

Review of Wind Power Grid Integration Technologies

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ABSTRACT

With the continuous expansion of renewable energy, wind power generator has become an important part of modern power system. However, the characteristics of easy interruption of wind energy and the rules of grid stability bring great difficulties to the operation and grid of wind turbines. This paper summarizes the key technologies of wind power generation systems. The content also includes the basic structure and action mode of wind turbines, and the system features of fixed-speed induction generator (FSIG) and doubly-fed induction generator (DFIG). We will also learn how to use air force to adjust output, stall control, active stall control and pitch control. In addition, the structure and usage of static var generator (SVG) technology for adjusting reactive power to support voltage are also discussed. In addition, in order to improve the performance and driving reliability when the grid fails, it is necessary to use low-voltage ride-through (LVRT) and high-voltage ride-through (HVRT). Finally, the future development direction and difficulties of connecting wind power to the grid are summarized. This summary introduces the key technologies to improve the efficiency, stability and adaptability of wind power systems.

Keywords: Wind Power Generation; Grid Integration; Low-Voltage Ride-Through, Reactive Power Control, High-Voltage Ride-Through, Wind Power Generation System

1. INTRODUCTION

1.1 Research Background and Significance

With the increasingly prominent global energy crisis and environmental pollution, countries around the world have accelerated the adjustment of their energy structures and vigorously promoted the development of renewable energy sources, such as wind and solar energy, in order to reduce fossil fuel consumption and greenhouse gas emissions. Wind power generation is rich in resources, environment-friendly and short in production time, and has become one of the fastest-growing renewable energy sources in the world.

In recent years, China's wind power industry has developed rapidly, and both onshore and offshore wind power generation have achieved amazing results. With the increasing installed capacity of wind power, the proportion used in power system is increasing, and large-scale wind power grid connection has become an important trend in the development of modern power system. However, the output of wind farm is very dependent on wind speed, which is very random, fluctuating and intermittent. Therefore, with the large-scale wind power connected to the system, new problems have emerged in the safe and stable operation of the power system, such as frequency fluctuation, voltage imbalance, deterioration of power quality, decline of system stability, etc., which put forward higher requirements for the operation, debugging and control of ordinary power systems.

Meanwhile, the construction of new power systems emphasizes the dominant role of renewable energy and requires coordinated operation among the power generation side, power grid side, load side, and energy storage side. Therefore, wind power generation is expected not only to improve its energy conversion efficiency but also to possess stronger grid adaptability and active support capability. Consequently, research on the key technologies of wind power grid integration is of great theoretical significance and engineering value for promoting renewable energy consumption, enhancing the secure and stable operation of power systems, and facilitating the development of new power systems.

1.2 Research Status at Home and Abroad

European and American countries started the development of wind power at an earlier stage and have accumulated extensive experience in wind farm development, grid integration control, and operation management. In recent years, with

the rapid development of offshore wind power, overseas research has gradually shifted toward emerging technologies such as flexible high-voltage direct current (HVDC) transmission, grid-forming converters, virtual synchronous generators (VSGs), and digital operation and maintenance. These technologies aim to improve the stability and operational flexibility of power systems with a high penetration of renewable energy.

Although China's wind power industry started relatively late, it has developed rapidly over the past decades. At present, a relatively complete industrial system covering wind turbine manufacturing, engineering construction, and operation management has been established. Significant progress has also been achieved in wind turbine design, grid integration control, low-voltage ride-through (LVRT), power forecasting, and intelligent operation and maintenance. Meanwhile, a series of national technical standards have been issued, imposing stricter requirements on the low-voltage ride-through capability, reactive power support, and frequency response of wind turbines, thereby promoting the continuous advancement of wind power grid integration technologies.

In recent years, emerging technologies such as artificial intelligence (AI), big data analytics, cloud computing, and digital twin technology have been increasingly integrated into the wind power industry. These technologies provide new approaches for wind farm operation optimization, fault diagnosis, equipment health management, and power forecasting. At the same time, the coordinated operation of wind power and advanced energy storage systems has become an important research topic. By allowing energy storage systems to participate in peak shaving, frequency regulation, and power fluctuation smoothing, the utilization efficiency of wind power and the operational stability of power systems can be further enhanced.

