single line are relatively low (see table A5 in appendix A for details). The high installed capacity of distribution and transformation will lead to idle capacity of transformer equipment and increase loss. It is recommended to replace large section conductor and increase outgoing line of substation to ensure economic operation of power grid. For lines with high line loss, new energy-saving lines and optimization of power supply radius can be adopted to reduce line loss.

Table 3. Energy efficiency grading standards for distribution network.

| Comprehensive score | >90 | 80-90 | 70-80 | 60-70 | <60 |
|---------------------|-----|-------|-------|-------|-----|
| Energy efficiency level | Fine | Good | Medium | qualified | Un-qualified |
Table 4. Weight of indices in MV distribution grid.

| Index | Intra group weight | Total weight | Index | Intra group weight | Total weight | Index | Intra group weight | Total weight |
|-------|--------------------|--------------|-------|--------------------|--------------|-------|--------------------|--------------|
| $p_1$ | 0.1136             | 0.0072       | $p_4$ | 0.1977             | 0.0125       | $p_7$ | 0.1219             | 0.0140       |
| $p_2$ | 0.3702             | 0.0234       | $p_5$ | 0.3196             | 0.0368       | $p_8$ | 0.2500             | 0.0523       |
| $p_3$ | 0.3186             | 0.0202       | $p_6$ | 0.5584             | 0.0643       | $p_9$ | 0.7500             | 0.1568       |

Table 5. Weight of indices in distribution transformer.

| Index | Intra group weight | Total weight | Index | Intra group weight | Total weight | Index | Intra group weight | Total weight |
|-------|--------------------|--------------|-------|--------------------|--------------|-------|--------------------|--------------|
| $p_{10}$ | 0.0974            | 0.0027       | $p_{14}$ | 0.2297            | 0.0116       |       |                    |              |
| $p_{11}$ | 0.3331             | 0.0092       | $p_{15}$ | 0.1220             | 0.0061       |       |                    |              |
| $p_{12}$ | 0.5695             | 0.0157       | $p_{16}$ | 0.8333             | 0.0761       |       |                    |              |
| $p_{13}$ | 0.6483             | 0.0326       | $p_{17}$ | 0.1667             | 0.0152       |       |                    |              |

Table 6. Weight of indices in low-voltage DC power distribution lines.

| Index | Intra weight | Total weight | Index | Intra weight | Total weight | Index | Intra weight | Total weight |
|-------|--------------|--------------|-------|--------------|--------------|-------|--------------|--------------|
| $p_{18}$ | 0.4512     | 0.0327       | $p_{22}$ | 0.5423     | 0.0714       | $p_{26}$ | 0.0958     | 0.0126       |
| $p_{19}$ | 0.2609     | 0.0189       | $p_{23}$ | 0.1323     | 0.0174       | $p_{27}$ | 0.3333     | 0.0798       |
| $p_{20}$ | 0.1190     | 0.0086       | $p_{24}$ | 0.0958     | 0.0126       | $p_{28}$ | 0.6667     | 0.1595       |
| $p_{21}$ | 0.1689     | 0.0122       | $p_{25}$ | 0.1338     | 0.0176       |       |            |              |

Table 7. Weight of indices in low-voltage AC power distribution lines.

| Index | Intra weight | Total weight | Index | Intra weight | Total weight | Index | Intra weight | Total weight |
|-------|--------------|--------------|-------|--------------|--------------|-------|--------------|--------------|
| $p_{29}$ | 0.3337     | 0.033        | $p_{33}$ | 0.0821     | 0.008        | $p_{37}$ | 0.1827     | 0.029        |
| $p_{30}$ | 0.2415     | 0.024        | $p_{34}$ | 0.0652     | 0.006        | $p_{38}$ | 0.0884     | 0.014        |
| $p_{31}$ | 0.1691     | 0.017        | $p_{35}$ | 0.3529     | 0.055        | $p_{39}$ | 0.3333     | 0.014        |
| $p_{32}$ | 0.1084     | 0.011        | $p_{36}$ | 0.3759     | 0.059        | $p_{40}$ | 0.6667     | 0.028        |

Table 8. Index values and comprehensive scores table of distribution network in X district.

