A summary of impacts of wind power integration on power system small-signal stability

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Abstract. Wind power has been increasingly integrated into power systems over the last few decades because of the global energy crisis and the pressure on environmental protection, and the stability of the system connected with wind power is becoming more prominent. This paper summaries the research status, achievements as well as deficiencies of the research on the impact of wind power integration on power system small-signal stability. In the end, the further research needed are discussed.

1. Introduction
The influence of the access of large-scale wind power to the system on small-signal stability is an important subject which can't be ignored. On one hand, randomness is the inherent characteristic of wind power, and it is also the main factor affecting the safe and stable operation of wind power grid. The large capacity power fluctuation caused by the randomness of wind power will lead to a series of problems, such as frequency stability, voltage stability and low frequency oscillation, which are serious threats to the safe operation of the power system [1]. On the other hand, most of the large wind farms in China are hundreds or thousands of kilometers away from load center, so the large scale wind power usually needs to be given across the region, resulting in a loss of regional oscillation damping and intensifying the instability of a large power system.

Under the above background, the research of influence of wind power grid on power system small-signal stability are reviewed. At the beginning, the principle and method of power system small-signal stability analysis are outlined. According to the literature in recent years, then the research of the influence of wind power on power system small-signal stability is reviewed from two aspects of modeling of wind turbine (WT) and the oscillation modes and damping characteristics of power system with wind power integration. At last, the control strategies to improve the system damping characteristics are introduced.

2. Power System Small-signal Stability
Small-signal stability refers to the ability of the power system to maintain synchronism under small disturbances. Such disturbances are related to changes in the grid such as load and generation shifts. This variations occurs constantly in the grid. At the same time this changes are considered small enough for them to be linearized. Small signal stability is largely a problem of insufficient damping of oscillations; therefore instability is normally through oscillations of increasing amplitude.

Small-signal stability analysis methods mainly include the eigenvalue analysis, frequency domain method and the time domain simulation method. In recent years, some scholars put forward some new
methods for small signal stability analysis, such as method based on the analysis of the measured signals of power system, the wide-area measurement information analysis method and normal form method based on the nonlinear theory [1].

Eigenvalue analysis method is most widely used in the small-signal stability analysis, which is based on linear system theory and the lyapunov's first law. Because eigenvalue analysis theory is highly reliable and can reveal the nature of stability of the systems with complex dynamic behavior, it is a powerful tool for analyzing system oscillation mode and damping characteristics and has been successfully applied in small signal stability evaluation and the controller’s design, configuration, site selection and parameter setting, etc. [2].

3. Impact of Wind Turbine on Power System Small-signal Stability
WT system normally consists of wind turbine, generator and grid interface converters. During the development of the WT techniques, squirrel cage induction generator (SCIG), doubly fed induction generator (DFIG) and direct-drive permanent magnet synchronous generator (DDPMSG) were employed to convert wind power to electrical power, and DFIG is applied most.

3.1. Wind Turbine Modeling
Establishing proper dynamic models of WT and wind farm is the top priority to study the influence of WT on power system small-signal stability, and the accuracy of the models and parameters will be directly related to the precision of the analysis and calculation. Doubly-fed induction generator, as the mainstream of the current wind power equipment, is mostly researched in the wind turbine modeling.

A mathematical model for DFIG was earlier proposed by [3], and this documents simulated the respond of this WT model to two kinds of wind model. [4] established an improved type of DFIG small signal stability model, the authors took into account the characteristics of mechanical system of DFIG, the electromagnetic characteristics of generator of DFIG and the control strategies of the stator and rotor when establishing equation of state of DFIG. Thus, this model can reflect the electromechanical mode for DFIG connected to the power system more accurately. [5] set up a simplified three-order dynamic model of DFIG in the reference frame of stator’s circumrotatory magnetic field, which considered rotor field voltage and mechanical torque received by generator as controlled variables, and compared the response of simplified DFIG model’s and accurate DFIG model’s various state variables to small disturbances by using MATLAB simulation. According to the characteristics of variable speed WT shafting of DFIG, [6] established a dynamic model of DFIG gearbox shafting system, and constructed an eight order simultaneous differential equations based on the dynamic equations of generation. This model can be used to analyze the dynamic behavior of DFIG under various operating conditions. [7] Studied the wind farm equivalent modeling method based on operating data, made comparison with traditional wind farm modeling method, and the analysis shows that the equivalent modeling method based on operating data is more consistent with the physical condition.

Researches on WT have achieved fruitful results, and some commercial software do quite well in WT modeling. However, because the control system of WT is quite complex and each manufacturer applies their own control strategies, among which there are some difference, it has certain difficulty to establish a more realistic model.

3.2. Impact of Grid-connected Wind Farm on Power System Small-signal Stability
Document[8] firstly began to do the research on the impacts of constant speed WT and variable speed WT on power system small-signal stability, and studied the impact of WT on oscillation mode and damping characteristic by using eigenvalue analysis method and time domain simulation; [9] studied the effect of grid-connected wind power in multi-aspects, and pointed out that power system small-signal stability could be effected by the capacity of wind power, access point of wind power and blocking level of the grid, where the influence may be positive or negative depending on the operating conditions. The above conclusions were verified by simulation of an example. [10] Studied the
changes of small signal stability and transient stability with the increase of output of DFIG, and analyzed the problem of the selection of wind farm access points by using sensitivity analysis method. [11] Researched power system small-signal stability with high wind power penetration, and draw a conclusion that power system stability could be improved by controlling terminal voltage of DFIG. [12] Calculated the example of WSCC 3-machine-9-bus system to study the impacts of output and terminal voltage control unit of generation on oscillation mode. The author found that the terminal voltage control unit of DFIG had much to do with the characteristics of the regional oscillation mode. Applying inertia control can help DFIG provide the support of inertia to the power system. According to the above theory, document [13] analyzed the mechanism of the effect of the inertia of DFIG on power system small-signal stability, made a quantitative analysis of this effect, and inspected the influence of different control strategies and control parameters on the system small signal-stability by the mode analysis. [14] Researched the influence of wind power fluctuation on the power system small-signal probability stability, which was based on the analysis of probability distribution function of eigenvalues applying Gram-Charlier series expansion, and verified the effectiveness of the above method by using Monte Carlo simulation.

