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Variable-speed Constant-frequency (VSCF) Wind Power Generation (WPG) Based on Production Function Research

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Abstract: With the rapid development of the power industry, a large number of WPG equipment has been put into operation. The increasing single-unit capacity of WTs and the increase in the ratio of WP access to the power grid undoubtedly put forward more stringent requirements for WP system technology and equipment. Based on the production function research, this paper analyzes the key technologies of VSCF WPG. In order to fundamentally solve the technical bottleneck of the current WP industry and provide effective technical solutions for larger-scale wind energy (WE) utilization, this paper conducts in-depth and systematic analysis and research on the control strategy and GC operation performance of the system. Research shows that in recent years, the capacity of newly installed WTs at sea is 62,000 kW more than that on land, accounting for 3.4% of the world's total. The newly installed capacity of WTs in the world is 180GW.

1. Introduction

As a renewable and clean energy, WP is also known as a clean PG method, and has been widely used at home and abroad. Compared with traditional PG methods, WPG can omit the consumption of fossil energy, with low investment cost and strong adaptability. It can be foreseen that in the future PG system, the WPG system will have a very important position [1-2].

In a related study, Safaeinejad et al. first proposed a topology for connecting a VS WT (WT) based on a double stator winding induction generator (DSWIG) to the grid, where both the power winding (PW) and the control winding (CW) have It helps to transmit active power to the grid [3]. Reigstad et al. obtain energy from the rotating mass of the turbine and generator through a power electronic converter, and at the same time restore the rotational speed by controlling the opening of the guide vane of the turbine to achieve fast active power control [4]. In order to improve the response of wind farms, Prasad proposed a Synergistic Frequency Regulation Control Mechanism (SFRCM) [5].

This paper studies the key technologies of VSCF WPG based on the production function. First, the research status of the control method of the WPG system is analyzed, and the mathematical model structure of the WT is analyzed according to the problems existing in the WT. Then, the variable pitch of the WT is designed. System, analyze the working state of the fuzzy PID electric pitch control system, and interpret the operating state of the WPG system; finally, conduct an investigation to analyze the PG structure of electric energy and the capacity of new WTs.

2. Design Research

2.1. Research Status of Control Methods for WPG Systems

There are two main operating modes of current wind PG system. Among them, the grid-connected (GC) power supply system is the most economical one; the constant-speed CF and VSCF PG systems are the most common [6-7].

(1) Constant-speed and CF operation mode, which can achieve CF by continuously maintaining the speed of the generator during the PG process. However, because the speed can only be maintained regularly. The wind speed (WS) also has great uncertainty, which greatly reduces the PG effect. With the constant change of WS, the air turbine deviates from the optimal speed, and the WE consumption factor cannot reach the maximum value, resulting in a large reduction of wind sources and a decrease in energy production [8-9].

(2) VS constant rate operation mode, when the external WS changes, the WS can adjust the rotor generator speed in time according to the external WS, so that the generator always maintains the best speed. Improve the utilization rate of wind power, the fan can complete the maximum wind power consumption at any WS. It not only improves the PG efficiency of the WT, but also makes the working effect of the complete generator set more perfect, and the working effect is greatly improved [10-11].

2.2. Problems Existing in WTs

The WP system based on power electronic technology realizes VSCF operation, using full power frequency conversion or partial power frequency conversion equipment to make the changing rotor speed and constant grid frequency independent of each other, which can better meet the basic needs of the current WE industry. However, with the increasing single-unit capacity of WP and the increasing size of WP equipment, the related design and manufacturing difficulties are constantly increasing, and countries have put forward higher requirements for WP GC technology and WP output power quality [12-13]. This has also led to the increasingly prominent problems of existing mainstream WTs that rely on generator design and power electronics technology, mainly in the following aspects:

(1) Impact on power quality

The random fluctuations of wind energy, the GC mode and operating characteristics of WTs, and related additional equipment will cause voltage fluctuations, flicker and current harmonics of WP output, thus affecting the power quality of the power system. With the continuous change of grid load, this will lead to the unbalance of the operating power of the power system, resulting in voltage deviation and flicker. The switching of the operating conditions of the WT will also have a certain impact on the grid electricity.

