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Effects of Drive Train Model Parameters on a Variable Speed Wind Turbine

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Abstract- The wind turbine generator system is the only generator unit in utility network where mechanical stiffness is lower than electrical stiffness or synchronizing torque coefficient. The inertia constants of the wind turbine and generator system have significant effects on the transient stability of the wind generators and the wind farm. This paper investigates the effects of two-mass drive train parameters in a doubly fed induction generator (DFIG) variable speed wind turbine (VSWT) system. Extensive simulations were carried out using power system computer aided design and electromagnetic transient including DC (PSCAD/EMTDC) considering two strategies. In the first strategy, different values of the wind turbine and generator inertia parameters were investigated. The wind turbine and generator inertia parameters that give best response during transient in the first strategy were used to determine the best shaft stiffness in the second strategy. The simulation results show that high values of the wind turbine and generator inertia parameters could lead to more oscillations, hence takes longer time for the VSWT to become stable during and after the transient condition. However, the larger the shaft stiffness parameters of the two-mass drives train system for VSWT, the better the response of the VWST system during transient condition. Moreover, simulations were also carried out to recheck the effects of changing the optimized shaft stiffness and inertia parameters obtained to ensure proper stabilization of the VSWT system.

Keywords- DFIG-VSWT; transient condition; two-mass drive train; wind energy; stability; inertia and shaft parameters.

1. Introduction

It is necessary to analyze the transient stability of power systems, including wind turbine generator systems, since it is eminent that a huge number of generators are going to be connected to the existing power network. The development of electrical generation from wind energy is due to the absence of harmful emissions on the environment and the infinite availability of the energy that is converted into electrical energy [1]. Some of the challenges in integrating large wind farms into power systems are voltage control, voltage stability of power system, reactive power management, dynamic power swing stability, power quality and behavior following disturbances in the power grid [2-6].

Nowadays, the most widely used wind turbine in wind farms is based on doubly fed induction generator (DFIG) due to noticeable advantages: the variable speed generation, the decoupled control of active and reactive powers, the reduction of mechanical stresses and the improvement of power quality [7, 8].

In power systems simulations, the drive train model is usually represented by two masses [9, 10], first mass stands for the wind turbine rotor (blades, hub and low-speed shaft), while the second mass stands for generator rotor (high speed shaft). Valuable studies have been performed for transient stability, fault analysis, reactive power compensation and other simulation analyses of wind turbine generator system by using two-mass shaft model [11-16]. The effects of the two-mass train parameters have been investigated for fixed speed wind turbine in the literature, however, this is yet to be widely reported for the variable speed wind turbine DFIG based driven system.

This paper studies the transient response of variable speed wind turbine driven by DFIG system. The proposed control schemes of the DFIG wind turbine to achieve stability of the system are presented in details. The two-mass shaft model was used for the wind generator, as it has great influence on the transient stability feature [11, 17-19]. Based on the wind turbine model, the stability of the DFIG wind turbine during and after a short-circuit fault has been investigated, considering various values of the two-mass drive train parameters. Two strategies were considered in the simulation analysis. In the first strategy, different values of the wind turbine and generator inertia values were investigated. The best wind turbine and generator inertia values obtained in the first strategy were used to determine the best shaft stiffness in the second strategy. The simulation results in PSCAD/EMTDC [20] show how the control schemes effectively manage to restore the wind turbines to their normal operation after the network disturbance. The simulation results also show that high values of the wind turbine and generator inertia parameters could lead to more oscillations, hence takes longer time for the DFIG variable speed wind turbine to become stable during and after the transient period. However, the larger the shaft stiffness parameters of the two-mass drive train system for VSWT, the better the response of the VWST system during the network disturbance. Extensive simulations were also carried out to recheck the effects of changing the optimized shaft stiffness and inertia parameters obtained to ensure proper stabilization of the VSWT system.

2. Model System of Study

The simple model system considered for this study is shown in Fig.1, where a 20MW aggregated doubly fed induction generator (DFIG) variable speed wind turbine (VSWT) system is connected to an infinite bus. The line parameters for self capacity base and system base are also shown in the model system. A fault point is shown for a three-line to ground fault, which is the most severe case considered in this study, in order to demonstrate the effectiveness of the controllers employed in the DFIG control system. The fault is applied when the wind turbine is on its steady state, running at its rated velocity in m/s and its rated power. There are circuit breakers on the faulted lines that help for protection during the grid fault. The DFIG wind turbine parameters used for this study in the model system are given in Table 1.

