Effect of PLL on transient performance of wind turbines generator under voltage phase jump

Chao Liu1, Xinshou Tian1, Kai Chen2, Yuanyuan Su1, Yan Li1

Abstract: With the increasing proportion of wind power installed capacity, the influences of transient characteristics of wind turbines generator on safety and stability of power grid is becoming more and more important. The rotor side of doubly fed induction generator (DFIG) is connected to the grid through a back-to-back inverter, and vector control based on phase-locking synchronisation is used generally. Phase-locked loop (PLL) drive internal potential phase changes to achieve synchronous operation with the grid. Therefore, PLL has great influence on transient characteristics of DFIG. A dynamic model of PLL is built in this study. Phase-locking performance of PLL under voltage phase jump is studied by changing its parameters, and its impact mechanism on transient characteristics of DFIG is proposed. Simulation models are built with DiSILENT/PowerFactory. The influence of parameters of PLL on phase-locking performance of DFIG under voltage phase jump is simulated.

1 Introduction

In recent years, wind power has developed rapidly. At the end of 2017, wind power installed capacity exceeded 164 million kilowatts in China [1], ranking first in the world. With the increasing scale of wind power, the proportion in the power system is constantly increasing, and the interaction between wind power and power system is more and more complicated [2]. Doubly fed induction generator (DFIG), as one of the main models for wind turbines generally use the vector control method based on the induction generator (DFIG), which is connected to the grid through a back-to-back converter [4]. To ensure that the inverter runs synchronously with the grid, it is necessary to quickly and accurately lock the phase of the grid voltage through a phase-locked loop (PLL) [5]. At present, the wind turbines generally use the vector control method based on the phase-locking synchronous, and PLL drives internal potential phase changes to achieve synchronous operation with the power grid. Therefore, the performance of the PLL has an important influence on the transient performance of the DFIG.

The paper [6] focuses on the improvement of the PLL structure, in order to improve phase-locking performance, the frequency-locked performance in the situation as phase mutation, frequency changes, voltage imbalance, or distortion. The paper [7] verifies that the PLL phase-locking performance has a great influence on the transient performance of the wind turbines through theoretical analysis and simulation. The paper [8] further points out that the dynamic model of PLL has an important influence on the dynamic performance of the wind turbines in the weak grid. Therefore, the influence of PLL on wind turbines characteristics needs to be considered in the study of wind turbines dynamic characteristics. The paper [9] researches on the influence of different types of wind turbines and different parameters on the transient stability of the power system. The papers [10–13] analyse the influence of wind power integration and different wind power permeability on the power system transient stability. All the studies above focus on the influence of wind power integration on power system stability and the PLL performance on the transient characteristics of wind turbines. However, few studies have investigated the influence of PLL parameters on the transient characteristics of wind turbines’ and parameters’ selection.

In this paper, the working principle of PLL is introduced, and the transfer function model of PLL is established. This paper studies relationship between the transient characteristics of wind turbines and parameters of PLL. The influence of PLL parameters on the PLL phase-locking characteristics under voltage phase jump is researched. The correctness of the theoretical analysis is verified by simulation.

2 PLL working principle and model

PLL is commonly used in power electronics control systems for asynchronous power supplies. PLL is a closed-loop control system that automatically locks the frequency and phase of an input signal. Its basic function is to detect and output the frequency and phase of the input signal (which may contain noise or interference). Under the disturbance, its dynamic performance directly affects the transient characteristics of variable speed wind turbines.

2.1 PLL structure and working principle

2.1.1 PLL structure: PLL circuit is a typical feedback control circuit, the output signal to automatically lock the input signal in frequency and phase. PLL is mainly composed of three parts: phase detector (PD), low-pass filter (LPF), and voltage-controlled oscillator (VCO). The PD compares the phase of the periodic input signal with the phase of the VCO output signal to detect the phase difference between the input signal phase and the feedback signal phase. The error voltage is filtered by the LPF, which rejects the phase noise and high-frequency signal components of the PD. In addition to low-pass characteristics, more importantly, LPF plays a decisive role in adjusting the loop parameters, and has an important impact on the performance of the loop. The output of the LPF is used as a control voltage for the VCO. The VCO has an inherent integration stage, and its output is an instantaneous phase. PLL has various forms of loops in the practical application, but all the forms are evolved from this basic loop. The basic structure of PLL used commonly by DFIG is shown in Fig. 1.

2.1.2 Working principle: PLL compares the input signal with the VCO output signal to produce a voltage signal corresponding to the phase difference between the two signals, where the high-frequency portion and the noise are filtered by the LPF. The above
voltage signal acts on the VCO and drives the VCO frequency to the input signal frequency until the frequency difference cancels into the locked state. Then, the output signal and the input signal frequency difference is 0, the phase difference is fixed.