Overall, future research on wind power grid integration technologies will focus on intelligent control, adaptation to high renewable energy penetration, highly reliable operation, and coordinated optimization of generation, grid, load, and energy storage (source-grid-load-storage integration).

2. OVERVIEW OF WIND POWER GRID INTEGRATION SYSTEMS

2.1 Composition of the Wind Power Generation System

A wind power generation system mainly consists of a wind rotor, transmission system, generator, nacelle, yaw system, tower, control system, and foundation. The overall structure and energy change mechanism of wind power generation system are written in Figure 1. This diagram shows the relationship between the main components of wind turbine and the functions of the components when converting wind energy into electric energy. These components work together to convert the energy of the wind into electric energy. Wind rotor is the first device to capture wind energy. Driven by the wind, rotor's blades rotate, transforming the kinetic energy of the wind into mechanical energy. According to the direction of rotor axis, "wind turbine" can be divided into two types. Horizontal-axis wind turbines (hawts) and vertical-axis wind turbines (vawts). At present, most wind turbine use the horizontal-axis form ^[1].

Transmission system can transfer the mechanical energy generated by wind rotor to generator, and adjust the rotating speed according to the type of turbine. After that, the generator converts mechanical energy into electrical energy. Nacelle put the transmission system, generator and auxiliary device together, which became the structural platform for windmill movement and also protected the contents. Yaw system will automatically adjust the direction of nacelle when the wind direction changes, so that rotor can keep the wind direction and use wind energy as much as possible. The control system can always observe and control the wind speed, wind direction, rotating speed and the motion state of the windmill, automatically start and stop, prevent faults and improve motion. Tower and foundation are the structural parts supporting the whole windmill, which can move safely, stably and reliably for a long time.

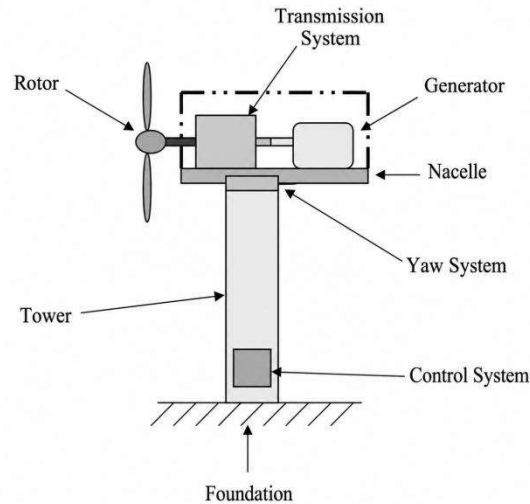


Figure 1. Composition of the Wind Power Generation System.

2.2 Types of Wind Turbine Generators

2.2.1 Doubly Fed Induction Generator (DFIG)

Doubly-Fed Induction Generator (dfig) is one of the commonly used variable-speed constant-frequency generators. Stator winding is directly connected to the power grid, and rotor winding is connected to the power grid through a back-to-back pulse-width modulation (PWM) converter, so that the active power supply and the reactive power can be controlled respectively. The structure of the representative DFIG wind turbine is written in Figure 2. This figure shows the connection mode of wind turbine, generator, rotor-side converter, grid-side converter and power grid, where converter stands for variable-power. Compared with the ordinary speed guidance generator, DFIGs can move in a larger speed range, and can also perform maximum power point tracking (MPPT). Therefore, the energy of wind can be used more, and the influence of speed change of wind on turbine action can be reduced. Moreover, the capacity of the converter is only about 20%~30% of the rated capacity of wind turbine, so DFIGs has the advantages of small converter, low cost and high movement efficiency.

When working, the stator winding will generate a magnetic field with the same frequency as the grid. When the rotor speed is different from the synchronous speed, the power converter controls the induced electromotive force (EMF) by adjusting the magnitude, frequency and phase sequence of the rotor current, and realizes the doubly-fed movement [2].

