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Research on the Technical and Economic Development of Large Megawatt Wind Turbines Based on Medium-Voltage Electrical System

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Abstract

INTRODUCTION: With the advent of the "bidding era" and "parity era" in the wind power market, the competition of the whole machine factory is becoming more and more fierce, and the capacity of the single fan is getting larger and larger, which becomes the key to the design of the fan electrical system of the large-capacity unit (5.XMW or more). At present, the low-voltage wind power system (690V,1140V) is the common solution for wind turbines. However, due to the limitation of the cable section of low-voltage electrical system and the increase of the rated current of the generator, the increase of the capacity of a single machine makes more cables from the generator side to the grid, and the cost also increases.
OBJECTIVES: Aiming at the future large megawatt wind power market, the medium voltage Doubly-Fed electrical system solution is proposed to increase the higher generation and electricity income of wind farms and reduce the manufacturing cost of wind farms.
METHODS: The technology and economy of medium voltage and low voltage electrical system are compared.
RESULTS: With the gradual increase of single capacity, the economy of medium pressure wind power generation system is getting better and better, and the higher the height of the tower, the better the economy. At the same time, the reduction of the rated current of the generator brings about the reduction of line loss and the increase of power generation. The number of cables is greatly reduced, and the construction cost and difficulty of cable laying will be greatly reduced.
CONCLUSION: In response to the technical trend of large-capacity wind turbines in the future, the medium-voltage wind power generation system has a good application prospect, both from the economic and technical point of view.

Keywords: Medium voltage wind power system, Large megawatt wind power, Economic analysis, line losses

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1. Introduction

With my country's "carbon peak" and "carbon neutral" goals [1], all countries are vigorously promoting the development of new energy sources and the low-carbon electricity [2]. wind power has gradually become an important part of the sustainable development strategies in many countries [3].China will continue to vigorously develop renewable energy. According to the technical reserves of wind turbine companies, the visibility of future upgrades to 6-7MW models is high, and the market demand for wind power has gradually entered models above 5MW [4]. After a certain period of domestic wind turbine technology introduction and industrialized production, the single-unit capacity has gradually approached the international leading level [5].Meanwhile, the source of wind energy is abundant in China, the potential capacity for both onshore and offshore wind energy is around 700–1200 GW, according to the third National Wind Energy Resources Census [6].

With the introduction of the long-term goal outline for 2035, achieving carbon peaking and carbon neutrality has

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become one of the key tasks of the country. The annual new installed capacity of the wind power market will remain above 20GW. At the same time, large megawatt units can effectively reduce the land used for wind farms. Cost, stand-alone power is expected to further increase. Due to the advancement of wind turbine technology, the available wind energy resource reserves continue to expand. As long as the current resource conditions are intensively cultivated and developed, it can fully meet the 2035 vision target outline [7].

At present, low-voltage wind power generation systems are commonly used in onshore wind farms [8]. Since the number and cross-section of cables on the generator side increase with the increase of the capacity of a single wind turbine, as the scale of onshore wind farms increases and the capacity of a single unit increases, if low-voltage wind power generation systems are still used, the cross-section and number of tower cables are bound to be With the increase, the cable investment and corresponding construction cost and difficulty also increase [9].

An effective solution to this problem is to increase the voltage level on the generator side to reduce the stator current and reduce the number and cross-section of cables. Based on this, this paper proposes a medium-voltage wind power generation system program, and is conducting economic comparisons between low-voltage and medium-voltage programs. Based on the comparison results, combined with the development trend of wind power technology,the applicability of the medium-voltage wind power generation system is discussed and the economic and social benefits of wind power multi-energy combined technology are considered [10,11].

As a source of clean energy with high storage, no pollution, and using mature technology, many countries are seeking to utilize wind energy [12] and consider wind power to be a promising energy [13], Though as a newcomer, China had installed a total of 5.93 GW by 2019 [14]. It is expected that China will become the second-largest offshore wind market by 2040, following the European Union [15].

