Indices System and Improvement Measures of Distribution Network Equipment Utilization Rate Considering PV Connection

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Abstract. With the expansion of China's power system and the advancement of the power market, more and more extensive attentions have been paid on the issue of equipment utilization. The number of distribution equipment accounts for a large proportion, but the utilization of equipment is limited by many factors and distribution utilization is rather low. However, the PV penetration in distribution networks has been increasing in recent years, which changes the way distribution system operates. Therefore, it is necessary to study the distribution equipment utilization considering the PV connection. This paper summarizes the impact factors of the utilization and analyzes the impact of PV on the distribution equipment utilization. An evaluation index system for the utilization is proposed with the consideration of PV connection, which includes electric utilization indices, quantity utilization indices, life-cycle utilization indices, system-coordination indices. In addition, a typical distribution system is established analyzed to explore the impact of PV capacity and location on utilization. And the effect of several technical strategies for utilization improvement is compared and analyzed to guide the actual work of the distribution network.

1. Introduction

In recent years, with the expansion of China's power system and the advancement of the power market, the issue of low utilization of distribution equipment has surfaced and been paid increasing attention on. The equipment utilization in distribution network is affected by many factors such as safety guideline, network structure, load characteristics and economic environment. In addition, problems such as high losses caused by unreasonable operation and poor management will lead to the high operation cost, causing the reduction in the equipment utilization [1-4]. And the low utilization has become one of the problems that currently limit the development of China's power economy. In the past researches on the evaluation indicators of the utilization, indices such as capacity rate is widely used, which only can describe utilization from the supply side based on the maximum load and cannot evaluate utilization comprehensively and sufficiently [5].

On the other hand, new energy generation has long been a research hotspot in the energy sector because fossil fuels are becoming depleted. Distributed generation (DG) is widely used in distribution networks [6-10], making the grid more flexible and effective. However, due to the intermittent, volatility and other characteristics of DG, the control becomes more difficult, which causes an adversely impact on the utilization to an extent [11-13]. Therefore, it is necessary to analyze the
impact that DG exerts on the utilization, so is the opinions and treatment methods for utilization improvement, which will promote sustainable development and enhance the operation benefits. However, at present, there are not many discussions about the influence of DG on the equipment utilization and improvement measures.

Equipment utilization is an economic and technical index to measure the working status and production efficiency of power equipment [14-16]. Lots of studies on evaluation models and improvement measures for the utilization has been conducted. The literature [17] proposed the evaluation method for the efficiency rating of power facilities considering the life cycle cost. Literature [18] pointed out that a comprehensive model can be created to include multiple indices such as load rate, which can be used to evaluate the utilization rate of transmission equipment, and also put forward measures to improve the utilization. Literature [19] pointed out the real-time planning can improve the utilization of transformer by grade measuring and capacity setting. Literature [20] used heuristic improvement measures to improve the energy efficiency of the transmission and distribution system, and then further increase the utilization rate of the equipment. At present, relatively uniform assessment index system has not yet been established about the equipment utilization. Generally, the most commonly used indices are capacity rate and load rate [21], the former indices can reflect many defects in the current construction and operation of the power grid, such as uniform load distribution, unreasonable structure and so on.

2. Factors affecting the distribution equipment utilization

2.1. Factors Affecting the Utilization of Traditional Distribution Equipment

2.1.1. Security Guidelines. In order to response the failure effectively, and guarantee the power supply sustainably, the “Distribution Network Planning and Design Guideline” points out that the distribution network planning and design must to meet the “N-x” safety standards [22-23]. That’s to say, if any lines, transformers or other equipment in the distribution are disconnected during normal operation, the lost user can be restored by the switch operation, and the sustainable power supply must be guaranteed to the user without any overload.

In order to ensure the stability and safety of the distribution operation, based on the “N-x” standard, it is necessary to ensure that there are certain margins for the line and transformers to avoid outages after line and main transformer failures. So, the distribution equipment cannot run at full load, naturally there is no way to ensure 100% utilization of the equipment. And the utilization corresponding equipment under various standards is also different. The larger $x$ in the standard, the spare capacity should be provided, and equipment utilization is lower. For example, comparing lines that match the “N-1” standard, lines that match the “N-2” standard need more margins which reduce their own utilization.

