Modal Analysis of DFIG-based Wind Farms Considering Converter Controllers

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Abstract—Wind power generations are now being installed widely in the power systems throughout the world. Due to the differences between conventional synchronous generators and doubly-fed induction generator (DFIG)–based wind farms (WFs), the impacts of WFs on power system stability should be investigated. In this paper, the impacts of DFIG-based WF on power system small signal stability are analyzed. The converter controllers are modeled and the effects of controller parameters on system dominant modes are studied in a single machine infinite bus (SMIB) system. The appropriate values for controller parameters are decided according to the eigenvalue analysis results. Besides, the impacts of shaft model and its parameters on dominant modes are evaluated.

Keywords—Doubly-fed induction generator, Power system small signal stability, Eigenvalue analysis.

I. INTRODUCTION

The document rate of rise of installed wind power generation capacity has been substantially increased worldwide. Compared to the other renewables, wind energy has received more attention with higher growth. The remarkable advancements which have been reached during the past decade in wind power generation technology along with the environmental issues pertaining to the fuel-consuming power plants have made the wind power one of the most economical resources for replacing the conventional power plants. Wind power integration, in turn, will introduce new issues to the existing power systems in several aspects, especially when the level of penetration is significant. Among these aspects, the system stability is from crucial importance. Conventional generators are generally synchronous machines with high inertia, coupled to the steam or hydro turbines. The reciprocal effects of these types of machines were broadly studied in detail [1]. Since the nature of the wind turbine generators (WTG) is basically different from the synchronous generators due to the power electronic interfaces and induction generators application, the well-known stability problems have to be investigated.

Several types of WTGs are commercially available today including: squirrel cage induction generators (SCIG), doubly-fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG). Two more general categories are fixed-speed and variable-speed turbines. The dominant technology today, however, is the DFIG.

Some research work has been conducted to study the stability issues corresponding to the WFs. In [2], an approach for sensitivity analysis of electromechanical modes (EMM) to the inertia of the generators is introduced and the results have shown both detrimental and beneficial impacts of increased DFIG penetration into the power system. Inter-area and local oscillations have been investigated in [3] in a test system; the results are reported for both the variable and fixed-speed turbines replacing the conventional generation units. It is shown that the damping of EMMs is improved as the level of penetration is increased. However, in the case of large amounts of installed WFs, there is a possibility for the inter-area modes to be adversely affected.

Different control strategies for DFIGs and their impacts on the system stability were investigated in [4]. It is shown that DFIGs operating in frequency control mode and the SCIGs could increase the eigenvalues damping.

Different control modes for DFIGs including VAR control mode, power factor control mode and voltage control mode were extensively analyzed in [5]. The impacts of DFIGs on the EMMs are demonstrated to be highly dependent on their control strategies. The authors in [6] have reported the likelihood of the contribution of DFIGs to the system damping with application of appropriate controllers.

Besides the mentioned studies, other related studies are also available in the literature with similar conclusions [7], [8]. All the aforementioned research was conducted with the assumption that wind speed is fixed. In other words, the simulations are performed for different WF capacities. It is, however, known that a WF output power may significantly alternate throughout a day; thus, affecting power system variables such as voltages and tie-line flows. Therefore, in this paper, the effects of changing WF output power (due to changing in wind speed) on system small signal stability are examined.

Modal analysis is carried out in [9] for DFIG-based WF and the impacts of system parameters, operating points and grid strengths are studied. However, the controllers for rotor-side and grid-side converters are not modeled which highly affect...
the results. The mentioned shortcoming is addressed in present study.

This paper is organized as follows: Section II describes the modeling procedure of WTG and introduces the test systems used in this work. Section III presents the results of small signal analysis in a SMIB system. The main findings of this paper are reported in Section IV.

