Transient Behaviors of Full and Reduced Order Doubly Fed Induction Generator Models in a Grid Integrated Wind Farm

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Abstract

Accurate dynamic modeling is important in transient analysis of grid connected wind farm having doubly fed induction generators (DFIG). Transient events occurring in both distribution and transmission level of the grid affect the system dynamic behavior. In this study, the impact of these events was examined as DFIG was modeled based on Full Order Model (FOM) and Reduced Order Model (ROM). ROM neglects the stator flux derivation, and represents the stator as a voltage source behind a transient reactance. System modeling and simulations were carried out using MATLAB/SIMULINK. Two transient events were created, such as opening of breakers at medium and high voltage level, all for very short time. A comparison of system behaviors was drawn between FOM and ROM against these transient events. The comparison results show that the transient stability of the grid integrated wind farm is well-achieved for each event in the case of reduced order DFIG model.

Key words: FOM, ROM, DFIG, transient stability

1. Introduction

Renewable energy sources are accepted as an alternative to fossil fuels in power generation due to resultant high carbon emission and escalating fuel prices. Wind energy is the most popular renewable energy sources. Wind power plants can be either operated as stand-alone or integrated into the grid. Grid integration of large wind plants may result in some stability problems with the rising penetration of wind power into electricity networks, therefore more comprehensive analyses become essential to identify the interaction between the wind farm(s) and the power system. These require accurate models of doubly fed induction generator and their associated control and protection circuits. Dynamic modeling is crucial in handling transient events. Simplified accurate models may shorten the computation time. Studies realized in the literature investigate the impact of DFIG integration on the operation and control of the power system. The order of the generator model and the numerical integration methods are compared in [1-3]. Control schemes for variable speed turbines, using doubly-fed induction generators (DFIG), are described and simulated. Speed control characteristics and converter protection of the DFIG are implemented in the model. Refs. [4] and [5] propose a model for speed and pitch angle control when wind and rotor speed variations are significant. Equivalent wind turbine models are presented in [6], recommending those models be used for grid integration studies. Another study is conducted demonstrating that the integration of variable-speed wind systems with doubly fed induction generators (DFIGs) and a four-quadrant ac-to-ac converter connected to the rotor

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windings may increase the transient stability margin of the electrical grids [7]. Control strategy for wind plants is also important in grid integration studies. Regulating rotor current through a controlled voltage source representing the power converter may meet the command of real and reactive power production, where the voltage control strategy is essential. This coordinated voltage control strategy is taken into consideration in Refs. [8] and [9]. Another control strategy is developed in [10] providing a wind plant with the capability of short term frequency regulation. The system and controller parameters may substantially influence the system stability. The effects of turbine and system parameters on voltage stability are evaluated and discussed in Refs [11] and [12]. ROM and associated controls are developed and compared with detailed models in [13] and [14]. The steady state equivalent circuit and reduced order dynamic DFIG models are described in many studies. One of those [15] presents these models and shows how to implement them within power system dynamic simulation software. Power quality issues are also important in grid integrated wind plants. Steady state power quality impact is covered in [16] by measuring and analyzing flicker emission, harmonic emission and reactive power.

This study compares the transient behaviors of grid integrated DFIG with FOM and ROM. Impact of different models on grid connected wind power plant are examined against breaker openings. The simulation results are discussed to see the impact of models on various transient events.

2. Modeling of Wind Power Plant with DFIG

The generation system includes the induction generator and power converters. Rotor side and stator side power converters are given in this part before describing the full order and reduced order doubly fed induction generator models.