2.1.2. Network Structure. The distribution network structure specifically refers to connections between substations and lines. The network structure determines the extremum of equipment capacity rate, which in turn determines the equipment utilization. For example, in the case of a single connected line, the capacity can only extremely reach 50%, that is, the capacity rate of this line is always within 50% during operation.

2.1.3. Development Margin. The distribution equipment utilization is also affected by the margin left for load development. In some fast-growing areas, there is a large demand for development, so it is necessary to keep more marginal capacity, and equipment utilization is relatively small. On the contrary, if the development speed is not fast, the margin capacity will be smaller and equipment utilization will also increase.
2.1.4. Load Characteristics. The load characteristic can reflect the actual load the equipment supplied, and affect the equipment load rate and equipment utilization further. The load characteristics can be described by the load peak-valley difference, which refers to the load difference between the highest value and the lowest value in a load curve for a certain period. The larger the difference, the worse the load characteristics. In addition, the load rate can describe the relationship between the average load and the maximum load in a certain period. The higher the value of the load rate, the smaller the difference between the peak and the mean load, and the better the load characteristics of the load supplied by this equipment, which makes equipment utilization rate much higher. The factors affecting the load characteristics are: user category and proportion, season and region, user intelligence level and so on.

Factors affecting the utilization

![Diagram showing factors affecting the utilization]

Fig. 1 Impact of PV connection on distribution equipment utilization

2.2. Impact of PV Connection on Distribution Equipment Utilization

PV connecting to distribution, can supply power to the users and reduce the net load of the system. As a result, the user's dependence on the traditional energy is reduced. In addition, in order to ensure the reliability of distribution network power supply, the power system needs to increase the operating standby margin because of the PV volatility, which will affect the equipment utilization.

2.2.1. Impact on the Distribution Construction. In order to meet the requirements of distribution network reliability, the system should build standby lines to assume backup capacity before PV grid-connected. This will result in the partial substations and distribution lines being idle for some time. In addition, in terms of supply region in remote areas, the power company often needs to increase distribution equipment in order to implement DG connection. Therefore, the newly built equipment capacity for DG cannot be fully utilized, further lowering the utilization efficiency of equipment in the distribution network.

2.2.2. Impact on the Load Characteristics. After the PV is connected to the distribution network, the regional load characteristics will contain the dynamic characteristics of PV. Part of the user load can be supplied by the PV output, and the load curve will change accordingly. Thus, PV connection has a significant impact on the load characteristics. The regional net load will fluctuate with the fluctuation of PV output, and if the PV penetration increases, the net load will also increase. But the bigger
fluctuation of the net load should need more standby capacity, causing the decrease of load rate. Thus, the equipment utilization rate will decline finally.

2.2.3. Impact on the Development Margin. The PV characteristics, such as uncertainty and instability, make the distribution face higher random risk, and the fluctuation of net load become more uncertain. Thus, it is rather difficult to predict load accurately. However, the accuracy of load prediction will affect the construction margin left for development. If the load prediction results show that the regional load in a certain period has a rapid growth, but the actual value is lower than expected, the margin for development in the construction will be too large. The excess margin will lead to low equipment utilization.

3. Evaluation Index System of Equipment Utilization

3.1. Definition of Equipment Utilization

For a long time, the definition of the utilization rate of distribution network equipment is not accurate enough. Usually, it refers to the utilization rate of a certain equipment. However, the meaning of the utilization rate is far more than that. It is a multilevel comprehensive description of the distribution network's operation capability. To study the evaluation index system of the utilization, we must first define it. This paper defines the capacity ability of equipment from different levels and gives the definition as follows:

a) Equipment extreme capacity

Due to the limitations of the design and manufacture of the distribution equipment, the maximum load that can be supplied under normal operation has a maximum value. Generally speaking, the extreme capacities of the lines and transformers are their own rated power.

