The SSR Mitigation with Energy Storage in the DFIG Based Series Compensated Wind Power System

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Abstract. The Sub-synchronous resonance (SSR) in the series compensated wind power system has greatly threatened the safety and the stability of the electrical power system. It is caused by the interaction between the doubly-fed induction generator (DFIG) and the series compensated capacitor. However, few researches focus on the application of the energy storage in the wind farms to mitigate the SSR. In this paper, the additional SSR damping control strategy applied with energy storage is proposed. The effectiveness of the proposed control strategy is verified with the PSCAD model. The results demonstrate that the sub-synchronous current could be suppressed successfully. Therefore the damping of the series compensated wind power system at the sub-synchronous frequency can be greatly improved.

Introduction

The utilization of the wind power in China has greatly increased in recent years. The installed capacity of the wind turbine generators is expected to be 210 GW in 2020[1]. Most of the applied wind turbine generators are the Doubly Fed Induction Generators (DFIGs) with the advantages of cost-effectiveness, reliability, light weight, and easy maintenance[2]. However, the large-scale DFIG based wind farms connected with the series compensated capacitors introduce great risk of the sub-synchronous resonance (SSR). In October 2009, a wind farm in Texas, United States, suffered SSR accidents due to the fixed series compensation, resulting in a large number of generators being disconnected from the grid and damage to the crowbar circuit of the generators [3]. In addition, the SSR accidents have also occurred several times since the series compensation was applied in the DFIG based wind farms in North China [4]. These SSR events caused the tripping of wind turbine generators, abnormal vibration of the transformer and loss of the electrical power[4]. On July 1, 2015, a large PMSG based wind farm in the Hami region of Xinjiang, China, sustained power oscillations in the sub-synchronous frequency range without the influence of the series compensation. As a result, the accident caused multiple wind turbine generators tripping near the DC transmission end. What's more the frequency of northwest grid was reduced[5].

There has been plenty of research about the SSR suppression countermeasures in the traditional thermal power units. The commonly used methods include the modification of generator control system and the network topology such as the installation of blocking filters, additional excitation damping control, and the use of FACTs equipment [6,7]. Until now, most of the research about the suppression of the SSR in DFIG based series compensated wind power system can be summarized in three aspects, such as the modification of DFIG control system, changing of the topology of the grid and the application of the FACTs with additional damping controller. The control system of the wind turbine generator was improved to increase the damping of the wind power system at sub-synchronous frequency[8]. The current loop and the phase-locked loop of the converter controller in the wind turbine generator was optimized to reduce the risk of the SSR[9]. In addition, the rotor-side converter control loop and the grid-side converter control loop of DFIG with the additional damping control can also suppress the SSR of the wind farm[10-13]. What's more, the rotor-side
controller with the addition damping presents better than the grid-side controller. Literature [14] proposed a measure with a notch filter on the d-axis or q-axis of the current loop of the rotor converter controller of the DFIG to provide the damping to mitigate the SSR. The literature [15] designed a sub-synchronous damper based on VSC which is specially used for the SSR problem of DFIG based wind farm. By injecting positive damping into the grid side, the SSR of the wind power grid-connected system is suppressed. Literature [16-18] designed a scheme to suppress the wind field SSR using the unified power flow controller (UPFC) and thyristor controlled series compensation capacitor (TCSC). The static synchronous compensator (STATCOM) with auxiliary SSR damping controller has also been utilized to provide positive damping [18].

However, few research have been conducted about the SSR suppression with the energy storage equipment. In this paper based on the typical wind power system in the North China, the SSR suppression strategy applied with the energy storage device is proposed. Theoretical analysis and time-domain simulation show that the proposed scheme has a good suppression effect.

The Analysis of SSR

The Model of the DFIG

The model of the DFIG based wind power system with fixed series compensation is shown in Figure 1. DFIG is mainly composed of wind turbine, shafting, induction generator, rotor side converter (RSC), DC link and grid side converter (GSC) [18].

![Figure 1. The model the series compensation system.](image1)

The wind wheel and the shaft system belong to the mechanical transmission system. The mechanical power output by the wind turbine is transmitted to the rotor of the generator, which is transformed into electricity by the induction generator and then sent to the power grid. DFIG adopts back-to-back, two-level voltage type PWM converter connected through DC link to achieve variable speed constant frequency operation and optimal speed tracking control. Due to the decoupling of the DC link, the functions of the rotor-side converter RSC and the grid-side converter GSC are independent. RSC can adjust the rotor dq-axis component current to achieve DFIG power control, GSC is mainly used to control the DC bus voltage stability and power factor.

The Reason of SSR

The interaction between the DFIG converter and the series-compensated transmission line can led to SSR [12]. It is essentially an induction generator effect with DFIG control [13] and is related to the RSC control system, while the impact of GSC is smaller [14]. As shown in Figure 2, the RSC based on the stator voltage vector oriented control strategy consists of two parts: a power outer loop and a current inner loop.

