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The LCOE-Indicator-Based Comprehensive Economic Comparison between AC and DC Power Distribution Networks with High Penetration of Renewable Energy

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Abstract: DC distribution networks are operationally economical from the perspective of renewable energy penetration due to the reduction of power loss from the simplified power conversion structure. However, the initial investment cost of a DC network is high because DC technology is in the early stage of development. So, selecting AC or DC technology becomes an important issue in the planning stage of a distribution network, where a comprehensive quantitative economic comparison between AC and DC distribution networks is necessary. To compare the economy between AC and DC distribution networks with high penetration of a renewable energy scenario, this paper introduces a comprehensive economic evaluation method. In this study, first, typical system models for AC and DC distribution networks were proposed as the foundation of the research. Then, a levelized cost of energy (LCOE)-indicator-based comprehensive economic evaluation model was established, where the operation cost was classified into power loss cost, reliability loss cost, and operational cost. A time sequential simulation model was applied to calculate the power loss. The simulation results showed that a DC distribution network has higher initial investment, operation, and maintenance costs than an AC distribution network, but the loss cost is far lower than an AC distribution network. A sensitivity analysis showed that the equipment cost and proportion of renewable energy are two of the most important factors that affect the economics of DC distribution networks at present.

Keywords: comprehensive economic evaluation; levelized cost of energy (lcoe) indicator; dc distribution network; ac distribution network

1. Introduction

Due to its advantages of high power supply capacity, large power supply radius, and controllable power flow [1,2], the DC distribution network has gradually attracted the attention of scholars in the industry. However, at present, because DC power distribution is in its early stage of development, the cost of equipment is relatively high, and the operating life of power electronic devices is lower than that of AC equipment. Thus, the economics of DC and AC power distribution networks is of particular interest in the industry [3]. With the rapid development of distributed energy sources (wind power, photovoltaic, energy storage, etc.) and DC loads (charging piles, inverter air conditioner, etc.), more DC/AC and AC/DC converters are required in AC power distribution networks, which not only increases the equipment investment and operation costs but also sacrifices the overall operational efficiency and reliability of the system.

On the other hand, due to urbanization, the power consumption density of load centers is increasing rapidly, while the power supply capacity is limited by the shortage of power distribution network corridors. A DC power distribution network has greater power supply capacity [4], which reduces the investment cost of corridors compared with AC power distribution networks. Therefore, it is of great significance for the development of DC distribution networks and related scenario planning to establish a comprehensive economic evaluation model of AC and DC distribution networks by integrating investment costs, corridor costs, equipment life, energy efficiency, reliability, and so forth [5].

So far, scholars worldwide have carried out studies on the economic evaluation of distribution networks from the perspectives of index definition, power supply mode, voltage level, safety, and so forth. Combining the economic and technical parameters of distribution networks, Yang Fu et al. proposed an overall evaluation index system of a distribution network based on the modified interval DEA (data envelopment analysis) method [6], which is suitable to deal with uncertainty in distribution networks by introducing the interval form. However, the physical meaning of the evaluation indicator is unclear for this method. For traditional AC distribution network economic evaluation, research has focused on the impact of various factors on system economics and reliability, such as topology type and power [7–9], distribution network voltage level [10], and safety [11]. However, these works only focused on traditional AC distribution networks and did not consider the economic evaluation of DC distribution networks. In order to solve this problem, a comparative study on the economics of AC and DC distribution networks from the perspectives of investment and operation costs has been proposed [12,13], which provides a theoretical basis for the economic comparison of AC and DC distribution networks. However, the above research only applied simplified experiential method to calculate the operation cost of DC distribution network, the detailed time sequential simulation is not considered. Furthermore, the various types of distributed renewable energies are also neglected in the modeling process. Some scholars have also drawn attention to the comparative reliability [14] and energy efficiency [15–17] between AC and DC distribution networks, which is closely related with the operational economics of distribution grids. However, the relation between operation cost and reliability as well as energy efficiency is not analyzed in the above research.

In general, the abovementioned studies have the following three problems: (1) The analysis of a high proportion of distributed renewable energy, DC loads, and other scenarios is insufficient in its economic evaluation, which makes it difficult to objectively and comprehensively compare the economics of AC and DC distribution networks. (2) The considered voltage levels of DC distribution networks are ±7.5 and ±15 kV, which are inconsistent with the ±10 kV that has been adopted in demonstration projects and standards. (3) Some factors such as reliability and energy efficiency, which can reflect the differences between AC and DC distribution networks, are not considered in the economic evaluation stage.

In light of the lack of comprehensive and objective indicators and methods for comparing and evaluating the economic performance of AC and DC distribution networks, and considering multiple scenarios such as distributed renewable energy and DC load integration, we have developed indicators and calculation models for evaluating the economic performance of AC and DC distribution networks in four dimensions: investment costs (with corridor costs), loss costs, reliability costs, and operation and maintenance costs. Firstly, the typical models of AC and DC power distribution networks were introduced, including voltage level, power supply mode, load type, and so forth. Then, the maximum power supply capacity of AC and DC power distribution networks was considered. Secondly, an overall economic evaluation model of a distribution network was established from two aspects: investment and operation costs. The operation costs include three dimensions, namely, power consumption costs, reliability costs, and operation and maintenance costs, which serve as the basis for an energy efficiency evaluation model based on time series simulations. Finally, considering the typical "hand-in-hand" topology structure of urban distribution networks, a comparison system between AC and DC distribution networks was designed. Then, comprehensive economic and sensitivity analyses of key factors were separately carried out, and a conclusion based on the comparison between AC and DC distribution networks was drawn.