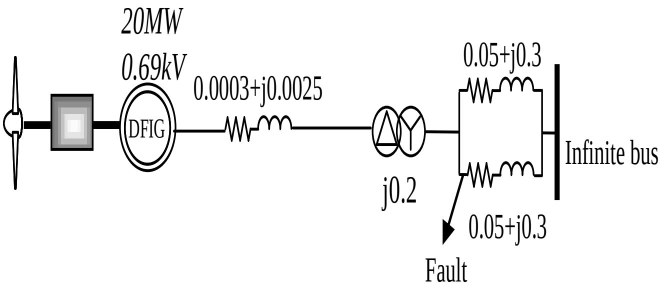

Fig. 1. Model system

Table 1. DFIG parameters

Generator Type	DFIG
Rated voltage	690V
Stator resistance	0.01pu
Stator leakage reactance	0.15pu
Magnetizing reactance	3.5pu
Rotor resistance	0.01pu
Rotor leakage reactance	0.15pu
Inertia constant	1.5sec

3. Wind Turbine and Two-mass Drive Train Modeling

The equations for the wind turbine modeling used in this study are given in equations (1)-(6) [21]. A lumped model of the two-mass drive train is presented [22] in Fig. 2. It includes turbine inertia J_T (N ms^2/rad), generator inertia J_G (N ms^2/rad), turbine friction damping D_T (N ms/rad), generator friction damping D_G (N ms/rad) and shaft stiffness K_{sh} (N m/rad). This lumped model is simple and it is considered as a more exact simulation model, as described in equations (7)-(9).

$$P_{wt} = 0.5\rho C_P \pi R^2 V_w^3 [W] \tag{1}$$

$$C_p(\lambda,\beta) = \frac{1}{2}(\Gamma - 0.022\beta^2 - 5.6)e^{-0.17\Gamma} \tag{2}$$

$$\lambda = \frac{\omega_{wt} R}{V_w} \tag{3}$$

$$\Gamma = \frac{R}{\lambda}(2.2374) \tag{4}$$

Where the constant 2.2374 in equation (4), is a conversion factor from miles to metres.

The torque coefficient and the turbine torque are expressed as follows.

$$C_t = \frac{C_p(\lambda)}{\lambda} \tag{5}$$

$$T_M = \frac{1}{2}\rho C_t(\lambda)\pi R^3 V_w{}^2 \text{ [NM]} \tag{6}$$

Where, P_{wt} is the extracted power from the wind, is the air density $[kg/m^3]$, R is the blade radius [m], V_w is wind speed [m/s], blade pitch angle is β[deg] , ω_{wt} is the rotational speed [rad/s] of wind turbine, and T_M is the wind turbine output torque [Nm].

$$T_T - K_{sh}(\theta_T - \theta_G) - D_T\omega_T = J_T \frac{d\omega_T}{dt} \tag{7}$$

$$K_{sh}(\theta_T - \theta_G) - T_G - D_G\omega_G = J_G \frac{d\omega_G}{dt} \tag{8}$$

$$T_{sh} - K_{sh}(\theta_T - \theta_G) \tag{9}$$

Where T_T, T_G and T_{sh} are turbine, generator and shaft torques (Nm), ω_G is the generator angular speed (rad/s), θ_T and θ_G are turbine and generator angular positions (rad).

Figure 2 shows the various parameters as explained in the equations above for the two-mass drive train modeling.

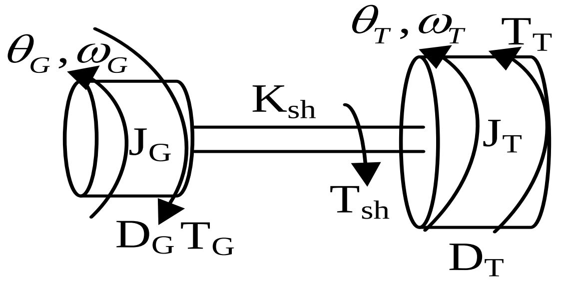

Fig. 2. Two-mass shaft model of wind turbine

4. Control System for the DFIG VSWT

The schematic diagram of DFIG VSWT including the basic control of the voltage controlled voltage source converters are shown in Fig. 3.