2.2 PLL model

This paper focuses on synchronous reference frame PLL (SRF-PLL) and researches SRF-PLL response characteristics. SRF-PLL is mainly composed of two parts: Clark and Park transform and feedback system with proportion–integration (PI) loop. SRF-PLL is mainly composed of two parts: Clark and Park transform and feedback system with proportion–integration (PI) loop. SRF-PLL converts the three-phase voltage in the abc coordinate system to the dq-axis voltage in the positive rotation coordinate system through Clark and Park transform, as shown in Fig. 2. Taking the q-axis voltage equal to 0 as the control target, the d-axis voltage can be controlled to lock the grid voltage and obtain the phase of each phase voltage. Corresponding to the principle, SRF-PLL voltage vector in the q-axis projection as a PD, the PI loop as an LPF. The dynamic performance of PLL depends mainly on PI parameters.

SRF-PLL model is built with DlgSILENT/PowerFactory, as shown in Fig. 3.

The LF of SRF-PLL generally adopts PI structure, which is \( L(s) = k_p + (k_i/s) \), where \( k_p \) is the proportion factor and \( k_i \) is the integration factor.

On the basis of the basic structure of PLL of DFIG shown in Fig. 3, PLL can be expressed by the transfer function below:

\[
G(s) = \frac{\theta_i(s)}{\theta(s)} = \frac{k_p s + k_i}{s^2 + k_p s + k_i}
\]

The characteristic equation of the second-order system of (1) is as below:

\[
s^2 + k_p s + k_i = 0
\]

The solution of (2) can be expressed by the equation below:

\[
\{s_1 = -k_p/2 + \sqrt{k_p^2 - 4k_i}/2 \\
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\]

The response characteristic of PLL depends on \( k_p \) and \( k_i \).

3 Effect of PLL parameters on transient characteristics under voltage phase jump

3.1 PLL transient characteristics

Suppose the phase jumps \( \Delta \phi \), so the frequency of phase jump is \( \Delta \omega(s) = \Delta \phi/s \). The response of PLL can be expressed as below:

\[
\theta_i(t) = \frac{\Delta \phi}{\Delta \omega} = \frac{k_p s + k_i}{s^2 + k_p s + k_i} \Delta \phi
\]

According to different proportion factor \( k_p \) and integration factor \( k_i \), the transient response characteristics of PLL under phase jump can be expressed as the below: (see (5)) According to (5), the transient response characteristics of PLL under phase jump with different proportion factor \( k_p \) and integration factor \( k_i \) is shown in Fig. 4.

It can be seen from (5) and Fig. 4 that when the phase changes, the smaller the proportion factor is, the larger the PLL overshoot is. The larger the proportion factor is, the smaller the PLL overshoot is. Moreover, the proportion factor exceeds a certain value, the effect of increasing the proportion factor on the PLL overshoot is getting smaller and smaller. The influence of the proportion factor on the PLL phase-locking performance is obviously exponential. When the proportion factor is constant, the larger the integration factor is, the faster the PLL response speed is, which helps to improve the PLL overshoot. When the integration factor exceeds a certain value, the PLL can almost lock the phase change of the grid, and the impact on PLL performance is no longer notable. The integration factor has a greater effect on the phase-locking performance of the PLL than the proportion factor.

3.2 DFIG transient characteristics

The terminal voltage phase jumps when the fault occurred and fault cleared. Since the stator of DFIG connected to the grid, the terminal voltage vector is the same as the grid voltage vector, the grid voltage is directed at the d-axis. However, due to the dynamics vector in the q-axis projection as a PD, the PI loop as an LPF. The dynamic performance of PLL depends mainly on PI parameters.

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coordinate system, and the dotted line is the PLL control system can be expressed as below:

\[
\begin{align*}
\theta_e = \sin \theta_e \theta_e' \sin \theta_e' \\
-\cos \theta_e \theta_e' \cos \theta_e'
\end{align*}
\]

Owing to phase deviation \(\theta_e\), the active power and reactive power decoupling controls of the DFIG are destroyed. The active power and reactive power of DFIG are the functions of voltage phase deviation \(\theta_e\), active power reference \(P_0\), and reactive power reference \(Q_0\). Neglecting the influence of DFIG control strategy and electromagnetic transient process, the active power and reactive power of DFIG can be expressed as below:

\[
\begin{align*}
P_e &= P_0 \cos \theta_e - Q_0 - \frac{3}{2} \frac{U_e^2}{\alpha_0 L_s} \sin \theta_e \\
Q_e &= \frac{3}{2} \frac{U_e^2}{\alpha_0 L_s} + P_0 \sin \theta_e + \left( Q_0 - \frac{3}{2} \frac{U_e^2}{\alpha_0 L_s} \right) \cos \theta_e
\end{align*}
\] (7)

With the stator voltage orientation of DFIG, when terminal voltage phase jumps, there is a deviation between the actual \(dq\) rotating coordinate and the measuring \(dq'\) rotating coordinate due to the phase-locking technique. The active power and reactive power of DFIG are no longer equal to the reference, and the power control ability of DFIG is reduced, which makes the transient stability of DFIG worst. On the basis of (7), the active power and reactive power characteristics of DFIG under voltage phase jump are shown in Fig. 6.