The rotor-side converter controller controls the output active power for tracking the input of the wind farm torque, and to maintain the output voltage to control regulating. The active power and voltage are controlled independently by v_{dr} and v_{qr} respectively. With the intermediate variables (x_1, x_2, x_3 and x_4), control equations are given by the following equations:

$$\frac{dx_1}{dt} = P_{ref1} + P_s \tag{1}$$

$$I_{qr\_ref1} = K_{p1}(P_{ref1} + P_s) + K_{i1}x_1 \tag{2}$$

$$\frac{dx_2}{dt} = I_{qr\_ref1} - I_{qr} = K_{p1}(P_{ref1} + P_s) + K_{i1}x_1 - I_{qr} \tag{3}$$

$$\frac{dx_3}{dt} = v_{s\_ref1} - v_s \tag{4}$$

$$I_{dr\_ref1} = K_{p3}(v_{s\_ref} + v_s) + K_{i1}x_3 \tag{5}$$

$$\frac{dx_4}{dt} = I_{dr\_ref1} - I_{dr} = K_{p3}(v_{s\_ref} - v_s) + K_{i3}x_{13} - I_{dr} \tag{6}$$

$$v_{qr} = K_{p2}(K_{p1}\Delta P + K_{i1}x_1 - I_{qr}) + K_{i2}x_2 + sw_sL_mI_{ds} + sw_sL_{rr}I_{qr} \tag{7}$$

$$v_{dr} = K_{p2}(K_{p3}\Delta v + K_{i3}x_3 - I_{dr}) + K_{i2}x_4 - sw_sL_mI_{qs} - sw_sL_{rr}I_{dr} \tag{8}$$

where K_{p1} and K_{i1} proportional and integrating gains of the power regulator, respectively; K_{p2} and

K_{i2} proportional and integrating gains of the rotor-side converter current regulator, respectively; K_{p3} and K_{i3} proportional and integrating gains of the grid voltage regulator, respectively; I_{dr_ref1} and I_{qr_ref1} current control references for the d and q axis components of the generator side converter, respectively; v_{s_ref1} specified output voltage reference; P_{ref1} active power control reference.

The grid-side converter controller maintains the DC link voltage and controls the terminal reactive power. With introducing the intermediate variables x_5, x_6 and x_7, the following equations can be obtained.

$$\frac{dx_5}{dt} = V_{dc\_ref1} - V_{dc} \tag{9}$$

$$I_{dgrid\_ref1} = -K_{pdgrid}\Delta v_{dc} + K_{1dgrid}x_5 \tag{10}$$

$$\frac{dx_6}{dt} = I_{dgrid\_ref1} - I_{dgrid} = -K_{pdgrid}\Delta v_{dc} + K_{1dgrid}x_5 - I_{dgrid} \tag{11}$$

$$\frac{dx_7}{dt} = I_{qgrid\_ref1} - I_{qgrid} \tag{12}$$

$$\Delta v_{dgrid} = K_{pgrid}\frac{dx_6}{dt} + K_{igrid}x_6 = K_{pgrid}(-K_{pdgrid}\Delta v_{dc} + K_{1dgrid}x_5 - I_{dgrid}) + K_{1grid}x_6 \tag{13}$$

$$\Delta v_{qgrid} = K_{pgrid}\frac{dx_7}{dt} + K_{igrid}x_7 = K_{pgrid}(I_{qgrid\_ref1} - I_{qgrid}) + K_{1grid}x_7 \tag{14}$$

where K_{pqgrid} and K_{idgrid} proportional and integrating gains of the DC bus voltage regulator, respectively; K_{pgrid} and K_{igrid} proportional and integrating gains of the grid-side converter current regulator, respectively; V_{dc_ref1} voltage control reference of the DC link; I_{qgrid_ref1} is the control reference for the q axis component of the grid-side converter current [14].