II. WTG MODELING PROCEDURE

A WTG consists of blades, rotor shaft, gearbox, the induction generator and the interface with the network. The blades and gearbox are modeled as the mechanical part, which converts the wind energy into the mechanical torque applied to the induction generator. The power extracted from wind speed by the turbine is given by (1):

\[ P_m = c_p(\lambda, \beta) \frac{\rho A v^3}{2} \]

where \( P_m \) is the mechanical output power of the turbine (W), \( c_p \) is the performance coefficient of the turbine, \( \rho \) is the air density (kg/m\(^3\)), \( A \) is the turbine swap area (m\(^2\)), \( v \) is the wind speed (m/s), \( \lambda \) is the ratio of the rotor blade tip speed to wind speed and \( \beta \) is the blade pitch angle (deg). \( c_p \) is related to \( \lambda \) and \( \beta \) as:

\[ c_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda} - c_3 \beta - c_4 \right) e^{\lambda} + c_5 \lambda + c_6 \frac{1}{\lambda - 0.08 \beta - 0.035} (\beta + 1) \]  

Values of the parameters \( c_1 \) to \( c_6 \) are given in [10]. A typical turbine speed–output power characteristic, which is used in this study, is given in [11].

The generated power is then given to the generator through the shaft as the prime mover torque \( T_m \). It has been shown that the single mass model for the shaft is not suitable for stability studies in case of squirrel cage induction generator [12]. Therefore, the two-mass model shown in Fig. 1 is used. Considering this model, the following equations are derived for the motion of rotating mass:

\[ J_t \ddot{\theta}_t + D_{tg} \dot{\theta}_t + K_{tg} \theta_t = T_m + D_{tg} \dot{\theta}_g + K_{tg} \theta_g \]

\[ J_g \ddot{\theta}_g + D_{tg} \dot{\theta}_g + K_{tg} \theta_g = -T_e + D_{tg} \dot{\theta}_t + K_{tg} \theta_t \]

in which \( J_t \) and \( J_g \) are the turbine and generator moment of inertias; \( \theta_t \) and \( \theta_g \) are the angular displacement of turbine and generator; \( K_{tg} \) and \( D_{tg} \) are the shaft stiffness and mutual damping, respectively; and \( T_m \) and \( T_e \) are the mechanical and electrical torques, respectively.

A. Induction Machine Modeling

The asynchronous machine model is obtained from [13]. A 4th order model is used for the electrical part with equivalent circuit shown in Fig. 2. The electrical torque is calculated as:

\[ T_e = \frac{3}{2} \left( \frac{p}{2} \right) L_m (i_{qs}^r i_{dr}' - i_{ds} i_{qr}') \]

where \( p \) is the number of pole pairs.

B. DFIG Controllers

Figure 3 portrays the general structure of DFIG-based WTG. Two converters, namely the rotor-side converter (RSC) and the grid-side converter (GSC), are coupled through a DC capacitor.

With the aid of RSC, the frequency and magnitude of the injected voltage to the rotor windings are determined. The block diagram representation of the RSC and GSC controllers are shown in Fig. 4. The subscript gc refers to the GSC. All the regulators are proportional-integral (PI) controllers with constants \( K_g \) and \( K_i \). The switch shown in Fig. 4 for RSC is used to select between the VCM and VARCM. Details about the control system are given in [11], [14].

The GSC is able to absorb or generate reactive power and keep the DC bus voltage constant. Parameters used for aforementioned controllers are reported in Appendix.
The time constants of pitch angle controller are large compared to power system transient period and the wind speed is kept between the allowable values. Therefore, this controller is not modeled here.

C. Test System Description

A single machine infinite bus (SMIB) model is employed to study the WF regardless of the network. This system is shown in Fig. 5. All parameters are given in the figure and the WF parameters are given in Appendix. For simplicity, the aggregated model of small wind turbines in a WF is used here which does not affect the results [15]. The corresponding data for each WTG is given in Appendix.

III. SMALL SIGNAL STABILITY ANALYSIS

Small signal analysis is performed here using the concepts of linearizing the system equations at the operating point and eigenvalue analysis. The system equations are described in the following general form:

$$\dot{x} = f(x,z,u), \quad z = g(x,u) \quad (7)$$

where $x$, $z$ and $u$ are vectors of state variables, control output variables and input variables, respectively. After performing the linearization procedure around the current operating point, the following relation is derived [1]:

$$\Delta \dot{x} = A \Delta x + B \quad (8)$$

where $A$ is the system state matrix. This matrix is then used for calculating the system eigenvalues.

In the present work, the Linearization block in MATLAB/SIMULINK is used for calculating this matrix at the operating point. Considering the model described above for DFIG, the resulted state space model for the SMIB test case is an 18-variable system.