As shown in Fig. 6, when the voltage phase jump is in the range of (0–90°), the larger the voltage phase jump is, the larger the PLL phase-locking deviation is, the larger the deviation between the power of DFIG and the given values is, the greater the transient performance of the DFIG is affected by the PLL phase-locking performance. With the increase of voltage phase jump, the control ability of DFIG is significantly deteriorated.

### 4 Simulation analysis

DFIG is taken as an example in this paper, in order to analyse the influence of PLL phase-locking performance on the transient performance of DFIG. The simulation system is built in DlgSILENT/PowerFactory, as shown in Fig. 7.

**Simulation system:** There are 30 DFIGs (1.5 MW); the acceleration time constant of the external grid is 5 s; and short-circuit capacity of the external grid is 1000 MVA.

By setting the short-circuit fault of the wind power transmission channel, the terminal voltage phase of DFIG jumps. The influence of PLL parameters on the phase-locking performance under voltage phase jump is analysed by simulation, as well as the transient characteristics of DFIGs.

#### 4.1 Influence of proportion factor on PLL performance

For example, 30 DFIGs all are full of power. Short-circuit fault of the wind power transmission system occurs at 0.2 s, resulting in voltage phase jump, the fault is cleared 120 ms later. First of all, analyse the influence of proportion factor on PLL phase-locking performance. Set the integration factor \(k_i = 400\), the proportion factors \(k_p\) are 10, 100, 200, 400, 800, 1000, separately. The phase-locking result of PLL is shown in Fig. 8.

As shown in Fig. 8, the smaller the proportion factor \(k_p\) is, the larger the PLL overshoot is, the worst the phase-locking performance is; the larger the proportion factor \(k_p\) is, the better the phase-locking performance is. When proportion factor \(k_p\) is very small, the curve of PLL phase-locking oscillates under voltage phase jump after a fault. The larger proportion factor \(k_p\) can restrain oscillation effectively, and improve PLL performance. However, when \(k_p\) is bigger than 800, the improvement effect of continuing to increase \(k_p\) on the PLL performance is no longer obvious. This is consistent with the theoretical analysis that the influence of the proportion factor on the PLL phase-locking performance is obviously exponential. Moreover, no matter how much proportion factor, there is always a certain overshoot.
4.2 Influence of integration factor on PLL performance

In the same situation as above, set integration factor $k_i = 10$, the integration factors $k_i$ are 200, 400, 600, 800, 1000, separately. The phase-locking result of PLL is shown in Fig. 9.

As shown in Fig. 9, the integration factor $k_i$ is strongly related to the response speed of PLL. The larger the integration factor $k_i$ is, the faster the response speed of PLL is, and the better the PLL performance is. When the integration factor $k_i$ exceeds 800, the PLL response speed can lock the phase change of the voltage phase. However, the effect of increasing the integration factor $k_i$ on the PLL performance is no longer obvious. This is consistent with the theoretical analysis that the influence of the integration factor $k_i$ on the PLL phase-locking performance is obviously exponential. Larger integration factor can improve the PLL response speed, and also help to improve the PLL phase-locking oscillation.

4.3 PLL parameters’ selection rule

From the above analysis, the PLL proportion factor and PLL phase-locking overshoot are closely related; the integration factor is strongly concerned with PLL response speed. On the other hand, the proportion factor reflects the amount of adjustment of PLL phase-locking. The larger proportion factor and integration factor of the PLL are, the larger the PLL phase-locking adjustment amount is, the faster the adjustment speed is, the stronger the PLL capability is, and the better the PLL performance is. However, it should also be noted that the proportion factor and the integration factor exceed a certain value; PLL phase-locking performance improvement is no longer obvious. So the proportion factor and the integration factor should not be too large. Reasonable proportion factor can effectively restrain the phase oscillation when PLL locking phase, and also can effectively reduce the PLL overshoot; reasonable integration factor can ensure the PLL locking phase response speed, and also improve the PLL phase-locking oscillation.

For example, set $k_p = 200$ and $k_i = 800$. The phase-locking result of PLL is shown in Fig. 10.

As shown in Fig. 10, PLL can lock the voltage phase of power grid good enough.