In modeling DFIG, the FOM is represented by five equations. d-q coordinate voltages of stator and rotor along with torque are given in equations (15)-(19) as follows:

$$v_{ds} = R_s i_{ds} - w_s\lambda_{qs} + \frac{d}{dt}\lambda_{ds} \tag{15}$$

$$v_{qs} = R_s i_{qs} + w_s\lambda_{ds} + \frac{d}{dt}\lambda_{qs} \tag{16}$$

$$v_{dr} = R_r i_{dr} + sw_s\lambda_{qr} + \frac{d}{dt}\lambda_{dr} \tag{17}$$

$$v_{qr} = R_r i_{qr} - sw_s\lambda_{dr} + \frac{d}{dt}\lambda_{qr} \tag{18}$$

$$M = \lambda_{ds}i_{qs} - \lambda_{qs}i_{ds} \tag{19}$$

Flux linkage inductance equations can be expressed in d-q coordinates as follows:

$$\lambda_{ds} = (L_s + L_m)i_{ds} + L_m i_{dr} \tag{20}$$

$$\lambda_{qs} = (L_s + L_m)i_{qs} + L_m i_{qr} \tag{21}$$

$$\lambda_{dr} = (L_r + L_m)i_{dr} + L_m i_{ds} \tag{22}$$

$$\lambda_{qr} = (L_r + L_m)i_{qr} + L_m i_{qs} \tag{23}$$

ROM of DFIG is employed to ease computation for transient analyses. In this model, a stator is represented by a transient voltage source behind a transient reactance where stator fluxes are neglected. The main idea is that the dc component is omitted from the stator transient current. Four electrical and one mechanical equations describing stator side and unchanged equations of rotor side in the ROM of the machine are given below [19];

$$v_{ds} = R_s i_{ds} - X^{'} i_{qs} + E_{ds} \tag{24}$$

$$v_{qs} = R_s i_{qs} + X^{'} i_{ds} + E_{qs} \tag{25}$$

$$\frac{dE_{ds}}{dt} = -\frac{1}{T_0}[E_{ds} - (X - X^{'})I_{qs}] + sw_s E_{qs} - w_s \frac{L_m}{L_m + L_s} v_{dr} \tag{26}$$

$$\frac{dE_{qs}}{dt} = -\frac{1}{T_0}[E_{qs} + (X - X^{'})I_{ds}] - sw_s E_{ds} + w_s \frac{L_m}{L_m + L_s} v_{qr} \tag{27}$$

$$v_{dr} = R_r i_{dr} + sw_s \lambda_{qr} + \frac{d}{dt}\lambda_{dr} \tag{28}$$

$$v_{qr} = R_r i_{qr} - sw_s \lambda_{dr} + \frac{d}{dt}\lambda_{qr} \tag{29}$$

$$M = E_{ds} i_{qs} + E_{qs} i_{qs} \tag{30}$$

Transient reactance of the model is expressed in equation (31), while transient open circuit time constant is given in equation (32)[20].

$$X^{'} = w_s (L_m + L_s - \frac{L_m^2}{L_m + L_r}) \tag{31}$$

$$T_0 = \frac{L_r + L_m}{R_r} = \frac{L_{rr}}{R_r} \tag{32}$$

3. Full Order Model and Reduced Order Model Controller

Control of the wind turbine consists of two parts: Mechanically turbine blade pitch angle control and electrically power converter control. Both mechanical and electrical control must be in collaboration for effective operation. Full order electrical and mechanical models of DFIG and control of the turbine are shown in Fig. 1, while reduced order models of DFIG are given in Fig. 1. As can be seen from those figures, slip and angular speed are used in current equations in addition to d-q axes voltage and current variable.

ROM is preferred in transient stability analyses due to retained several capabilities such as observing maximum current level which can be important for fault-ride-through performance [9]. While FOM is based on flux, ROM uses voltage source modeling as stator flux derivation is neglected in calculating d-q axes stator current, i_{ds} and i_{qs}. Stator currents are computed using FOM equations (15)-(16) and ROM equations (24), (25), (26), (27), and they are approximately related to rotor current according to (17), (18), (28) and (29). When the rotor voltage is adjusted appropriately, thus desired stator currents and torque which is proportional to the currents can be obtained. A protection system is also considered in the simulation along with the DFIG and relevant controller models. This system has three functions: protection to over/under voltage, protection to overcurrent and protection to over/under speed. Specific range is determined for each quantity. If measured values are out of ranges, then the required actions are taken to protect the wind power plant [21-22].

