Sub-synchronous resonance mitigation by a STATCOM in doubly fed induction generator-based wind farm connected to a series-compensated transmission network

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Abstract: With the fast development of wind power generation, large-scale wind farms are connected to an electrical network which is series compensated to increase transmission capacity. However, a series-compensated power system may encounter with a sub-synchronous resonance (SSR) problem. Flexible AC transmission systems controllers are widely applied to mitigate SSR and improve the transient stability of the power system. A static synchronous compensator (STATCOM) with an SSR damping controller is proposed to mitigate the potential of SSR in a series-compensated doubly fed induction generator-based wind farm. The local signal is used as the input of the damping controller, which is feasible to be implemented in a practical project. Taking account of different series compensation levels and operating conditions, extensive transient simulations have been carried out using power systems computer aided design/electromagnetic transients including DC (PSCAD/EMTDC) to demonstrate the capability of STATCOM in damping SSR. It is shown that the SSR is successfully alleviated by STATCOM, which also verifies the effectiveness of the proposed STATCOM controller in improving the stability of the transmission system.

1 Introduction

With the rapid increase of the installation of wind farms, large wind turbine generators are integrated into power system networks. As wind farms and load centres are usually asymmetrically distributed, series capacitive compensation is widely utilised to improve the transmission capacity [1]. However, the presence of series capacitors in the line may potentially increase the risk of sub-synchronous resonance (SSR) in wind turbine generators [2–4].

SSR is a potential phenomenon which may arise in a power system when the mechanical system exchanges energy with the electrical network [5]. The first time SSR attracted people’s attention in the 1970s due to the shaft failures at the Mohave power station [6]. Since then, extensive studies have been carried out. The early research mainly focused on the SSR issue pertinent to thermal power. SSR is a relatively newly experienced phenomenon in the wind farm and needs to be further studied [7]. Traditionally, the SSR issue is divided into three categories [8]: torsional interaction (TI), induction generator effect (IGE), and torsional amplification (TA). The TI would take place when the electrical resonant frequency is close or coincides with the complement of a torsional resonant frequency of the shaft system [9]. The IGE is purely an electrical phenomenon, and it depends on the damping of the electrical system. The TA is nonlinear transient dynamics and is generally caused by faults or switching operations. For wind power generation, besides the SSR issue, sub-synchronous control interaction also exists [10] due to the application of power electronic controllers. These interactions are collectively referred to as sub-synchronous interaction.

Among many types of wind generation, the doubly fed induction generator (DFIG) is highly popular in engineering due to its high capacity, low cost, and flexible control [11]. In northern and western China, most large wind farms employ the DFIG-based wind turbines. Su et al. [8] presented the impact of the DFIG-based wind farm on the small-signal stability of a power system. Several events observed in practical wind farms have indicated that the DFIG is most vulnerable to SSR [10–12], and the SSR was mainly attributed to the IGE instead of the TI.

To mitigate this SSR phenomenon, many mitigation measures have been proposed. A simple measure is to change network topology or operation conditions [12]. However, this measure limits the flexibility and efficiency of the power transmission system. Another solution is to place a sub-synchronous resonance damping controller on the rotor side converter or the grid side converter of the DFIG [13]. This is an economical measure since no additional devices need to be installed. However, this measure needs large numbers of DFIGs to be upgraded, resulting in a huge workload. Recently, it is widely accepted that flexible AC transmission system (FACTS) controllers, such as the thyristor-controlled series capacitor, the static volt-ampere reactive compensator, and the static synchronous compensator (STATCOM), can provide an effective solution to relieve the SSR [2, 14, 15]. However, series FACTS are challenging to implement, as each installation requires an individual solution. STATCOM can be placed at the centre of the transmission line or the generator terminal to improve power system stability.

This paper proposes an SSR mitigation technique with STATCOM in a DFIG-based wind farm connected to a series-compensated transmission line. Through the design of a suitable controller for the STATCOM, the SSR is mitigated. Electromagnetic transient simulations are carried out using PSCAD/EMTDC software. The rest of this paper is organised as follows. Section 2 describes the structure and parameters of the studied system. The mathematical model and control strategy of STATCOM are introduced in Section 3. In Section 4, electromagnetic transient simulation results are presented to verify the effectiveness of the STATCOM. The conclusions of this paper are provided in Section 5.

2 Studied system

The studied system is shown in Fig. 1. The wind farm is aggregated by 40 numbers of 1.5 MW, 0.69 kV DFIG-based wind turbines, which is connected to the grid through a 35 kV series-compensated line. The STATCOM is installed on the 35 kV bus via a 10/35 kV step-up transformer. The base operating frequency of the studied system is 50 Hz. Other employed system parameters are listed in the Appendix for conciseness.
3 STATCOM model

STATCOM is a well-known shunt-connected FACTS controller based on the voltage source converter. In this section, the STATCOM model is presented, and the STATCOM control circuit in order to mitigate SSR in series-compensated wind farm system is introduced.

