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# Research on Frequency Adaptability of Doubly-fed Induction Generator under Asynchronous Power Grid

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**Abstract.** In the paper, double-fed induction generator (DFIG) and asynchronous power grid are taken as the research object, and the adaptability of DFIG to grid frequency is studied. The mechanism of the influence of frequency change on DFIG is revealed. It is suggested that proper settings of frequency converter protection and PLL parameters can ensure that the frequency change of power grid has little effect on DFIG. In Matlab / Simulink, the simulation of the wind turbine operating in the frequency change is realized, and the simulation results verify the correctness of the theoretical analysis.

## 1. Introduction

Yunnan Power Grid and China Southern Power Grid have achieved asynchronous operation, and the issue of frequency after asynchronous networking has replaced the transient stability issue as its main problem[1]. At present, the main type of renewable energy generator in Yunnan is DFIG, once the frequency adaptability of the DFIG does not meet the requirements of the new grid environment, there will be a large area of off-grid, which seriously threatens the safe and stable operation of the regional grid. Therefore, the frequency adaptability of DFIG in asynchronous networking has become an important issue that must be considered.

At present, there are few studies on the response characteristics of DFIG under the condition of power grid frequency fluctuation. The literature [2] only points out that the DFIG response characteristic is different from the conventional generator in the frequency fluctuation of the power grid. In the literature [3], by comparing the dynamic characteristics of different types of wind generator, it is pointed out that the frequency fluctuation has a great influence on the fixed-speed wind turbine and little influence on DFIG. Literature [4] indicates that when the system frequency changes, the speed and the electromagnetic power fluctuation of the DFIG are much less than the ordinary asynchronous generators. The literature [5][6] analyse the dynamic response characteristics of DFIG in frequency fluctuations in detail, and point out that the maximum power output of the DFIG changes varies by tens of kilowatts in milliseconds only at the moment of power grid frequency reduction, and the output current, electromagnetic torque, active power hardly change in steady state. Literature [7] proposes that slight frequency fluctuation has little influence on the wind turbine, while large frequency fluctuation can have serious influence on the components of the wind turbine. In summary, the current research is still relatively simple, mainly considering the slight frequency fluctuation. Since the problem of frequency

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stability of Yunnan power grid after asynchronous networking is highlighted, it is necessary to conduct adaptive research on the larger frequency fluctuation range.

Based on the Matlab/Simulink, the response characteristics of DFIG under the grid frequency fluctuation are studied. The simulation results show that setting the converter protection settings and PLL parameters properly can make grid frequency change less influence on DFIG.

## 2. Mathematical Model of DFIG

### *2.1. The control for grid-side converter*

In this paper, the GSC adopts the double closed-loop control strategy of voltage-oriented which is the DC bus voltage outer loop and the current inner loop . The control block diagram is shown in Figure 1.

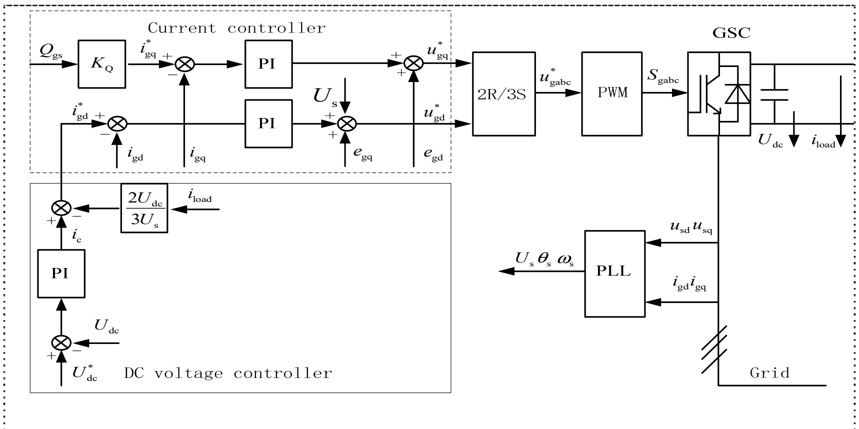


Fig. 1. The vector control under d-axis grid voltage orientation

### *2.2. The control for rotor-side converter*

In this paper, the RSC adopts the stator flux directional control strategy. The control block diagram is shown in Figure 2.