b) Equipment safety capacity

The distribution equipment is limited by factors such as operation principle, network structure and the margin left for development. And the power system must be safe and reliable. So, equipment must operate under the safety capacity, the equipment safety capacity can be described as:

\[ B = b_R \times \beta \left(1 + \alpha\right)^n \]  

(1)

Where \( b_R \) is the theoretical value of the maximum capacity of the equipment considering only the principle of safety and reliability, \( \alpha \) is the regional load growth rate, \( n \) is the time for margin, and \( \beta \) is the load rate.

c) Equipment economic operation range

The economical operation range is mainly for transformers evaluation. In the economic operation range, the efficiency rating of the transformer is high, and the power loss is small. The economic operation range can be calculated with the corresponding load rate \( \beta_0 \) when the annual power energy loss rate is minimum [24-25].

\[ \beta_0 = \sqrt{\frac{T_0 (P_0 + KQ_0)}{\tau (P_0 + KQ_k)}} \]  

(2)

Where \( T_0 \) is the operation time of the transformer, \( \tau \) is the hours of active power loss of the transformer, \( P_0 \) is the active power loss of the transformer under no-load, \( P_k \) is the transformer active power loss under short-circuit, \( K \) is the reactive economic equivalent, \( Q_0 \) is the reactive power loss of transformer under no-load, \( Q_k \) is the reactive power loss of transformer under short-circuit condition.
3.2. Indices Structure of Distribution Equipment Utilization

A scientific evaluation system of indices for the distribution equipment utilization can effectively evaluate the actual operation of the regional distribution network and the utilization of equipment, accurately identify the weakness, and guide the development, construction and transformation timely. With clear, comprehensive and practical principles, this paper proposes an index system for the utilization considering PV connection. The utilization index system is divided into two levels, the first-level indices include the equipment electric utilization indices, quantity utilization indices, life-cycle utilization indices and system-coordination indices rate; the second-level indices include the equipment actual utilization rate, equipment extreme utilization rate, equipment relative utilization rate, equipment capacity factor, equipment efficiency rating, life cycle utilization, unit cost of electricity assets.

3.3. The Definition and Calculation of each Index

3.3.1. Equipment Electric Utilization Indices. The equipment electric utilization indices are used to evaluate the power transmitted by this equipment in a certain time. Electric utilization indices include the actual utilization rate, the extreme utilization rate and the relative utilization rate of the main transformer and the line. There are three secondary indicators.

a) Actual utilization rate

The actual utilization rate of the equipment is defined as the ratio of the maximum load supplied by the equipment to the extreme capacity of this equipment, which can be expressed as:

$$R_p = \frac{L_{\text{max}}}{P_{\text{lim-max}}} \times 100\%$$  \hspace{1cm} (3)

Where $L_{\text{max}}$ is the maximum load supplied by this equipment, $P_{\text{lim-max}}$ is the extreme capacity, usually the rated power of this equipment.

b) Extreme utilization rate

The equipment extreme utilization rate is defined as the ratio of the limit power value carried by this equipment to the extreme capability when meeting the safety and stability constraints, which can be expressed as follows:

$$E_p = \frac{P_{\text{sav-max}}}{P_{\text{lim-max}}} \times 100\%$$  \hspace{1cm} (4)

Where $P_{\text{sav-max}}$ is the max power transmitted by the equipment under the limits of the safe and stable operation. The equipment extreme utilization rate reflects the restrictions of factors such as security standard, network structure and construction margin. The larger the $E_p$ value is, the closer the equipment's safety load rate is to the extreme capacity, which indicates the grid structure and construction margins are more reasonable. While the small $E_p$ indicates that the grid structure is unreasonable or the margin for development and construction is too large, improvements need to be made.

c) Equipment relative utilization rate

The relative utilization rate is defined as the ratio of the maximum load supplied by the equipment to the limited power transmitted by this equipment under the constraints. And it can be expressed as:

$$D_p = \frac{L_{\text{max}}}{P_{\text{sav-max}}} \times 100\%$$  \hspace{1cm} (5)

This index can also be regarded as the ratio between the Actual utilization rate $R_p$ and extreme utilization rate $E_p$. The relative utilization rate can reflect the difference between the maximum
utilization during actual operation and the maximum utilization under the constraint of security and stability. To a certain extent, the closer $R_p$ and $E_p$ are, the higher the utilization.