PLL parameters’ selection rule is given as follows: (i) the proportion factor is closely related to phase overshoot and oscillation of the PLL phase locking. When the proportion factor is too small, the overshoot is too large, and PLL phase-locking oscillation tends to occur. When the proportion factor exceeds a certain value, the influence of proportion factor on the PLL performance improvement is no longer obvious. So, the proportion factor should not be too large. (ii) The integration factor is strongly related to the PLL phase-locking response speed. When the integration factor is too small, the PLL phase-locking speed is too slow, and the larger integration factor is also beneficial to improve the PLL phase-locking oscillation. Integration factor should not be too large.
too large, when the integration factor exceeds a certain value, the influence of integration factor on the PLL performance improvement is no longer obvious. (iii) When the PLL parameter selected, the match of the proportion factor and the integration factor should be considered. The proportion factor is equivalent to the amount of the PLL phase-locking adjustment, and the integration factor is equivalent to the speed of the phase-locking adjustment. Only when two parameters matched, the best performance of PLL can be achieved.

5 Conclusion
Phase-locking performance of PLL has a significant impact on the transient performance of DFIG. In this paper, the influence of the PLL parameters on the PLL performance under voltage phase jump is studied. The main conclusions are as follows:

(i) The proportion factor is closely related to the phase overshoot and oscillation of the PLL. When the phase jumps, the smaller the proportion factor is, the larger the overshoot of the PLL is, and the oscillation of the PLL tends to occur. The influence of the proportion factor on the PLL performance is obviously exponential.

(ii) The integration factor is strongly related to the PLL response speed. When the phase jumps, the faster the PLL response speed is, which helps to improve the overshoot and oscillation of PLL. Relative to the proportion factor, the integration factor has a larger influence on PLL performance. Moreover, the influence of the integration factor on the PLL performance is obviously exponential too.

(iii) The PLL parameters’ selection rule is given. The proportion factor reflects the adjustment amount of the PLL in the phase-locking process. The integration factor reflects the adjustment speed of the PLL. Only two parameters are properly configured to achieve the best performance.

6 References

[1] ‘Renewable energy – add power for high quality development’. Available at http://www.nea.gov.cn/xwzx/nyyw.htm, accessed 20 December 2017
[2] Zhang, Y., Tong, R., Zhao, J., et al.: ‘Transient characteristics analysis and low voltage ride-through scheme of doubly fed wind turbines generators’, Autom. Electr. Power Syst., 2013, 37, (6), pp. 7–11
[3] Liu, Q., He, Y., Zhang, J.: ‘Operation control and modelling simulation of AC-excited variable speed constant frequency (AEVSCF) wind power generator’, Proc. CSEE, 2006, 26, (5), pp. 43–50
[4] Zhao, Q., Guo, X., Wu, W.: ‘Research on control strategy for single-phase grid-connected inverter’, Proc. CSEE, 2007, 27, (16), pp. 60–64
[5] Arricibita, D., Marroyo, L., Barrios, E.L.: ‘Simple and robust PLL algorithm for accurate phase locking under grid disturbances’. 2017 IEEE 18th Workshop on Control and Modelling for Power Electronics, Stanford, USA, July 2017, pp. 1–6
[6] Gorestan, S., Guerrero, J.M., Vasquez, J.C.: ‘Three-phase PLLs: a review of recent advances’, IEEE Trans. Power Electron., 2017, 32, (3), pp. 1894–1907
[7] Zhang, D., Wang, Y., Hu, J., et al.: ‘Impacts of PLL on the DFIG-based W TGs electromechanical response under transient conditions: analysis and modelling’, CSEE J. Power Energy Syst., 2016, 2, (2), pp. 36–39
[8] Wang, Y.: ‘Modelling and analysis of electromechanical transient characteristics of DFIG-based wind turbines’. PhD thesis, Huazhong University of Science & Technology, 2015
[9] Hao, Y., Li, P., Li, X., et al.: ‘Analysing the impact of wind plant on power system transient stability’, Proc. CSU-EPSA, 2012, 24, (2), pp. 41–46
[10] Zhang, M., Xu, J., Li, J.: ‘Research on transient stability of sending power grid containing high proportion of wind power’, Power Syst. Technol., 2013, 37, (3), pp. 740–745
[11] Tang, Y., Zhao, L., Guo, X.: ‘Impact on wind power penetration on angle transient stability of wind-thermal combined system’, Autom. Electr. Power Syst., 2013, 37, (20), pp. 34–40
[12] Tian, X., Wang, W., Chi, Y., et al.: ‘Performances of DFIG-based wind turbines during system fault and its impacts on transient stability of power systems’, Automat. Electr. Power Syst., 2015, 39, (10), pp. 16–21
[13] Tian, X.: ‘Research on the interactions between DFIGs based wind farms and power grid and related optimal control strategies’. PhD thesis, North China Electric Power University, 2016