Two methods for damping torsional vibrations in DFIG-based wind generators using power converters

Zuyi Zhao, Yupu Lu, Da Xie, Songtao Yu, Wangping Wu
1 Shanghai Jiaotong University, 200240, Shanghai, China

Email: feier199106@sjtu.edu.cn

Abstract. This paper proposes novel damping control algorithms by using static synchronous compensator (STATCOM) and energy storage system (ESS) to damp torsional vibrations in doubly fed induction generator (DFIG) based wind turbine systems. It first analyses the operating characteristics of STATCOM and ESS for regulating power variations to increase grid voltage stability. Then, new control strategies for STATCOM and ESS are introduced to damp the vibrations. It is followed by illustration of their effectiveness to damp the drive train torsional vibrations of wind turbines, which can be caused by grid disturbances, such as voltage sags and frequency fluctuations. Results suggest that STATCOM is a promising technology to mitigate the torsional vibrations caused by grid voltage sags. By contrast, the ESS connected to the point of common coupling (PCC) of wind turbine systems shows even obvious advantages because of its capability of absorbing/releasing both active and reactive power. It can thus be concluded that STATCOM is useful for stabilizing power system voltage fluctuations, and ESS is more effective both in regulating PCC voltage fluctuations and damping torsional vibrations caused by grid voltage frequency fluctuations.

1. Introduction

Due to the increasing environmental concerns regarding to electricity generation, wind energy has gained worldwide attention and taken up a big proportion in energy mix globally [1]. Among various types of wind turbines, variable speed turbines equipped with doubly fed induction generators (DFIGs) have attracted extraordinary attention because of their advantages over other wind turbines. One is that their power converters only need be rated to handle a fraction of the total DFIG power in order to achieve full control, normally below one-third [2][3]. Since a DFIG includes a wound rotor induction generator supplied on the stator side by the grid connection, grid faults such as voltage sags and frequency fluctuations can excite low frequency torsional oscillations of the mechanical components of DFIG-based wind generators. It can fatally result in electric torque ripples as well as shaft torsional oscillations [4]. Moreover, shaft torsional oscillations may cause a considerable reduction in the fatigue life of the shaft system. Therefore, it is extremely important to investigate the torsional vibrations of DFIG in order to improve the fatigue life of systems and ensure reliable wind energy integration.

Static Synchronous Compensator (STATCOM) is a shunt connected flexible AC transmission system (FACTS) device, which is commonly utilized in transmission systems to overcome the limitations of transmission distance [5]. A comprehensive study was conducted in [6] to investigate how STATCOMs could improve the steady-state stability and dynamic properties of wind farms. It is found that they are able to enhance their low-voltage ride-through capability [7] and improve transient voltage stability during grid disturbances [8]. It is also concluded that suitable controllers of STATCOM can provide auxiliary damping during power system oscillations in a series of compensated wind parks [9]. Because of its capability to increase voltage stability margins, STATCOM is a promising solution to mitigate torsional vibrations in wind turbine shafts, particularly during grid voltage disturbances. However, due to low capability of active power output, the performance of
STATCOM can be compromised when applied to wind farms with active power oscillation or bus frequency fluctuations.

Early research has shown that battery storage shunts connected to a wind energy system can avoid the dramatically change of generator voltage and rectifier voltage to a wind gust [10], [11]. Energy Storage System (ESS) is commonly installed within an electricity system to absorb the excess generation or to meet peak loads [12]. Currently, Battery Energy Storage System (BESS) is one of the most used storage technologies on the market [13], which is also employed in this paper. It has been reported that ESS can greatly contribute to improving the power quality and stability margin of a wind farm [14], [15]. Nevertheless, little research has addressed the contributions of ESS to torsional vibrations in the drive-train shaft of a wind turbine system.

In order to fill the research gap, this paper introduces the mathematic model and control strategy of the DFIG system. The principle of STATCOM is analyzed to damp the torsional vibrations. A new damping control algorithm is developed for ESS to deal with torsional vibrations caused by both voltages sags and frequency deviations. The real-time simulation implemented in Matlab/Simulink is conducted to verify the proposed damping strategy. The major contribution of this paper is: i) a model of DFIG-based wind generator suitable for torsional vibrations modeled; ii) a wind turbine equipped with STATCOM to damp torsional vibration caused by voltage fluctuations; iii) a new damping control algorithm for ESS to mitigate torsional vibrations caused by both voltage and frequency fluctuations.

This paper is organized as follows. Section 2 illustrates the principle of STATCOM to damp the torsional vibrations caused by voltage fluctuations. Section 3 introduces the model of ESS and proposes the novel control strategy of vibration damping. The case study in Section 4 shows the damping efficacy of STATCOM for torsional vibrations caused by voltage sags. Finally, conclusions are drawn in Section 5.