### 3.3.2 Equipment quantity utilization indices

The equipment quantity utilization indices can evaluate how much energy is delivered by the equipment within a certain time, including the capacity factor and efficiency rating of the transformers and the lines.

#### a) Capacity factor

The capacity factor is an international index for calculating the utilization rate of power equipment. It can evaluate the utilization rate of equipment in service, which is equal to the ratio of the actual amount of electricity energy that passes through the equipment and the maximum theoretical amount in a certain period.

$$R_a = \frac{E_{\text{real-tol}}}{P_{\lim\text{-max}} \times T_a} = \frac{L_{\text{avg}} \times T_a}{P_{\lim\text{-max}} \times T_a} = R_p \times \beta \quad (6)$$

Where $E_{\text{real-tol}}$ is the actual energy transmitted by the equipment, $L_{\text{avg}}$ is the mean of the actual load supplied by the equipment, $T_a$ is the actual service life, and $\beta$ is the load rate. The capacity factor is related to the amount of electricity delivered by the equipment. It can evaluate the utilization of the equipment in a fixed period and evaluate the equipment utilization from the level of the average value. Compared with the electric utilization index, the capacity factor, reflects the average utilization rate of the equipment in a certain fixed period considering the fluctuation of the load and the randomness of the load development.

#### b) Equipment efficiency rating

Equipment Efficiency Rating (EER) can quantitatively calculate the deviation of the actual operating status from the economic operation range based on the load curve. Taking the annual continuous load curve as an example, the equipment efficiency rating calculation model [26] is shown in Fig. 2.

In Fig. 2, $P_2$ and $P_1$ are the upper and lower limits of the economic operation range of the equipment, and $S_2$ is the amount of electricity in the economical operation range, that is, the power amount within the range of the load curve between $P_1$ and $P_2$. Which is related to equipment selection and operation methods. $S_1$ and $S_3$ are the amount of the part of load curves that are beyond (or lower than) the economic operation range; $S_4$ is the lost power due to the power failure of the equipment, which is related to equipment quality, grid structure, automation level, operation and maintenance level. $S_5$ is the power loss of the equipment, which is related to equipment selection, operation mode.
and management level. \( a \) is the correction factor of the power production value, which is used to improve the importance of the S4, and it is equal to the ratio of the power production value to the average power price, while the power production value is equal to the GDP generated using 1kWh in the region.

From the point of the life cycle, equipment operating in the economic operation range has the best in-put-output ratio, and the equipment is utilized most fully within a certain evaluation cycle. At this time, the equipment operation efficiency can be regarded totally as "optimization." The equipment efficiency rate is defined as:

\[
EER = \frac{S_2}{(S_1 + S_2 + S_3 + a \times S_4 + S_5)}
\]

According to the definition, if annual load curve supplied by the equipment is all within the economic operation range, the equipment operating efficiency is the highest, meaning EER=1; if the annual curve is all outside, the equipment operation efficiency is the lowest, EER=0. In other words, in a certain evaluation cycle, only equipment of a region all are operating in the economic operation range and coordination among various equipment is made, the equipment has the best operation efficiency.

3.3.3. Equipment life cycle utilization. The equipment life cycle utilization indices are used to evaluate the economical utilization status of the distribution network equipment considering operation and recycle, including the life cycle utilization rate, and the asset cost of unit electric quantity.

a) Life cycle utilization rate

The life cycle utilization index is defined as the ratio of the actual transmission electric quantity to its theoretical value during the equipment life or its expected operation life. The formula is:

\[
W_a = \frac{E_a}{P_{lim-max} \times T_d} \times 100\%
\]

Where \( E_a \) is the actual transmission electric quantity during the equipment life; \( T_d \) is the theoretical life of equipment.