Research on the effect of grid-connected wind power on power system small-signal stability still has many problems. First, while there are many documents researching on wind-power-connected system small-signal stability, most of them are studied based on the simulation of test system and few researches are based on the analysis of the actual system. Second, it’s difficult to get consistent conclusion due to varying simplification degree of the examples and the models, the complexity of control of variable speed WT and many other factors which influencing the power system damping. In addition, few papers studied the mechanism of oscillation modal of wind-power-connected system, and so did the analysis of the relation between WT components and power system oscillation mode from physical perspective.

4. Strategies For Improving Power System Small-signal Stability With Wind Power Integration

The strategies for improving power system small-signal stability with wind power integration can be classified into two types, which are the primary system strategy and the secondary system strategy. The primary system strategy include the enhancement of the grid structure and the installation of energy storage devices, etc. The secondary system strategy include the installation of PSS (PSS Power System Stabilizer) and FACTS (flexible AC installed transmission system) devices, and the use of modulation function of HVDC (high-voltage direct current) transmission system, etc[35]. The above strategies are the general measures to improve power system small-signal stability, without considering the influence of wind power access to the system. As for the question of improving power system small-signal stability considering wind power integration, many scholars have made fruitful research [15-43].

To improve the damping of the system, the control of asynchronous WT pitch PID was proposed in [15]. The pitch angle of the blades is adjusted to increase (decrease) mechanical torque and improve (lower) WT power output, thus the system positive damping is increased. This method is similar to the control strategy of power system stabilizer, which can enhance the system damping and improve power system small-signal stability. [16] Proposed the control method of amplitude and angle of rotor field magnetic flux, which can enhance system damping by additional control. Electrical variables related to system oscillation mode were regarded as the input signal and output signal was regarded as the additional control signal of active or reactive power ring, and the low frequency oscillation can be suppressed through adjusting the angle of the rotor field magnetic voltage angle. In paper [17], a new type of power system stabilizer applied to DFIG was designed, and it was different from the traditional power system stabilizer PSS. This type of power system stabilizer was installed inside the WT regarded the local slip signals as additional signals which are transported to the rotor converter of WT to suppress low frequency oscillation. The result showed that it did well in suppressing the active power oscillation of the wind farm. Aiming at the problem of low frequency oscillation between regions, the damping control strategy applying wide-area measurement system (WAMS) has attracted
the attention of many scholars. In document [18], the DFIG wide-area damping controller was designed, where the active power reference value of the DFIG rotor-side converter and power angle difference of inter-area synchronous generator were regarded as the input signals. The simulation results showed that the DFIG applied wide-area damping controller could provide more reactive power to the system and provide the system a stronger voltage support, thus improving the system damping and achieving the inhibition of the inter-area oscillation. However, for a large power system, it’s difficult to achieve an ideal effect for these reasons: a large amount of system parameters are needed in the PSS design; the structural changes of the system may have a great impact on the damping effect; the PSS of some wind turbines may exist the operating state for some reasons in the actual operation. [19] Designed an adaptive damping controller based on variable frequency transformer, which could automatically calculate and optimize the parameters of the damping controller according to the Prony method.

In general, mechanical control, active power control and reactive power control are applied to improve the damping of power system connected with wind power. As a new control strategy, energy function of power system is also put forward. Wind turbine PSS are researched most in all control strategy, but it’s still difficult to achieve an ideal effect due to the nonlinear characteristics of wind power system and the difference of various WT. At the same time, it’s difficult to do the commissioning and setting of wind turbine PSS because of the large amount of wind turbines in a wind farm. So, it still needs more effort to study the wind turbine PSS.

5. Conclusion
With the increase of wind power capacity in China, and the intrinsic characteristic of randomness of wind power, it becomes an important subject to research on the impact of grid-connected wind power on power system small-signal stability.

Wind farm modeling is the foundation of the research on wind power, and the accuracy of the model and parameters will be directly related to the accuracy of analysis and calculation. Many freeware and commercial software have obtained certain experience, but it still needs more effort to establish a more realistic model because of the complexity of the wind power system and the diversity of wind turbines applied by the grid.

Squirrel cage induction generator, doubly-fed induction generator and permanent magnet direct-drive generator are employed most in current power system. Constant speed WT itself has no synchronization stability problem, and generally presents positive damping effects on the system. Due to the complexity of control system, variable speed wind power system may present positive or negative damping effect on power system, and there is no certain conclusion. So, it still needs further study on the mechanism of the effect of wind turbines on the system damping characteristics.

From the point of WT control strategy, the research mainly focuses on the WT additional damping control strategy. However, because the wind turbine PSS has some inherent shortcomings, the energy storage technology, FACTS and HVDC modulation are widely applied in system damping control, which makes the damping coordination control become a hot issue.

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