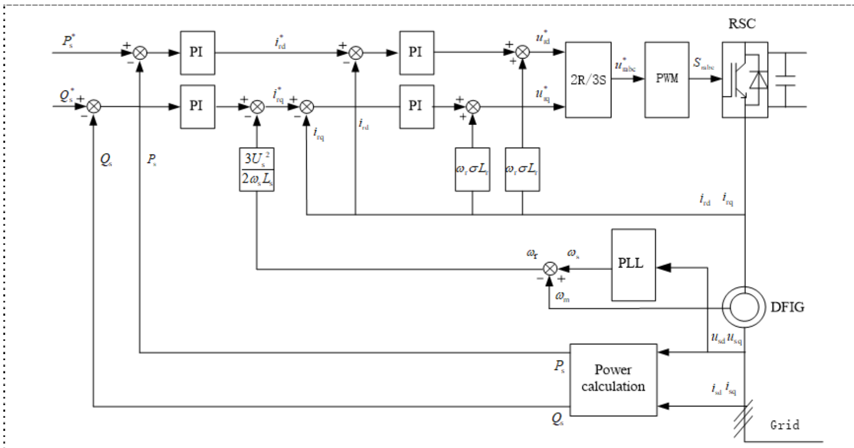


Fig. 2. The vector control based on the stator flux orientation

### *2.3. phase locked loop*

In order to ensure that the PLL can quickly lock the frequency when the grid frequency changes, the paper uses the single-synchronous coordinate system algorithm(SRF-PLL), in which $u_q$ represents the phase difference $\sin(\theta-\widetilde{\theta})$. The advantage of the algorithm is that fast phase locking can be achieved

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when $u_q$ is adjusted to 0 rapidly.

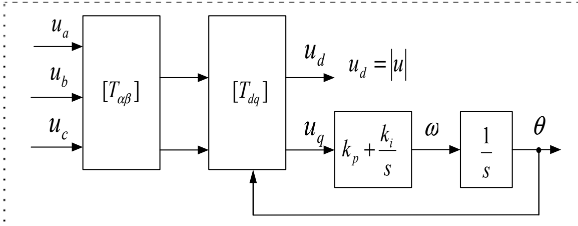


Fig. 3. The structure of SRF-PLL

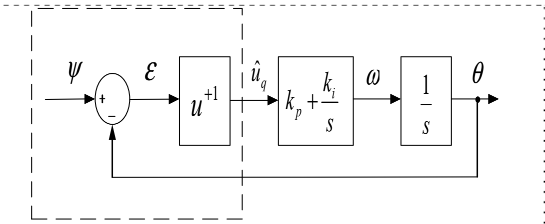


Fig. 4. The feedback loop of SRF-PLL

When $u_q = 0$, $\hat{u}_q \approx u_{+1}(\omega t - \theta)$. Assume $\psi = \omega t$, then

$$\frac{\theta}{\psi} = u^{+1}\frac{k_p s + k_i}{s^2 + k_p s + k_i} = \frac{2\zeta\omega_r s + \omega_r^2}{s^2 + 2\zeta\omega_r s + \omega_r^2} \quad (1)$$

In equation (1), $\zeta = k_p\sqrt{u^{+1}/k_i}/2$ represents the damping ratio of the system. $\omega_r = \sqrt{u^{+1}k_i}$ represents the system resonance angle frequency, when $\omega_r$ is greater, the system bandwidth is greater. According to the values of voltage amplitude, system damping ratio $\zeta$ ($\zeta = 0.707$) and resonance angle frequency $\omega_r$, the parameters $k_p$ and $k_i$ of PI in SRF-PLL can be obtained.

## 3. Study on frequency adaptability of DFIG

### *3.1. Dynamic response characteristics when frequency changes instantaneously*

Considering the extreme situation when the grid frequency changes instantaneously, the paper sets frequency step voltage signal as the input of PLL. When frequency change is small and within pull-out range, PLL can capture and lock quickly. When frequency change is lager and exceeds pull-out range, PLL is unable to track the frequency change, and it takes a certain amount of capture time to lock.The capture time is determined by the maximum tracking rate and the amplitude of frequency change of PLL. When PLL is in pull-in range, the reference value of rotating speed decreases, and maximum power point tracking (MPPT) cannot be achieved. The current, speed, power and electromagnetic torque oscillate, and its oscillation rule is similar to that of asynchronous motor.Specifically, when the grid frequency increases instantaneously, the electromagnetic torque of DFIG decreases, the rotational speed starts to rise, the active power decreases, and the stator and rotor current decrease. When PLL reaches synchronization, its estimated frequency is consistent with the frequency of the grid voltage after the mutation. When the grid frequency drops instantaneously, the oscillation of each parameter is opposite to the frequency increases.