2. Typical Models of AC and DC Distribution Networks

2.1. Voltage Class and Load Type of AC and DC Distribution Networks

At present, the voltage level of a DC distribution network demonstration project mainly corresponds to 10 kV AC distribution network. Therefore, the voltage level of 10 kV and below for an AC distribution network was mainly considered in this study. According to the National Standard Medium- and Low-Voltage DC Distribution Voltage Guidelines [18] and the DC Distribution Voltage Standards [19] issued by the China Electricity Council, and in combination with the current actual voltage level of low-voltage DC equipment, the voltage levels of AC and DC distribution networks considered in this paper are shown in Table 1.

Table 1. The voltage level of AC and DC distribution networks considered in this paper.

	Medium Voltage	Low Voltage
AC	10 kV	380 V
DC	±10 kV	±375 V 48 V

In order to compare the effects of different types of loads on the economics of AC and DC power distribution networks, we mainly considered two types of loads—medium-voltage loads (connected to a 10 kV system) and low-voltage loads (connected to a 380 V system)—of which high-voltage loads include AC and DC loads, and low-voltage loads mainly consider four types of loads as follows:

Class A: load can be supplied by both AC and DC powers, such as lighting equipment, water heaters, and so forth.

Class B: AC load without frequency conversion technology. With the rapid development of frequency conversion technology, electrical appliances that use frequency conversion technology have become widespread, but there are still AC loads that only use AC motors, such as electric fans.

Class C: AC load using converter techniques, such as frequency conversion air conditioners, frequency conversion washing machine, and so forth.

Class D: load can only be supplied by DC power, such as computers, mobile phones, and DC charging piles.

2.2. Typical Topology of AC and DC Distribution Networks

Distribution networks have many types of topological structures, and the economics and reliability of different topological structures are quite different. In order to objectively compare the economics of AC and DC distribution networks, it is necessary to ensure that both have the same topological structure. Without sacrificing generality, we selected the ring network design and the open-loop-operation, hand-in-hand topology commonly used in China's current urban distribution networks as comparative analysis objects. A typical topology of an AC distribution network design is shown in Figure 1.

The AC system considered included 10 kV and 380 V voltage levels, including F1 and F2 main feeders, eight branch lines, six load points, and two distributed power sources. In order to be representative, the two types of loads introduced in Section 2.1 were considered. Medium-voltage loads were independently connected to 10 kV feeders, and medium-voltage DC loads were connected through AC/DC converters. The low-voltage load was connected to a 10 kV feeder through a common bus and transformer step up. In addition, two types of distributed power sources were considered. A small-capacity distributed power source was connected through a low-voltage bus, and a large-capacity distributed power source was connected through a 10 kV feeder. The two feeders were connected to each other through circuit breakers and tie switches.

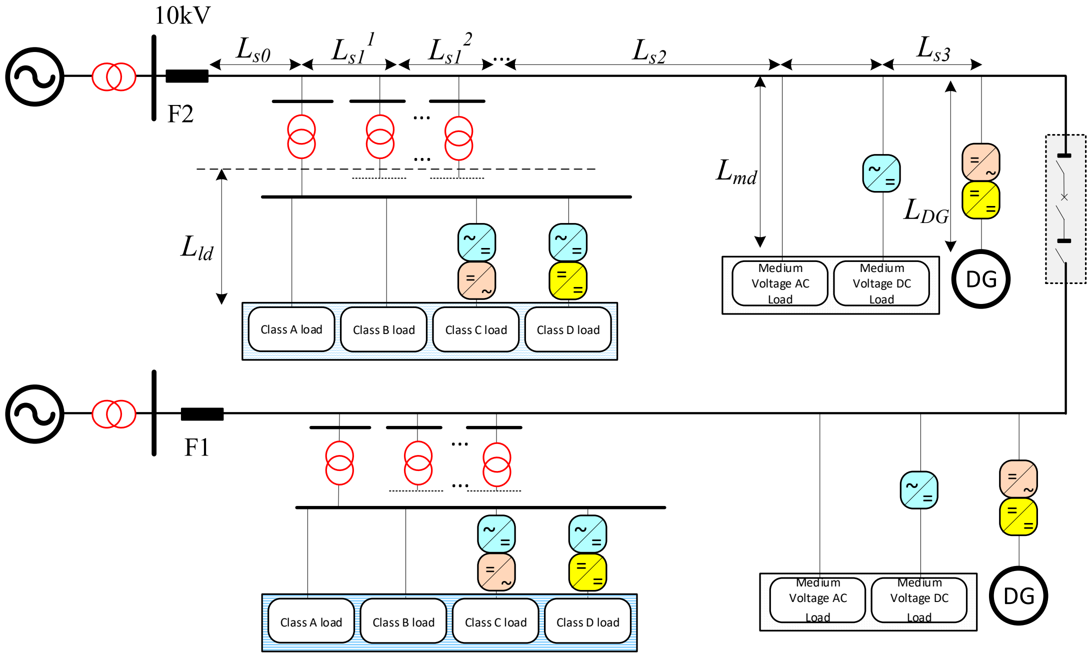

Figure 1. Topology of the AC distribution network.

Regarding the AC power distribution network, the DC power distribution network topology was designed adopting the hand-in-hand topology with two terminal power supplies, as shown in Figure 2. AC power sources at both ends were independently converted into ±10 kV DC voltage through AC/DC converters, and medium-voltage loads were independently connected to 10 kV DC buses, wherein medium-voltage AC loads were connected through DC/AC converters.