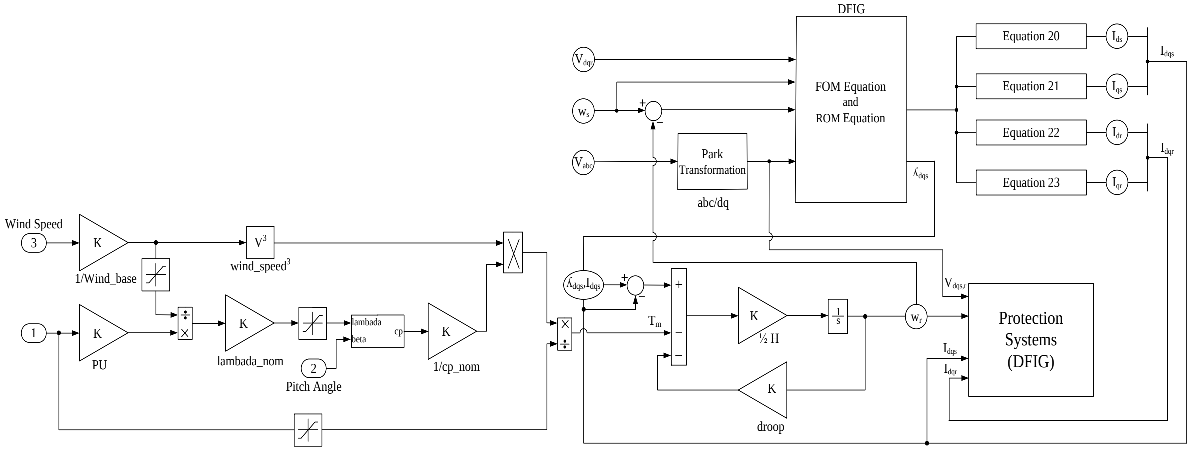

Figure 1. FOM-ROM electrical and mechanical modeling of DFIG

4. Grid Integration Simulation Study

A 2.3 MW wind power plant having DFIG is used to study the behavior of the system against various transient events. The DFIG is represented with both full and reduced order model as explained in the previous section. The plant is connected to a 34.5 kV system through a 2.6MW, 0.69kV Y/34.5kV Δ transformer. A 50 MVA 34.5kV Y/154kV Y transformer provides the transmission grid connection. Modeling of the whole system is carried out as depicted in Fig. 2.

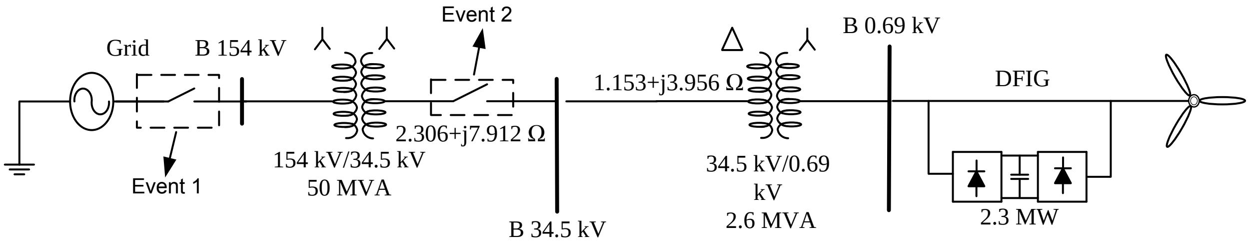

Figure 2. Modeling of the whole system

In the simulated cases, wind speed is assumed to be 8m/s constant and saturation of transformers is neglected. The following parameters are selected for the induction generator: Stator resistance (R_s) is 0.00706 ohm, rotor resistance (R_r) is 0.005 ohm, stator inductance (L_s) is 0.171 henry, rotor inductance is (L_r) 0.156 henry, magnetic inductance (L_m) is 2 henry, and inertia constant (H) 3.5s.