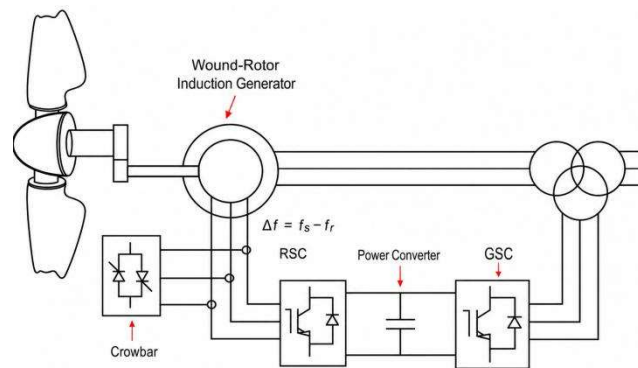


Figure 2. DFIG Schematic Diagram.

2.2.2 Fixed-Speed Induction Generator (FSIG)

Fixed-Speed Induction Generator (FSIG) is one of the most commonly used types of wind turbine generator that was first created at the beginning of wind power. We use squirrel-cage induction generator, which is directly connected to the power grid. The speed of rotation is almost constant during the movement, and the change of slip is only about 1% to 2%. Therefore, it operates in a mode with a certain speed and a certain frequency. FSIG has many good places. Its structure is simple, the manufacturing cost is low, it is not easy to break down during operation, and the maintenance is simple. Therefore, it is widely used in wind farm of medium-sized land. The basic structure of wind turbine using FSIG is recorded in Figure 3. The figure also shows that Squirrel-cage induction generator is directly connected with power grid, and reactive power compensation device is used to improve the movement.

The representative FSIG wind turbine are mainly wind rotor, gearbox, squirrel-cage induction generator, soft starter and reactive power compensation unit. Since the induction generator will get reactive power from the grid when it works, it will generally add shunt capacitors to supplement reactive power to improve the power factor.

In addition, the overall structure and action steps of FSIG are relatively simple, so it is not easy to break down and easy to operate. Because of this advantage, a lot of FSIG was used at the beginning of wind power generation, which played an important role in the development of wind power industry and social economy. However, with the increasing capacity of wind power generation and stricter rules for connecting to grid, the original shortcomings of FSIG have gradually become obvious. Because of the weak speed adjustment, the inability to control reactive power and the poor performance of fault ride-through, it is difficult to use in the current large-scale wind power generation system [3].

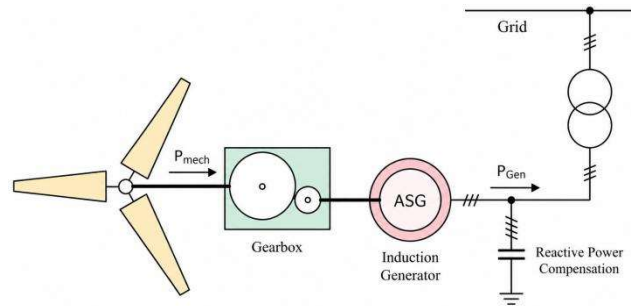


Figure 3. FSIG Schematic Diagram.

3. KEY TECHNOLOGIES FOR WIND POWER GRID INTEGRATION

3.1 Aerodynamic Power Regulation Methods

The output of wind turbine has a deep relationship with wind speed, but natural wind is always strange and unstable. Therefore, even if the wind speed changes, using wind energy as much as possible has become an important research topic of wind turbine control system. Wind turbine can capture the power of the wind, which can be written as:

$$P_{\text{Wind Turbine}} = C_p P_{\text{air}} = C_p \times \frac{1}{2} \rho A V^3 \quad (1)$$

where $P_{\text{Wind Turbine}}$ denotes the output power of the wind turbine, ρ is the air density, A is the swept area of the wind rotor, V is the wind speed, and C_p is the power coefficient of the wind turbine.

Commonly used wind turbine power control methods are as follows:

3.1.1 Stall Control

Stall control is one of the earliest registered power storage in wind turbine system. Rotor blades with fixed pitch will produce aerodynamic stall effect when the wind speed is fast, thus limiting the energy of the wind that the rotor enters. When the wind speed exceeds the specified value, the angle of attack of the blade becomes larger, and the air flow peels off on the blade surface. As a result, the lift is reduced, the drag is increased, the aerodynamic torque is limited, and the output is kept within the specified range to prevent the turbine from being overloaded.