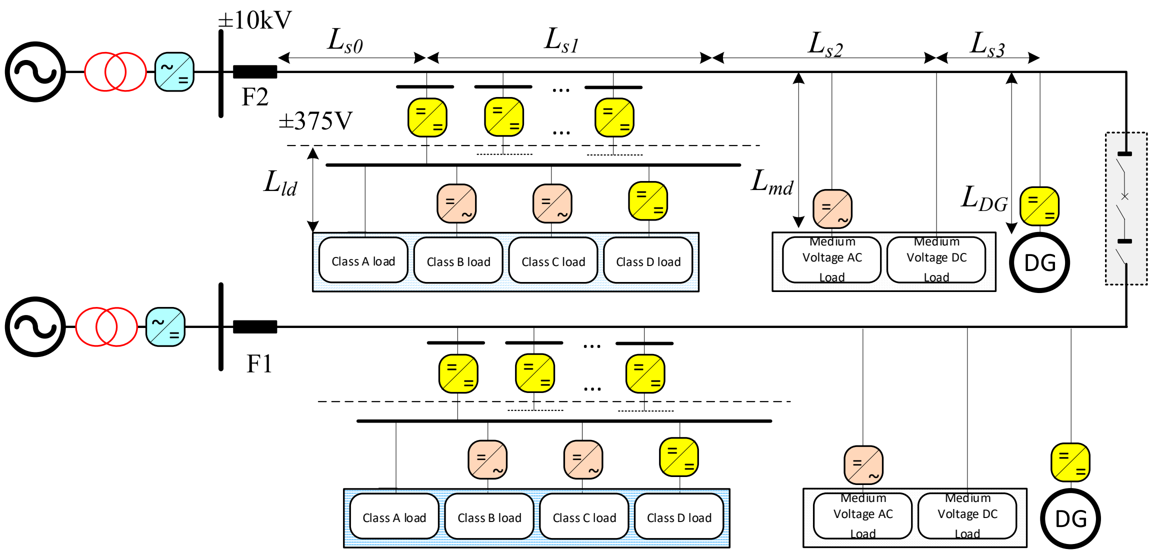

Figure 2. Topology of the DC distribution network.

Due to different types of loads and distributed power sources, the links connected to the AC or DC distribution networks are also different, which has a certain influence on the subsequent economic and energy efficiency analysis. Table 2 summarizes the links required for the interconnection of various types of loads and distributed power sources, in which the converter direction is from the network side to the equipment.

Table 2. The grid connection links of various loads and distributed generation.

Type	AC Distribution Network	DC Distribution Network
Medium-voltage AC load	Direct interconnection	DC/AC
Medium-voltage DC load	AC/DC	Direct interconnection
Class A load	Direct interconnection	Direct interconnection
Class B load	Direct interconnection	DC/AC
Class C load	AC/DC + DC/AC	DC/AC
Class D load	AC/DC + DC/DC	DC/DC
Low-voltage distributed power supply	DC/DC (photovoltaic, energy storage) or AC/DC (wind power) + DC/AC	DC/DC (photovoltaic, energy storage) or AC/DC (wind power)
Medium-voltage distributed power supply	DC/DC (photovoltaic, energy storage) or AC/DC (wind power) + DC/AC	DC/DC (photovoltaic, energy storage) or AC/DC (wind power)

As can be seen from Table 2, the grid connection of most loads and distributed power sources can be simplified by adopting a DC power supply mode, which reduces equipment costs and operational losses and has better operational economics.

2.3. Maximum Transmission Capacity of AC and DC Distribution Networks

According to research, under the same line construction costs and corridor width, a DC distribution network has greater power supply capacity than an AC distribution network. In urban distribution networks where corridor resources are increasingly tight, corridor costs may account for a large proportion of the whole distribution network project. Due to the different power supply capacities of unit corridors between AC and DC distribution networks (i.e., the different occupancies of corridor resources by unit power supply capacity), it is necessary to consider the impact of the transmission capacity of AC and DC distribution networks on their economics.

If a DC distribution network adopts a bipolar structure, the rated transmission power of the AC and DC distribution networks can be calculated by Equations (1) and (2):

$$P_{ACn}(t) = \sqrt{3}U_{ACn}I_{ACn}\cos\varphi_n \tag{1}$$

$$P_{DCn}(t) = 2U_{DCn}I_{DCn} \tag{2}$$

where U_{ACn}, I_{ACn} respectively refer to the rated voltage and rated current of the AC distribution network; $\cos\varphi_n$ refers to the rated power factor; and U_{DCn}, I_{DCn} respectively refer to the rated voltage and rated current of the DC distribution network. If the conductor section, current density, and insulation level of AC and DC cables are kept the same, while the skin effect is considered, then there are $I_{DCn} > I_{ACn}$ and $U_{DCn} = \sqrt{2/3}U_{ACn}$. Taking the rated power factor $\cos\varphi_n$ as 0.85, the rated power ratio of the DC and AC distribution network can be deduced as follows:

$$\frac{P_{DCn}}{P_{ACn}} = \frac{2U_{DCn}I_{DCn}}{\sqrt{3}U_{ACn}I_{ACn}\cos\varphi_n} > \frac{2U_{DCn}}{\sqrt{3}U_{ACn}\cos\varphi_n} = 1.109 \tag{3}$$

Considering that a bipolar DC distribution network only needs two power lines, while an AC distribution network needs three lines, under the same corridor width and line costs, the power supply capacity of a DC distribution network is more than 1.5 × 1.109 = 1.66 times that of an AC distribution network [20]. Considering that the current actual voltage level of DC distribution network engineering is mostly ±10 kV, that is $U_{DCn} = U_{ACn}$, then the power supply capacity of a DC distribution network is about two times that of an AC distribution network.

