Mitigation Sub synchronous Resonance and Improvement Low-Voltage Ride-Through Capability of Series Compensated Doubly-Fed Induction Machine Based Wind Farms by Using Bridge-Type Solid-State FCL

Abstract. Series-Capacitor compensation approach is widely used in transmission lines to expand the active power capacity of transmission lines. They provides a practical solution for Connection large-scale wind farms (WFs) to grid in order to transmit the wind power to grids in long distance load centres. Integration large-scale WFs to power system may lead to sub synchronously resonance (SSR) phenomenon and low-voltage ride through (LVRT) challenges in WFs connected through series capacitive compensated transmission lines. This paper suggest the employment of bridge-type solid-state fault current limiter (BSFCL) for damping the SSR and enhancing the LVRT performance of series capacitive compensated WFs integrated to power system. The WF modelled in this study is an aggregated doubly fed induction machine (DFIM). The first standard benchmark IEEE system is modified and is simulated in PSCAD/EMTDC software to show the BSFCL capability for damping the SSR and improving the LVRT requirements of WFs in this paper. Considering simulation results, it is found that the BSFCL effectively mitigates the SSR oscillations and fulfills the LVRT requirement of series capacitive compensated WF integrated to power system.

Introduction

Escalating the contribution and transmission of wind-power are two main challenges of WFs connected to power grid. Generally, WFs are far from load centres and require long transmission lines to transmit the wind power to them. Compensation transmission line by series capacitors is a practical approach to increase the transmission lines power transfer capacity for long distance [1]. However, the application of series capacitors may causes to occur the sub-synchronous resonance (SSR) in WFs [2]. In addition, using the series capacitor reduces the transmission impedance and cause to increase the WF fault current during short-circuit faults [1-2]. SSR in WFs cause to increase the energy exchange with power system and generator shaft at one or more sub synchronous frequencies, which may load to failure of wind turbines and subsequently disconnection from power system unlike the WF integration grid codes. Based on the LVRT requirements, WFs must remain in-service in during different faults to guarantee the power system stability [3]. SSR events in WFs are classified in to self-excitation and transient SSR events. The details of both SSR events are presented in references [2-3].

In 2009, large number wind turbines of WFs were destroyed due to a SSR incident in southern Texas. USA [4]. In 2012, this phenomenon was repeated at the WF in the Guyuan area of China. In 2017 from August to October, three SSR circumstances were occurred in Texas, USA. All of these were occurred in the DFIM-based series compensated WFs connected to power systems.

There are two approaches to mitigate the SSR in DFIM-based WFs including using the hardware additional flexible AC transmission systems (FACTs) devices and the software modification control of DFIM converters [5]. Application of different types of shunt and series FACTs devices is the prominent approach to control the SSR events in WFs [4-5]. In [5]-[6], the static VAR compensator (SVC) is used to mitigate the SSR in WFs. In [7], the authors of ref [8], a damping controller has been proposed and incorporate to the GCSC to control the SSR events in WFs. In general, the fuzzy-logic controller (FLC) method is used to obtain the different gains of GSCS supplementary damping controller to increase the active power capacity of transmission lines and suppress the SSR events simultaneously. In [10], the unified power flow controller (UPFC) is used for controlling the SSR in series-capacitor compensated WFs.

In [13], a new supplementary damping controller has been designed to integrate the thyristor controlled series capacitor (TCSC). This approach provides an efficient result for reducing the SSR phenomenon. In [14], the performance of TCSC and SVC for suppressing the SSR oscillations...
SSR events have been compared. Simulation results were shown that the application of TCSC in WF is efficient for controlling the SSR. In [15], the static-synchronous compensator (STATCOM) is another FACTS controller, which has been used for damping the SSR in series compensated WFs. In [16], a supplementary -damping controller was designed to integrate the STATCOM for SSR mitigating. Reference [17], the static-synchronous series compensator (SSSC) with an auxiliary SSR damping controller is suggested to damp the SSR in WFs. In [18], Bypass filters are used for damping the SSR in WFs.

To present the BSFCL capability for damping the SSR in WFs, the first standard benchmark IEEE system has been modified according to Fig. 1. The specifications of this system are presented in Table 1. The grid voltage sag and remain connected under fault conditions [21]. In researches, the application of FCLs has been recognized as an efficient approach to overcome these challenges [22]. The applications of FCLs, not only reduces the WFs fault current contribution, but also reduces the WF connecting point voltage. This characteristics of FCLs effectively fulfills the LVTR requirement of WFs [23]. Generally, FCLs are classified into solid-state type [24-25], superconducting type [26] and LC series [27], and parallel resonance type, which are used in both DC and AC grids [29]. BSFCLs incorporated by DC reactors are promising solution and getting more acceptance for installation in WFs [30]. It can provide a controllable impedance for connection WFs to AC grid.

Considering the mentioned background, this paper uses the BSFCL for mitigating the SSR in the series-capacitor compensated doubly fed induction machine (DFIM)-based WFs. To verify the performance of BSFCL for mitigating the SSR in DFIM-based WFs, the PSCAD/EMTDC software is used.