The pitch angle of the blade is fixed, so stall control does not need complicated pitch adjustment mechanism. It has the advantages of simple structure, low manufacturing cost, high reliability and simple maintenance. Therefore, it is widely used in wind turbines of Fixed-Speed Induction Generator (FSIG). The working principle of stall control is shown in Figure 4. This figure shows that when the blade angle of attack increases, the airflow will separate, the aerodynamic torque will decrease, and the output power will be suppressed when the wind is strong.

In order to stop the turbine safely, adjustable clutch, mechanical brake, tip brake and other auxiliary braking devices are generally used. These devices will slow down or stop the rotor in case of emergency and strong wind, thus reducing the rotation speed and protecting the safe and reliable action of the wind turbine when the wind is very strong.

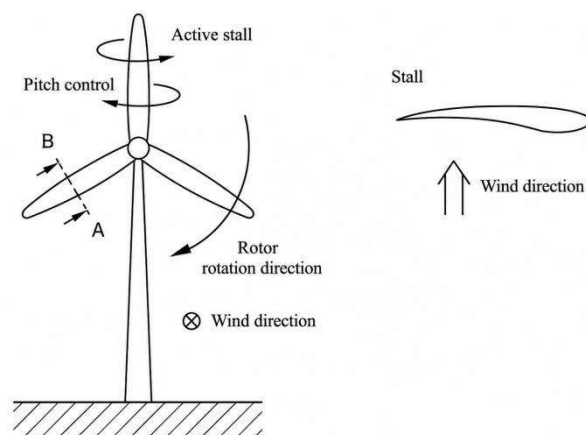


Figure 4. Schematic Diagram of Stall Control.

3.1.2 Active Stall Control

Active stall control is a wind turbine power adjustment method, which combines the characteristics of traditional stall control and pitch control. The control method actively adjusts the pitch angle of the blade server by using the rotatable blade. When the wind speed is less than the rated value, the blade keeps the best angle of attack, so that the air flow smoothly passes through the surface of the blade and absorbs the most wind energy, thus improving the efficiency of converting wind energy into electricity. When the wind speed approaches or exceeds the rated value, the control system will turn the bulldozer to the stall position, increase the angle of attack, and make the air flow fall off the surface of the bulldozer. In this way, the active stall effect is produced, the aerodynamic lift is reduced, the output power and rotor speed are suppressed, and the safe and stable action of wind turbine is protected. Figure 5 shows how active stall control works. Compared with ordinary stall control, we can find that we can adjust the characteristics of air force by moving the angle of blades, so that we can match it even if the strength of wind changes.

Compared with ordinary stall control, active stall control can move the position of the blades according to the change of wind speed, thus improving the wind resistance of wind turbine, and it also has the advantages of relatively simple structure and stable action. However, the accuracy of adjusting the power supply is not as good as that of the current pitch control system, and the efficiency of using wind energy is also relatively low. Therefore, in today's larger wind power generation system, activity control is gradually replaced by pitch control technology.

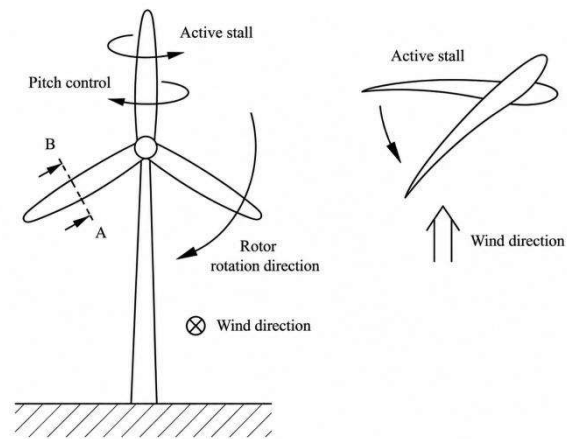


Figure 5. Schematic Diagram of Active Stall Control.

