



Virtual Synchronous Control Strategy for Frequency Control of DFIG Under Power-Limited Operation

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Abstract. Large scale application of wind power in power system will reduce the system equivalent inertia and primary frequency control ability. This paper proposes a frequency coordination control scheme for DFIG under power-limited operation to increase the amount of system inertia via virtual synchronization control, so DFIG can provide a transient frequency support for system. The released reserve power caused by decrease of pitch angle can compensate the output power sag, and reduce steady state frequency deviation. The characteristics of virtual synchronization control and the pitch angle control of DFIG are combined to effectively suppress the system frequency fluctuation caused by load change. Simulation results show that the proposed coordinated control strategy can make full use of the wind turbine's own load reduction operation and virtual synchronous generator technology to effectively improve the frequency stability and inertia support effect of the grid-connected system, which is conducive to the safe and stable operation of the power system.

Keywords: Wind generation · Virtual synchronization control · Virtual inertia · Pitch angle · Primary frequency regulation

1 Introduction

In order to meet the sustainable development needs of resources and the environment, China has vigorously developed new energy power generation in recent years, and the installed capacity of wind power continues to grow rapidly. The proportion of new energy in the power grid in some regions has exceeded 50%. While the proportion of new energy permeability increases continuously, the inertia response and primary frequency regulation ability of the power grid are also declining, which brings risks to the frequency stability and recovery ability of the power grid under high-power shortage shocks. Therefore, increasing the inertia of the system, enhancing the frequency regulation ability of the wind turbine and improving the stability of the system have become the research hotspots, and are receiving more and more attention worldwide.

Many theoretical studies focus on inertial control and primary frequency regulation control of wind turbines. Some scholars have proposed the virtual inertia method [1–3], that is, when the frequency changes, let the wind turbine quickly release the kinetic

energy stored in the wind turbine to the power grid, or absorb energy from the power grid to increase the kinetic energy, so as to simulate the inertial constant and transient frequency response characteristics similar to synchronous machines. Some scholars have proposed to use the power backup method, which can allow wind turbines to better participate in primary frequency regulation. For example, the control method of overspeed deceleration operation of the wind farm by modifying the power curve is described, and the frequency regulation is completed by using active/frequency droop control [4–6]. A load-reduction control scheme combining overspeed and pitch angle control is proposed, so that the wind turbine can use pitch angle/frequency sag control for primary frequency regulation [7–9].

In order to make the wind turbine simulate the frequency regulation characteristics of synchronous generator, virtual synchronous generator technology has been widely concerned. Taking the traditional mathematical model of synchronous generator as a reference and simulating its rotational inertia and damping characteristics, the concept of virtual synchronous machine was first proposed [10]. It is proposed to build a traditional synchronous generator model in a three-phase inverter to achieve electromagnetic characteristics, rotational inertia, frequency regulation and voltage regulation characteristics similar to traditional synchronous machines [11, 12]. The virtual synchronous machine control strategy has been initially applied.

By analyzing the research of the above scholars, this paper proposes a virtual synchronization control strategy for DFIG under de-loading operation mode. First, the operating characteristics of the DFIG are analyzed. Secondly, the wind turbine is put into the load limiting operation mode through pitch control. On this basis, the virtual synchronous control strategy is introduced into the wind turbine for control, and the active output is added through the inertia response link to achieve the purpose of improving the system inertial support and primary frequency regulation. Finally, a system simulation model is built on the Matlab/Simulink platform to verify the correctness and effectiveness of the proposed control strategy, thus providing theoretical and experimental basis for large-scale wind power consumption.

2 Analysis of the Operating Characteristics of DFIG

Figure 1 is the structure diagram of DFIG. The system consists of doubly-fed induction motor, gearbox, wind turbine, power converter, grid-connected transformer, etc. DFIG is a wound-rotor asynchronous generator whose rotor circuit can be controlled by an external power device to achieve variable speed operation. The stators of doubly-fed induction motor are directly connected to the power grid, and the rotors are also connected to the power grid through AC converters. Both the stators and the rotors are involved in the feeding [13]. Double-fed wind turbines achieve maximum wind energy capture through motor rotor side converters to improve energy efficiency.