The existing mainstream VSCF GC WTs need to use high-power power electronic frequency conversion devices to realize the decoupling between the time-varying speed of the wind rotor and the CF of the power grid. The rectifier-inverter link will inevitably bring current harmonic pollution, and as the output power increases, the magnitude of the harmonic current will also increase accordingly. Multi-pulse rectifier circuits or active power filters are often considered to reduce harmonic pollution caused by WP grid integration, thereby improving power quality. However, the breakthrough effect cannot be achieved in essence, and the additional equipment will increase the cost of the unit and the difficulty of the overall system control, and may also reduce the reliability of the operation of the WT to a certain extent [14-15].

(2) Influence on the safe and stable operation of the power grid

The reactive power consumption of the existing WP system is large, and the large-scale operation makes the problems related to the GC of WP more prominent. The GC operation capability of WP is reflected in both low and high voltage ride-through.

(3) Technical bottleneck of research and development of super-large WP equipment

The special generators and complex power electronic conversion devices required by the existing GC WP system make the open and closed loop control loops of the PG system complex, and it is difficult to define the output characteristics of the generator through the frequency converter. In addition, the high cost, high failure rate, and difficulty of operation and maintenance of large-scale inverters are also urgent problems to be solved in the current research and development of large and extra-large WP equipment [16-17].

2.3. Mathematical Model and Analysis of Wind Turbine (WT)

(1) WTs

The WT is mainly composed of impeller, gear transmission system and generator [18]. Figure 1 shows the structural block diagram of the WT; where βref is the set value of the pitch angle, V is the WS, β is the pitch angle, ωl is the blade tip speed, Tl is the aerodynamic torque, and ωe is the The rotor-side rotational speed and Te of the DFIG are the rotor-side torque of the DFIG.

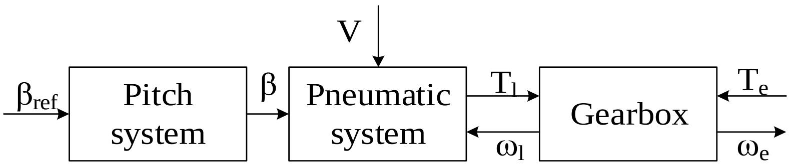

Figure 1. Block diagram of the structure of the WT

2.4. Mathematical Model and Analysis of WT

(1) Theoretical basis of wind energy conversion

Here, the theoretical basis of wind energy conversion of the unit is expounded from the aspects of WP calculation method, WT energy conversion and wind energy utilization coefficient, in order to provide the necessary theoretical basis for subsequent simulation modeling research.

1) WP calculation

According to the theory of aerodynamics and fluid mechanics, if the airflow with air density ρ and velocity V flows through a plane with cross-sectional area A, the WP of the airflow can be calculated as:

$$P = \frac{1}{2} \rho A V^3 \tag{1}$$

From the above, the size of WP is directly related to ρ, A and V3, which is proportional to linear relationship. At the same time, airflow density and WS are related to many external factors such as location, altitude, terrain, and weather.

(2) Mathematical model of WT

Wind energy is an uncertain renewable energy in nature. Although wind energy is intermittent and random, its changes have certain regularity; in general, WS can be composed of two parts: average WS and turbulent WS, and the WT collects The arrived WS V is expressed as:

$$V(t) = \bar{v}_w(t) + v_l(t) \tag{2}$$

In, vw(t) represents the average WS, that is, the stable value of the WS for long-term operation; vl(t) represents the turbulent WS, that is, the WS fluctuates above and below the average WS.

The rotor speed and WS of the DFIG affect the change of the upper speed ratio, which in turn affects the change factor of the utilization of WP.The tip speed ratio λ can be expressed as:

$$\lambda = \frac{2\pi R n}{V} = \frac{\omega_l n}{V} \tag{3}$$

In, R represents the blade radius; n represents the rotational speed of the WT; V represents the natural WS; ωl represents the rotational speed of the low shaft of the transmission system.

In the aerodynamic control system, the WT output electromagnetic torque Tl and wind energy absorption power Pl should meet the following conditions:

$$P_l = T_l \omega_l \tag{4}$$

From the above, the input power of the gearbox (ie the output power of the transmission system) is mainly determined by the output electromagnetic torque Tl of the WT and the rotational speed ωl of the low shaft of the transmission system, and the output electromagnetic torque Tl of the WT is different from The relationship between the WE utilization coefficient Cp is as follows:

$$T_l = \frac{1}{2} \rho \pi C_p(\lambda, \beta) V^2 \tag{5}$$

According to the theoretical knowledge of Betz, the energy that the WT can absorb is limited, and the optimal WE utilization rate of the WT is Cp=0.593. In practical applications, in general, the WE utilization rate of the WT is selected from 0.2 to 0.5. At this time, the absorbed power Pl of the WT is:

$$P_l = \frac{1}{2} \rho \pi C_p(\lambda, \beta) R^2 V^3 \tag{6}$$

$$C_p(\lambda, \beta) = \frac{C_q(\lambda, \beta)}{\lambda} \tag{7}$$

In, ρ represents the air density (kg m^{-3}); Cq represents the power coefficient of the WT.