Compared with the capacity factor, the life cycle utilization index can not only evaluate equipment utilization efficiency from the electric quantity, but cover a wider range and the life rate of the equipment.

Assuming the annual load growth rate of the equipment is \( \alpha \), the actual transmission electric quantity of the equipment during its life is:

\[
E_a = \sum_{i=1}^{T} E_i = E_i + (1 + \alpha)E_i + \cdots + (1 + \alpha)^{T-1} E_i = \lambda E_i
\]

Where \( E_i \) is the actual transmission electric quantity of the \( i \)-th year; \( \lambda \) is annual value. Therefore, Eq.(8) can be expressed as:
\[ W_a = \frac{E_a}{P_{\text{lim-max}} \times T_d} = \frac{\lambda E_1}{P_{\text{lim-max}} \times T_d} = \frac{L_{\text{avg1}}}{L_{\text{max1}} \times T_d} \times \frac{E_1}{T_d} \times \frac{T_a}{T_d} = \eta_1 \times \eta_2 \times \eta_3 \times \gamma \]  

(10)

Where \( L_{\text{avg1}} \) is the average load in the first year during the equipment operation; \( L_{\text{max1}} \) is the maximum load in the first year; \( \eta_1 \) is the load rate in the first year; \( \eta_2 \) is the capacity rate; \( \eta_3 \) is life rate of the equipment; \( \gamma \) is the average load coefficient of equipment.

b) Asset cost of unit electric quantity

Different equipment investment costs have different life cycles. The asset cost of unit electric quantity is used to evaluate the utilization of equipment assets, which is the ratio of the total investment cost of equipment to the theoretical transmission electric quantity during the life of the equipment or its expected operation life.

\[ I_a = \frac{LCC}{E_a} \]  

(11)

\( LCC \), is the sum of all costs during the life cycle of the equipment or its expected operation life, including the directly or indirectly costs that have been incurred or may be incurred during the period of the product development, design, production, operation, maintenance [27]. The asset cost of unit electric quantity can evaluate the equipment asset utilization efficiency. According to the investment, service and retirement process of the equipment, the life cycle of the distribution equipment can be divided into three periods: equipment selection, equipment operation and maintenance, equipment retirement. The life cycle cost can be considered as the sum of costs of the three periods:

\[ LCC = C_I + C_M + C_R \]  

(12)

Where \( C_I \) is the acquisition cost of equipment in the selection period; \( C_M \) is the operation and maintenance cost of equipment in the service period; \( C_R \) is the retirement cost of equipment in the retirement period.

3.3.4. Coordination degree. Because all kinds of equipment that make up the regional distribution network are a whole system, different equipment must coordinate with each other to ensure the overall operation efficiency of the distribution network. This requires that the operation efficiencies of different equipment should be as small as possible, otherwise they will be mutually constrained. The system coordination degrees are proposed to reflect the coordination between various equipment, which is of great significance to system planning and equipment selection. The system utilization coordination degree is defined as follows:

\[ C = e^{-\frac{1}{K} \sum_{i=1}^{K} (X_i - X_0)^2} \]  

(13)

Where \( X_i \) is system utilization of the \( i \)-th equipment, which can be any of the indices described in the previous section; \( X_0 \) is the system average equipment utilization; \( K \) is the number of equipment in the system, including high voltage line, main transformer, medium voltage line, distribution transformer and low voltage line; \( e \) is a constant.

The system average equipment utilization can reflect the overall utilization efficiency of the distribution network system in a certain region. Since different types of equipment are difficult to
unify in size estimation, the importance of the equipment in the system is indirectly reflected by the input of assets, and the equipment utilization efficiency of different categories is weighted by the weight of the total assets of the equipment, and the equipment utilization rate of the system is calculated as:

\[ X_i = \sum_{n=1}^{N} \omega_n x_n \quad (i = 1, 2, \cdots, K) \]  

(14)

Where \( N \) is the total number of equipment; \( \omega_n \) is the input asset value of the \( n \)-th equipment accounts for the weight of the total assets of the equipment; \( x_n \) is the utilization of the \( n \)-th equipment. The system average equipment utilization is:

\[ X_0 = \frac{1}{K} \sum_{i=1}^{K} X_i \]  

(15)

4. Case Study
This section takes the distribution system of S area in a China province as an example to apply the evaluation indices proposed in this paper. The impact of PV connection capacity and location on equipment utilization is explored, and the actual effect of specific technical strategies for utilization improvement analyzed by simulating, whose result can guide the actual planning and operation of distribution network.