Figure 2 shows the power characteristic curve of the DFIG. Each curve corresponds to a different wind speed. When the rotation speed is constant, different wind speeds cause the wind turbine to output different power. When the wind speed v changes within a certain range, adjust wind turbine speed ω in time, so that wind turbine blade tip speed ratio λ is the optimal blade tip speed ratio λ to track the P_{mppt}

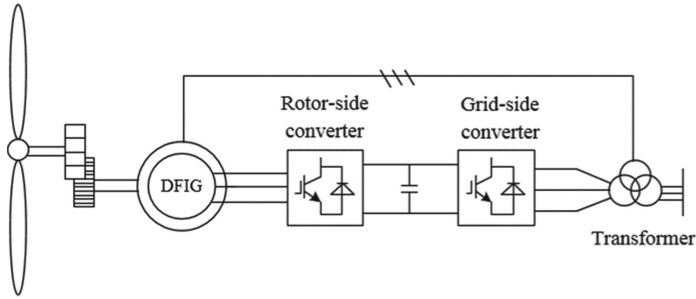


Fig. 1. Structure diagram of DFIG.

curve, and at the same time the generator shaft obtains the maximum input mechanical power [14], so that wind turbine can maintain the best efficiency within a certain range.

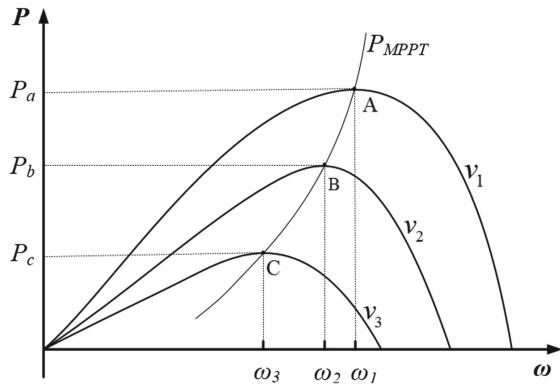


Fig. 2. Power characteristic curve of the DFIG.

However, the weakness of this strategy is that it does not provide active support for the grid to participate in frequency regulation and that the turbine speed ω is decoupled from the grid frequency. Loss of inertia response capability. Especially when the frequency dip voltage flicker and other faults occur in the power system, the performance of DFIG unit itself to withstand voltage and frequency fluctuations Poor, easy to large-scale off-grid when the system is disturbed, triggering a chain reaction and expanding the scope of the accident.

Inertial response of traditional generator set is inherent and uncontrollable, and its primary frequency regulation is accomplished by adjusting the mechanical power of the prime mover through the governor according to the static frequency characteristics of the system. DFIG needs to realize both inertia and primary frequency regulation to provide frequency support for the system, so that it has similar frequency response characteristics to traditional synchronous generator sets, in order to effectively solve the

problem of inertia loss and frequency instability caused by large-scale wind power grid-connected.

3 DFIG Integrated Frequency Regulation Strategy

3.1 Pitch Angle Control

Without considering the configuration of energy storage, in order to realize the coordinated control of inertia response and primary frequency regulation of virtual synchronous control, the wind turbine needs to perform load reduction operation for primary frequency regulation, and the operating characteristics of wind turbine after load reduction also need to be applicable to virtual synchronous generator technology.

There are two schemes for load shedding operation of wind turbine, one is rotor speed control, the other is pitch control. Load shedding operation is to give up the maximum capture of wind energy, so that the wind turbine can maintain a certain level of reserve capacity, so as to participate in the primary frequency regulation of the system. In this paper, the pitch control scheme is used to reduce the load, so that the wind turbine can also provide power reserve at high wind speed.

Figure 3 shows the relationship between power and speed at different pitch angles. At a certain rotor speed, the greater the pitch angle, the lower the power of the wind turbine. The principle of pitch control is to increase the pitch angle in advance to make the wind turbine run at the sub optimal power point, so as to reserve the active power for the system frequency adjustment. When the system frequency is reduced, the pitch angle is reduced, the output of the wind turbine is increased, and the frequency response of the system is supported.