At the beginning of the wind power industry, the single-unit capacity of the fan is mainly 1.XMW-2.XMW, at this time, the output voltage of the wind power is 690V. In 2018, the capacity of single fan between 3.X-4.XMW has gradually become the mainstream capacity of the market. The capacity of the single machine is twice the previous, and the current is doubled, at this time, the application of the converter three-level technology will raise the output voltage of the generator from 690V to 1140V, and since then, this technology is applied in the industry. In the advent of the "parity era" of wind power, the increase in single-unit capacity has become a means to reduce the cost of wind power, so large megawatt (5.X-8.XMW) fans will become the mainstream. The capacity of a single machine is 3 to 5 times that of the previous one. Therefore, the medium-voltage double-fed wind power generation system came into being, lifting the fan output cable 1140V to 10.5kV, reducing the internal output current of the fan by 10 times, reducing the internal loss of the fan and reducing the number of cables, bringing economic and power generation efficiency to the fan.

2. Introduction of Medium Voltage Wind Power System

The medium voltage wind power generation system mainly consists of Doubly-Fed generators, medium voltage switch cabinets, converters and transformers. The electrical topology is shown in Fig. 1.

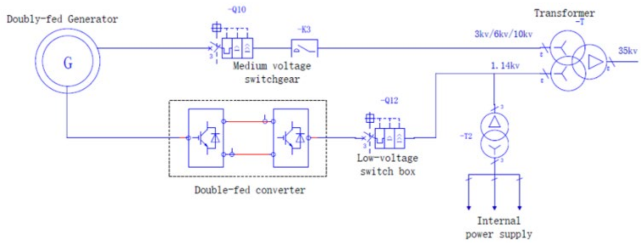

Figure 1. Medium Voltage Wind Power System

In the medium-voltage wind power system, the rated voltage of the stator of the Doubly-Fed generator is medium voltage, and the rotor is a low-voltage system of 1140V. According to the opening voltage of the generator, a combination of converter and medium voltage switchgear is adopted, and the main circuit breaker and parallel The grid contactor is integrated from the converter into the independent medium voltage switch cabinet. The converter controls the unit to be connected to the grid through the medium voltage switch cabinet. At the same time, the converter body is basically the same as the low voltage converter, and the mechanical interface of the converter is the same as the original one. There are tower platforms to be consistent. Finally, the generator-side voltage level is boosted to 35kV through the three-winding transformer to complete the grid connection.

The medium voltage Doubly-Fed wind power generation system adopts a variable speed constant frequency wind power generation system combining speed regulation system and variable pitch adjustment technology, and the main advantage is that the wind wheel can run at variable speed. The AC motor realizes speed adjustment by adjusting the size, phase and frequency of the generator rotor current, and maintains a close to constant optimal blade tip speed ratio in a wide wind speed area, thereby achieving the maximum conversion efficiency of wind energy. The speed regulation system can realize the active and reactive power regulation of the system through the control strategy, reduce losses, suppress harmonics and improve the efficiency of the system. Medium voltage Doubly-Fed wind power generation system is mainly composed of medium voltage Doubly-Fed generator (stator 10.5kV, rotor 1140V), switchgear (10.5kV), Doubly-Fed converter, medium voltage cable and accessories, three-winding box substation .

Compared with the traditional low-voltage Doubly-Fed wind power system, the stalled opening voltage of the rotor winding can be kept unchanged by changing the ratio of the effective turns of the stator and rotor winding. The stator side 1140V of the low-voltage Doubly-Fed wind power generation system is raised to 10.5kV, and the rotor side of 1140V remains unchanged. Medium-voltage Doubly-Fed wind turbines can be applied to all wind farms, and the relevant electrical components are mature to meet the needs of both distributed and centralized wind power projects.

The core of adopting medium-voltage wind power generation system lies in the investment in cables, which reduces project costs. Taking a single unit capacity of 5.5MW as an example, the required stator cables in the low-voltage electrical system tower are 10 1x220mm (1.8/3kV), and the rotor cables are 10 1x150mm (1.8/3kV), a total of 20 low-voltage cables, and the number of cables is multi-section Big. When the rated voltage of the generator is increased by 10.5kV, the required stator cables are two 3x70+3x25mm (6/10kV).

As the capacity of a single unit increases, the stator current of the generator also increases. The large capacity of the unit can be solved by increasing the cable cross-section or increasing the number of cables. However, the increase of the cable cross-sectional area leads to an increase in weight, and the increase in engineering costs such as transportation and laying, and the economic efficiency of the wind farm will decrease.