![Figure 2. The control block diagram of RSC.](image2)

The power fluctuation and rotor dq-axis synchronized current affect the rotor voltage through the RSC inner loop control. According to the RSC control block diagram, the rotor dq-axis voltage increment caused by the sub-synchronous stator current can be expressed as equation (1).
\[ \Delta u_{rd} = \Delta P_r (K_{p1} + \frac{K_{d1}}{j\omega}) - \Delta i_{rd} (K_{p2} + \frac{K_{d2}}{j\omega}) - \Delta i_{rd} (\omega_0 - \omega) X_p \]
\[ \Delta u_{rq} = \Delta Q_r (K_{p1} + \frac{K_{d1}}{j\omega}) - \Delta i_{rq} (K_{p2} + \frac{K_{d2}}{j\omega}) + \Delta i_{rd} (\omega_0 - \omega) X_p \]

(1)

The sub-synchronous current is introduced in the rotor windings, which in turn creates changes in the stator current. The disturbance currents also appear in the stator windings. The oscillation is aggravated when the new sub-synchronous current is added to the original sub-synchronous current to form a positive feedback.

During the SSR of the wind farm, the DFIG continuously injects sub-synchronous frequency energy into the grid system through the control link, which changes the damping state at the sub-synchronous frequency of the system. When this energy is large enough and the system damping is relatively weak, the active power and reactive power will continue to oscillate and diverge, and it will cause a serious SSR accident in the wind farm.

The Principle of the SSR Mitigation

The Model of Energy Storage

The model of the energy storage is shown in Figure 3. The main power supply circuit, thermal kinetic phenomena, activation phenomena and ohmic losses are considered. This model can effectively predict voltage \( V_E \), operating current \( i_E \), temperature \( T \) and pressure \( P \). The parameters of the model have been explained in [19] and is only briefly enumerated here.

![Figure 3. Model of the energy storage.](image)

![Figure 4. The SSR suppression control block diagram.](image)

The Proposed SSR Control Strategy

The line current of the series compensated transmission line is the feedback signal for the SSR suppression control system. The input signal is sent to the filters to extract the sub-synchronous component after the signal pre-processing. In the filtering step, the oscillation component needs to be extracted at the sub-synchronous frequency. The oscillation frequency of the target power has only one mode to be extracted without considering the multimodal control, but if there is multimode the frequency of the state needs to be designed with certain algorithms to identify it. Then, after the phase shifting and proportional amplification, the reference signal is added as a reference auxiliary control signal for the converter of energy storage device, participate in the preparation of the voltage. By this method, a power corresponding to the oscillating power component is formed in the hydrogen producing apparatus. The component could increase the electrical damping of the device and improve the suppression of sub-synchronous oscillations.

The filters include a band stop filter and a band pass filter. The band stop filter is to filter out the fundamental frequency component and the band pass filter is designed to extract the sub-synchronous component. The transfer function is shown in (2) and (3) respectively.

\[ F_s(s) = \frac{s^2 + \omega_0^2}{s^2 + 2\xi_0 \omega_0 s + \omega_0^2} \]
\[ F_p(s) = \frac{2\xi \omega_p s}{s^2 + 2\xi \omega_p s + \omega_p^2} \]  

where, \( \xi \) represents the damping ratio, \( \omega \) represents the considered frequency of the filter.

The phase shift function is shown in (4),

\[ G(s) = K \frac{(1-T_a s)^n}{(1+T_a s)^n} \]

where, \( T_a =0.1 \) is the time constant, \( n=2 \) is the number of the phase-shifting links, \( K=15 \) is the gain.

**Simulation**

In order to verify the effect of the designed energy storage device based additional damping controller, the PSCAD model adapted from the typical series compensated wind power system in North China is utilized. The capacity of the wind power system is 1GMW. All of the wind turbine generators are 1.5 MW DFIG. The series compensation degree is 45\%. All of the DFIG are with the same operation condition. The capacity of the energy storage device is 20MW. It is installed at the 35kV public connection point. Assuming that all DFIGs have the same parameters and operating conditions. The wind speed is 10m/s. When the series capacitor is put in, the SSR current at 7Hz is aroused, presented in Figure 6. Then, when the energy storage is switched on, the SSR current is suppressed in 1.5s. After that, if the energy storage is switched off, the SSR current appears again.

**Conclusion**

With the continuous increase of grid-connected wind power capacity, the phenomenon of sub-synchronous oscillation caused by wind turbines creates a severe challenge to the safety and stability of the power system.

In this paper, a method based on energy storage damping control to suppress SSR in the DFIG based series compensated wind power system is designed, by introducing the processed line current to the energy storage controller. The research work provides a novel method for solving the similar SSR in the wind power system. The results demonstrated that the energy storage device with SSR...
additional damping controller could suppress the sub-synchronous current of the series compensated wind power system successfully.

References