A DFIG VSWT is basically a standard wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a converter. The AC/DC/AC converter is divided into two components: the rotor side converter (RSC), and the grid side converter (GSC) as shown in Fig. 3. These converters are voltage sourced converters that use force commutated power electronic devices to synthesize an AC voltage from a DC source [23].

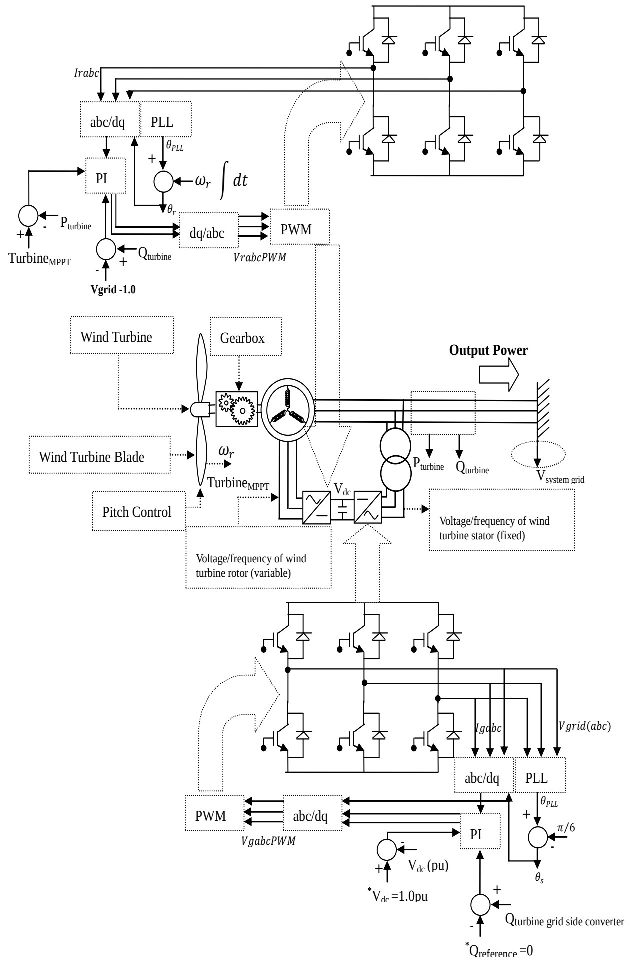

Fig. 3. Control blocks for variable speed wind turbine (rotor and grid side converter systems)

A capacitor connected on the DC-link acts as the DC-link voltage source. A coupling inductor is used to connect the GSC to the grid. The three phase stator winding are directly connected to the grid. The control system generates the pitch angle command and the voltage command signals for the RSC and GSC respectively. Thus, the power of the wind turbine, the DC-link voltage, and the reactive power or the voltage at the grid terminal are effectively controlled both in steady and transient states of the DFIG. The detail control structure of the DFIG VSWT system is shown in Fig. 3.

A phase lock loop (PLL) is used to determine the angle of transformation (abc-dq0 or dq0-abc) for the stator and the rotor side converters respectively, based on the line voltage detections. The voltage controlled voltage source converters are incorporated with a proportional integral (PI) controller, which has both time and gain constants.

The values of the PI in this study were determined by trial and error method, which makes it quite tedious.

The RSC controls the terminal (grid) voltage to 1.0pu. The d-axis and q-axis currents of the d-q transformation control the active power and reactive power of the wind turbine respectively. The voltage and frequency are variable for the RSC, while for the GSC, the voltage and frequency are fixed as shown in Fig. 3.

Also, the GSC system of the DFIG is used to regulate the DC-link voltage V_{dc} to 1.0pu. The d-axis current controls the DC-link voltage, while the q-axis current controls the reactive power of the grid side converter to be maintained at 0 p.u.

It should be noted that in the RSC and the GSC systems, a carrier wave is compared with the obtained reference voltages via a signal comparator system. The resultant signal is thus used for the IGBTs (insulated bipolar transistors) switching system as displayed in Fig. 3, which is obtained from the pulse width modulation (PWM).