In today's rising copper price, the investment in cables will greatly affect the construction cost of the entire wind turbine. Increasing the voltage level on the generator side and reducing the rated current on the generator side are one of the effective solutions to this problem. The number of cables on the wind turbine side is reduced. Greatly reduce the difficulty and cost of cable construction.

3. Case study of medium voltage wind power generation system

In order to comprehensively analyze the technical and economic efficiency of low-voltage and medium-voltage wind power generation systems, this paper is based on a set of typical cases.

3.1. Research case

The case is based on a wind turbine with a single capacity of 5.5MW, a low-voltage electrical system generator stator and rotor voltage of 1140V, medium voltage electrical system generator stator voltage of 10.5kV, and rotor voltage of 1140V as a basis for technical and economic comparison and analysis.

The topology of the low-voltage wind power generation system is shown in Fig. 2.

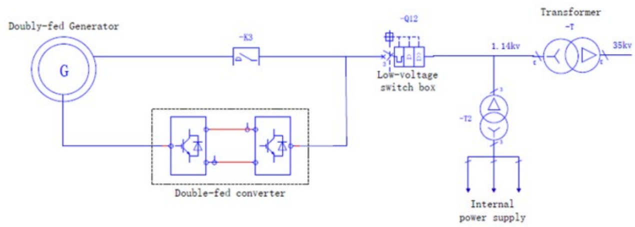

Figure 2. Low-voltage wind power System

Compared with medium-voltage wind power generation systems, medium-voltage electrical system electrical equipment adds medium-voltage switch gear. At the same time, due to the increase of voltage levels, the unit price of generators and transformers will increase. Now it will be divided into two parts of cable and electrical equipment cost for economic analysis and comparison.

3.2. Cable cost analysis

For the selection of wind turbine tower cable materials, different owners have different requirements for cable materials, so the Table 1 takes the 5.5MW Double-Fed Wind turbine as an example and calculates copper and aluminum alloy cables and different tower heights as a comparative analysis. Since copper prices fluctuate, at the time of writing, copper prices are now used as prices for economic research.

Table 1. 5.5MW Wind turbine Cable cost analysis

5.5MW Double-Fed Wind turbine		
Double-fed Generator	1140V	10.5kV
Power cable calculated current(A)	Stator: 3046 Rotor: 1024	Stator: 331 Rotor: 1024
Conversion factor	Stator: 0.78*0.87 Rotor: 0.84*0.87	Stator: 0.86*0.94 Rotor: 0.86*0.87
Number of tower power cables	Stator: 8-1*220-1*185 Rotor: 10-1*160-1*150	Stator: 2-3*70+3*25 Rotor: 10-1*150-1*150
Tower power cable price (w)	100m Cu cable:62.1 100m Al cable:34.3 140m Cu cable:82.1 140m Al cable:41.4	100m Cu cable:28.1 100m Al cable:14.7 140m Cucable:37.8 140m Al cable:18.2
Transformer cable current	3095A	312/383A
Conversion factor	0.77	0.92
Number of box	1.8/3:	8.7/15: 2-

transformer cables	10-3*240+1*120	3*240+1*120 1.8/3: 2-3*70+1*35
Transformer cable price (w)	18.75	3.1

Through the calculation of cable current carrying capacity and cable price, the cable cost of low-voltage and medium-voltage electrical systems can be obtained, as shown in the Table 2.

Table 2. Comparative analysis of cable costs

Cable Type	Low voltage system(w)	Medium voltage system(w)
Tower 140,Copper cable	101	41
Tower 100,Copper cable	80.9	31.4
Tower 140,Aluminum cable	60.2	21.4
Tower 100,Aluminum cable	53.2	17.9

From the histogram, it can be concluded that the medium voltage electrical system scheme has an absolute advantage over the low voltage electrical system in terms of cable cost, and the higher the tower height, the more obvious the advantage.

3.3. Cost analysis of electrical equipment

Due to the increase in voltage levels, the increase in the material cost of the copper and silicon steel sheets of the generator has led to an increase in the price of a single device. At the same time, compared with low-voltage converters, the medium-voltage system uses a combination of converters and medium-voltage switch gear. The price of a single converter is reduced, but a switch gear is added, which increases the overall price.