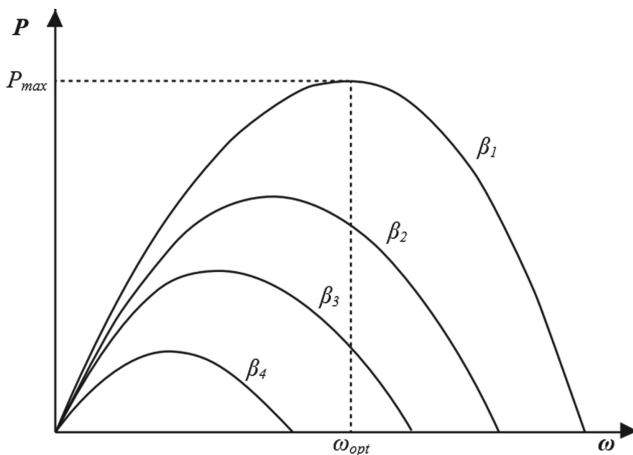


Fig. 3. Power-rotor speed diagram.

Figure 4 shows de-loading operation by pitch angle control schematic diagram. The initial value of the pitch angle is calculated by the power $(1 - d\%) P_{MPPT}$ (where $d\%$ is the load reduction level) after the load is reduced, and the pitch angle is reserved. The relationship between frequency deviation and pitch angle is introduced to enable wind turbine pitch angle to respond to the change of system frequency, thereby adjusting wind turbine output to support system frequency. The pitch angle limiting module [15] is added to prevent the pitch angle from exceeding the allowable range of wind turbine.

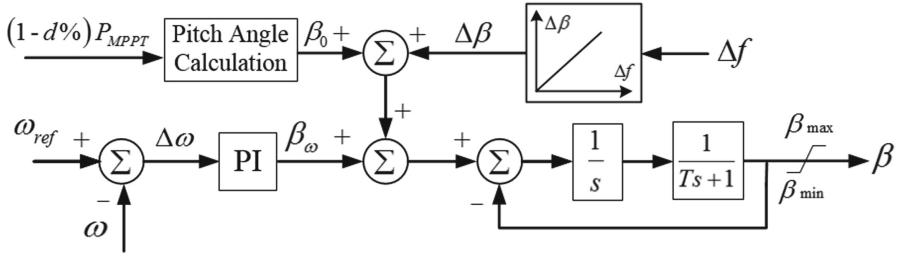


Fig. 4. De-loading operation by pitch angle control block diagram.

3.2 Virtual Synchronization Control

The system inertia has a certain buffering effect on the grid frequency disturbance, and the inertia response capability of the synchronous generator is simulated by virtual synchronous generator (VSG) control. The classic second-order model of the synchronous generator is used as a reference to establish the VSG mathematical model, which is composed of mechanical and electromagnetic characteristics. The mechanical characteristics are expressed by the rotor motion Eq. (1)

$$\begin{cases} 2H \frac{d\Delta\omega}{dt} = P_m - P_e - D(\omega - \omega_N) \\ \frac{d\delta}{dt} = \omega - \omega_N \end{cases} \quad (1)$$

In the formula, H is the inertial time constant; D is the damping coefficient; P_m and P_e are the mechanical power and electromagnetic power of the grid-side converter; ω is the rotor angular velocity; ω_N is the system rated angular velocity; δ is the rotor power angle.

The electromagnetic part is modeled with the stator electrical equation as the reference object, as shown in Eq. (2).

$$\dot{E}_{0i} = E_0 \sin \theta = \dot{U}_i + \dot{I}_i(r_s + jx_s) \quad (2)$$

In the formula, \dot{E}_{0i} , \dot{U}_i , \dot{I}_i are the three-phase induced electromotive force, stator terminal voltage and stator current; θ is the phase angle; r_s is the stator armature resistance; x_s is the line equivalent impedance.

In the control algorithm, power control is the core link of VSG, and the instantaneous electromagnetic power output by the change of rotor kinetic energy can be expressed as [16].

$$P_e(t) = -\frac{P_N H}{f_N^2} f(t) \frac{df(t)}{dt} \tag{3}$$

In the formula, $P_e(t)$ is the instantaneous electromagnetic power; P_N is the rated power of the synchronous machine; f_N is the rated frequency of the system; $f(t)$ is the instantaneous frequency of the system.

Because the absolute value of the system frequency change exceeds a certain fixed value, low-frequency load shedding action can be caused, and its relative value is very small, so $f(t) \approx f_N$, then Eq. (3) can be simplified to

$$P_e(t) \approx -\frac{H}{f_N} \frac{df(t)}{dt} P_N \tag{4}$$

In order to prevent the momentary inertia support power output from causing torque imbalance and causing severe torque shock to DFIG, in the VSG inertia response design, an additional first-order inertia module with adjustable time constant K was introduced [17], thereby slowing the torque mutation, as shown in Fig. 5.