5. Simulation Results and Discussion

5.1. Investigation of two-mass model wind turbine and generator inertia parameters

To show the effects of the two-mass shaft model parameters in the proposed DFIG-based control scheme, seven cases were analyzed on simulation analyses. Table 2 summarizes the cases considered using different values of the wind turbine inertia (J_T) and generator inertia (J_G). The shaft stiffness is kept constant at Ksh = 90pu in the cases considered here. The model system explained in Fig. 1 is used for all cases.

The wind generator is assumed to be operated at its rated wind speed. A three line to ground (3LG) fault (severe case) is considered as the network disturbance at point F in the model system in Fig. 1. The fault occurs at 0.1 sec and the circuit breakers on the faulted lines are opened at 0.2sec, and finally, at 1.0sec, the circuit breakers are re-closed. Some responses of the DFIG VSWT in the network system are shown in Figs. 4-15.

Figures 4 and 5 shows the responses of the rotor speed and wind turbine hub speed respectively, for the DFIG during the grid fault, for the various cases considered. It is observed that in case 7, fewer oscillations of the rotor and turbine hub speeds of the DFIG were achieved during and after the network disturbance compared to other cases. Hence the DFIG was able to assume its normal state faster in case 7, after the fault clearance as could also been seen in the figures. The impact of the grid fault and oscillations of the rotor and wind turbine hub speeds are much in the other cases (i.e. 1-6) during the grid fault. Thus, showing that the inertia parameters have a great influence during transient condition on the DFIG system, and also, demonstrating the effectiveness of the control system employed in Fig. 3. Figure 6 shows that the reactive power from the grid side converter can be dissipated faster during the transient condition in case 7, which eventually leads to faster assumption of steady state of the DFIG system with fewer oscillations.

Table 2. Considered cases of generator and wind turbine inertia parameters

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
J_T (pu)	4.5	4.5	3.0	3.0	3.0	1.5	1.5
J_G (pu)	0.45	0.3	0.45	0.3	0.15	0.3	0.15

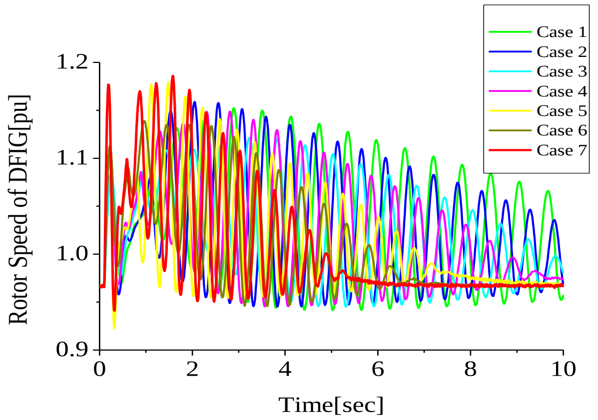

Fig. 4. Rotor speed of DFIG (cases 1-7)

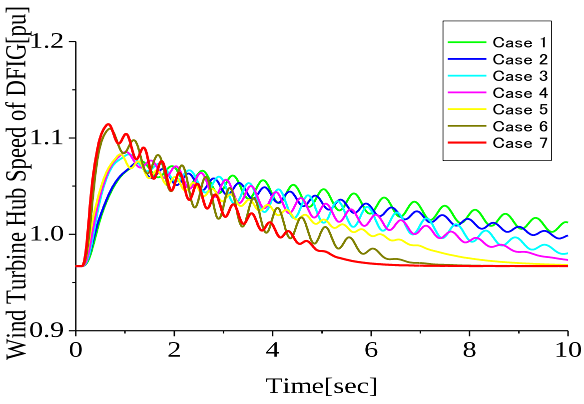

Fig. 5. Wind turbine hub speed of DFIG (cases 1-7)