4.1. Utilization of distribution equipment before and after PV connection
In S area, the distribution network is mainly based on the 66kV substation as source, 10kV power grid as the backbone line. The number of 10kV distribution transformers is 118 with the total capacity of 7330kVA. The maximum load is 2649kW, normal operating load is 1340kW.

The network structure of distribution system is shown in Fig. 3. The PV power station is located in node 36, which is connected to the power grid through the line via node 3, and the installed capacity is 6WM.

![Fig. 3 The topological structure of distribution network in S region](image-url)

The calculation results of distribution equipment utilization before and after PV connection are shown in table I and table II.
### Table 1 The equipment utilization of distribution network before PV connection

|                         | Equipment utilization of lines | Equipment utilization of transformers | Average equipment utilization of system | Coordination degree |
|-------------------------|--------------------------------|---------------------------------------|----------------------------------------|---------------------|
| the actual utilization of equipment | 0.0653                         | 0.2525                                | 0.1381                                  | 2.0020              |
| the extreme utilization of equipment | 0.0760                         | 0.2808                                | 0.1784                                  | 1.7750              |
| the relative utilization of equipment | 0.0549                         | 0.3420                                | 0.1984                                  | 2.0609              |
| capacity factor          | 0.1136                         | 0.4393                                | 0.2765                                  | 1.8023              |
| the efficiency rating of equipment | 0.2350                         | 0.3072                                | 0.2711                                  | 1.1426              |
| life cycle utilization   | 0.2410                         | 0.0897                                | 0.1654                                  | 1.5798              |
| unit power asset cost    | 2.1998                         | 0.4971                                | 1.3525                                  | 3.0372              |

### Table 2 The equipment utilization of distribution network after PV connection

|                         | Equipment utilization of lines | Equipment utilization of transformers | Average equipment utilization of system | Coordination degree |
|-------------------------|--------------------------------|---------------------------------------|----------------------------------------|---------------------|
| the actual utilization of equipment | 0.0642                         | 0.2267                                | 0.1350                                  | 1.9989              |
| the extreme utilization of equipment | 0.1847                         | 0.3030                                | 0.1890                                  | 0.0166              |
| the relative utilization of equipment | 0.0225                         | 0.2974                                | 0.1375                                  | 0.3128              |
| capacity factor          | 0.1117                         | 0.4292                                | 0.2704                                  | 1.7988              |
| the efficiency rating of equipment | 0.6744                         | 0.2635                                | 0.4680                                  | 1.5553              |
| life cycle utilization   | 0.0079                         | 0.0835                                | 0.0814                                  | 1.0281              |
| unit power asset cost    | 1.9642                         | 0.4022                                | 1.3297                                  | 3.1085              |

It can be seen that the equipment utilization of the distribution network is reduced and only the line operation efficiency is increased after the PV connection. Before the PV connection, the line utilization is low, and most of them do not within the economic operation range. The connection of the PV increases the transmission power quantity of the line, but the load is constant, so that the transmission power proportion in the line economic operation area increases.
4.2. Factors affecting the equipment utilization of the distribution network considering the PV connection

4.2.1. Impact analysis of PV access capacity. Change the capacity of PV capacity by expanding the capacity by 10%, 20%, 30%, and reducing 10%, 20%, and 30%, respectively, to compare the utilization. The result is shown in Fig. 4:

![Figure 4](image)

Fig. 4 The trend of distribution network equipment system coordination degree with PV access capacity

As is shown in the above figure, the utilization of equipment is inversely related to the PV installed capacity. With the increase of PV installation capacity, the utilization indices of electric power, quantity indices and life cycle indices are all decreasing. This is due to the rapid random fluctuation characteristics of PV, when PV connection capacity is large, peak valley difference of net load increases sharply, the system stability is reduced causing the reduce of equipment load rate.