After the grid frequency changes, the RSC adjusts the operating status of DFIG. Through the variable frequency excitation of the rotor, the rotation speed is increased to the rated value, and MPPT and power adjustment are realized. At the same time, the GSC suppresses the DC bus voltage fluctuation caused by the power adjustment and controls the power factor to meet the requirements.

When a change of grid frequency is detected, RSC adjusts the frequency (the rotation angle velocity) and slip ratio of the rotor current to match the grid frequency change, adjusts the amplitude of rotor current for power adjustment, and finally makes DFIG run stably at the new grid frequency. According to $\omega_s = \omega_m + \omega_r$, RSC adjusts the rotor current frequency to be equal to the frequency change of the grid voltage, and the two cancel each other out so that the rotor speed is restored to the steady-state operating value before the frequency fluctuation occurs.When the frequency of the power grid suddenly drops, the absolute value of the rotor current frequency and the slip rate increase. When the frequency of the power grid increases, the absolute value of the rotor current frequency and the slip ratio of the RSC decreases. In the process of frequency change, the active power command value of the DFIG remains unchanged, and the reactive power command value is generally set to 0. RSC makes the magnitude of the DFIG current and power consistent with the command value.

When the frequency increases, the rotor current decreases, and the actual active power decreases. The increase of the power difference leads to the increase of the reference value of rotor current. The deviation between the actual value of the rotor current and the reference increases, causing the reference of the rotor voltage to increase. At this time, RSC controls the converter to change the switching pulse so that the actual value of the rotor voltage increases, thereby generating a larger current in the rotor winding. The change of the rotor voltage and current leads to the increase of the active power. When the frequency of the power grid decreases, the change of each parameter is opposite to when the frequency increases. As a result, the rotor speed and the power are unchanged, the stator and rotor currents return to normal, and the power is the same as that before frequency changes. At the same time, since no energy is accumulated on the DC bus, the DC bus voltage remains stable throughout the process.

Due to the mechanical inertia, the response of DFIG is a process of continuous oscillation after the instantaneous change of grid frequency. Under the control of the converter, the oscillation amplitude of each parameter decreases continuously, eventually reaching a steady state. The oscillation amplitude depends on whether the grid frequency change is in pull-out range of PLL. When a change of the instantaneous frequency is small and in pull-out range, the capture time of PLL is short and the parameter fluctuation is small. When a change of the instantaneous frequency is out of pull-out range, the capture time is long, the parameter fluctuation is large, and it takes some time to recover to the steady state. In summary, the maximum frequency that the DFIG can withstand is determined by whether the rotor current, electromagnetic torque, and maximum DC bus voltage are out of pull-out range of PLL or not.

### *3.2. Dynamic response characteristics when frequency changes gradually*

In actual operation, the frequency of the power grid generally does not change instantaneously, and the normal frequency change is gradually reduced or increased at a certain rate. When the grid frequency changes gradually, the rate of the frequency change is much lower than the maximum tracking rate of the PLL. The PLL can be locked quickly only through the transient capture process, and it is in the tracking state during the frequency changes, the frequency of the estimation is consistent with the change of frequency. Therefore, in the process of frequency change, the reference value of the speed calculated by MPPT is the rated speed, DFIG operates in normal mode. and the RSC control can adjust the frequency of rotor current to compensate for the change of grid frequency, the current, power and other parameters only oscillate slightly at the beginning of the frequency change and then return to steady state.