Transient events considered can be listed as follows.

- Normally closed breaker located at 154kV level opens at 5s and closes at 5.05s.
- Normally closed breaker located at 34.5kV level opens at 5s and closes at 5.05s

5. Results of Simulation Study

The impact of generator models on system parameters is examined against transient events given in the previous section. FOM and ROM behaviors are compared for each event.

The first transient event is considered as isolating wind power plant from the grid. This is performed by opening three phase breakers for very short time, located at the buses of B154kV and B 34.5kV shown in Fig. 2. For both cases, the period of transient event is taken to be 0.05s, between the time interval of [5- 5.05]. Variations in DFIG output voltage, DFIG angular speed, DFIG electrical torque, and DFIG d-q axes stator current have been observed for full order and reduced order DFIG model, and comparisons are made. While these variations for those parameters are depicted and compared in Fig.3-6 for the case of 154kV side outage, they are given in Fig. 7-10 for the case of 34.5kV side outage.

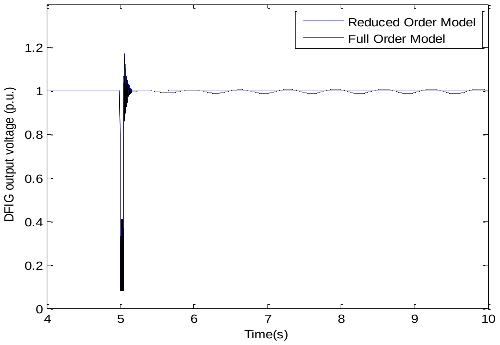

Figure 3. DFIG output voltage for the 154 kV side outage

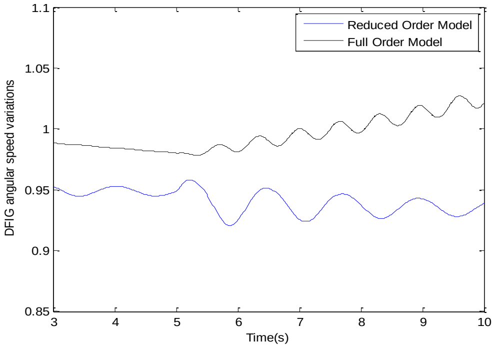

Figure 4. DFIG angular speed for the 154 kV side outage

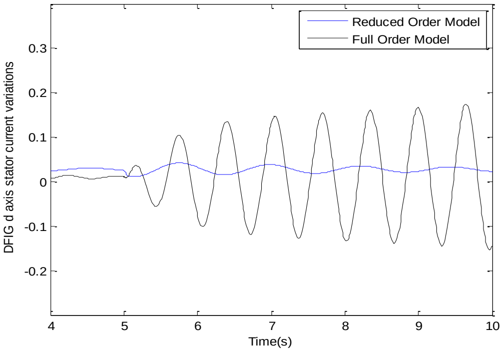

Figure 5. DFIG d axis stator current for the 154 kV side outage

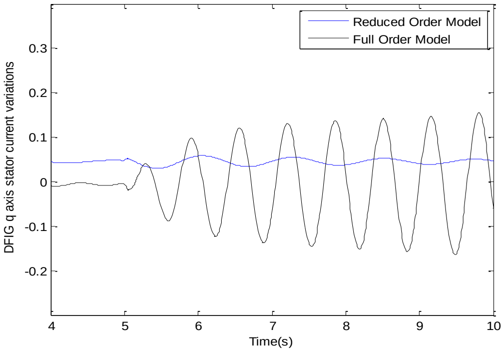

Figure 6. DFIG q axis stator current for the 154 kV side outage

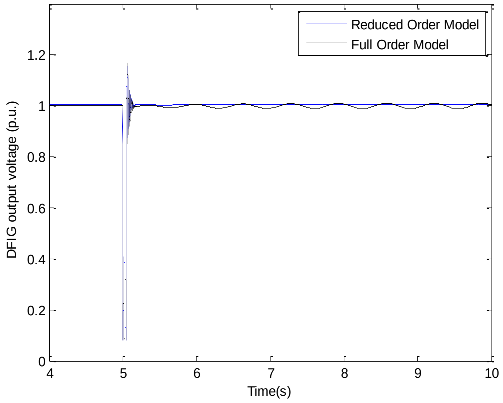

Figure 7. DFIG output voltage for the 34.5 kV side outage.