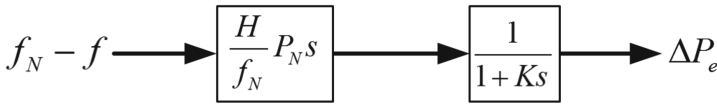


Fig. 5. Inertia support control of VSG schematic diagram.

When VSG control is introduced in DFIG grid-connected control, the wind turbines exhibit inertial response characteristics to the grid by establishing a link between the power variation and the internal potential. When disturbed, the frequency change of power grid is suppressed and the system stability is improved.

3.3 The Integrated Control Strategy for Primary Frequency Control

The virtual synchronous control strategy of wind turbine based on load shedding mentioned in this paper is mainly designed for primary frequency regulation and inertia response of power system. The control method is divided into three parts, as shown in Fig. 6.

- (1) The load shedding level of the wind turbine is set according to the operating status of wind turbine.
- (2) The pitch angle of wind turbine is adjusted according to the load reduction level and the rotational speed of the wind turbine, and the electromagnetic power is adjusted by setting P_{ref} by PI controller and VSG inertia response module.

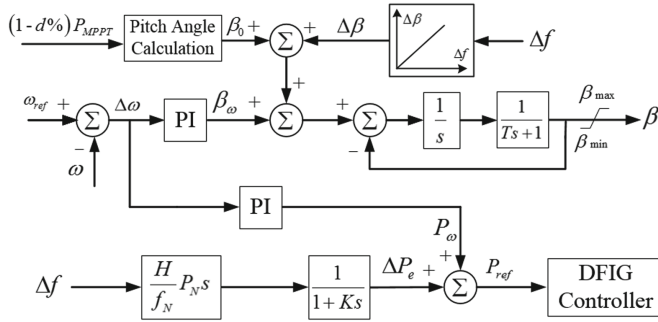


Fig. 6. VSG inertial support and primary frequency control structure diagram.

- (3) When the system frequency changes, the VSG inertia response control module can increase the active power, and wind turbine adjusts the pitch angle, so that the whole control structure simulates the frequency response characteristics similar to the traditional synchronizer. Under the joint action of the two parts, the system inertia response and primary frequency regulation ability are improved.

4 Simulation Analysis

This article establishes the simulation system shown in Fig. 7 in MATLAB/Simulink. The simulation system includes 4 synchronous generators with a capacity of 50 MW and 20 DFIG with a capacity of 2 MW. L_1 and L_2 are system loads with capacities of 100 MW and 80 MW respectively. C_1 and C_2 are reactive power compensation devices.

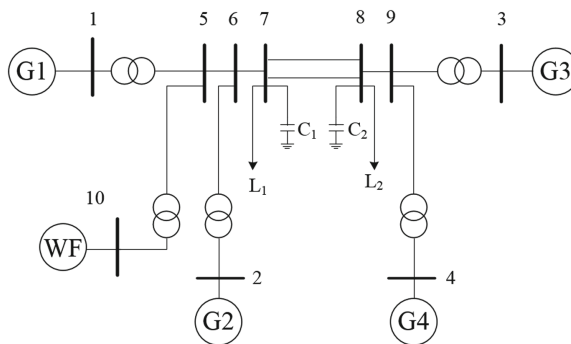
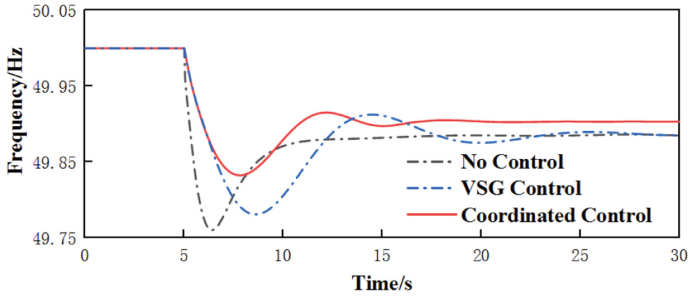
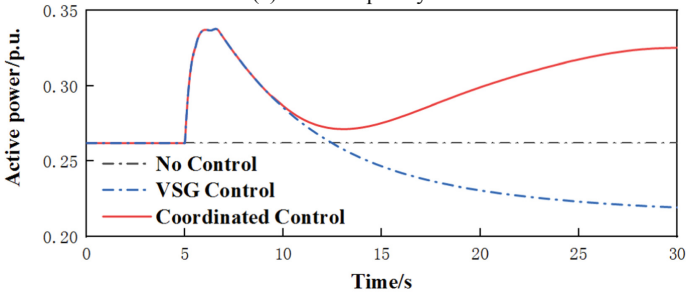