In practice, allowable voltage deviation is also an important factor that affects the power supply capacity of a distribution network, especially when the line distance is long. Formulas (4) and (5) for calculating the voltage deviation between AC and DC distribution networks are as follows:

$$\Delta U_{AC} = \frac{P_{AC}}{\sqrt{3}U_{AC}\cos\varphi}(r\cos\varphi + x\sin\varphi)l \tag{4}$$

$$\Delta U_{DC} = \frac{P_{DC}}{2U_{DC}} rl \tag{5}$$

where $\Delta U_{AC}, \Delta U_{DC}$ are the voltage deviation of AC and DC distribution networks, respectively; r, x are the resistance and reactance per unit length of the line, respectively; and l is the line length.

According to the Technical Guidelines for Planning and Design of Distribution Networks [21], the allowable deviation of the three-phase power supply voltage for a 10 kV and below distribution network is ±7% of the rated voltage, while the allowable deviation for a DC distribution network is ±7%. Therefore, the maximum power supply capacity of AC and DC distribution networks under the constraint of voltage deviation are shown in Equations (6) and (7):

$$P_{AC} \leq P_{AC\max} = \frac{U_{AC}{}^2 \cos\varphi}{(r\cos\varphi + x\sin\varphi)l} \cdot 7\% \tag{6}$$

$$P_{DC} \leq P_{DC\max} = \frac{4U_{DC}{}^2}{rl} \cdot 7\% \tag{7}$$

Under the same transmission distance and the condition of $U_{DC} = U_{AC}$, the power supply capacity ratio of a DC to AC distribution network can be deduced as follows:

$$\frac{P_{DC\max}}{P_{AC\max}} = 4\left(1 + \frac{x}{r}\tan\varphi\right) > 4 \tag{8}$$

It can be seen that under the constraint of voltage deviation, the power supply capacity of a DC distribution network is more than four times that of an AC distribution network.

3. Comprehensive Economic Evaluation Model for AC and DC Distribution Networks

Considering the construction investment (including corridor costs), operation costs, and the reliability costs of power distribution networks, we established a comprehensive economic evaluation model for AC and DC power distribution networks. Considering the different life spans of DC and AC equipment, in order to compare the economics of AC and DC power distribution networks objectively and comprehensively, we considered the life cycle cost of equipment, where the levelized cost of energy (LCOE) was applied to reflect the economics, which is commonly used in economic evaluations of wind farms (i.e., the comprehensive life cycle cost for evaluating unit power supply of power distribution networks). The economic evaluation model of LCOE is shown in Formula (9):

$$LCOE = \left(I + \sum_{t=1}^{n} \frac{E_t + R_t + M_t}{(1+r)^t}\right) \Bigg/ \sum_{t=1}^{n} \frac{W_t}{(1+r)^t} \tag{9}$$

where n is the maximum operating life of the equipment; I is the initial construction investment cost of the distribution network; E_t, R_t, and M_t represent the operating cost of the distribution network in the year t, respectively representing the cost of power consumption, reliability, and operation and maintenance of the system; W_t is the power supply in the year t; and r is the currency discount rate.

3.1. Investment Cost

The investment cost mainly includes the primary investment cost of equipment, corridor costs, project construction costs, and so forth. Its evaluation model is shown in Formula (10):

$$I = \sum_{i=1}^{M} C_i N_i + C_l + C_p \tag{10}$$

where C_i is the unit investment cost of class i equipment, N_i is the number or capacity of class i equipment, M is the number of equipment types, and C_l and C_p are the construction and corridor costs of the project, respectively.

For AC and DC distribution networks, the main types of initial investment equipment are shown in Table 3.

Table 3. Type of initial investment equipment for AC and DC distribution network construction.

Distribution Network Type	Device Type	Voltage Level
AC distribution network	Substation	110 kV AC/10 kV AC
	Distributed generation grid-connected inverter	DC/DC, DC/AC
	AC breaker	10 kV AC
	AC cable	10 kV AC, 0.4 kV AC
	Medium-voltage rectifier	10 kV AC/±10 kV DC
DC distribution network	Converter station (including AC substation)	110 kV AC/10 kV AC/±10 kV DC
	Direct current transformer	10/0.7 5kV(DC/DC)
	DC circuit breaker	±10 kV DC
	Direct current cable	±10 kV DC
	Inverter	±10 kV DC/10 kV AC
	Distributed generation grid-connected converter	DC/DC

For urban distribution networks, cables are generally used for newly built 10 kV lines, so a cable trench was considered as the calculation object of corridor costs in this study. In order to save corridor resources for a project, many lines are often laid in the same cable trench. Considering this factor, the evaluation model of corridor costs for distribution networks and lines can be calculated according to Equation (11):

$$C_l = c_{l0} m_l L / n_l \tag{11}$$

where c_{l0} is the cost per unit length of a cable trench, L is the length of a cable trench, n_l is the total number of lines that can be laid in a cable trench, and m_l is the actual number of lines laid in distribution network engineering.

According to the power distribution project, the project construction cost is generally selected according to the percentage of the total investment cost of the project, as shown in Equation (12):

$$C_p = \alpha \times \left(\sum_{i=1}^{M} C_i N_i + C_l \right) \tag{12}$$

where α is generally taken as 5–10%.