**Studied System Model**

To present the BSFCL capability for damping the SSR in WFs, the first standard benchmark IEEE system has been modified according to Fig. 1. The simulated WF in this study includes 100*2MW, which is modelled by an aggregated DFIM driven by a 200MW wind turbine. The studied WF is incorporate to the grid through a compensated single transmission-line by series capacitor and the BSFCL. The grid is modelled by Thévenin equivalent circuit model transmission-line by series capacitor and the SBFCL. The ratio of X and R 5.

<table>
<thead>
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<th>Parameters</th>
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<td>Rated Voltage</td>
<td>230 kV</td>
<td>Rated Frequency</td>
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<td>The ratio of X and R</td>
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<tr>
<td>Induction Generator</td>
<td>Active power</td>
<td>2MW</td>
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<td>Resistance of stator</td>
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<td>Transmission Lines</td>
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**DFIM-based Model**

Fig. 2(a) shows different components of a DFIM type wind turbine. It includes an induction machine with wounded rotor configuration, two converters including the rotor side converter (RSC) and grid side converter (GSC). DC link capacitor and a wind turbine to drive the DFIM. According to the DFIM control system presented in Fig. 2(b), the RSC controls the output active power and reactive power of the DFIM through \( i_{qr} \) and \( i_{qs} \), respectively. \( i_{qs} \) and \( i_{qr} \) are q-axis and d-axis components of the rotor currents. Also, the GSC control system regulates the DC link and PCC voltages in reference values. It is achieved this objective by \( i_{qs} \) and \( i_{qr} \), respectively. \( i_{qs} \) and \( i_{qr} \) are the q-axis and d-axis components of the stator currents [31-32]. The DFIM equivalent circuit is presented in Fig. 2. Equations (1)-(4) present the d-axis and q-axis components of the flux, and voltage equations of DFIM in the dq synchronous-reference frame as follows:

1. \( V_{dqs} = R_{sidqs} + \frac{d\lambda_{dqs}}{dt} - \omega L_{midqs} i_{dr} \)
2. \( V_{dqr} = R_{sdr} i_{dqr} + \frac{d\lambda_{dqr}}{dt} - \omega L_{midqr} i_{dq} \)
3. \( \lambda_{dqr} = L_{midqr} i_{dqr} + L_{rmi} i_{dq} \)
4. \( \lambda_{dqs} = L_{midqs} i_{dqs} + L_{rmi} i_{ds} \)

![Fig. 1. Study modified IEEE first benchmark-system](image)

![Fig. 2. DFIM, (a) power circuit, (b) Equivalent circuit and control system](image)
In (1)-(4), \( L_s = L_sL_m/(L_s+L_m) \) and \( L_r = L_rL_m/(L_r+L_m) \); \( \omega_r \) and \( \omega_p \) are angular frequencies of the rotor and grid, respectively. Equations (5) and (6) present the dynamic equations of GSC and DC link as follows:

\[
\begin{align*}
V_{ds} &= V_{dgs} + R_d\frac{d}{dt}i_{dgs} + L_d\frac{di_{dgs}}{dt} + \alpha_3L_gi_{dgs}d\theta_d
\end{align*}
\]

and

\[
\begin{align*}
V_{ac} &= P_r - P_{loss}
\end{align*}
\]

where, \( P_r \) and \( Q_r \) are:

\[
\begin{align*}
P_r &= \frac{1}{2}V_{qsi}i_q + V_{ds}i_d
\end{align*}
\]

\[
\begin{align*}
P_s &= \frac{1}{2}V_{qsi}i_q + V_{ds}i_d
\end{align*}
\]

The DFIM output active and reactive powers are expressed as follows:

\[
\begin{align*}
P_s &= \frac{1}{2}V_{qsi}i_q + V_{ds}i_d
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\begin{align*}
Q_s &= \frac{1}{2}V_{qsi}i_q + V_{ds}i_d
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Wind Turbine Model

To study the dynamic performance of wind turbine drive-train system, the two-mass shaft model is utilized from the PSCAD/EMTDC software library. The two-mass turbine train system, the two-mass shaft model is utilized from the.

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Bridge-Type Solid-Sate FCL (BSFCL)

Fig. 4 demonstrates the circuit configuration of the BSFCL, which are composed by following parts:

1. A diode-bridge rectifier circuit contains \( D_1-D_4 \)
2. An IGBT semiconductor switch (T)
3. A DC reactor to suppresses the instantaneous over current and the \( \frac{dv}{dt} \) in bridge circuit to protect the semiconductor switches
4. A limiting-resistor (R) and,
5. A single-phase coupling transformer.

As shown in Fig. 4, the parallel limiting-resistor (R) and IGBT switch (T) in series with the DC reactor. The DC reactor in this figure is modeled by rd and Ld. They represent the resistance and inductance of DC reactor.