The gradual change of the grid frequency has little effect on the DFIG. DFIG can tolerate the slow change of frequency in a large range, and its limit is affected by the protection of wind turbine, the protection of inverter and the performance of PLL. First of all, the maximum frequency change is determined by the protection of wind turbine. The frequency protection value is generally set to 47.5~51.5Hz, but it can be modified according to the actual situation. Secondly, the protection of wind turbine must be matched with the protection of the converter. Otherwise, even if the frequency protection limit of wind turbine is expanded, a large frequency change may trigger inverter frequency protection to cut off the converter, and the frequency protection limit of the converter is generally 48~52Hz.

If the protection of wind turbine and the protection of inverter are not considered, the maximum frequency is determined by hold-in range of PLL. Because of the difference in manufacturing, different wind turbines have different hold-in range of PLL. When the frequency change beyond the hold-in range without considering the protection of the wind turbine and converter, the PLL frequency phase estimation error will increase continuously, and the frequency will change several times, and the power and speed waveform will be seriously distorted, as shown in Figure 5.

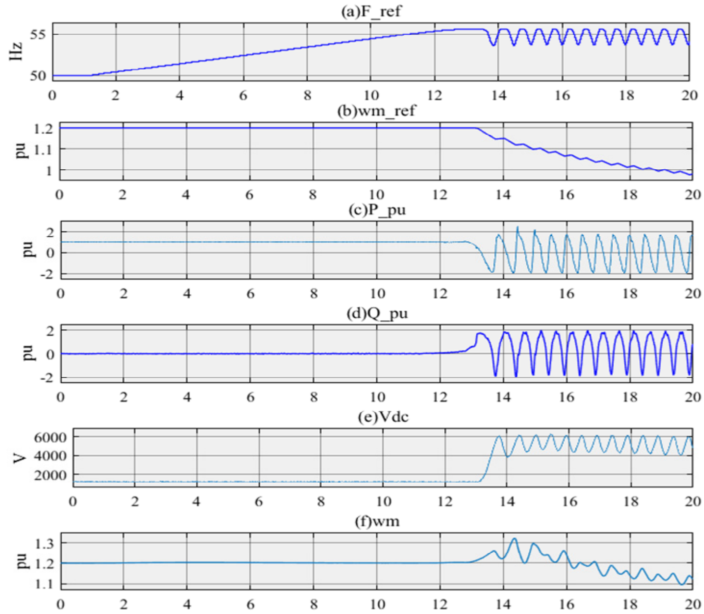


Fig.5. The waveforms when frequency change exceeds hold-in range of PLL

Since hold-in range of PLL is much larger than the protections of wind turbine and inverter, in the actual operation, the maximum frequency range allowed by DFIG needs to consider the limit range of the wind turbinet protection and the converter protection.

## 4. simulation analysis

Using MATLAB/Simulink, this paper combines the power grid frequency variation range of Yunnan power grid after the occurrence of ac/dc locking fault, and dynamically simulates and validates the response characteristics of a single 1.5MW DFIG.

### *4.1. Simulation of Response Characteristics of DFIG with Frequency Change*

The rated frequency of the power grid is set to 50Hz, and the wind speed is kept constant. MPPT is adopted to make the generator rotor run at rated speed and output rated power. A frequency rise disturbance is set at the grid point. When t= 0.5s, the frequency instantly rises from 50Hz to 51Hz and runs for a period of time, as shown in Figure 6. Considering the actual fluctuation, the paper sets the frequency gradually rises and recovers. When t = 1s, the frequency rises by 4s to 52Hz at a rate of change of 0.5Hz/s and, after a period of operation, decreases to 50Hz s at a rate of change of -0.5Hz/s at 4 Hz, as shown in Figure 7.

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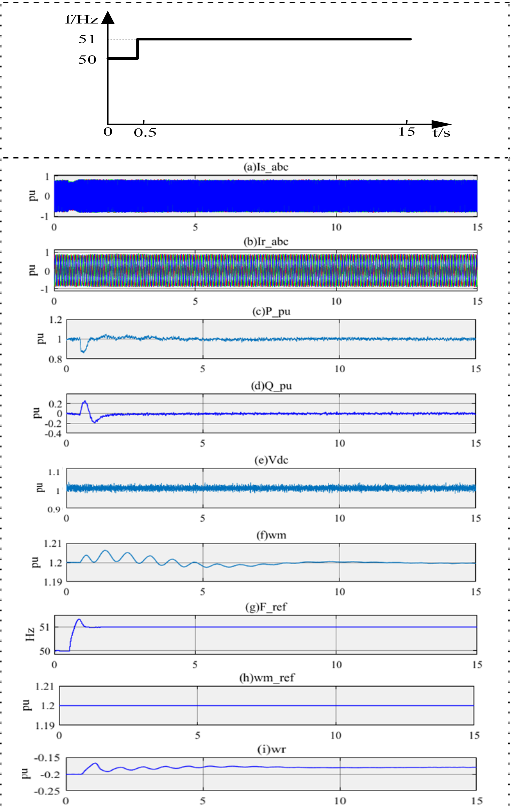