3.2. Comprehensive Operating Cost Considering Multiple Factors

Due to low line loss and few commutation links, the overall energy efficiency level of a DC distribution network is higher than that of an AC distribution network. At the same time, the reliability of the power supply is improved due to the loop-closing operation [22]. In order to compare the economics of AC and DC distribution networks more comprehensively, it is necessary to consider the effects of energy efficiency and reliability on operating costs. In this work, we established a comprehensive operation cost evaluation model for AC and DC distribution networks considering three aspects: loss, reliability, and operation and maintenance costs, which are introduced below.

3.2.1. Power Loss Cost

The cost of lost power is defined as the additional operating cost caused by lost power in the process of power transmission in a distribution network. The power loss mainly includes two parts—line loss and converter equipment loss—of which the line mainly includes the distributed power grid-connected line and the power supply line, and the converter equipment mainly includes the distributed power grid-connected converter and the equipment-side converter. Considering the different costs of power loss in different locations, the cost calculation of power loss in AC and DC distribution networks is shown in Equations (13) and (14):

$$E_{tAC} = \sum_{\tau=1}^{8760/\Delta T}\left(\Delta T\left(p_{t,DG,\tau}\sum_{i=1}^{n_{DG}}\left(P_{t,DGcon,\tau,i} + P_{t,DGline,\tau,i}\right) + p_{t,g,\tau}\left(\sum_{i=1}^{n_L} P_{t,GridLine,\tau,i} + \sum_{i=1}^{n_D}\left(P_{t,LoadCon,\tau,i} + P_{t,LoadLine,\tau,i}\right)\right)\right)\right) \quad (13)$$

$$\begin{aligned} E_{tDC} = \sum_{\tau=1}^{8760/\Delta T}\Bigg(\Delta T\Bigg(& p_{t,DG,\tau}\sum_{i=1}^{n_{DG}}\left(P_{t,DGcon,\tau,i} + P_{t,DGline,\tau,i}\right) + p_{t,g,\tau}\left(\sum_{i=1}^{n_L} P_{t,GridLine,\tau,i} + \sum_{i=1}^{n_C} P_{t,GridCon,\tau,i}\right) \\ & + p_{t,g,\tau}\sum_{i=1}^{n_D}\left(P_{t,LoadCon,\tau,i} + P_{t,LoadLine,\tau,i}\right)\Bigg)\Bigg) \end{aligned} \quad (14)$$

where $P_{t,DGcon,\tau,i}$ and $P_{t,DGline,\tau,i}$ respectively represent the power losses of converters and grid-connected lines of the distributed power source i in year t at time τ; $P_{t,GridLine,\tau,i}$, $P_{t,GridCon,\tau,i}$ respectively represent the losses of the distribution network lines i and converters i (for a DC distribution network); $P_{t,LoadCon,\tau,i}$, $P_{t,LoadLine,\tau,i}$ respectively represent the converter losses and line losses of the load point i; $p_{t,DG,\tau}$, $p_{t,g,\tau}$ respectively represent the power consumption cost LCOE of the distributed power source and the average power purchase cost of the distribution network; and ΔT is the time resolution of energy efficiency calculation in hours.

Using AC/DC hybrid power flow calculation, the power flow distribution results of AC and DC power distribution networks can be obtained. Then, the losses of each part in Equations (13) and (14) can be counted, and the power loss cost of the system in the year t can be calculated.

3.2.2. Reliability loss Cost

Reliability loss cost is defined as the economic loss caused by load power failure due to distribution network failure. Generally, the reliability cost can be derived by multiplying the power shortage of the system and the ROVTUE (the ratio of output value (GDP) to unit electric energy consumption), as shown in Equation (15):

$$R_t = EENS_t \times \mathrm{ROVTUE}_t = EENS_t \times \frac{GDP_t}{W_{st}} \quad (15)$$

where $EENS_t$ refers to the expected energy not supplied in the year t of the system, GDP_t refers to the total GDP (Gross Domestic Product) in the year t of the society, and W_{st} refers to the total power consumption in the year t of the society. Lack of power supply value can be obtained by the AC or DC distribution network reliability evaluation method. For specific methods, please refer to [22].

3.2.3. Maintenance Cost

The annual maintenance cost of a distribution network mainly includes material and labor costs in equipment operation and maintenance. According to actual engineering operation experience, operation and maintenance costs can be simplified to a certain proportion of initial investment, namely,

$$M_t = \beta \times (1+\alpha) \times \left(\sum_{i=1}^{M} C_i N_i + C_l\right). \quad (16)$$

In the formula, the maintenance rate of the project is generally 2%.

4. Case Studies

4.1. Introduction to the System of Numerical Examples

The example used a hand-in-hand topology with a ring network design and an open-loop operation, which mainly included three types of loads: renewable energy generation, a medium-voltage AC/DC load, and a low-voltage load. On the low-voltage side, multiple transformers existed in parallel to separately supply power to four types of loads. The medium-voltage load was mainly divided into a medium-voltage AC load and a medium-voltage DC load, which were directly connected with a 10 kV line. Renewable generation was photovoltaic power generation in this example. Specific line lengths in the topology are shown in Table 4.

Table 4. Line length of example system.

Line Type	Length	Quantity
L_{S0}	2 km	1
L_{S1}	2 km	1
L_{S2}	2 km	1
L_{S3}	2 km	1
L_{ld}	0.02 km	4
L_{md}	0.05 km	2
L_{DG}	0.2 km	1

According to the investigation, the current cost of equipment in AC and DC distribution networks is shown in Table 5 [22,23].

Table 5. Investment cost of AC and DC distribution networks.