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degree, which is defined as \( k = X_C/X_L \). Due to a small disturbance in grid side, it may cause the currents of frequency \( f_n \) to pass through the stator circuit. They can lead to a magnetic-flux of frequency \( 2\pi f_n \) in the DFIM. This rotating-field induces currents in rotor circuit at following frequency:

\[
f_r = f_0 - f_n
\]

Fig. 5. Equivalent circuit in normal condition, (a) positive-half cycle, (b) negative-half cycle

Fig. 6. Equivalent circuit in fault condition, (a) positive-half cycle, (b) negative-half cycle

The speed of magnetic field is slower than the electrical speed of rotor. Therefore, \( f_r \) would be negative and would result in the negative equivalent rotor resistance. If this the sum of the DFIM and grid resistance becomes less than the negative resistance, it can lead to the SSR. The SSR phenomena in WFs are classified in two aspects including torque amplification (TA) and self-excitation (SE). The SE phenomena is occurred under steady-state grid condition. The TA occurs due to short-circuit faults or during switching in grid side.

Simulation Study

To validate the proposed BSFCL capability to damp the SSR in WFs and transmit the max wind power, the system demonstrated in Fig. 4 is utilized. It is modelled and simulated by PSCAD/EMTDC. To capture rated power, the wind speed is regulated at 14m/s. To validate the effectiveness of the BSFCL for SSR damping two different scenarios has been simulated in this study. In scenario 1, the compensation degree is increased from 20% to 70% under steady-state condition. In scenario 2, the compensation degree is set to 50% and a 3-LG fault is simulated in the study system at \( t=15s \) and then is cleared after 0.15s. All simulations for both scenarios are made for cases 1 and 2 as follows:

Case 1: No FCL applied to system
Case 2: By using BSFCL

Scenario 1: Increasing Compensation degree

In this scenario to show the BSFCL performance to damp the SSR, the output power and series compensation level of the WF are adjusted in \( P=200MV \) and \( k=20\% \). The practical compensation level is limited to 70-75\% [37]. In this scenario, the compensation level is changed from 20\% to 70\% at \( t=1s \). Fig. 9 demonstrates the WF response in scenario 1. Fig. 9(a) demonstrates the output power oscillations for both cases. It is shown that, there are no oscillations for output power in case 2 by using BSFCL unlike case 1. Fig 9(b) demonstrates the DFIM speed in response to increasing the compensation degree. It is observed from Fig. 9(b), the speed oscillations is effectively damped in case 2, however, the speed osilation is increased in case 1. Fig. 9(c) shows the DFIM torque due to increasing the compensation degree. It is shown that by increasing the compensation degree, the torque oscillation is increased in case 1. However, it is effectively damped in case 2. Fig. 9(d) presents the PCC voltage in this scenario. Considering this figure, the PCC voltage is oscillated by increasing the compensation degree in case 1. However, it is remain constant in case 2 by using the BSFCL. Fig. 10(a) and (b) demonstrates the line current in response to increasing the compensation degree for case1 and case 2, respectively. It is shown that, the line current is oscillated and increase. However, it is damped in case 2.

Fig. 8. (a) Compensated test-system, (b) equivalent circuit of test-system

Scenario 2: Using BSFCL
Scenario 2: 3LG Short Circuit Fault

In this scenario to investigate the BSFCL performance to enhance the LVRT and damp the SSR due TA,a 3LG fault is applied at t=10s to the study system shown in Fig. 2 and it is cleared after 0.15s. The output power and series compensation level of the WF are adjusted in P=200MV and k=50%. Also, the wind speed is regulated at 15m/s in this scenario. Fig. 11 demonstrates the WF response to 3LG fault in this scenario.

Fig. 11(a) demonstrates the output power of WF for both cases. It is shown that, the BSFCL effectively mitigate the output power oscillation in case 2. Fig. 11(b) shows the DFIM speed in response to 3LG fault. According to this figure, the speed oscillation is effectively damped in case 2. Fig. 11(c) shows the DFIM torque. It is shown that the BSFCL effectively mitigates the torque oscillation in case 2. Fig. 11(d) presents the PCC voltage in this scenario. As presented in this figure, the PCC voltage is reduced to 0.5 pu for both cases due to 3LG fault in study system. In case 1, the PCC voltage starts to oscillate and is damped for long time. In case 2, the PCC voltage recovers to pre-fault level without any oscillations after fault clearance.

Fig. 12(a) and (b) demonstrates the line current in response to 3LG fault for cases 1 and 2, respectively. It is shown that, the line current is oscillated and is increase in case 1. However, it is limited in case 2. Fig. 12(c) and (d) demonstrate the rotor current for cases 1 and 2, in this scenario. By comparing Fig. 12(c) and Fig. 12(d), the rotor current oscillation and over current effectively is damped in case 2.

Conclusion

This paper proposes the BSFCL application for damping the SSR oscillations due to IGE and TA and enhancing the LVRT capability of a series-capacitor compensated WF equipped with DFIM-based wind turbines. Considering simulation results, the BSFCL effectively mitigate the SSR oscillations in WF even without integration SSR-damping controller and operation of BSFCL control system. Also, it effectively limits fault currents in stator and rotor circuit of DFIM without any oscillation under 3LG fault. Also, It enhances the LVRT performance, when a large disturbance is occurred in the WF.
References