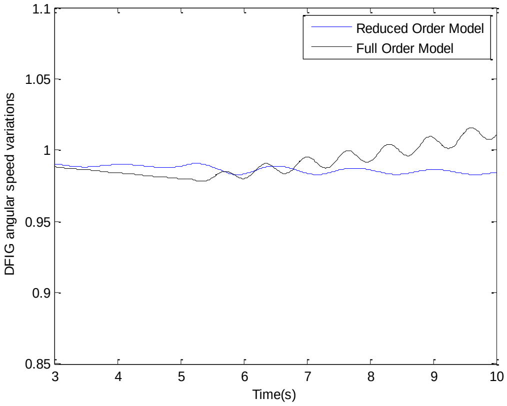

Figure 8. DFIG angular speed for the 34.5 kV side outage.

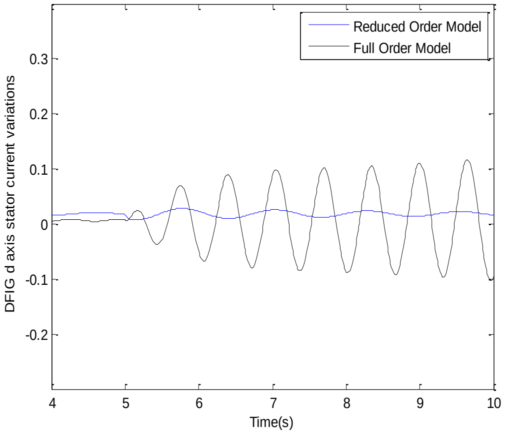

Figure 9. DFIG d axis stator current for the 34.5 kV side outage.

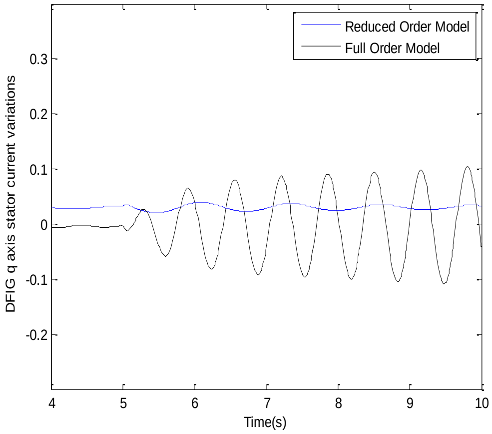

Figure 10. DFIG q axis stator current for the 34.5 kV side outage.

When DFIG is modelled in both full order and reduced order, the output voltage decrease approximately to 0.1 pu value during the transient period. After this transient period, it can be seen that reduced order modeled DFIG recovers faster and more stable behavior is obtained for each event. Besides, angular speed, and d-q axes currents of DFIG becomes unstable after the transition when the DFIG is full order modelled.

Conclusions

This study investigates the transient behaviors of a grid connected wind power plant against several events. These behaviors are compared when the plant has been represented with a full order and reduced order doubly fed induction generator model. Modeling of the plant has been detailed before the simulation studies. Behaviors of several DFIG parameters such as output voltage, angular speed, and d-q axis currents have been observed against each transient event. When the wind farm is isolated form the grid for short time, output voltage recovers well, on the other hand, unstable trend exists for other DFIG parameters with full order DFIG model. Two case studies captured in this paper showed that simplified DFIG model is more effective in transient stability analyses of grid integrated wind farms, as this model represents that stator as a voltage source behind a transient reactance.

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