4.2.2. Impact analysis of PV connection location. In order to explore the influence of PV location on equipment utilization, this section selects the grid terminal node 18 to connect PV and compares the results with the original location. The result is shown in Table III
Table 3 The equipment utilization compared between PV locations

| Coordination degree | equipment utilization of lines | equipment utilization of transformers | average equipment utilization of system | equipment utilization of system |
|---------------------|-------------------------------|--------------------------------------|----------------------------------------|---------------------------------|
| the actual utilization of equipment | 0.0176 | 0.1146 | 0.0236 | 0.0017 |
| the extreme utilization of equipment | -0.5132 | -0.0876 | -0.2024 | 98.9906 |
| the relative utilization of equipment | 1.0892 | 0.1684 | 0.4351 | 5.8457 |
| capacity factor | 0.0176 | 0.0242 | 0.0228 | 0.0021 |
| the efficiency rating of equipment | -0.6518 | 0.1658 | -0.4209 | -0.2653 |
| life cycle utilization | 21.7356 | 0.8573 | 1.0584 | 0.0479 |
| unit power asset cost | 0.1396 | 0.0270 | 0.2553 | 0.0831 |

Generally, the end voltage quality of the line is improved when PV connects to the end of line. The data shows that the comprehensive utilization of the equipment is increased, the extreme utilization, the equipment efficiency rating is reduced, and other indices are all rising when PV is connected to the end node. The reason is that PV connected to the end can reduce the partial network loss, causing the power of the whole distribution network reducing. As a result of the increase of power supply after the PV connected, the average transmission power is reduced, the unit power asset cost of transformer is increased. Compared with the original scheme, six degrees are improved. So, the better plan is that PV is connected to terminal, which can improve the coordination between different equipment.

4.3. Analysis on the practical effect of strategies for utilization improvement considering PV connection

To explore the practical effect of specific technical strategies for utilization improvement, simulation is conducted under three strategies, installation of reactive power compensation devices, installation of energy storage equipment, and adoption of reactive power control methods.

4.3.1. Effect analysis of installation of reactive power compensation devices. Installing 0.5M, 1M, 1.5Mvar reactive power compensation devices in the PV grid-connected node, the equipment utilization can be analyzed by simulation. The result is shown in Table IV:

Table 4 Coordination degrees of distribution with reactive power compensation devices

| Capacity of reactive power compensation devices (MVar) | 0 | 0.5 | 1 | 1.5 |
|-------------------------------------------------------|---|-----|---|-----|
| the actual utilization of equipment                   | 1.9989 | 2.0024 | 2.0022 | 2.0024 |
| the extreme utilization of equipment                  | 0.0166 | 1.6329 | 1.6484 | 1.6566 |
| the relative utilization of equipment                 | 0.3128 | 2.1638 | 2.1525 | 2.1468 |
| capacity factor                                       | 1.7988 | 1.8028 | 1.8025 | 1.8027 |
| the efficiency rating of equipment                    | 1.5553 | 1.1428 | 1.1418 | 1.1431 |
| life cycle utilization                                | 1.0281 | 1.0411 | 1.1338 | 1.0540 |
| unit power asset cost                                 | 3.1085 | 3.3348 | 3.2763 | 3.2194 |
As is seen from the table, with the increase of the capacity of reactive power compensation device, the comprehensive utilization of the distribution equipment is increased. Compensating the reactive power on-site can reduce the transmission of the reactive power by lines, and the average transmission power of the system is improved, so installing reactive power compensation devices is helpful to improve the equipment actual utilization, capacity factor and full life cycle utilization.

In theory, the best measure of reactive power compensation is compensating wherever need, to make no reactive current flow through the system. But it is impossible to come true actually, because whether transformer, transmission line or various load are all needing reactive power.