2. Torsional damping using STATCOM

The STATCOM is a shunt-connected FACTS device to regulate the voltage at the point of common coupling (PCC) by absorbing or generating reactive power to the grid. It works as a voltage source converter and generates a set of balanced three-phase sinusoidal voltages with rapidly controllable amplitude and phase angle.

![Figure 1. Schematic diagram of STATCOM system connected to the grid](image)

Figure 1 shows the diagram of a STATCOM system connected to the grid, where $U_s$ is the PCC voltage, $U_i$ is the output voltage of the STATCOM, and $i_e$ is the current through the transmission line. In normal conditions, the STATCOM output voltage $U_s$ is synchronous with $U_i$ under voltage control. By neglecting the resistor $R_c$ of the transmission line, the current $i_e$ and the reactive power $Q_c$ exchanged between STATCOM and the grid are

$$i_e = \frac{U_i - U_s}{jX_c} = -j \frac{U_i - U_s}{X_c}$$

$$Q_c = \text{Im}\{i_e^*\} = \frac{1}{2} \frac{U_i (U_i - U_s)}{X_c}$$

Therefore, when $U_s$ is lower than the PCC voltage $U_i$, the STATCOM acts as an inductance, absorbing reactive power from the grid. When $U_s$ is higher than $U_i$, the STATCOM works as a capacitor generating reactive power to the grid. In steady state, the PCC voltage always leads the output voltage of STATCOM by a small angle to supply the active power consumed due to inverter losses.
In this paper, the control objective of the STATCOM is to support the PCC voltage of wind turbine systems during grid voltage sags, which contributes to torsional vibration damping. The control loops have two objectives: 1) the q-axis loop consisting of an inner current-control loop and an outer voltage-control loop is to achieve flexible output voltage of DFIG; 2) the d-axis loop is to keep the dc-link voltage constant. The control block ensures the stable regulation of the voltages of PCC and dc link.

3. Torsional Damping Using ESS

ESS able to supply active power to the grid and active power modulation is an advantage to introduce additional damping to torsional vibration caused by frequency fluctuation of grid voltage and load variations.

Battery is considered to have high energy density and is a very promising option to realize energy storage system. The diagram of the proposed energy storage system is shown in Figure 2, which consists of two individual power electronic converters. The bidirectional DC/DC converter and PWM converter are required to link the battery and the PCC through coupled inductor to make the system more compact and cost efficient. The two-stage converter device is the key component of ESS to increase grid frequency/voltage stability by absorbing or generating required active/reactive power. The DC/DC converter is responsible to boost the battery voltage and control the delivered or absorbed power, while the PWM converter is used for power factor correction.

![Figure 2. Diagram of Energy Storage System connected to the grid](image)

Figure 2 graphically shows the relationship between the PCC voltage \( \hat{U}_t \), the ESS output voltage \( \hat{U}_E \), and ESS input current \( \hat{I}_E \). The PCC voltage \( \hat{U}_t \) leads \( \hat{U}_E \) by \( \delta \) determined by the output power of the ESS. The relationship between \( \hat{U}_E \) and the PCC voltage \( \hat{U}_t \) is

\[
\hat{U}_E + jX_E \hat{I}_E = \hat{U}_t \tag{2}
\]

Figure 3. Phasor diagram of the operating principle of ESS

The ESS input current \( \hat{I}_E \), which lags the PCC voltage by \( \theta \), is decomposed into two components: \( \hat{i}_{Ed} \) in phase with the PCC voltage \( \hat{U}_t \) and \( \hat{i}_{Eq} \) in quadrature. The active and reactive power interchanges with the grid are also decoupled and controlled by \( \hat{i}_{Ed} \) and \( \hat{i}_{Eq} \), which are

\[
P_E = u_i \hat{i}_{Ed} = u_i \hat{I}_t \cos \theta = \frac{u_i \hat{U}_E}{X_E} \sin \delta
\]

\[
Q_E = u_i \hat{i}_{Eq} = u_i \hat{I}_t \sin \theta = \frac{u_i \left( \hat{U}_t - u_i \hat{U}_E \cos \delta \right)}{X_E}
\tag{3}
\]

When \( \hat{U}_E \) lags the PCC voltage \( \hat{U}_t \), i.e., \( \delta > 0 \), the ESS acts as load absorbing active power from the grid. Under this condition, the PWM converter works in rectification mode and charges batteries through the DC/DC
converter working in buck mode. When \( \dot{U}_E \) leads the PCC voltage \( \dot{U}_t \), i.e., \( \delta > 0 \), the ESS acts as a voltage source generating active power to the grid. Under this condition, the batteries discharge to the grid through the two-stage converter device. The DC/DC converter works in boost mode and the PWM converter works in inverter mode. Similarly, the reactive power exchange between the ESS and the grid can be calculated according to the relationship between \( u_t \) and \( u_e \cos \delta \). Therefore, the two-stage converter device can be controlled to realize operation in four-quadrant, and absorbs or generates the desired active/reactive power by adjusting the ESS output voltage \( \dot{U}_E \).