| Energy efficiency | $A_1$ | $B_1$ | $B_2$ | $B_3$ |
|-------------------|-------|-------|-------|-------|
| Total             | 92.5102 |
| $A_1$             | 27.0269 | 2.0111 | 8.3698 | 16.4640 |
| $A_2$             | 9.4420  | 1.4684 | 3.6058 | 4.3678  |
| $A_3$             | 29.1459 | 3.4177 | 9.3542 | 16.3740 |
| $A_4$             | 26.8954 | 3.0330 | 8.8061 | 15.0563 |

Table 9. Index values and comprehensive scores table of distribution network in Y district.

| Energy efficiency | $A_1$ | $B_1$ | $B_2$ | $B_3$ |
|-------------------|-------|-------|-------|-------|
| Total             | 88.4178 |
| $A_1$             | 23.0723 | 2.5206 | 6.2785 | 14.2732 |
| $A_2$             | 9.4420  | 1.4684 | 3.6058 | 4.3678  |
| $A_3$             | 29.1459 | 3.4177 | 9.3542 | 16.3740 |
| $A_4$             | 26.8954 | 3.0330 | 8.8061 | 15.0563 |
5. Conclusion
In this paper, analyzes the topology structure and working principle of AC-DC hybrid power distribution network. An energy efficiency index system is established based on the characteristics of AC-DC hybrid distribution system and the factors affecting the energy efficiency level of power grid, which covers the static index, operation index and loss index from the four aspects of medium-voltage distribution network, distribution transformer, low-voltage AC distribution network and low-voltage DC distribution network, ensuring the integrity of indicators. Finally, combined with some project operation data and simulation data for case analysis, according to the results, the analysis shows that the AC/DC hybrid distribution network has a high energy efficiency level. Due to the poor energy efficiency level of the traditional AC distribution network, in the future, the AC-DC hybrid power distribution system is more possibly become a distribution network mode.

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## Appendix A

**Table A1.** Original data, reference value, and scalar of indexes in X district.

| Static Index | Actual Value | Reference Value | Scalar | Operation Index | Actual Value | Reference Value | Scalar | Loss Index | Actual Value | Reference Value | Scalar |
|--------------|--------------|-----------------|--------|----------------|--------------|-----------------|--------|------------|--------------|-----------------|--------|
| $p_1$        | 13.0500      | 4.0000          | 30.6513| $p_5$         | 12333.3333   | 22000.0000      | 178.3784| 0.0686     | 0.0700       | 101.9762        |        |
| $p_2$        | 0.5000       | 0.9300          | 53.7634| $p_6$         | 0.6000       | 0.8900          | 67.4157| 1.0000     | 0.8500       | 117.6471        |        |
| $p_3$        | 0.1200       | 0.9000          | 13.3333| $p_7$         | 0.6800       | 0.9000          | 75.5556|            |              |                 |        |
| $p_4$        | 8.0000       |                 | 90.0000|              |              |                 |        |            |              |                 |        |
| $p_{10}$     | 0.1897       | 0.3000          | 63.2184| $p_{13}$      | 0.7500       | 0.8000          | 93.7500| 0.0310     | 0.0200       | 64.5161         |        |
| $p_{11}$     | 5.0000       |                 | 90.0000| $p_{14}$      | 0.8365       | 0.9000          | 92.9444| 0.7000     | 0.8000       | 87.5000         |        |
| $p_{12}$     | 0.2100       | 0.3000          | 70.0000| $p_{15}$      | 0.0600       | 0.1000          | 166.6667|            |              |                 |        |
| $p_{18}$     | 0.3000       | 0.2000          | 66.6667| $p_{22}$      | 0.8300       | 0.8000          | 103.7500| 0.0792     | 0.0800       | 101.0101        |        |
| $p_{19}$     | 120.0000     | 200.0000        | 60.0000| $p_{23}$      | 0.8200       | 0.9000          | 91.1111| 0.8170     | 0.8500       | 96.1176         |        |
| $p_{20}$     | 0.1650       | 0.2000          | 82.5000| $p_{24}$      | 0.1200       | 0.1000          | 83.3333|            |              |                 |        |
| $p_{21}$     | 0.1760       | 0.2500          | 70.4000| $p_{25}$      | 0.0160       | 0.0200          | 125.0000|            |              |                 |        |
| $p_{26}$     | 0.8000       | 0.9000          | 88.8889|              |              |                 |        |            |              |                 |        |
| $p_{29}$     | 0.3200       | 0.2000          | 62.5000| $p_{35}$      | 3.1000       | 3.0000          | 96.7742| 0.0746     | 0.0800       | 107.2386        |        |
| $p_{30}$     | 0.8800       | 0.9000          | 97.7778| $p_{36}$      | 0.8400       | 0.9000          | 93.3333| 0.8700     | 0.8500       | 102.3529        |        |
| $p_{31}$     | 75.0000      | 200.0000        | 37.5000| $p_{37}$      | 3.1000       | 3.5000          | 88.5714|            |              |                 |        |
| $p_{32}$     | 0.0000       | 0.9000          | 0.0000 | $p_{38}$      | 0.0000       | 0.2000          | 0.0000|            |              |                 |        |
| $p_{33}$     | 16.0000      | 50.0000         | 32.0000|              |              |                 |        |            |              |                 |        |
| $p_{34}$     | 0.0000       | 0.9000          | 0.0000 |              |              |                 |        |            |              |                 |        |
Table A2. Original data, reference value, and scalar of indexes in Y district.