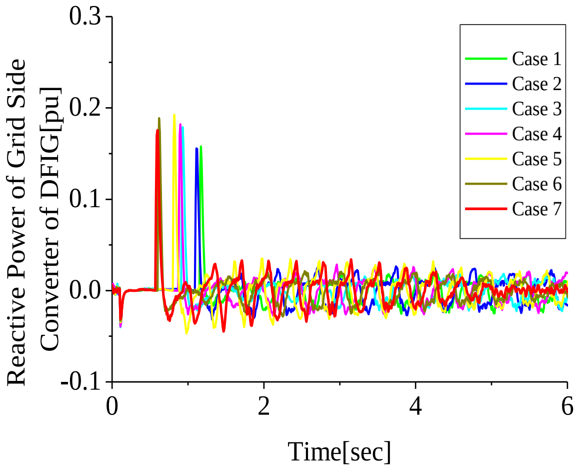

Fig. 6. Reactive power of grid side converter of DFIG (cases 1-7)

5.2. Investigation of two-mass shaft stiffness parameters

Based on the best wind turbine and generator inertia parameters obtained in case 7 in the above analysis, an extensive simulation analysis is carried out to determine the best shaft stiffness of the two-mass drive shaft model.

The same model system was used in the analysis, where the wind generator is assumed to be operated at its rated speed. The fault sequence is same as that used in section 5.1. Table 3 summarizes the three cases considered for the two-mass shaft stiffness parameter effects.

Figure 7 shows the response of the DFIG rotor speed for the three cases considered using different shaft stiffness parameter. It could be observed that case 10 with the highest shaft stiffness parameter gives a better performance during the grid fault. Hence the rotor speed of the DFIG was able to assume its steady state faster with reduced oscillation peaks, compared to cases 8 and 9.

Table 3. Considered cases of shaft stiffness parameters

	Case 8	Case 9	Case 10
K_{sh}(pu)	80	90	100

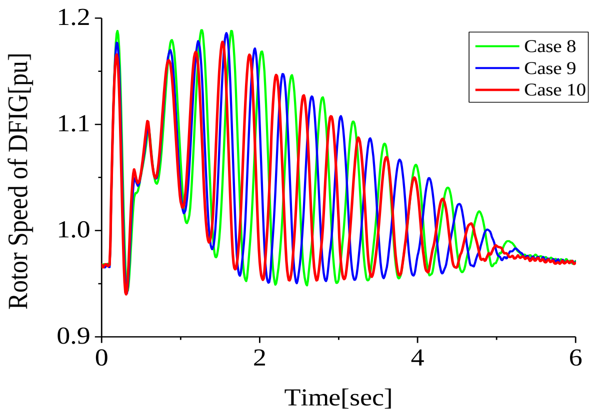

Fig. 7. Rotor speed of DFIG (cases 8-10)

5.3. Recheck of optimized inertia and shaft stiffness parameters for proper stabilization

Extensive simulations were also carried out to recheck the effects of changing the optimized shaft stiffness and inertia parameters obtained to ensure proper stabilization of the VSWT system. Tables 4, 5 and 6 presents the various cases considered for thorough investigation of the system. Some of the simulation results are shown in Figs. 8-15.

Table 4. Considered cases for parameters recheck-1

	Case A	Case B	Case C
J_T (pu)	4.5	3.0	1.5
J_G (pu)	0.45	0.3	0.15
K_{sh} (pu)	90	90	90

Table 5. Considered cases for parameters recheck-2

	Case D	Case E	Case F
J_T (pu)	4.5	3.0	1.5
J_G (pu)	0.45	0.3	0.15
K_{sh} (pu)	100	100	100

Table 6. Considered cases for parameters recheck-3

	Case G	Case H	Case I
J_T(pu)	4.5	3.0	1.5
J_G (pu)	0.45	0.3	0.15
K_{sh} (pu)	80	80	80

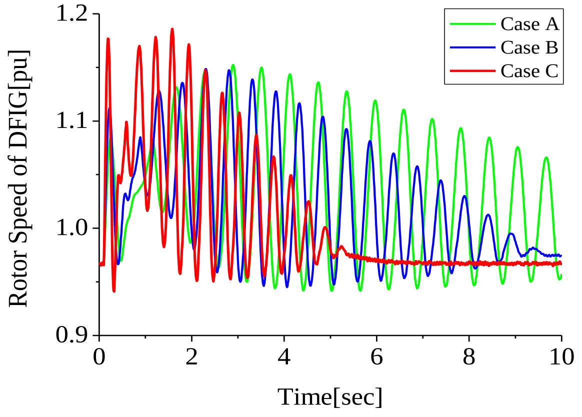

Fig. 8. Rotor speed of DFIG (cases A-C)