In the WT system, the WE utilization coefficient can directly reflect the performance of the WT, that is, its performance index; so far, the WE utilization rate Cp and the tip speed ratio λ of the WT are expressed as:

$$C_p = 0.5176(\frac{116}{\lambda} - 0.4\beta - 5)e^{(\frac{-21}{\lambda})} + 0.0068\lambda \tag{8}$$

in,

$$\frac{1}{\lambda} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{9}$$

3. Experimental Study

3.1. WT Pitch System

At present, WT pitch systems can be roughly divided into two categories according to different driving methods: electric pitch and hydraulic pitch.

(1) Electric pitch actuator: the advantages are easy assembly, small footprint, easy maintenance, etc., especially suitable for independent pitch control with fans; the disadvantage is that the inertia is large, it does not have good kinetic energy performance, and it is relatively large time lag.

(2) Hydraulic pitch actuator: the advantages are large torque, fast response, and good dynamic performance, especially suitable for the unified pitch control of fans; the disadvantage is the structural load, the large size of the unit, and the frequent occurrence of liquid leakage and jamming. and other phenomena, not easy to maintain.

WTs are usually built on open grasslands or seasides with harsh environments, and are often eroded by wind, sand or seawater. Their operating characteristics change with time, and the nonlinearity is strong, and the system is prone to various unpredictable problems.

3.2. Working State of Fuzzy PID Electric Pitch Control System

The working state of pitch control in WPG system is:

(1) Power-on state: At this time, the blades of the WT maintain an angle parallel to the natural wind, the wind does not push the blades to generate kinetic energy, and the wind rotor does not work at this time.

(2) Starting state: When the outside WS reaches the starting WS, the pitch controller starts to start, and adjusts the blades to the position perpendicular to the wind. The larger the area that the wind blows on the blade, the greater the kinetic energy generated, and the rotor starts to work.

(3) Maintain state: The pitch controller does not act, and continues to keep the blades adjusted to the vertical wind position, which is the maximum thrust generated by WE, thereby realizing the control of maximum WE capture.

(4) Adjustment stage: At this time, the external WS is higher than the safe WS, and the pitch controller makes the blades rotate in the direction parallel to the wind, so that the system can reduce the absorption of wind, and the system can output rated power stably.

3.3. Operation Status of WPG System

The control of the direct-drive permanent magnet synchronous PG system can be studied in two stages:

(1) When the natural wind is below 11m/s (rated WS), adjust the speed by controlling the speed of the generator to achieve the maximum PG;

(2) When the natural wind is above 11m/s (rated WS) and below 25m/s (safe WS), adjust the pitch angle to control the air force received by the rotor shaft to limit the force and maintain constant power operation.

In order to better study the operating state of the WP system, the operating state of the WP system is divided into four stages according to the relationship between power and WS:

(1) Start-up stage: It is the process of the WP system from a static state to a start-up state, but since the natural WS is lower than the start-up WS, the WE cannot generate enough mechanical energy to rotate the wind rotor, so the WP system is basically in a standby state at this time. At this stage, the wind can push the blades to rotate, but there is no power output and no electrical power is generated. This stage is to prepare for the WE capture stage.

(2) WE capture stage: In this stage, the natural WS is higher than the starting WS and lower than the rated WS. In this stage, by changing the speed of the generator, the system runs in the optimal speed mode to maximize WPG. , so that the system can use WE as much as possible to improve the use efficiency of WE.

(3) Constant speed stage: The current natural WS is lower than the rated WS, and the generator speed has reached the rated value. At this stage, the method of increasing the electrical power of the generator can be used to make the output power of the WP system reach the rated value.

(4) Constant power output stage): In this stage, the natural WS is higher than the rated WS and lower than the safe WS. In this stage, all WE cannot be absorbed by any means. If the absorption of WE is not limited, the mechanical load of the system will be excessive. It will affect the safety of system operation. Therefore, it is necessary to adjust the pitch angle to limit the intake of WE, reduce the mechanical load of the blades, and stabilize the output of the WP system.