Attribute			**AC Distribution Grid**		**DC Distribution Grid**	
Equipment	Voltage	Unit price (10,000 RMB)	Quantity	Total price (10,000 RMB)	Quantity	Total price (10,000 RMB)
Substation	110/10 kV	20/MW	6 MW	120	6 MW	120
Convertor station	110/10 kV	50/MW	–	–	6 MW	480
AC transformer	10/0.4 kV	10/MW	3 MW	30	–	–
Direct current transformer	10/0.75 kV	50/MW	1 MW	50	4 MW	200
Inverter	10 kV	65/MW	1 MW	65	1.5 MW	97.5
Rectifier	10 kV	65/MW	1.5 MW	97.5	–	–
AC breaker	10 kV	2/set	3 sets	6	–	–
DC circuit breaker	±10 kV	60/set			3	180
AC cable	10 kV	20/km	4.2	84	–	–
	380 V	10/km	0.18	1.8	–	–
Direct current cable	±10 kV	20/km			4.2	84
	±375 V	10/km			0.18	1.8
Corridor cost		7/km	150	1050	100	700
Total			1504.3		1863.3	

4.2. Comparative Analysis of Economy Between AC and DC Distribution Networks

Based on the economic evaluation model proposed in this paper, the investment cost of AC and DC distribution networks and the comparison of various types of operating costs were calculated, as shown in Figure 3, where the investment costs were converted into equivalent annual values according to the economic data in Table 5. Considering that the operation life of DC equipment is about 10 years, it was assumed that the operation time was 10 years.

As can be seen in Figure 3, a DC distribution network has higher initial investment, operation, and maintenance costs than an AC distribution network, but the loss cost is far lower than an AC distribution network. Therefore, DC distribution networks have certain advantages in terms of total cost, of which the reliability cost is relatively small, mainly because the current domestic ratio of output value to unit electric energy consumption (ROVTUE) is not high.

Considering that the service life of DC equipment can be improved, it is of great significance to analyze the relationship between the LCOE value of AC and DC distribution networks with their operating years. According to the above-mentioned economic calculation results, the variation trend of LCOE values of AC and DC power distribution networks with their operation years were obtained, as shown in Figure 4.

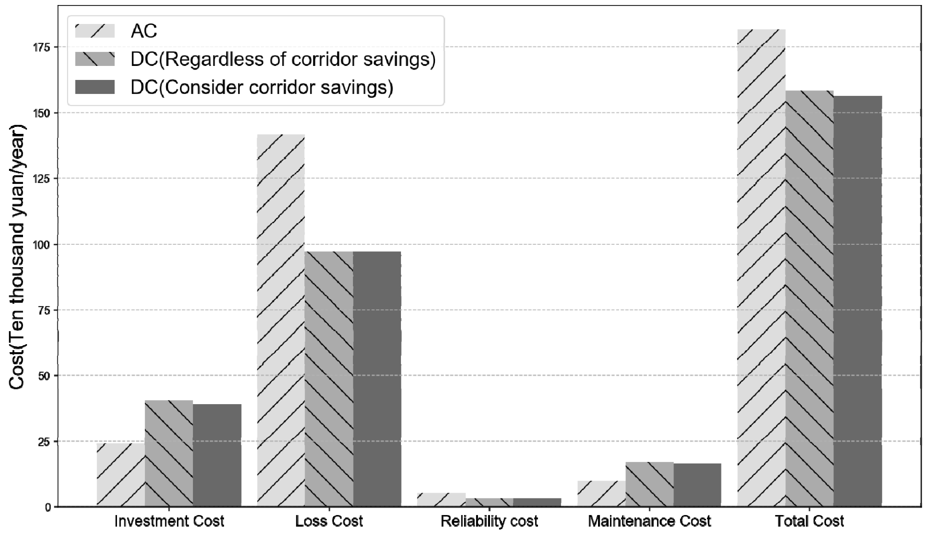

Figure 3. Economic analysis results of AC and DC distribution networks.

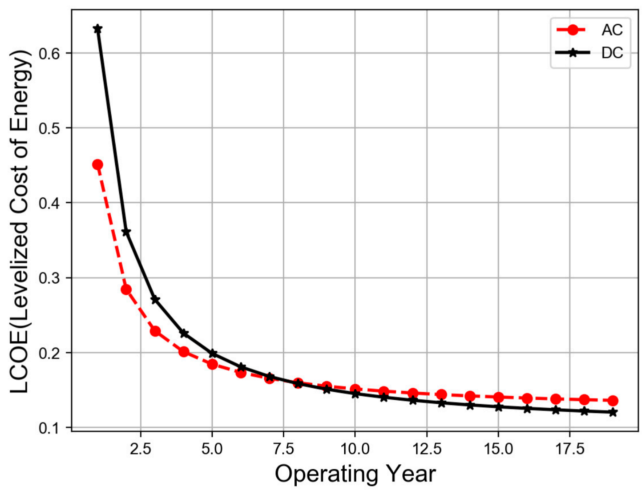

Figure 4. Relationship between LCOE and years of operation in AC and DC distribution networks.

As can be seen from Figure 4, the LCOE values of both AC and DC distribution networks show a decreasing trend and gradually approach saturation with the increase of operation years. The two intersect at about 10 years, which indicates that the economics of a DC distribution network is better than that of an AC distribution network when the number of years of operation is more than 10 years. According to the current operating life of DC equipment (about 10 years), the economic level of DC and AC distribution networks is equivalent. With the improvement of the service life of power electronic devices in the future, the economics of DC distribution networks will have obvious advantages.