![Figure 4. Circuit configuration of ESS](image)

Figure 4 shows the circuit configuration of ESS. The DC/DC converter works in boost/buck mode by controlling the boost switch \( S_d \) and the buck switch \( S_u \). In boost mode, the switch \( S_d \) is pulse modulated width and the switch \( S_u \) is always in off state. In buck mode, the switch \( S_u \) is pulse modulated width and the switch \( S_d \) is always in off state. The DC/DC converter is to keep the dc-link voltage constant, provided by the capacitor \( C_{dc} \). The PWM converter is to achieve independent control of the active and reactive power exchanged between ESS and the grid. The instantaneous three-phase \( i_{abc} \) currents are sampled and transformed to d-q components \( i_{Ed} \) and \( i_{Eq} \). The voltage balance across the inductors in voltage vector oriented d-q frame is

\[
\begin{align*}
    u_{Ed} &= u_{Ed} + \alpha L_E i_{Eq} \frac{d i_{Ed}}{dt} + R_E i_{Ed} \\
    u_{Eq} &= u_{Eq} - \alpha L_E i_{Ed} \frac{d i_{Eq}}{dt} + R_E i_{Eq}
\end{align*}
\]

(4)

The DC/DC converter control loop consisting of an inner current-control loop and an outer voltage-control loop keeps the dc-link voltage constant. The control loops of PWM converter have two objectives: 1) the q-axis loop with inner current-control loop and outer voltage-control loop achieves flexible regulation of the PCC voltage; and 2) the d-axis loop regulates active power exchange between ESS and the grid according to the frequency fluctuations of infinite bus voltage. Therefore, the control block ensures the regulation of the PCC voltage and the required active power due to frequency fluctuations.

The advantages of ESS operation are that it is: 1) able to support PCC voltage during grid voltage sags, which contributes to the damping of torsional vibrations; and 2) expected to damp the torsional vibrations caused by frequency fluctuations in the power network by absorbing or generating active power during transient state.

4. Torsional Damping Using ESS

4.1. Simulation results of STATCOM control

Grid faults, such as voltage sags and frequency fluctuations, even if far away from the location of the wind turbine system may cause torsional vibrations in the drive train. In order to test the performance of the proposed damping approach, a wind turbine equipped with STATCOM has been modeled and simulated in the Matlab/Simulink, as shown in Figure 5. The objective of the wind turbine system is to enhance the capability of the wind turbine to ride through transient voltage sags in the grid. The STATCOM employs a 7-level series H-
bridge topology. The PCC of the wind turbine connects to an infinite bus of 10kV through a 10km-long transmission line. In this case, voltage sags occurring at the infinite bus are treated as small electric disturbances to excite torsional vibrations of the drive train.

**Figure 5.** Simulink diagram of wind turbine system equipped with STATCOM

The case of a three-phase grid voltage sag is taken into consideration. The voltage command of the infinite bus is step changed from 1.0 p.u. to 0.92 p.u. at \( t=1 \) s and back to 1.0 p.u. at \( t=1.1 \) s. Figure 6(a) shows the waveforms of the voltages of PCC and infinite bus. Figure 6(b) shows the waveforms of current outputs of the wind turbine and STATCOM, and reactive power exchange between the STATCOM and the grid. At beginning, the system operates in normal state and the STATCOM neither absorbs nor provides reactive power to the grid. At \( t=1 \) s, the infinite bus voltage is decreased by 7% and the STATCOM current increases to compensate the voltage decrease by generating reactive power. The PCC voltage maintains at the normal level, as shown in Figure 6. At \( t=1.1 \) s, the infinite bus voltage comes back to the normal state and the corresponding reactive power drops to zero. It indicates the dependence of the PCC voltage on the voltage variation at the infinite bus due to the reactive power generated from the STATCOM.

**Figure 6.** PCC voltage Reactive and power output of STATCOM during during grid voltage sags

Figure 7 shows the low speed shaft torque \( T_{ls} \) and the wind turbine angle speed \( \omega_{rot} \) response with and without the STATCOM. The red curves denote the case without the STATCOM. The vibrations last over 4 s for both low speed shaft torque and wind turbine angle speed. The black curves representing the system equipped with STATCOM present better damping feature, where the torsional vibrations are damped effectively and rapidly in 1 s.