4. Experiment Analysis

4.1. Structure Analysis of PG Capacity

In recent years, the WP in my country, it has developed into the largest source of electricity in China's new energy sources. Table 1 shows the structural analysis of PG capacity in the past three years:

Table 1. Analysis of China's PG structure in the past three years

	Energy type	Thermal power	Hydro power	WP	Nuclear power	Solar energy	Total
1	PG (GW)	49316	12318	3654	2950	1770	70008
	Proportion	70.4%	17.5%	5.2%	4.2%	2.7%	
2	PG (GW)	50465	13021	4053	3487	2240	73266
	Proportion	68.87%	17.77%	5.54%	4.76%	3.06%	
3	PG (GW)	51743	13552	4665	3662	2611	76233
	Proportion	67.9%	17.8%	6.1%	4.8%	3.4%	
	Compound annual growth rate	2.43%	4.89%	13.0%	11.4%	21.5%	

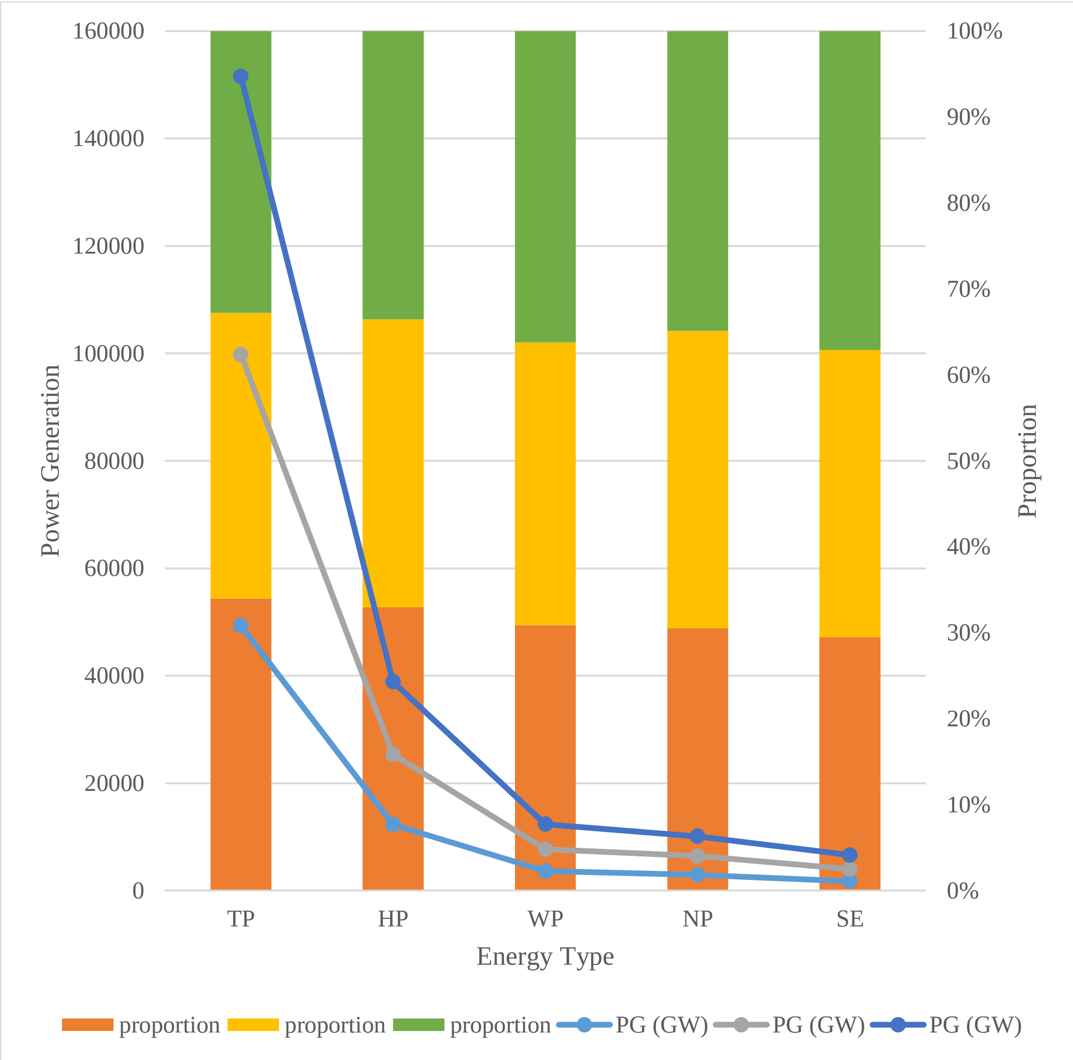

Figure 2. Analysis of the structure of China's PG in the past three years

It can be seen from Figure 2 that the WPG in the past year was 405.7 billion kWh, accounting for 5.54% of the country's total PG.

