A Comparison of Energy Efficiency in AC and DC Microgrid with New Energy

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Abstract. As photovoltaic, wind power and other new energy sources are connected to the power grid on a large scale, the research on key technologies of microgrid needs to be further improved. Since most distributed generation and energy storage devices are mostly powered by direct current, DC distribution technology has got more and more attention. Aiming at the difference of energy efficiency between AC and DC microgrid, this paper proposes the analysis method of “the efficiency of source side with distributed generation”, establishes a mathematical model of system loss of AC and DC microgrid with distributed generation and sets up a selection principle of distribution system mode through the intersection point of system loss rate, from the perspective of energy efficiency. The calculation results show that the loss rate of DC microgrid with distributed power source is lower than that of AC microgrid supposing the DC load ratio is 50%. The system loss rate curve confirms the necessity of DC distribution system technology research. With the continuous access of distributed generation and energy storage devices to microgrids, and the increasing improvement of DC load rate, the DC microgrid with distributed generation will have more advantages in the future.

1. Introduction
In recent years, issues on environmental and energy have become the focus of attention due to greenhouse gas emissions and energy depletion. Obviously, renewable energy is an important way of energy supply in the future. Most renewable energy are powered by direct current, which needs to be connected to the AC power grid through DC-AC inverter. From the demand side, many DC loads, such as electric vehicles, computers and air conditioners, need to be connected to AC microgrid through DC-AC inverter. These devices heavily weaken the overall efficiency and reliability of the system. By using direct DC power source, appropriate voltage level and efficient DC-DC converter, we can reduce the AC and DC converters at both source and load sides, thus reducing system loss[1-2].

At present, the researches on DC distribution system focus on topology, system protection, voltage level standards and so on [3-6]. But from the perspective of system operation economy, the researches on DC distribution system loss rate are limited. Reference [7] makes economic analysis on AC distribution system, ±7.5kV and ±15kV DC distribution system from the perspective of investment cost and network loss, but it overlooks the losses of both circuit and converter at low-voltage level.
Reference [8] puts forward the method of contribution rate of distributed power source to distribution system loss, but its apportionment is too complex.

According to the voltage level and power source mode, this paper defines the current load as five categories, through the AC 10 kV and DC ± 7.5 kV voltage distribution mode. Based on the losses of AC and DC circuits with medium and low voltage, and the losses of transformer and converter, a mathematical model of AC and DC microgrid system with distributed power source is established, and the analysis method of the source efficiency with distributed photovoltaic is proposed. Based on the calculation and comparison of the system loss rate of both AC and DC microgrids containing photovoltaic, and from the perspective of energy efficiency, a principle of distribution system mode selection can be established and the significance of DC microgrid technology research can be confirmed through the curve of system loss rate.

2. AC and DC Microgrid Systems with New Energy

2.1. Topology of New-Energy AC and DC Microgrids

The topology of AC and DC microgrid with distributed power source is suitable for an open-loop operation system. The topology structures of AC and DC microgrid with distributed photovoltaic power [9-10] are shown in Figure 1 and Figure 2.

![Figure 1. Topology structure of AC microgrid with distributed photovoltaic power](image)

![Figure 2. Topology structure of DC microgrid with distributed photovoltaic power](image)

In Figure 1, electrical components mainly include AC power source, photovoltaic system, transformer substation, photovoltaic inverter, AC circuit breaker, AC and DC cables, AC transformer, rectifier and five types of loads; in Figure. 2, electrical components mainly include AC power source, converter station, photovoltaic system, photovoltaic inverter, DC circuit breaker, DC and AC cables, DC transformer Inverter and five types of loads. Assuming that the capacity of photovoltaic system is
1.5MW and the output is 1MW [11-12], the efficiency of photovoltaic grid connected inverter is about 96%, and the efficiency of photovoltaic grid connected DC/DC converter is about 99.5%.

2.2. Load Types

According to the microgrid structure shown in Figure 1 and 2, different loads are defined as five types in this paper [13]:

1) Medium voltage AC load is defined as load of A. For example, AC distribution system can directly supply power for ordinary industrial load. Supposing the DC distribution mode is adopted, the inverter equipment needs to be added.

2) Medium voltage DC load is defined as load of B, such as variable frequency motor, subway, electric vehicle charging station, etc.

3) Low voltage DC load is defined as load of C, such as air conditioning, computers in the data center, etc.

4) Low voltage 380V AC load is defined as load of D, such as AC motor, electric fan, etc. Medium voltage AC distribution system needs AC transformer, while medium voltage DC distribution system needs DC transformer and low voltage inverter.