| Static index | Actual value | Reference value | Scalar | Operation index | Actual value | Reference value | Scalar | Loss index | Actual value | Reference value | Scalar |
|--------------|--------------|-----------------|--------|----------------|--------------|-----------------|--------|------------|--------------|----------------|--------|
| $p_1$        | 5.1667       | 4.0000          | 77.419 | $p_5$          | 19038.3333   | 22000.0000     | 115.5563 | $p_4$      | 0.0610       | 0.0700         | 114.7541 |
| $p_2$        | 0.7000       | 0.9300          | 75.2688| $p_6$          | 0.5000       | 0.8900          | 56.1798 | $p_6$      | 0.7800       | 0.8500         | 91.7647 |
| $p_3$        | 0.0700       | 0.9000          | 7.7778 | $p_7$          | 0.7100       | 0.9000          | 78.8889 | $p_7$      | 0.7200       | 0.8000         | 90.0000 |
| $p_4$        | 9.0000       | 90.0000         |        |                |              |                 |        |            |              |                |        |
| $p_{10}$     | 0.2000       | 0.3000          | 66.6667| $p_{13}$       | 0.7200       | 0.8000          | 90.0000 | $p_{16}$   | 0.0300       | 0.0200         | 66.6667 |
| $p_{11}$     | 6.0000       | 90.0000         |        | $p_{14}$       | 0.8470       | 0.9000          | 94.1111 | $p_{17}$   | 0.7200       | 0.8000         | 90.0000 |
| $p_{12}$     | 0.2300       | 0.3000          | 76.6667| $p_{15}$       | 0.9000       | 1.0000          | 142.571 |            |              |                |        |
| $p_{18}$     | 0.3200       | 0.2000          | 62.5000| $p_{22}$       | 0.7500       | 0.8000          | 93.7500 | $p_{27}$   | 0.0746       | 0.0800         | 107.2386 |
| $p_{19}$     | 75.0000      | 200.0000        | 37.5000| $p_{23}$       | 0.8400       | 0.9000          | 93.3333 | $p_{28}$   | 0.8700       | 0.8500         | 102.3529 |
| $p_{20}$     | 0.1700       | 0.2000          | 85.0000| $p_{24}$       | 0.1070       | 0.1000          | 93.4579 | $p_{29}$   | 0.0792       | 0.0800         | 101.0101 |
| $p_{21}$     | 0.1800       | 0.2500          | 72.0000| $p_{25}$       | 0.0130       | 0.0200          | 153.8461| $p_{30}$   | 0.0800       | 0.0800         | 96.1176 |
|              |              |                 |        | $p_{26}$       | 0.8250       | 0.9000          | 91.6667 |            |              |                |        |
| $p_{29}$     | 0.3000       | 0.2000          | 66.6667| $p_{35}$       | 3.4000       | 3.0000          | 88.2353 | $p_{39}$   | 0.0792       | 0.0800         | 101.0101 |
| $p_{30}$     | 0.8500       | 0.9000          | 94.4444| $p_{36}$       | 0.8200       | 0.9000          | 91.1111 | $p_{40}$   | 0.8170       | 0.8500         | 96.1176 |
| $p_{31}$     | 120.0000     | 200.0000        | 60.0000| $p_{37}$       | 3.2000       | 3.5000          | 91.4286 | $p_{41}$   | 0.1000       | 0.0000         | 0.0000  |
| $p_{32}$     | 0.0000       | 0.9000          | 0.0000 | $p_{38}$       | 0.0000       | 0.0000          | 0.0000  | $p_{33}$   | 0.1000       | 0.0000         | 0.0000  |
| $p_{33}$     | 35.0000      | 50.0000         | 70.0000| $p_{34}$       | 0.9000       | 0.0000          | 0.0000  | $p_{34}$   | 0.1634       | 0.2970         | 0.5396  |