4.2. Newly Added WTs in the World

In the marine and terrestrial fields, the newly installed capacity of WTs around the world is as follows:

Table 2. Newly installed WT capacity in the world in the past five years (unit: GW)

Years	1	2	3	4	5
Onshore wp	52.69	50.42	45.31	53.98	87.13
Offshore wind	55.34	53.67	49.56	61.49	93.14

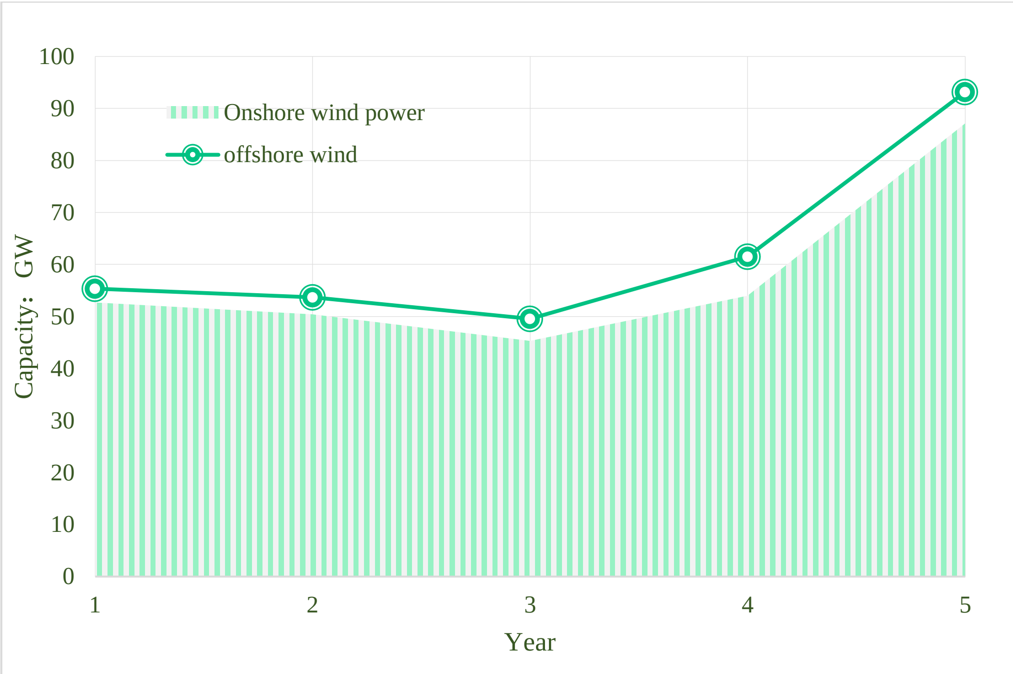

Figure 3. Analysis of new WT assembly capacity worldwide in the past five years

Figure 3 shows that at the end of the year, the capacity of newly installed WTs in the world reached 1.8 million kW, a year-on-year increase of 36.3%; the capacity of newly installed WTs on land and offshore was about 931,000 kW respectively. and 869,000 kW, an increase of 54.1% and 60.3% respectively year-on-year; the capacity of newly installed WTs at sea is 62,000 kW more than on land, and occupies 3.4% of the world's total. The unit capacity is 180GW.

5. Conclusion

In the 21st century, all production and life of human beings depend on electric energy, and the demand is constantly increasing. Thermal PG usually requires coal as fuel, which will not only destroy the land ecology but also produce harmful gases. Therefore, the development and research of clean energy has become an urgent problem to be solved in the modern scientific and technological society. WE is a kind of renewable and clean energy that can pollute the environment and other problems, but because my country's WPG technology is not perfect. Therefore, the primary goal at present is to develop the control technology of WPG system in order to make better use of WE, reduce the impact of conventional PG methods on the environment, and promote the good development of the world.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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