The onshore wind turbine transformer is partly purchased by the owner, and the transformer is changed from the original dual winding to the three winding, and the cost increases accordingly.

For the inquiry of electrical equipment, this research consulted the prices of mainstream equipment manufacturers in the current market as a reference. Taking the price difference between medium-voltage electrical equipment and low-voltage electrical equipment as the research content, the following results are obtained, as shown in the Table 3.

Table 3. Electrical Equipment cost analysis

Electrical Equipment	Cost difference (W)
Generator	3
Converter	-5
Switch gear	20
Box-type Transformer	10
Complete Fan	28
Fan manufacturer	18

According to market research, for the wind turbine as a whole, the increase in the voltage level will increase the cost of electrical equipment by about 28W.

3.4. Cost analysis of electrical equipment

Based on the above cost analysis of cables and electrical equipment, taking a single unit capacity of 5.5MW as an example, the cost of the low-voltage and medium-voltage electrical systems and the cost difference between the low-voltage and medium-voltage electrical systems and the cost of the low-voltage and medium-voltage electrical systems can be clearly obtained through the histogram. The comparison of the two results is shown in Table 4;

Table 4. 5.5MW complete unit cost and price difference analysis

Cable Type	Low voltage system (w)	Medium voltage system (w)	Prince difference (w)
Tower 140 Copper cable	101	69	32
Tower 100 Copper cable	80.9	59.4	21.5
Tower 140 Aluminum cable	60.2	49.4	10.8
Tower 100 Aluminum cable	53.2	45.9	7.3

From Table 4, the following conclusions can be drawn:.

(i) The higher the tower height, the more obvious the price difference between low pressure and medium pressure systems.

(ii) The use of Aluminum alloy cables can reduce the cost of the whole machine.

(iii) For fans with copper cables, the price difference between low-voltage and medium-voltage systems is much higher than for fans with Aluminum alloy cables.

(iv) The overall cost of the medium voltage electrical system is significantly lower than that of the low voltage electrical system.

4. Case study of medium voltage wind power generation system

With the trend of large-scale wind turbines, the demand for the domestic onshore wind power market has clearly entered 5MW and above. According to the technical reserves of wind turbine companies, the visibility of future upgrades to 6-7MW models is high. At the same time, the advent of the era of "bidding on the Internet" has further reduced the construction costs of wind power projects. Under the premise that the owner's rate of return on investment remains unchanged, it will inevitably force the Fan manufacturer to further reduce costs. Therefore, the electrical system technology and economy of large megawatt units are more important.

At present, the purchase of box-type transformers for onshore wind power is purchased by the owner. Therefore, this article will study the overall economics of the wind turbine from both the complete machine and the Fan manufacturer.

This case study takes the 5MW-8MW unit capacity as the research object, and takes the cost difference between the medium voltage electrical system and the low voltage electrical system as the research result, and the results are shown in the Figure 3;

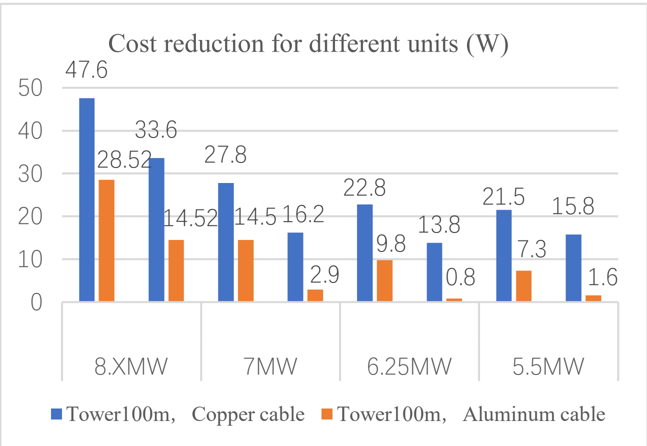

Figure 3. Cost reduction for different units (W)

According to the analysis of the research results, the technical economy of the medium voltage electrical system is better than that of the low voltage electrical system.