3.1.3 Pitch Control

Pitch control is a power regulation method, which adjusts the power and rotation speed by adjusting the blade angle of wind turbine. The basic working principle is to use “pitch actuator” to rotate the blade on the longitudinal axis, change the wind angle of the blade, adjust the wind force of the blade, and control the amount of captured window energy by itself. The working principle of Pitch control is shown in Figure 6. This figure shows that the angle of the blade is adjusted under different wind intensities, and the wind energy is captured as much as possible when the wind speed is lower than the rated wind speed, and the power is suppressed when the wind speed is higher than the rated wind speed. When the strength of the wind is less than the rated value, adjust the blades to the best angle so as to use “wind energy” as much as possible. When the wind speed reaches or exceeds the rated value, the control system will turn the blades to feathering according to the wind speed and the movement of wind turbine. In this way, the wind area will be smaller, the aerodynamic force and power will be reduced, and the wind turbine will work stably on rated power. When the wind speed is higher than “cut-out speed” or there is a fault, the pitch control system will immediately rotate the wiper blade to the “feathered” position and stop it quickly, thus ensuring the safety when moving the wind turbine.

Compared with stall control and active stall control, pitch control has higher accuracy in regulating power supply, higher efficiency in using wind energy, stronger force in relieving load and better performance in connecting with grid. Therefore, it has become the most popular power control method used in today’s large wind turbine generators.

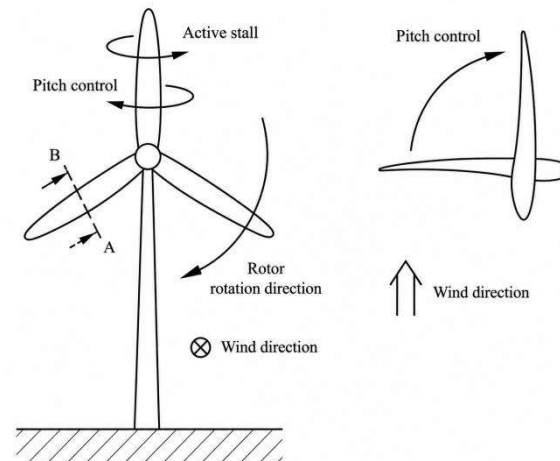


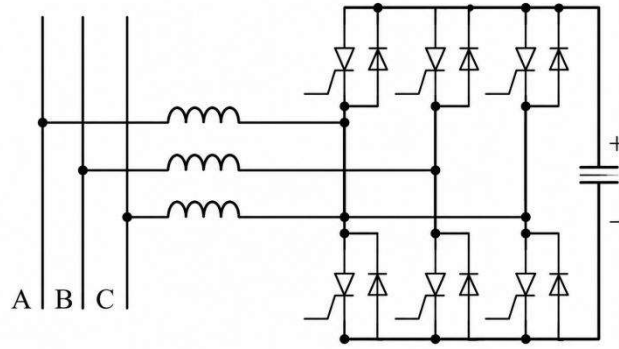
Figure 6. Schematic Diagram of Pitch Control.

3.2 Reactive Power Control

After wind power enters power grid, it will inevitably affect the voltage level of the system. This effect is greater, especially for long-distance transmission systems and weak power grid. Because wind turbine is easy to cause voltage changes there. Therefore, reactive power control is absolutely necessary for wind power grid integration. At present, voltage regulation in wind farms is mainly achieved through a combination of the reactive power regulation capability of wind turbines and external reactive power compensation devices. Among these devices, the Static Var Generator (SVG) is one of the most commonly used solutions.

An SVG generally adopts a voltage-source bridge converter as its main circuit topology. By controlling the switching states of the bridge-arm power semiconductor devices, the output AC voltage can be regulated. After the upper switch of the bridge arm is turned on and the lower switch is turned off, the A-phase output terminal is connected to the positive terminal of the DC bus to generate a positive output voltage. Conversely, if the lower switch is turned on and the upper switch is turned off, the A-phase output terminal will be connected to the negative terminal of the DC bus, resulting in a negative output voltage. See Figure 7 for the topology of voltage-source bridge converter used in SVG. This figure shows the structure of main power circuits such as semiconductor switch and DC link capacitor of bridge arm, which can generate adjustable AC voltage to compensate reactive power.

During operation, the voltage on the DC side changes to the AC output voltage with the same system frequency according to the switching action of the power semiconductor equipment. The working mode of SVG is basically the same as that of voltage-source inverter, but it is different from the AC output of ordinary inverter as a passive load. The AC end of SVG is directly connected with the power system, which can be used for dynamic reactive power compensation and voltage regulation ^[4].