A 9 MW WF consisted of 6×1.5 MW turbines is assumed in the SMIB system. At the operating point given in Table 1, small signal analysis is carried out and the results are reported in Table 2. In this table, the following notations are used:

$\psi_{ds}, \psi_{dq}, \psi_{dr}, \psi_{d'q}$ : Rotor and stator fluxes on the $d$ and $q$ axis

$I_{d_GSC}, I_{q_GSC}$ : d and q axis components of grid-side current regulator

$I_{d_RSC}, I_{q_RSC}$ : d and q axis components of rotor-side current regulator

$RL_d, RL_q$ : d and q axis components of coupling inductor

$C_{DC_Bus}, V_{DC}$ : DC bus capacitor and voltage regulator

$P_{reg}$ : Active power regulator

$\omega_e, \omega_r, \theta_l$ : generator and turbine rotational speeds and
angular displacement

There are two dominant modes in this system, namely the mechanical mode \( (\lambda_{11}) \) and the electromechanical mode \( (\lambda_8) \). The impacts of the control system parameters on the system modes are studied in the next section.

A. Wind Speed

Variation of wind speed would change the generated power and thus the operating point of the system. Figure 7 shows the variation of the dominant eigenvalues by increasing the wind speed from 8 to 14 m/s. The electromechanical mode heads to the right, while the mechanical mode is not considerably affected.

B. Active Power Regulation

The active power regulator is a PI controller which determines the power delivered into the grid. The proportional gain is increased from 0.3 to 4.5 and the resulted eigenvalue trajectory is depicted in Fig. 8. The integral gain is also increased from 100 to 220 and Fig. 9 shows the results. It can be seen that increasing \( K_p \) has beneficial impacts while increasing \( K_i \) has detrimental effects.

C. Rotor-Side Current Regulator

Both the \( K_p \) and \( K_i \) for rotor-side current regulator are varied and only the electromechanical mode was influenced. This is depicted in Figs. 10 and 11. It is obvious that increasing \( K_p \) from 0.1 to 7 is of interest. Also, increasing \( K_i \) from 5 to 12 is beneficial. No significant impact on mechanical mode was observed.
select the mechanical parameters suitable for power system were studied. The results could be used for tuning the PI investigated. Modeling procedure for converter controllers would make the opposite impact, as shown in Fig. 12. Depicted in Fig. 13.

D. Mechanical Parameters

The mechanical part of the turbine is shown in Fig. 1. Increasing \( H_i \) would displace the mechanical mode toward lower stability and increasing \( H_g \) would do the same for electromechanical mode. On the other hand, increasing \( K_{tg} \) would make the opposite impact, as shown in Fig. 12.

Mutual damping \((D_{eg})\) increment has made beneficial impacts on both mechanical and electromechanical modes, as depicted in Fig. 13.

IV. Conclusion

Small disturbance stability of DFIG-based WFs was investigated. Modeling procedure for converter controllers was described. The impacts of changes in wind speed and influential controller parameters on dominant modes of DFIG were studied. The results could be used for tuning the PI controllers. In addition, the effects of shaft parameters were studied. The results can be used in manufacturing process to select the mechanical parameters suitable for power system stability.

APPENDIX

<p>| Induction Generator |<br />
|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>( P ) (MW)</th>
<th>( V ) (V)</th>
<th>( f ) (Hz)</th>
<th>( R_i )</th>
<th>( L_i )</th>
<th>( R_s' )</th>
<th>( L_s' )</th>
<th>( L_s )</th>
</tr>
</thead>
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<tr>
<td>1.5</td>
<td>575</td>
<td>60</td>
<td>0.00706</td>
<td>0.171</td>
<td>0.005</td>
<td>0.156</td>
<td>0.92</td>
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Turbine Shaft

<table>
<thead>
<tr>
<th>( H_i )</th>
<th>( D_{eg} )</th>
<th>( K_{tg} )</th>
<th>( H_g )</th>
<th>( V_{DC} ) (V)</th>
<th>( C_{DC}(mF) )</th>
<th>( R_{GS} )</th>
<th>( L_{GS} )</th>
</tr>
</thead>
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REFERENCES