Fig. 7. Structure of the simulation system

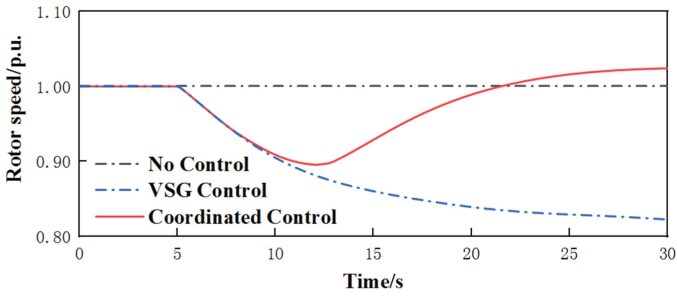
Assuming that the wind speed is set at a fixed value of 10 m/s, the wind turbine initially maintains the operating state of 10% load reduction, and the load L_1 suddenly



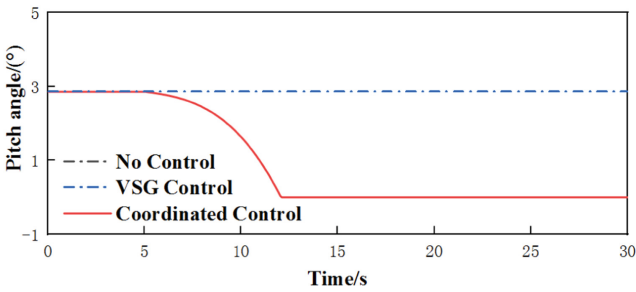
(a) Grid frequency



(b) Active power of DFIG



(c) Rotor speed of DFIG



(d) Pitch angle of DFIG

Fig. 8. Comparison of dynamic response of system after sudden increase of load L_1 .

increases from 100 MW to 110 MW at 5 s, resulting in a decrease in the system frequency. The simulation results are shown in Fig. 8.

Figure 8 compares the dynamic response of the system frequency, active output of the wind turbine, rotor speed, and pitch angle in DFIG without additional control, VSG control, and frequency coordination control. It can be seen from Fig. 8 that when there is no additional control of the wind turbine, the rate and amplitude of the frequency decrease is the largest, and there is almost no response to the system frequency change. Using VSG control can make the wind turbine to suppress the maximum frequency deviation to a certain extent, and make the lowest frequency 49.76 Hz to 49.78 Hz. During the frequency regulation process, wind turbine can play a certain role in supporting the system by reducing the speed to release kinetic energy. However, due to the limited kinetic energy provided by wind turbines, DFIG cannot continuously share the unbalanced power of the system. However, under the coordinated frequency control of DFIG load reduction operation and VSG technology, DFIG can not only maintain the inertial support of the system, but also participate in the system frequency adjustment. Compared with DFIG without control, the maximum frequency offset is The reduction of 0.24 Hz to 0.17 Hz, a reduction of 29.2%, can be seen that the frequency characteristics of the system have been significantly improved. Among them, the active spare capacity reserved for DFIG load reduction operation can provide continuous active power support for the system, and reduce the power change rate at the initial stage of the system frequency drop, which is conducive to the recovery of the system frequency.

5 Conclusion

Based on the proposed load reduction control scheme for DFIG, this paper further proposes a virtual synchronous control method for wind turbines under limited power operation. This method uses the pitch method to reduce the load of the wind turbine, thereby generating a certain amount of reserve capacity for the system's primary frequency regulation, and combined with the virtual synchronous generator technology to support the system frequency. Simulation results show that the proposed control strategy can suppress the system frequency fluctuations caused by wind speed changes and grid load mutations. Compared with traditional virtual inertial control methods, it can effectively improve the system's inertia response and primary frequency regulation capability.

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