Fig. 6. Frequency changes instantly

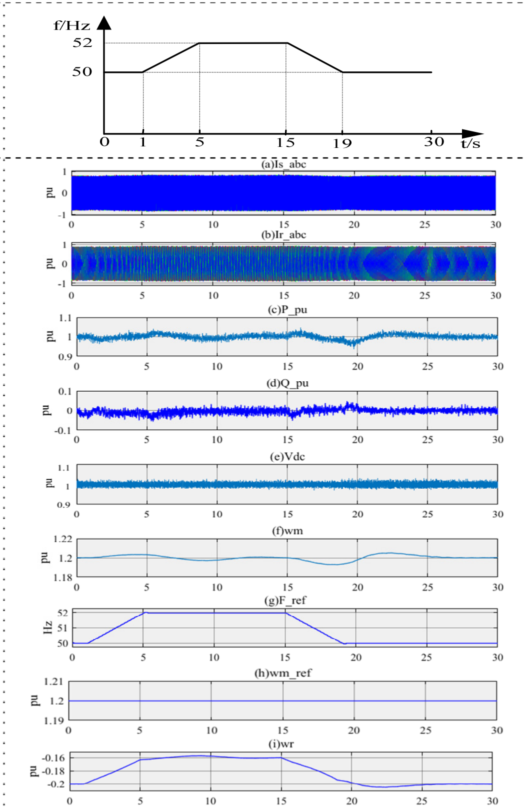


Fig. 7. Frequency changes gradually

According to Figure 6, when the PLL loses lock, each parameter of the DFIG oscillates, the stator and rotor currents decrease, the speed increases, the active power decreases, and a large amount of reactive power is generated. When the PLL is locked again, the amplitude of the parameter oscillation continuously decreases and eventually reaches the steady state value.

Figure 7 shows that when the frequency rises at a certain rate of change and then recovers, the PLL can accurately track the frequency change, and the speed reference value is maintained at the steady state of 1.2 pu. In the steady state, the speed of DFIG, the output power are all the same as before the disturbance. The amplitude of current returns to the rated, and the frequency recovery also triggers the second oscillation.

In summary, the DFIG is operated under the maximum wind energy tracking control mode. The mechanical power and electromagnetic power are controlled independently, and the speed and power grid frequency control are independent. Therefore, only when the grid frequency fluctuates greatly, and PLL is in the initial stage of the capture state, power and current oscillate. Once PLL is locked again, each parameter returns to the initial steady state value. In the actual power grid, RSC controls the frequency of the rotor current to accurately track and compensate for grid frequency change. The power, electromagnetic torque, and speed have slight fluctuations.

In actual operation, the maximum frequency variation range that DFIG can tolerate is usually determined by the protections of wind turbine and inverter. The frequency response characteristics of DFIG can be summarized as Figure 8.

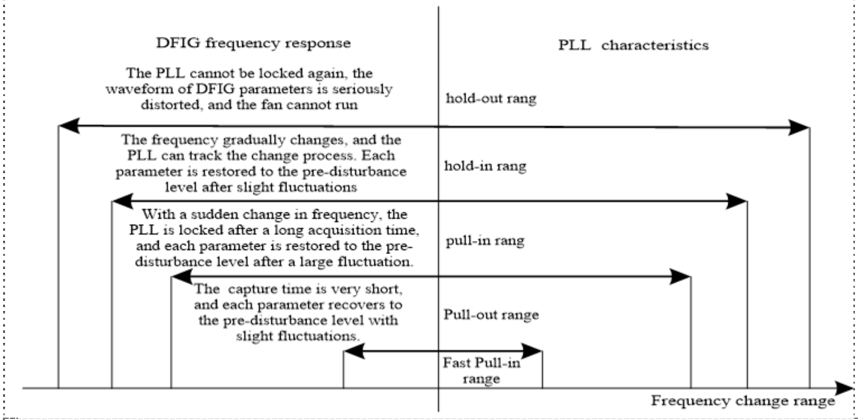


Fig.8. The frequency response characteristics of DFIG.