Voltage Source Bridge Circuit

Figure 7. Voltage-Source Bridge Converter Circuit.

An SVG can be equivalently regarded as a controllable AC voltage source whose frequency and phase are synchronized with those of the power grid, while its output voltage magnitude can be continuously adjusted ^[5]. Taking phase A as an example, a single-phase equivalent circuit model of the SVG can be established. Let the phasors of the grid voltage and the SVG output voltage be denoted by U_s and U_i , respectively. The voltage phasor across the coupling reactor, U_L , is equal to the phasor difference between the two voltages, i.e.,

$$U_L = U_i - U_s \quad (2)$$

Figure 8 illustrates the equivalent circuit model and voltage vector relationship of the SVG under different operating conditions. It explains how the adjustment of SVG output voltage magnitude influences the reactive current direction, thereby achieving voltage regulation.

Due to the presence of the coupling reactor, the magnitude and direction of the current flowing through the reactor can be controlled by adjusting the amplitude of the SVG output voltage U_i . When $U_i > U_s$, the current flowing through the coupling reactor leads the grid voltage U_s by 90° , and the SVG injects capacitive reactive power into the grid, thereby increasing the system voltage. Conversely, when $U_i < U_s$, the current lags behind the grid voltage U_s by 90° , and the SVG absorbs inductive reactive power from the grid, resulting in a reduction of the system voltage.

Therefore, by regulating the magnitude of the SVG output voltage, bidirectional reactive power regulation can be achieved, thereby stabilizing the grid voltage and improving power quality.

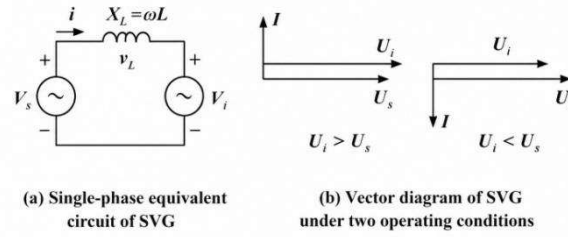


Figure 8. Schematic Diagram of the Static Var Generator.

3.3 Voltage Ride-Through (VRT) Technology

3.3.1 Low-Voltage Ride-Through (LVRT) Technology

Low-Voltage Ride-Through (lvrt) is one of the most important technologies in the research of connecting wind power supply to grid. When there is a short circuit fault or a sharp voltage drop in the power grid, if the wind turbine is removed from the grid immediately, there may not be much power generation at once. In this case, the frequency and voltage of the system will change more seriously, and even a large-scale power outage will occur. Therefore, the latest wind turbine generator needs the function of Low-Voltage Ride-Through (lvrt), so that it can continue to run even if the grid fails. The necessary circuit of LVRT is written in Figure 9. This diagram shows the allowable voltage drop range and the time required for the wind turbine to be connected to the grid during the voltage fault.

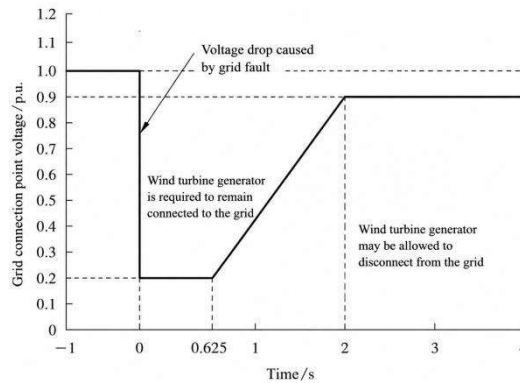


Figure 9. Low-Voltage Ride-Through (LVRT) Requirement Curve.