4.3. Sensitivity Analysis of Influencing Factors

According to the above economic analysis results, it can be seen that AC and DC distribution networks account for a relatively high proportion of economic efficiency, mainly investment costs and loss costs. At present, the cost of a DC distribution network is relatively high because most equipment requires customized research and development. With the maturity of future technology and market-oriented scale production, the initial investment cost of DC distribution network equipment will drop significantly, which will greatly affect the economics of DC distribution networks. In addition, the proportion of renewable energy has a significant impact on the losses of AC and DC distribution networks, thus affecting their economics. Therefore, we mainly analyzed the impact of the following two main influencing factors on the economics of AC and DC distribution networks: the investment cost of DC distribution network equipment and the access ratio of distributed power sources.

4.3.1. Economics of DC Distribution Network Equipment

Based on the benchmark scenario, we considered three scenarios where the cost of DC distribution network equipment was reduced by 20%, 40%, and 60% compared with the benchmark. The variation trend of the LCOE index ratio between AC and DC distribution networks with the number of operation years under the three scenarios was obtained, and the comparison results are shown in Figure 5.

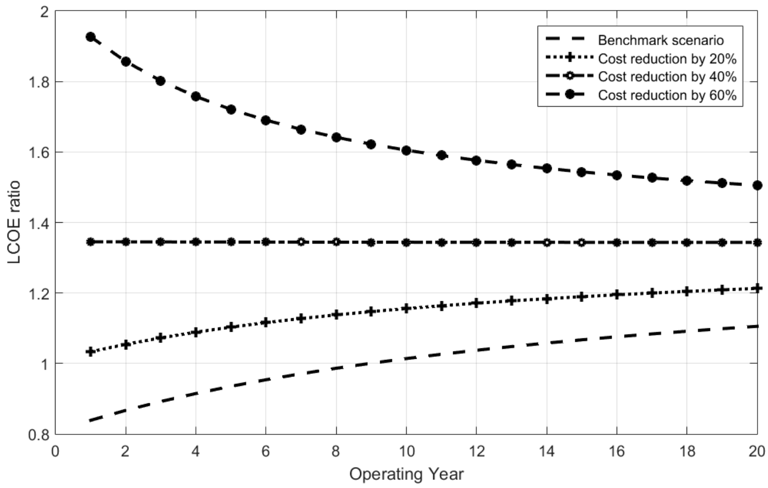

Figure 5. Effect of equipment cost on LCOE ratio of AC and DC distribution networks.

As can be seen from Figure 5, as the cost of the DC distribution network equipment decreases, the LCOE ratio of AC and DC distribution networks shows an increasing trend, indicating that the economy of a DC distribution network gradually exceeds that of a AC distribution network. Based on the analysis of the number of years of operation, with the current average life of DC equipment being about 10 years, as well as the current equipment cost and economic level of AC and DC distribution networks being equivalent, the economic level of a DC distribution network is slightly higher than that of an AC system.

4.3.2. Proportion of Renewable Energy Integration

Considering that the installed capacity of renewable energy is from 0 to 6 MW (peak load), the LCOE values of AC and DC distribution networks under different proportions of renewable energy were calculated in 0.5 MW steps, as shown in Figure 6.

As can be seen from Figure 6, with the increase of the renewable energy proportion, the LCOE values of AC and DC distribution networks both show a trend of "decreasing first and then increasing". There is an intersection between the two, namely, when the access ratio of distributed power exceeds 40%, the economy of a DC distribution network is better than that of an AC distribution network. Furthermore, the efficiency change curves of AC and DC distribution networks under different renewable energy proportions were analyzed, as shown in Figure 7. It can be seen that the efficiency (loss) of DC and AC distribution networks with renewable energy proportions also shows a trend of "increasing first and then decreasing", which results in a similar trend of LCOE values (Figure 7).

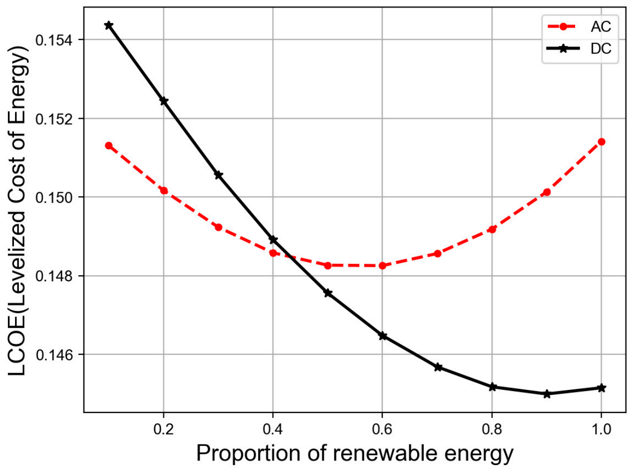

Figure 6. Influence of renewable energy proportion on the LCOE of AC and DC distribution networks.