5) Load of E is pure resistive load, such as incandescent lamp. AC distribution system and DC distribution system can supply power directly without additional AC or DC conversion.

In recent years, the utilization rate of low-voltage DC load air-conditioning and computer has been continuously improved [14]. Now, the total load capacity of low-voltage side is set to be 1MW, and the proportion of loads of C, D and E are 50%, 40% and 10%, respectively. The voltage level and load capacity of five types of loads are shown in Table 1.

| Table 1. Loads of AC microgrid containing photovoltaic and DC microgrid containing photovoltaic |
|-----------------------------------------------|-----------------|-----------------|
| Power-Load Types | Voltage Levels | Power /MW |
| Photovoltaic Power Generation System | AC Distribution Network | 10kV (AC) | 1 |
| | DC Distribution Network | ±7.5kV (DC) | 1 |
| Load of the Medium Voltage Side | Loads of A | 10kV (AC) | 2 |
| | Loads of B | ±7.5kV (DC) | 2 |
| | Loads of C | 400V (DC) | 0.5 |
| Load of the Low Voltage Side | Loads of D | 380V (AC) | 0.4 |
| | Loads of E | / | 0.1 |

3. Loss Rate of AC and DC Microgrids with New Energy

In this section, based on the calculation of the transmission efficiency of transmission circuits, a mathematical model of transmission efficiency of AC and DC microgrids in the traditional power source mode (excluding distributed power source) are firstly established. Under the condition of known load capacity, the total supply power of single power source of the two microgrids in traditional power source mode is obtained respectively. Secondly, the source side efficiency calculation model with distributed photovoltaic microgrid is established by using the total supply power of single power source, and the loss model of distribution system with distributed photovoltaic is established. This section takes 50% DC load ratio as an example to analyze the system loss rate of microgrid.

3.1. Efficiency of Transmission Cable
In Figure 1, the three parallel distribution cables in the first horizontal position from top to bottom of the system are represented as l1, with a length of 2km; the cable from AC or DC converter to load of B is represented as l2 with a length of 0.5km; the three parallel low-voltage cables at the output side of AC transformer are l3; In Figure 2, the three parallel distribution cables in the first horizontal position from top to bottom of the system are represented as l4, with a length of 2km; the cable from DC/AC inverter to load of A is represented as l5 with a length of 0.5km; the three parallel cables at the output side of DC transformer are l6. The formula of AC cable loss is shown below [15]:

\[ \eta_{ACloss} = \frac{0.0186(l + T)}{U_{AC}} \times 100\% \]  

In the formula, \( \eta_{ACloss} \) is the loss rate of AC cable; \( Q \) is the current density, A/mm²; \( T \) is the additional loss coefficient of AC cable (except resistance loss); \( l \) is the length of AC cable, km; \( U_{AC} \) is the effective value of the circuit voltage of AC distribution system, kV.

The formula of DC cable loss is expressed as (2):

\[ \eta_{DCloss} = \frac{0.036J}{U_{DC}} \times 100\% \]  

In the formula, \( \eta_{DCloss} \) is the loss rate of DC cable; \( l \) is the length of DC cable, km; \( J \) is the current density, A/mm²; \( U_{DC} \) is the effective value of DC distribution system circuit voltage, kV. Considering the same wiring investment level, both AC and DC cables adopt copper core material as cable conductor with the same cross-sectional area. The resistivities of both AC and DC cables are 18 Ωmm²/km.

According to figures 1 and 2, the AC micro grid circuit voltage \( U_{AC}=10\)kV, and the DC micro grid circuit voltage effective value \( U_{DC}=15\)kV. The results show that the current density \( Q=J=2\)A/mm²; the additional loss coefficient of AC distribution system \( T=1 \), from formula (1) and (2), we can get the transmission efficiency of cables at each position \( \eta_{l1}=96.5\% \), \( \eta_{l2}=99.7\% \), \( \eta_{l4}=99.0\% \), \( \eta_{l5}=99.1\% \).

In addition, suppose \( \eta_{l3} = \eta_{l6} = 99.5\% \) [16-17] , the loss of wiring is the same in both DC and AC configurations. Although the number of copper cables used may be slightly different, there is no difference in efficiency.

3.2. Loss Rates of Various Transformers and Converters

The change trend of efficiency of various transformers and converters under different DC load capacities is shown in Figure. 3.