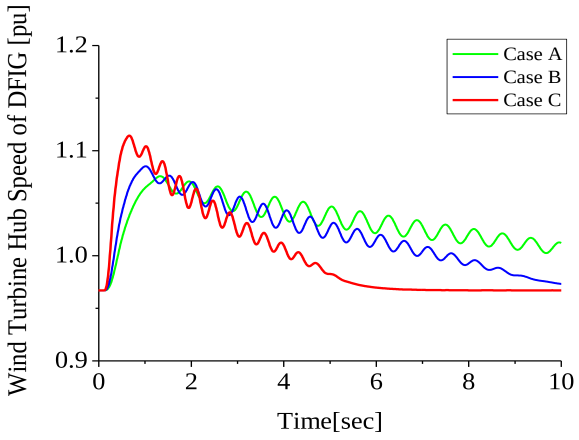

Fig. 9. Turbine hub speed of DFIG (cases A-C)

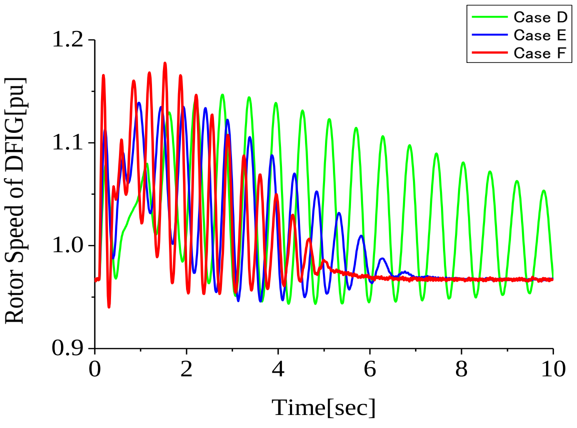

Fig. 10. Rotor speed of DFIG (cases D-F)

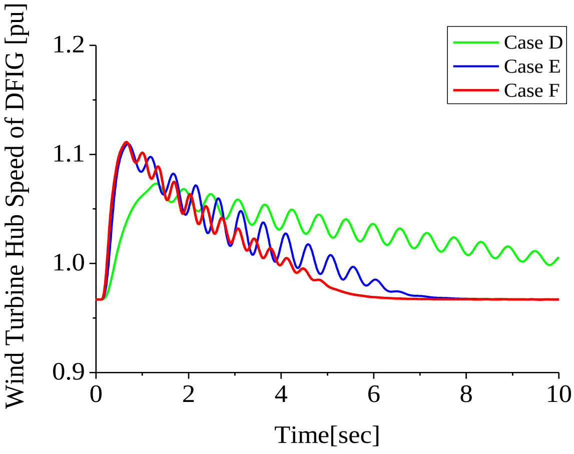

Fig. 11. Turbine hub speed of DFIG (cases D-F)

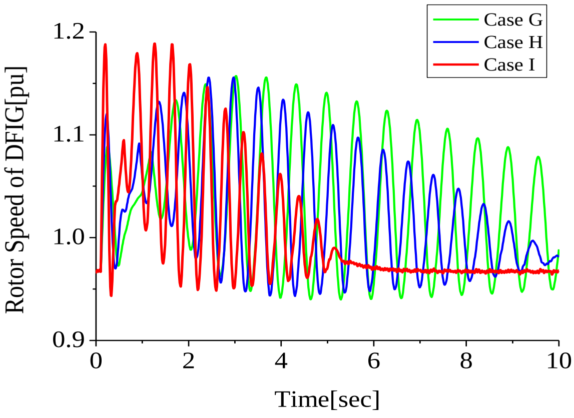

Fig. 12. Rotor speed of DFIG (cases G-I)

From Figs. 8 and 9, the settling time for case C is faster than cases A and B for the DFIG rotor and turbine hub speeds respectively. It can also be observed that in case E, the response of the DFIG rotor and turbine hub speeds was further improved compare to cases B and H due to the high shaft parameter. However, cases C, F and I with the optimized inertia parameters, gave the best responses considering the overall performance of the entire VSWT system. A plot of the best results using the optimized inertia parameters obtained for cases C, F and I as shown in Figs. 14 and 15, depicts that, the highest shaft stiffness in case F gives best results, with reduced oscillations peak and quicker settling time for the DFIG rotor and turbine hub speeds.