**Figure 7.** Low speed shaft torque and generator speed during grid voltage sag

4.2. *Simulation results of ESS control*
In order to test the performance of the proposed approach, the wind turbine system with ESS has been modeled and simulated in the Matlab/Simulink, shown in Figure 8.

**Figure 8.** Simulink models of wind turbine system equipped with ESS

**Figure 9.** Response of ESS on grid voltage sags

**Figure 10.** Torsional vibration damping effect due to reactive power output

4.2.1. Simulation analysis of voltage sags In the case of voltage sags, the voltage command of the infinite bus is step changed from 1.0 p.u. to 0.92 p.u. at $t=1.2$ s and back to 1.0 p.u. at $t=1.3$ s.
Figure 9 shows the response of ESS on the variations of infinite bus voltage. The battery output current $i_L$ is constant during the voltage vibrations, which suggests that the voltage sags have no effect on active power exchange between the ESS and the grid. The ESS output current $i_o$ increases to generate desired reactive power compensation for the PCC voltage sags, as shown in Figure 10. Initially, the ESS neither absorbs nor provides reactive power to the grid. At $t=1.2$ s, the infinite bus voltage is decreased by 8% and the ESS compensates the voltage decrease by generating reactive power $Q_{ess}$. At $t=1.3$ s, the infinite bus voltage is step changed back to the normal state and the corresponding reactive power drops to zero. Figure 10 shows the low speed shaft torque $T_{ls}$ response with and without the ESS. Without ESS, the vibration lasts over 2 s in low speed shaft torque, whereas the system with ESS is able to damp the torsional vibrations effectively and rapidly within 0.5 s.

### 4.2.2. Simulation analysis of voltage frequency decrease

The capability of the ESS in damping torsional vibrations caused by grid voltage frequency fluctuations is observed under conditions of frequency step changes. In the case of grid voltage frequency decrease, the frequency command of the infinite bus is step changed from 1.0 p.u. to 0.96 p.u. at $t=1$ s and back to 1.0 p.u. at $t=1.2$ s. Figure 11 shows response of ESS on variation of the infinite bus voltage. Initially, the ESS neither absorbs nor provides active/reactive power to the grid. The ESS output current $i_o$ increases to generate desired active power to compensate the frequency decrease.

Correspondingly, the batteries discharge to keep the dc-link voltage constant during the vibration. Figure 12 shows the low speed shaft torque $T_{ls}$ response with and without the ESS. Without ESS, the vibration lasts over 2 s in low speed shaft torque, whereas the system with ESS is able to damp the torsional vibrations effectively and rapidly within 0.5 s. However, due to the features of the wind turbine, there is no droop characteristic relationship between system frequency and active power. The ESS has no contribution to regulating the frequency of the PCC voltage.

Moreover, the stator active power $P_1$ is illustrated in Figure 13 to verify the effectiveness of the proposed control approach. For the system without ESS, the power oscillation can be seen due to the torsional vibrations in the drive train, whereas in the case of system equipped with ESS, the power vibrations have been effectively suppressed.

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**Figure 11.** Response of ESS on voltage frequency decrease

**Figure 12.** Torsional damping effect for bus frequency decrease
4.2.3. Simulation analysis of voltage frequency increase  Figure 14 shows the response of ESS on variations of the infinite bus voltage.

Initially, the ESS neither absorbs nor provides active/reactive power to the grid. Its output current $i_o$ increases to absorb active power due to the frequency decrease. Thus, the batteries charge from the capacitor to keep the dc-link voltage constant during the vibration. Figure 15 shows the low speed shaft torque $T_{fss}$ response with and without the ESS. In the case without ESS, the vibration lasts over 2 s in low speed shaft torque, whereas the system with ESS is able to damp the torsional vibrations effectively and rapidly within 0.5 s. Similarly, the ESS has no contribution to regulating the frequency of the PCC voltage.

5. Conclusions
This paper has proposed novel methods to damp the drive train torsional vibrations in a wind turbine system, based on STATCOM and ESS, respectively. The damping control scheme of ESS, including the bidirectional DC/DC converter and PWM inverter, has been proposed as well. Simulation results have shown that the STATCOM is a promising solution to suppress the torsional vibrations by stabilizing the bus voltage of wind
systems. Further, ESS making use of the bidirectional DC/DC converter and PWM converter is able to meet the bidirectional active/reactive power demand. Case studies revealed that ESS presents superiority performance over STATCOM on damping torsional vibrations caused by grid voltage sags and is especially irreplaceable for those caused by frequency disturbances.

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