3.1 Mathematical model

The configuration of STATCOM is shown in Fig. 2. The three-phase voltages of the AC system are expressed as $u_{sa}$, $u_{sb}$, and $u_{sc}$, respectively. The three-phase voltages of the STATCOM are $u_{ca}$, $u_{cb}$, and $u_{cc}$, respectively. The three-phase currents injected from STATCOM to AC system are $i_{sa}$, $i_{sb}$, and $i_{sc}$, respectively. The equivalent resistance and equivalent reactance of the line connected with STATCOM are expressed as $R$ and $L$, respectively. $C_{dc}$ is the DC capacitor, and $u_{dc}$ is the DC voltage.

The three-phase voltages of the AC system can be represented as

$$
\begin{align*}
    u_{sa} &= \sqrt{3}u_{a}\sin\omega t \\
    u_{sb} &= \sqrt{3}u_{b}\sin(\omega t - 2\pi/3) \\
    u_{sc} &= \sqrt{3}u_{c}\sin(\omega t + 2\pi/3)
\end{align*}
$$

The three-phase voltage output by STATCOM can be expressed as

$$
\begin{align*}
    u_{ca} &= ku_{dc}\sin(\omega t - \delta) \\
    u_{cb} &= ku_{dc}\sin(\omega t - 2\pi/3 - \delta) \\
    u_{cc} &= ku_{dc}\sin(\omega t + 2\pi/3 - \delta)
\end{align*}
$$

where $k$ is the scale factor and $\delta$ is the angle between the AC system voltage and the STATCOM output voltage.

The three-phase dynamic equation of STATCOM can be expressed as

$$
\begin{align*}
    \frac{d}{dt}i_a &= \frac{-R}{L}i_a + \frac{\omega}{L}u_{ca} - \frac{K_{\text{ssr}}}{L}\sin\delta \\
    \frac{d}{dt}i_b &= \frac{-R}{L}i_b + \frac{\omega}{L}u_{cb} - \frac{K_{\text{ssr}}}{L}\cos\delta \\
    \frac{d}{dt}i_c &= \frac{-R}{L}i_c + \frac{\omega}{L}u_{cc}
\end{align*}
$$

Substitute (3) with (1) and (2). Equation (3) can be rewritten as follows

$$
\begin{align*}
    \frac{d}{dt}i_a &= ku_{dc}\sin(\omega t - \delta) - \sqrt{3}iu_{a}\sin\omega t - Ri_a(t) \\
    \frac{d}{dt}i_b &= ku_{dc}\sin(\omega t - 2\pi/3 - \delta) - \sqrt{3}iu_{b}\sin(\omega t - 2\pi/3) - Ri_b(t) \\
    \frac{d}{dt}i_c &= ku_{dc}\sin(\omega t + 2\pi/3 - \delta) - \sqrt{3}iu_{c}\sin(\omega t + 2\pi/3) - Ri_c(t)
\end{align*}
$$

The power balance equation for dc capacitor can be expressed as

$$
\frac{d}{dt}(\frac{1}{2}C_{dc}u_{dc}^2) = u_{sa}(i_a + i_b + i_c) + u_{sb}(i_a + i_b + i_c) + u_{sc}(i_a + i_b + i_c)
$$

Substitute (5) with (2) we get

$$
\frac{du_{dc}(t)}{dt} = k\frac{C_{dc}}{i}(i_a\sin(\omega t - \delta) + i_b\sin(\omega t - 2\pi/3 - \delta) + i_c\sin(\omega t + 2\pi/3 - \delta))
$$

Based on (4) and (6), the mathematical model of STATCOM in the $d-q$ reference frame can be obtained as follows:

$$
\begin{bmatrix}
    \frac{d}{dt}i_d \\
    \frac{d}{dt}i_q
\end{bmatrix} =
\begin{bmatrix}
    -\frac{R}{L} & \omega \\
    -\omega & -\frac{R}{L} + \frac{K_{\text{ssr}}}{L}\cos\delta
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} +
\frac{3K_{\text{ssr}}}{2L}\sin\delta
\begin{bmatrix}
    0 \\
    0
\end{bmatrix}
$$

According to the theory of instantaneous reactive power, the instantaneous active power $P_s$ and reactive power $Q_s$ injected into the AC system by STATCOM are

$$
\begin{align*}
    P_s &= \frac{3}{2}\left[u_{dc}i_d + u_{dc}i_q\right] \\
    Q_s &= \frac{3}{2}\left[u_{dc}\overline{i_d} + u_{dc}\overline{i_q}\right]
\end{align*}
$$

3.2 STATCOM controller

STATCOM is capable of generating or absorbing reactive power. The interaction between the AC system voltage and the STATCOM-produced output voltage provides the control of reactive power flow [16]. Hence, the specific parameters of an electric power system such as voltage can be controlled by varying the output of reactive power [17].