![Figure 3. Loss curve of AC-DC distribution system device under different rations](image-url)
3.3. Total Power of Single Power Source in Traditional Distribution Mode

According to the above equipment and circuit operation loss rate, the total supply power of single power source is obtained. The efficiency formula of various load transmission in AC microgrid is shown in formula (3).

\[
\begin{align*}
\eta_{A1} &= (1 - \phi_1) \eta_{l1} \\
\eta_{B1} &= (1 - \phi_1)(1 - \phi_{AC/DC}) \eta_{l1} \eta_{l2} \\
\eta_{C1} &= (1 - \phi_1)(1 - \phi_{AC/DC})(1 - \phi_{T1}) \eta_{l1} \eta_{l3} \\
\eta_{D1} &= (1 - \phi_1)(1 - \phi_{T1}) \eta_{l1} \eta_{l3} \\
\eta_{E1} &= (1 - \phi_1)(1 - \phi_{T1}) \eta_{l1} \eta_{l3}
\end{align*}
\]

(3)

In this formula, \(\eta_{A1}, \eta_{B1}, \eta_{C1}, \eta_{D1}\) and \(\eta_{E1}\) refer to the efficiencies of load transmission of A, B, C, D and E respectively, and \(\phi_T\) is 110/10kV transformer loss, \(\phi_{T1}\) is 10/0.4kV transformer loss, and \(\phi_{AC/DC}\) is rectifier loss in transmission. \(\eta_{l1}, \eta_{l2}\) and \(\eta_{l3}\) are the transmission efficiency of AC cable in the transmission, which are 96.5%, 99.7% and 99.5% respectively.

The efficiency formula of various load transmission in DC distribution system is shown in (4):

\[
\begin{align*}
\eta_{A2} &= (1 - \phi_1)(1 - \phi_{DC/AC}) \eta_{l4} \eta_{l5} \\
\eta_{B2} &= (1 - \phi_1) \eta_{l4} \\
\eta_{C2} &= (1 - \phi_1)(1 - \phi_{T2}) \eta_{l4} \eta_{l6} \\
\eta_{D2} &= (1 - \phi_1)(1 - \phi_{DC/AC})(1 - \phi_{T2}) \eta_{l4} \eta_{l6} \\
\eta_{E2} &= (1 - \phi_1)(1 - \phi_{T2}) \eta_{l4} \eta_{l6}
\end{align*}
\]

(4)

In this formula, \(\eta_{A2}, \eta_{B2}, \eta_{C2}, \eta_{D2}\), and \(\eta_{E2}\) are the efficiency of load transmission of loads of A, B, C, D and E respectively. \(\phi_H\) is the loss of converter station, \(\phi_{T2}\) is the loss of DC transformer, and \(\phi_{DC/AC}\) is the loss of inverter in transmission. \(\eta_{l4}, \eta_{l5}\) and \(\eta_{l6}\) are the transmission efficiency of DC cable in transmission, which are 99.0%, 99.1% and 99.5% respectively.

Supposing the total power required by DC load is \(x\) MW, the capacity of DC load of C is 0.5MW, the capacity of AC loads of D and E are 0.4 and 0.1MW respectively, then the capacity of DC load of B is \((x-0.5)\) MW. If the known total load capacity is 5MW, then the capacity of AC load of A is \((4.5-x)\) MW. Therefore, the calculation of total supply power \(P_S\) of single power source can be shown in formula (5):

\[
P_S = \frac{4.5 - x}{\eta_{A}} + \frac{x - 0.5}{\eta_{B}} + \frac{0.5}{\eta_{C}} + \frac{0.4}{\eta_{D}} + \frac{0.1}{\eta_{E}}
\]

(5)

In the formula, \(P_S\) is the total power supplied by single source in traditional distribution mode, and \(\eta_{A}, \eta_{B}, \eta_{C}, \eta_{D}\) and \(\eta_{E}\) are the efficiency of five types of loads corresponding to AC or DC distribution system in the transmission.