4.3.2. Effect analysis of installation of energy storage. Installing 1MW/4MWh, 2MW/8MWh energy storage equipment in the PV grid-connected node, the equipment utilization of distribution network can be analyzed by simulation. The result is shown in Table V:

| Capacity of energy storage equipment | 0         | 1MW/4MWh | 2MW/8MWh |
|-------------------------------------|-----------|----------|----------|
| the actual utilization of equipment | 1.9989    | 2.0024   | 2.0022   |
| the extreme utilization of equipment| 0.0166    | 1.6329   | 1.6484   |
| the relative utilization of equipment| 0.3128   | 2.1638   | 2.1525   |
| capacity factor                     | 1.7988    | 1.8028   | 1.8025   |
| the efficiency rating of equipment  | 1.5553    | 1.1428   | 1.1418   |
| life cycle utilization              | 1.0281    | 1.0411   | 1.1338   |
| unit power asset cost              | 3.1085    | 3.3348   | 3.2763   |

As is seen from the table, with the increase of the capacity of energy storage equipment, the comprehensive utilization of the distribution network equipment is increased. The equipment actual utilization, capacity factor and life cycle utilization are improved after installing energy storage equipment. Because of the effect of cutting peak-valley difference, the fluctuation of PV output is improved, making the transmission power increase. As result, the extreme utilization of main transformer is increased. Then the coordination degree of the system is reduced, and the coordination between equipment is better. Therefore, taking an operating distribution network into account, the most effective measure to improve the equipment utilization of power distribution network is equipped with energy storage at present, and the larger the storage capacity, the better the utilization rate of the distribution network equipment will be.

4.3.3. Effect analysis of reactive power control methods. To explore the practical effect of reactive power control methods on utilization improvement, this section creating the following five Cases to simulate the system operation. The system is controlled by constant power factor and constant voltage control in the PV grid-connected node. The equipment utilization of distribution network can be analyzed and the result is shown in Table VI:

Case1: No reactive power control method
Case2: Constant power factor, cosφ=0.98;
Case3: Constant power factor, cosφ=-0.98;
Case4: Constant voltage control, reference voltage is 1.05;
Case5: Constant voltage control, reference voltage is 0.95.
### Table 6 Coordination degree of distribution with reactive power control

|                          | Case1   | Case2   | Case3   | Case4   | Case5   |
|--------------------------|---------|---------|---------|---------|---------|
| the actual utilization of equipment | 1.9989  | 1.6834  | 1.7005  | 1.8207  | 1.8145  |
| the extreme utilization of equipment | 0.0166  | 1.2683  | 1.0277  | 0.0138  | 0.0022  |
| the relative utilization of equipment | 0.3128  | 2.2624  | 2.3789  | 0.2995  | 0.3101  |
| capacity factor           | 1.7988  | 1.4363  | 1.4573  | 1.5971  | 1.5901  |
| the efficiency rating of equipment | 1.5553  | 1.5977  | 1.5994  | 1.5672  | 1.5733  |
| life cycle utilization    | 1.0281  | 1.4301  | 1.5968  | 1.1982  | 1.2096  |
| unit power asset cost     | 3.1085  | 1.0001  | 1.0001  | 1.0001  | 1.0001  |

As is seen from the data, when the constant voltage control (reference voltage 1.05) is adopted, the equipment utilization of the distribution network is the highest. But this is not the best way but the most suitable way to S area. Taking the reactive power control methods, the actual utilization, extreme utilization, capacity factor and unit power asset cost are all improved. However, as a result of the constraint of PV output power and the reduction of the transmission power, the efficiency rating and the life cycle utilization are reduced after the PV controlling by constant voltage method.

5. Conclusion

Due to the differences in regional economic development, distribution network planning requirements, and the user custom, the load varies greatly between different regions and between equipment. A comprehensive, scientific and unified index system for the equipment utilization is desperately needed, so is the practical methods for improving the equipment utilization. In this paper, through the further study on the evaluation indices and promotion measures of the equipment utilization, an evaluation indices system for the equipment utilization is proposed considering PV connection, and the influencing factors are summed up in detail. The effectiveness and practicability of the indices are verified through the typical areas as an example. And the practical effectiveness of three strategies for utilization improvement is analyzed.

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