The STATCOM main task is to control the voltage at the connection point to be within the permissible limits. It is also expected to mitigate SSR by adding an auxiliary SSR damping (SSRD) controller to the original control strategy. The proposed control strategy of STATCOM is shown in Fig. 3. Decoupled $d-q$ current control [18] is adopted as the basic framework of the controller. The $d$-axis controls aim at controlling the DC voltage, and $q$-axis aims to regulate the reactive power. The auxiliary SSRD controller is added to the inner current controller.

The configuration of the SSRD controller is shown in Fig. 4. It consists of a low-pass filter, a high-pass filter, a gain block, and a limiter. $I_{\text{rms}}$ denotes the RMS value of the line current, which is adopted as the feedback input signal. The gain $K_{\text{ssr}}$ is adopted to achieve the desired damping.
In this paper, the low-pass filter is applied in conjunction with the high-pass filter to extract the control signal, so that SSR over a wide frequency range can be mitigated. The low-pass filter is used to filter the harmonic component with a cut-off frequency of 100 Hz. The high-pass filter is used to eliminate the effect of the SSRD controller on the steady-state operating condition with a cut-off frequency of 10 Hz. The output of the SSRD controller is used to modulate the reference settings of STATCOM in order to provide the effective damping of SSR.

4 Electromagnetic transient simulation

To verify the effectiveness of the STATCOM proposed controller in damping SSR, the studied system as shown in Fig. 1 is simulated in an electromagnetic transient simulation programme PSCAD/EMTDC. In the simulation, a fixed series compensation capacitor is put into operation at 10 s. For better comparison, the results of the simulation with and without STATCOM are presented in the same figure. The study is performed for the compensation of 60, 70, and 80%.

4.1 60% series compensation

Fig. 5 shows the dynamic response of the studied system connected to 60% series-compensated line. For 60% series compensation, the oscillation caused by the operation of the capacitor can eventually be stable. When the STATCOM is connected to the bus, the damping of the system significantly improves. The oscillation can be stabilised more quickly. Fig. 5c illustrates the output active power and reactive power of STATCOM. The STATCOM output power exchanged with the grid effectively regulates the AC system voltage.

4.2 70% series compensation

Fig. 6 shows the dynamic response of the studied system connected to 70% series-compensated line. Without the STATCOM, it is seen from Figs. 6a and b that the oscillations of the electromagnetic torque and the active power are damped slowly due to the damping in the system. However, the oscillations are reduced significantly when the STATCOM is connected to the bus. This reveals the capability of STATCOM in the mitigation of SSR.

4.3 80% series compensation

Fig. 7 shows the dynamic response of the studied system connected to 80% series-compensated line. For 80% series compensation, Figs. 7a and b illustrate the unstable electromagnetic torque and active power oscillations, respectively. However, with the STATCOM, all oscillations are stabilised successfully as shown in the same figures with solid lines. Fig. 7c presents the active power and reactive power injection by the STATCOM. During the operation of a fixed series compensation capacitor, STATCOM offers dynamic power support, which successfully maintains the stability of the system. Results show that the STATCOM can mitigate the SSR significantly, which demonstrates the effectiveness of the SSRD controller.

5 Conclusion

This paper investigates the potential SSR issue in DFIG-based wind farms connected to series-compensated lines. A STATCOM employed at the generation terminal is presented for mitigating SSR. For the sake of achieving the best damping performance of oscillations, an auxiliary SSR damping controller is designed and added suitably to the main control system of the STATCOM.
Simulation studies are conducted for different series compensation levels by PSCAD/EMTDC software. It is found that DFIG-based wind farms are susceptible to the potential of SSR with higher levels of series compensation. It is also observed that the STATCOM equipped with the proposed controller can mitigate the SSR effectively. Thus, in a practical power system, when a STATCOM already exists in the vicinity of the wind farm, its controller may be modified to alleviate the SSR issue.

6 References

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7 Appendix

Doubly fed induction generator data: 
\[ R_s = 0.00756 \text{ pu}, \quad X_s = 0.1425 \text{ pu}, \quad R_r = 0.00533 \text{ pu}, \quad X_r = 0.1425 \text{ pu}, \quad X_m = 2.1767 \text{ pu} \]

Electrical network data:
\[ ST_1 = 100 \text{ MVA}, \quad XT_1 = 0.0895 \text{ pu}, \quad ST_2 = 55 \text{ MVA}, \quad XT_2 = 0.12 \text{ pu}, \quad RL = 2 \Omega, \quad LL = 0.01 \text{ H} \]