5. Advantages of line losses in medium-voltage electrical systems

In the wind power generation system, the output voltage level of the wind turbine is increased from 1140V to 10.5kV, the output current of the fan decreases exponentially, and the line loss is reduced due to the exponential reduction of the current. In the era of large megawatt wind power, the height of the tower is about 110 m, which can be calculated by the line loss formula.The calculation formula of cable line loss mainly includes:DC resistance of conductor (as defined in equations (1)), Skin effect factor (as defined in equations (2) and (3)), Proximity effect factory (as defined in equations (4)), AC resistance of conductor (as defined in equations (5)).

$$R_{90^\circ C} = R_{20^\circ C} \times [1 + \alpha(90 - 20)] \quad (1)$$

$$y_s = \frac{x_s^4}{192+0.8x_s^4} \quad (2)$$

$$x_p^2 = \frac{8\pi f}{R_{90^\circ C}} k_p \times 10^{-7} \quad (3)$$

$$y_p = \frac{x_p^4}{192+0.8x_p^4}\left(\frac{d_c}{s}\right)^2 \times \left[0.312\left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\frac{x_p^4}{192+0.8x_p^4}+0.27}\right] \quad (4)$$

$$R' = R_{90^\circ C} \times (1 + y_s + y_p) \quad (5)$$

Taking 6.0MW as an example, when the output voltage of the fan is 1140V, the output current of the fan is 3376A, and when the output voltage of the fan is 10.5kV, the output current of the fan is 366A.According to the above line loss formula (1)~(5), it can be obtained:The loss of low-voltage wind turbines is 26.73kW, and the loss of medium-voltage wind turbines is 4.3kW.

As a result, 1% increase in the power generation of a single medium-pressure wind power system will bring higher power generation and profits to the owners every year.

6. Summary and outlook

Based on the technical and economic research of low-voltage and medium-voltage electrical systems, this paper conducts a comprehensive analysis and comparison of the technical and economic efficiency of medium-voltage wind power generation systems through variables such as tower height, cable material, complete machine and main engine plant, and different single-machine capacities. Get the following conclusions:

- Large medium voltage Doubly-Fed wind turbines.

At present, the high-voltage Doubly-Fed generator used onshore wind turbine can be directly connected to the grid without the need for a transformer, reducing the system cost. Its structure is the same as that of conventional high-voltage generators, and the entire high-voltage cable is mainly used in the winding of the stator coil of the generator to solve the problem of high-voltage insulation. The use of high-voltage generators can reduce the copper consumption of the generators.

- The voltage is raised and the current is reduced, ensuring the safe and stable operation of the fan.

Medium voltage Doubly-Fed model raises the stator voltage of the Doubly-Fed generator from 1140V to 10.5kV, increases the voltage, the current drops, the temperature rise of the generator and converter is better, the reliability of the electrical components is higher, and the alarm and shutdown of the wind farm fan converter due to excessive current temperature rise is solved, and provides a good guarantee for the subsequent safe and stable operation of the station.

• Reduce costs and increase efficiency.

The 10.5kV medium voltage unit adopts 2-3×120+1×50 cables on the low voltage side and 2-3×95 cables on the medium voltage side. It greatly reduces the cable procurement cost,construction cost and construction difficulty, and also reduces the line loss and improves the transmission efficiency.

• It is conducive to the selection of low-voltage equipment and the optimization of equipment structure.

The voltage of the medium voltage fan rises and the current decreases, which is more conducive to the selection of complete sets of product components for medium voltage and low voltage in the box transformer, and at the same time, the amount of copper bar inside the box transformer is reduced, and the complexity of the internal structure of the box transformer is also avoided due to multiple cable wiring.

From the technical and economic comparison between the above low-voltage electrical system and the medium-voltage electrical system (10.5kV), it can be concluded that the medium-voltage electrical system has great advantages in the cost of large megawatt complete machine and the output efficiency of the fan. It is an effective solution for large megawatt fans. The medium voltage Doubly-Fed electrical system (10.5kV) promotes the development of wind power and is also a win-win solution for owners and wind turbine manufacturers.

From the perspective of the world's new energy development policy, the future development of new energy is still sustainable, and the "big with small" of fans, far-sea fans, and large-scale offshore units will be the future development direction. Offshore wind turbines will move towards 15MW~20MW, and at present, wind power manufacturers have begun to develop 15MW~20MW. In this case, what is the technical solution of the electrical system of wind power, and it is not impossible to raise the output voltage of the fan from 10.5kV to 35kV. The development of future wind power electrical systems also needs us to continue to explore.

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