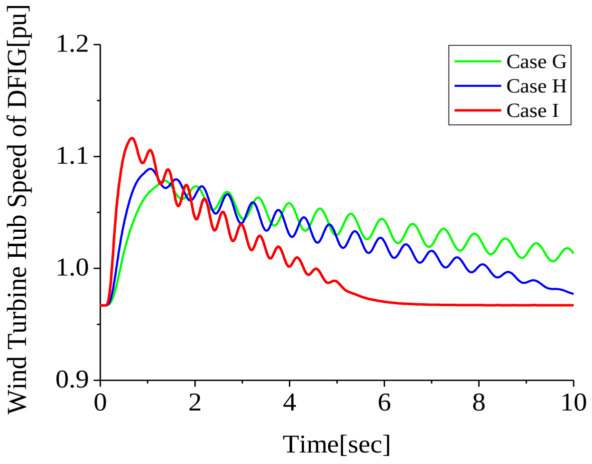

Fig. 13. Turbine hub speed of DFIG (cases G-I)

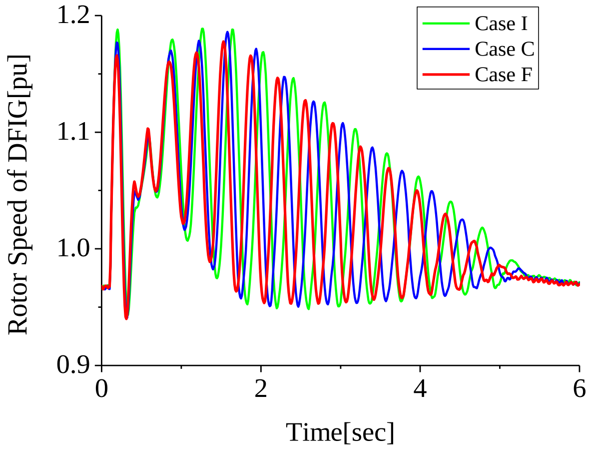

Fig. 14. Rotor speed of DFIG (cases I, C, F)

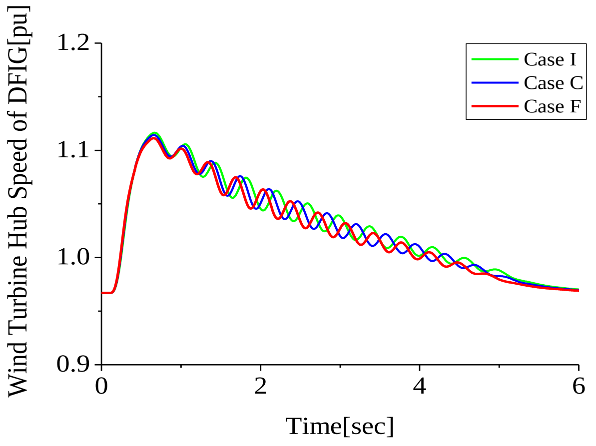

Fig. 15. Turbine hub speed of DFIG (cases I, C, F)

It could be observed also that, a plot of the three best cases for C, F, I give the same results obtained for cases 8, 9 and 10 for the rotor speed of the DFIG as shown in Fig. 7.

Thus, from the above analysis, it could be concluded that case F gives better response for all the cases considered for inertia and shaft stiffness parameters, during transient condition for the DFIG VSWT system.

6. Conclusion

The effects of the two-mass drive train parameters on a variable speed wind turbine driven by a doubly fed induction generator (DFIG) have been investigated in this paper. The performance of the variable speed wind turbine control systems have been assessed through simulations of DFIG wind turbine connected to an infinite bus.

The simulation results illustrate the capability of the described DFIG control systems to control both active and reactive powers; hence can effectively stabilize itself during transient condition. It was reported that high wind turbine and generator inertia parameters of the two-mass shaft model, could lead to longer time for the DFIG variable speed wind turbine (VSWT) in recovery to its steady state after a network disturbance. It was also reported that lower shaft stiffness parameter of the two-mass shaft model could also delay the assumption of steady state of the DFIG variable speed wind turbine after the network disturbance.

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