Table A3. The weights of indices in A layer.

| Index | $A_1$ | $A_2$ | $A_3$ | $A_4$ |
|-------|-------|-------|-------|-------|
| Weight| 0.4512| 0.1190| 0.2609| 0.1689|

Table A4. The weights of indices in B layer.

| Index | $B_1$ | $B_2$ | $B_3$ |
|-------|-------|-------|-------|
| Weight| 0.1634| 0.2970| 0.5396|
Table A.5. Comparison of indices value in \( p \) layer between X district and Y district.

| Static index | X area | Y area | Operation index | X area | Y area | Loss index | X area | Y area |
|-------------|--------|--------|-----------------|--------|--------|------------|--------|--------|
| Medium-voltage distribution network |  |  |  |  |  |  |  |  |
| \( p_1 \) | 0.2207 | 0.5574 | \( p_3 \) | 6.5643 | 4.2525 | \( p_6 \) | 5.3333 | 6.0016 |
| \( p_2 \) | 1.2580 | 1.7613 | \( p_6 \) | 4.3348 | 3.6124 | \( p_9 \) | 18.4471 | 14.3887 |
| \( p_3 \) | 0.2693 | 0.1571 | \( p_7 \) | 1.0578 | 1.1044 |  |  |  |
| \( p_4 \) | 1.1250 | 1.1250 |  |  |  |  |  |  |
| Distribution Tr |  |  |  |  |  |  |  |  |
| \( p_{10} \) | 0.1707 | 0.1800 | \( p_{13} \) | 3.0563 | 2.9340 | \( p_{16} \) | 4.9097 | 5.0733 |
| \( p_{11} \) | 0.8280 | 0.8280 | \( p_{14} \) | 1.0782 | 1.0917 | \( p_{17} \) | 1.3300 | 1.3680 |
| \( p_{12} \) | 1.0990 | 1.2037 | \( p_{15} \) | 1.0167 | 0.8714 |  |  |  |
| Low voltage DC grid |  |  |  |  |  |  |  |  |
| \( p_{18} \) | 2.1800 | 2.0438 | \( p_{22} \) | 7.4078 | 6.6938 | \( p_{27} \) | 8.0606 | 8.5576 |
| \( p_{19} \) | 1.1340 | 0.7088 | \( p_{23} \) | 1.5853 | 1.6240 | \( p_{28} \) | 15.3308 | 16.3253 |
| \( p_{20} \) | 0.7095 | 0.7310 | \( p_{24} \) | 1.0500 | 1.1776 |  |  |  |
| \( p_{21} \) | 0.8589 | 0.8784 | \( p_{25} \) | 2.2000 | 2.7077 |  |  |  |
|  |  |  | \( p_{26} \) | 1.1200 | 1.1550 |  |  |  |
| Low voltage AC grid |  |  |  |  |  |  |  |  |
| \( p_{29} \) | 2.2000 | 2.0625 | \( p_{35} \) | 4.8794 | 5.3516 | \( p_{39} \) | 1.3939 | 1.4799 |
| \( p_{30} \) | 2.2572 | 2.3369 | \( p_{36} \) | 5.3664 | 5.4973 | \( p_{40} \) | 2.6625 | 2.8352 |
| \( p_{31} \) | 1.0020 | 0.6263 | \( p_{37} \) | 2.6149 | 2.5331 |  |  |  |
| \( p_{32} \) | 0.0000 | 0.0000 | \( p_{38} \) | 0.0000 | 0.0000 |  |  |  |
| \( p_{33} \) | 0.5740 | 0.2624 |  |  |  |  |  |  |
| \( p_{34} \) | 0.0000 | 0.0000 |  |  |  |  |  |  |