Referring to Figure. 3, when the total DC load (the sum of loads of B and C) is 2.5MW, the data are substituted into formulas (4) and (5) to obtain the total power source in traditional single power source mode, as shown in Table. 2:

| Load Types | Load Power/MW | Efficiency of Various Load Transmission % | Supply Power of AC Power Source |
|------------|---------------|------------------------------------------|--------------------------------|
| Load types | AC10kV | DC±7.5kV | AC10kV | DC±7.5kV |
| Loads of A | 2 | 93.6 | 93.0 | 2.137 | 2.151 |
| Loads of B | 2 | 91.5 | 95.0 | 2.186 | 2.105 |
| Loads of C | 0.5 | 89.6 | 93.6 | 0.558 | 0.534 |
| Loads of D | 0.4 | 91.5 | 92.4 | 0.437 | 0.433 |
| Loads of E | 0.1 | 91.5 | 93.6 | 0.109 | 0.107 |

Table 2. Transmission efficiency of traditional AC and DC distribution system
### 3.4. Efficiency of Distribution System with Distributed Photovoltaic Power

The source side efficiency $\eta_{CPV}$ with distributed photovoltaic is obtained based on the total supply power of single power source in 2.3. The specific formula is shown in (6) and (7).

**AC microgrid with distributed:**

$$P_{S_1}(1-\phi_T) = m(1-\phi_T) + n\eta_1 \tag{6}$$

**DC microgrid with distributed:**

$$P_{S_2}(1-\phi_H) = m(1-\phi_H) + n\eta_2 \tag{7}$$

In formula (6) and (7), $P_{S1}$ and $P_{S2}$ respectively represent the total power source of traditional AC and DC microgrid modes, and $\phi_T$ and $\phi_H$ have the same meaning as the variables in formula (3) and (4), $m$ represents the output of AC power branch under the distribution system with distributed power source, and the unit is MW, and $n$ represents the branch output of photovoltaic power, $n=1$ MW; $\eta_1$ is the efficiency of photovoltaic DC/AC converter, $\eta_1 = 96\%$; and $\eta_2$ is the efficiency of photovoltaic DC/DC converter, $\eta_2 = 99.5\%$; formula (6) and formula (7) have different values of $m$ and $n$.

The calculation formula of the comprehensive efficiency of the distribution system containing photovoltaic of the power source side is as follows:

$$\eta_{CPV} = \frac{m}{m+n}\eta_3 + \frac{n}{m+n}\eta_4 \tag{8}$$

In the formula, $\eta_{CPV}$ represents the comprehensive efficiency of the distribution system containing photovoltaic of the power source side, $m$ and $n$ have the same physical meanings as those in formula (6) and (7), $\eta_3$ represents the operation efficiency of the transformer or converter station of the AC power branch, and $\eta_4$ represents the conversion efficiency of the photovoltaic DC/AC or DC/DC converter of the photovoltaic power source branch.

### 3.5. A Comparison of Losses of AC and DC Microgrid with Distributed Photovoltaic Power

**Supposing the DC Load Ratio is 50%**

The formulas of the transmission efficiency of various loads of AC and DC microgrids containing photovoltaic are shown in (9) and (10):

$$\eta_{A3} = \eta_{cpv1}\eta_{T1}$$
$$\eta_{B3} = \eta_{cpv1}(1-\phi_{AC/DC})\eta_{T2}\eta_{T3}$$
$$\eta_{C3} = \eta_{cpv1}(1-\phi_{AC/DC})(1-\phi_{T1})\eta_{T2}\eta_{T3} \tag{9}$$
$$\eta_{D3} = \eta_{cpv1}(1-\phi_{T1})\eta_{T2}\eta_{T3}$$
$$\eta_{E3} = \eta_{cpv1}(1-\phi_{T1})\eta_{T2}\eta_{T3}$$

$$\eta_{A4} = \eta_{cpv2}(1-\phi_{DC/AC})\eta_{T4}\eta_{T5}$$
$$\eta_{B4} = \eta_{cpv2}\eta_{T4}$$
$$\eta_{C4} = \eta_{cpv2}(1-\phi_{T2})\eta_{T4}\eta_{T6} \tag{10}$$
$$\eta_{D4} = \eta_{cpv2}(1-\phi_{DC/AC})(1-\phi_{T2})\eta_{T4}\eta_{T6}$$
$$\eta_{E4} = \eta_{cpv2}(1-\phi_{T2})\eta_{T4}\eta_{T6}$$

In formula (9) and (10), $\eta_{cpv1}$ and $\eta_{cpv2}$ are the efficiency of AC and DC distribution system containing photovoltaic of the source side respectively, and the other variables have the same meaning as formula (3) and (4). By substituting the solution into formula (5), the total power source of the
power source with distributed power source is obtained. Finally, the system loss rate under different microgrid modes can be obtained by substituting the solution into system loss formula (11).

\[ \eta_{\text{loss}} = \frac{(P_s - P_1)}{P_1} \quad (11) \]

In the formula: \( \eta_{\text{loss}} \) is the loss rate of distribution system with photovoltaic, \( P_s \) is the total supply power of both photovoltaic and AC powers, and \( P_1 \) is the total power of load.