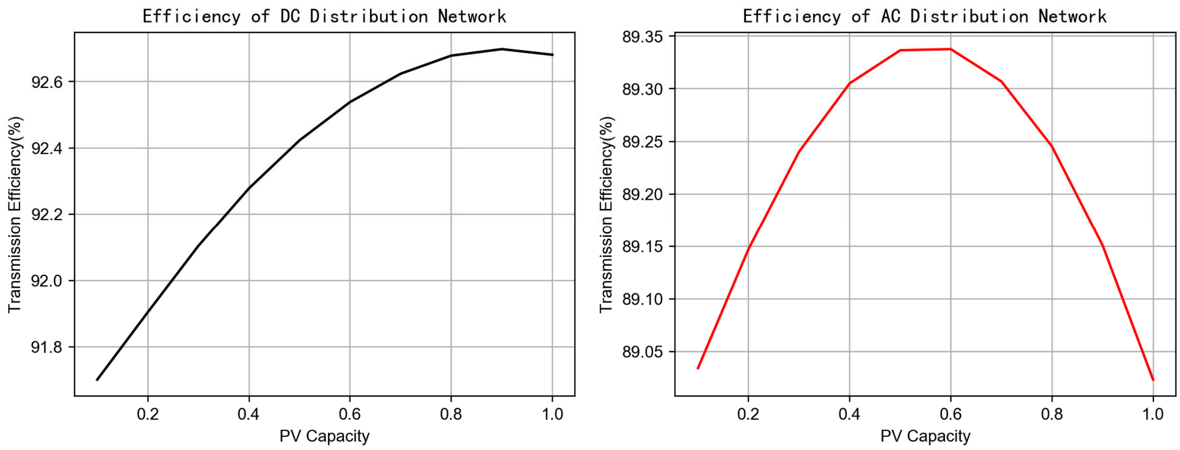

Figure 7. Effect of renewable energy proportion on distribution network efficiency.

4.3.3. Impact of ROVTUE Level

According to equation (15), the ROVTUE has a significant impact on the reliability cost. In the above analysis, the simulation results show that the impact of reliability cost is tiny because the ROVTUE is low. However, if the reliability is much more important for the distribution grid, the ROVTUE should be increased and then the reliability cost might have a significant impact on the economy. In this chapter, the impact of ROVTUE level on AC and DC distribution networks is researched. Considering the benchmark and the scenarios that ROVTUE multiplied by 10 and 100, then the LCOE ratio between AC and DC distribution networks with the number of operation years can be calculated and drawn in Figure 8.

Figure 8 indicates that with the increasing of ROVTUE, the LCOE ratio between AC and DC distribution networks increases obviously, reflecting that DC distribution is advantageous in the scenario where high reliability is required. The reason for this is that in the DC distribution network, the system can retain the power supply in the switching operation, which has a higher reliability and lower reliability cost. As a result, if the ROVTUE increases, the advantage of DC distribution in the economy becomes gradually obvious.

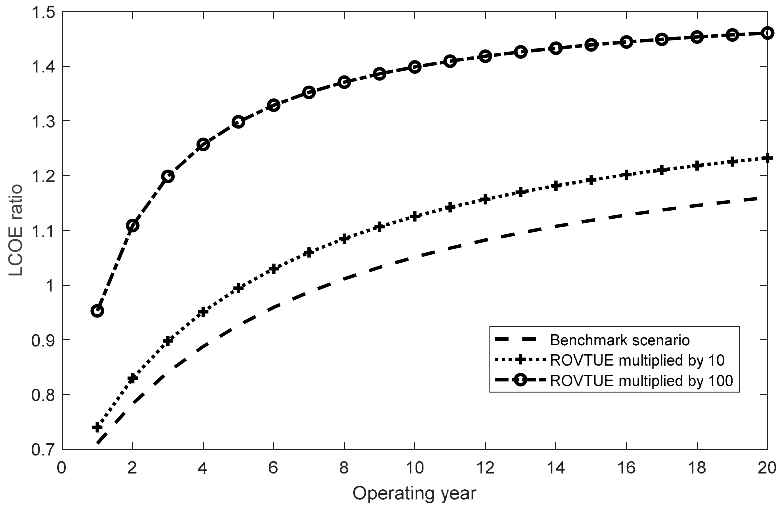

Figure 8. Effect of ROVTUE on LCOE ratio of AC and DC distribution networks.

5. Conclusions

In the future, distribution networks will be in a hybrid AC/DC structure. Quantitative evaluation and comprehensive comparative analysis of the economics of AC and DC distribution networks are of great guiding significance for the planning and development of future distribution networks. From the perspectives of investment costs and operation costs (including loss cost, reliability cost, and operation and maintenance cost), we established a comprehensive economic evaluation model for AC and DC distribution networks. Based on the same boundary conditions (power supply and load conditions), medium- and low-voltage AC and DC distribution networks were designed and various economic analysis calculations and analyses of influencing factors were performed. The following conclusions were drawn:

(1) A DC distribution network has higher initial investment, operation, and maintenance costs than an AC distribution network, but the loss cost is far lower than an AC distribution network. Under the current condition of the life cycle of the DC distribution network equipment, DC and AC distribution networks have a similar level of economy. With the improvement of the life cycle of power electronic devices in the future, the economics of DC distribution networks will have obvious advantages.

(2) Equipment investment cost is an important factor that presently affects the economics of DC distribution networks. With the reduction of the cost of DC equipment, the economics of DC distribution networks will be greater than that of AC distribution networks, even under the restriction of the low life cycle of current DC equipment.

(3) The proportion of renewable energy is another factor that affects the economics of AC and DC distribution networks. With the increase of the proportion of renewable energy, the efficiencies of DC and AC distribution networks both show a trend of increasing first and then decreasing. However, the inflection point of AC distribution networks appears earlier. Therefore, with the increase of the proportion of renewable energy, DC distribution networks have certain economic advantages compared with AC distribution networks.

(4) The ROVTUE level has a significant impact on the comparison of economy between the AC and DC distribution networks. Because of the high reliability of the DC distribution network, with the increasing ROVTUE level, the LCOE ratio between AC and DC distribution networks increases obviously, reflecting that DC distribution is advantageous in the scenario where high reliability is required.

In this paper, an economic evaluation model for medium- and low-voltage AC and DC distribution networks was proposed, which is also suitable for the scenario of a hybrid AC and DC system. Future research will focus on the optimal planning capacity of various renewable energy sources, energy storage, and other resources, as well as the planning method of AC and DC distribution networks based on the economic evaluation model proposed in this paper.

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