3.3.2 High-Voltage Ride-Through (HVRT) Technology

High-Voltage Ride-Through (HVRT) When the fault is repaired, the load changes suddenly, reactive power compensation is available, and the voltage rises temporarily, the wind turbine remains connected to the power grid. At present, there are two kinds of HVRT methods used in renewable energy systems. The first method is to turn on additional hardware to improve Ride-Through ability. The second method is to work hard on the control strategy to improve the system performance [6]. Figure 10 shows the demand curve of HVRT, indicating the tolerance of wind turbine to voltage when the voltage temporarily rises. This curve shows the time that the wind turbine must continue to run when the voltage of power grid rises. The recent wind turbine generators generally use advanced converter control method, DC-link voltage adjustment, dynamic reactive power control and joint protection mechanism to suppress the adverse effects of overvoltage on power electronic devices and maintain stable operation of the turbine. At the same time, turbine can adjust the output of active power and reactive power immediately according to the state of power grid, thus improving the voltage stability and transient support of the system.

With the increasing proportion of renewable energy in the recent power system, High-Voltage Ride-Through (HVRT) technology will improve the performance of connecting with the power grid of wind turbine generators.

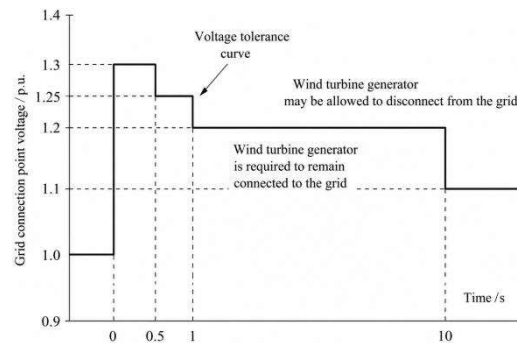


Figure 10. High-Voltage Ride-Through (HVRT) Requirement Curve.

4. CHALLENGES IN WIND POWER GRID INTEGRATION

The power grid industry in China is developing rapidly, and the technology of power grid integration is getting better and better. However, due to the increasing installed capacity of renewable energy, the power grid integration is still perfect.

First of all, wind energy is inherently unpredictable and sometimes interrupted. When the wind speed changes, the output of wind power will shake immediately, and the operation of power system becomes very difficult. With the increasing popularity of wind power, the frequency and voltage of the system are more prone to shake, which brings difficulties to the safe and stable operation of power grid.

Secondly, the traditional power supply system mainly uses synchronous generator to support the interior. But the wind turbine generator is connected to the grid through the power electronic converter, so it is not helpful to the system inertia. If the proportion of renewable energy is increasing, the inertia of the whole system will decrease, the frequency will become unstable, and the risk of frequency deviation or system instability will increase.

In addition, the forecast of wind power has made great progress, but due to the complicated state of the sky, the forecast error still exists. Because of the instability of this forecast, it is difficult to prepare the backup electricity, and it will cost more to open the power system.

Finally, with the increasing percentage of renewable energy, the traditional grid integration control method will not meet the needs of the new power system. New technologies such as grid format converter, digital twin technology and artificial intelligence are still under development, and their technical rules, application methods and practical experience in practical projects are also discussed.

5. CONCLUSION

As an important component of clean energy, wind power plays an increasingly significant role in promoting the green and low-carbon transformation of the energy sector, achieving the “Dual Carbon” goals, and facilitating the construction of new power systems. With the continuous expansion of installed wind power capacity, large-scale wind power grid integration has become a major trend in the development of China’s power system. However, due to the inherent characteristics of wind power, such as variability, randomness, and intermittency, its large-scale integration also poses new challenges to the secure and stable operation of the power grid.

This paper systematically reviews the current development of key technologies for wind power grid integration. Particular emphasis is placed on Maximum Power Point Tracking (MPPT) technology, grid integration control technology, Low-Voltage Ride-Through (LVRT) technology, reactive power regulation, active power control, wind power forecasting, and coordinated energy storage technologies. In addition, the major challenges associated with wind power grid integration are analyzed. Furthermore, the future development trends of wind power grid integration are discussed in conjunction with emerging technologies, including artificial intelligence (AI), digital twin technology, grid-forming control, and the coordinated operation of generation, grid, load, and energy storage.

Overall, wind power grid integration technologies are expected to continue evolving toward greater intelligence, higher reliability, enhanced operational stability, and improved adaptability to power systems with high renewable energy penetration. With continuous breakthroughs in key technologies and the further improvement of relevant technical standards, wind power will play an increasingly important role in China's energy transition and sustainable development, providing strong technical support for the construction of a safe, efficient, clean, and low-carbon new power system.

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