*4.2. Effects of operating conditions and capacity on frequency adaptability*

The frequency adaptability of DFIG under different operating conditions is analyzed. The wind speed VV is set to 17m/s, 14m/s, 11m/s, 10m/s, 9m/s, and 8.2m/s, respectively. The frequency range is -1.5Hz~1.5Hz. The maximum oscillation peak value of the rotor speed at the frequency change instantly of a 1.5MW DFIG is simulated and analyzed. The simulation results are shown in Figure 9.

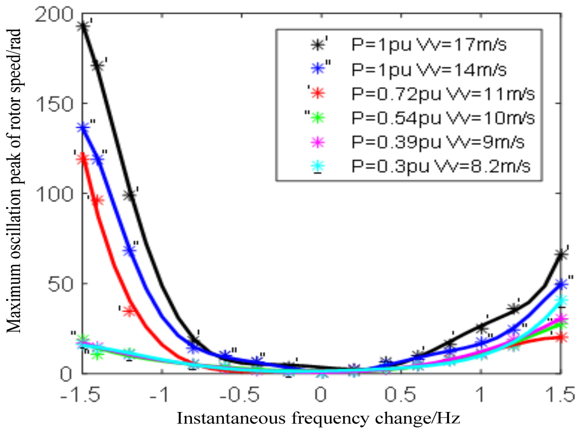


Fig. 9. The rotor speed of a 1.5 MW DFIG when frequency changes

From Figure 9, it can be seen that with the increase of the frequency change and the wind speed, the rotor speed oscillation becomes more and more serious. The larger the frequency change, the greater the fluctuation of the rotational speed. The reason is that when DFIG operates in MPPT mode,it can run at variable-speed and absorb the maximum wind energy under non-full load conditions.

The simulation of the rotor speed of a 49.5MW wind farm consists of 33 DFIG operating at the rated wind speed with frequency fluctuations. The rotor speed with frequency fluctuation for a 49.5MW wind farm consists of 33×1.5 MW DFIG is simulated and analyzed, and the results are shown in Figure 10. From the simulation results, it can be seen that the capacity change of the wind turbine has no effect on the frequency adaptability of the DFIG.

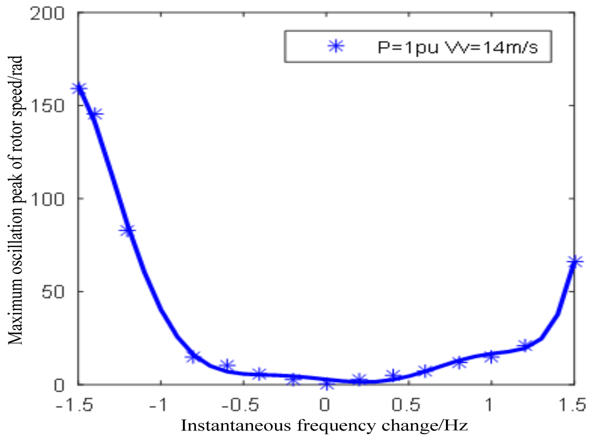


Fig. 10. The rotor speed with frequency fluctuation for a 49.5MW wind farm

## 5. Conclusion

The frequency adaptability of DFIG is influenced by the operation characteristics of PLL and the control of converter under different frequency. Because the actual grid frequency change rate is much lower than the PLL lock phase rate , PLL can quickly lock the grid frequency as long as the grid frequency variation range is less than the converter protection limit. When the grid frequency changes, the DFIG can control the rotor current frequency through the converter control, so that the generator can operate stably at the new grid frequency, and during the adjustment process, the parameters only fluctuate little. In summary, the grid frequency change has little influence on the DFIG, and the frequency limit that DFIG can operate is determined by the converter protection and the PLL parameters. In addition, because the converter over/under frequency protection range is much smaller than the PLL, the normal operating frequency range of DFIG is mainly determined by the converter frequency protection limit.

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