Supposing the DC load ratio is 50%, the calculation results of AC microgrid and DC microgrid can be shown in Table 3:

Table 3. Transmission efficiency of AC and DC distribution system with distributed photovoltaic

| Load Types | Load Power/MW | Transmission Efficiency of Various Loads /% | Total Supply Power of Photovoltaic and AC Power Sources /kV |
|------------|---------------|--------------------------------------------|----------------------------------------------------------|
|            |               | AC10kV | DC±7.5kV | AC10kV | DC±7.5kV |
| Loads of A | 2             | 93.4   | 93.6     | 2.141  | 2.137    |
| Loads of B | 2             | 91.3   | 95.7     | 2.191  | 2.090    |
| Loads of C | 0.5           | 89.5   | 94.3     | 0.559  | 0.530    |
| Loads of D | 0.4           | 91.3   | 93.0     | 0.438  | 0.430    |
| Loads of E | 0.1           | 91.3   | 94.3     | 0.110  | 0.106    |
| Total      | 5             | /      | /        | 5.439  | 5.293    |

According to the results in Table 3, the loss rate of AC and DC microgrid system containing photovoltaic is calculated as \( \eta_{\text{loss}1} = 8.78\% \), and \( \eta_{\text{loss}2} = 5.86\% \). \( \eta_{\text{CPV}} \) is the efficiency of distribution system containing photovoltaic of source side, which is larger in AC distribution system than in DC distribution system. The reason is that the loss of converter station of DC distribution system is high. However, the loss of AC distribution system containing photovoltaic is still greater than that of DC distribution system containing photovoltaic, indicating that the power loss amplitude of other links of AC distribution system containing photovoltaic is greater than that of DC distribution system.

4. Results and Analysis

As the proportion of DC load in the total load increases gradually, the loss rate of all electrical components is also changing. According to Figure 3, the data is put into the mathematical model established in sections 2.3 and 2.4, and the above algorithm is realized by programming in MATLAB. The curve of the system loss rate with distributed photovoltaic is obtained when the DC load proportion is 10% ~ 90% (0.5MW ~ 4.5mw). The trend and results are shown in Figure 4.

Figure 4. Variation curve of loss rate of AC and DC distribution system
with different proportions

In Figure 4, with the increase of DC load ratio, the loss of Distributed AC microgrid increases gradually, while the loss rate of DC microgrid shows a downward trend. The main reason for this trend is that the loss of 10/0.4kV transformer and rectifier in AC microgrid obviously increase with the DC load rate, and the loss of DC transformer and inverter in DC microgrid is continuously reduced, and the inverter loss decreases most rapidly.

5. Conclusion
In this paper, the mathematical model of loss of AC and DC microgrid with distributed photovoltaic power is established, and the analysis method of power side efficiency of photovoltaic system is proposed, and the best choice of distribution system mode in different DC load rate range is obtained. Through matlab programming, we can obtain the loss curve of AC and DC distribution system containing photovoltaic under different DC load ratios. From the perspective of energy efficiency, the advantages of DC distribution system are more intuitively illustrated supposing that the distributed power source is connected and the following conclusions are obtained:

1) Under 50% (2.5MW) of DC load (the sum of loads of B and C), the efficiency $\eta_{cpv1}$ of the source side of AC distribution network containing photovoltaic is greater than that of DC distribution network, and even so, the total system loss of DC microgrid containing photovoltaic is still smaller. With the further development of power electronic technology and the improvement of interface converter efficiency, the gap of loss rate between AC distribution system and DC distribution network will be further expanded.

2)The curve trend in Figure. 4 shows that, with the increasing proportion of DC load, the system loss of AC distribution network containing photovoltaic is on the rise, while the loss of DC distribution network containing photovoltaic is continuously reduced. Thus, the DC distribution network will be more efficient among all distribution modes in the future.

3)In order to ensure the minimum system loss, the optimal distribution system mode should be selected according to different DC load rates. Supposing the DC load rate is less than 27.15%, the AC distribution system is the best choice; supposing the DC load rate is greater than 27.15%, the DC mode is the priority.

With more and more application of distributed power sources such as solar energy, wind power generation, electric vehicle charging and replacement power station to the distributed grids, it can be seen that DC distribution network has the minimum network loss and maximum operation economy, from the perspective of energy efficiency.

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