

Small Signal Stability Analysis of DFIG Fed Wind Power System Using a Robust Fuzzy Logic Controller

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Abstract

This paper focuses on the small signal stability analysis of Doubly-Fed Induction Generator (DFIG) fed wind power system under three modes of operation. The system stability is affected by the influence of electromechanical oscillations, which can be damped using Power System Stabilizer (PSS). A detailed modeling of DFIG fed wind system including controller has been carried out. The damping controller is designed using fuzzy logic to damp the oscillatory modes for stability. The robust performance of the system with controllers has been evaluated using eigen value analysis and time domain simulations under various disturbances and wind speeds. The effectiveness of the proposed fuzzy based PSS is compared with the performance of conventional PSS implemented in the wind system.

Keywords

Doubly-Fed Induction Generator (DFIG), Conventional Power System Stabilizer (CPSS), Fuzzy Logic Based Power System Stabilizer (FPSS)

1. Introduction

The renewable sources of energy play a vital role in modern power system operation due to various features such as reduced carbon emissions, minimized global warming effect and reduction in dependence on fossil fuels. In recent years, there has been a tremendous interest in electric power generation using wind energy conversion

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systems. The doubly fed induction generator has been popular among various wind power generation techniques, because of its increased energy transfer capability and flexible control [1]. DFIG employs a series of voltage-source converter to feed the wound rotor. The feedback converters in DFIG system consist of a rotor-side converter (RSC) and a grid-side converter (GSC). The stability of these converters is better compared to other conventional induction generators [2].

In modern wind power systems, the small signal stability problem is the phenomenon of insufficient damping of low frequency electromechanical oscillations at frequency range from 0.1 to 2 Hz. The control using power system stabilizer is the best cost-effective method to damp the oscillations and to enhance the system stability [3].

Various authors have investigated the dynamic behavior of DFIG in the past. A third-order model for stability analysis using PSS has been reported in [4]. The dynamic model of the DFIG system integrated with grid has been presented in [5] whereas the stability improvement using modal analysis has been discussed in [6]. Also the control methods for DFIG and the fault ride-through capability have been reported in [7] [8] respectively. The decoupled control of DFIG has controllers namely P_{ref} , V_{sref} , V_{dcref} and q_{ref} . These controllers will maintain tracking of maximum power, terminal voltage of stator, dc voltage level, and reactive power level respectively. Bio-inspired computational techniques can be applied for optimization of the controller in the rotor side. As the settling time for rotor over current was not considered in the above work, the GSC parameters were not optimized and larger oscillations of the dc link voltage were observed [9] [10].

Eigen value approach was adopted to damp the larger oscillations in dc link voltage [11]. The GSC controllers were optimized to damp the power oscillations. A lead-lag power system stabilizer using a speed deviation input signal in DFIG-based wind generation is presented in [12]. Since the wind speed is of variable nature, the dynamic performances of the controllers under different wind speeds are to be analyzed for stability enhancement.

In this paper, the stability of DFIG fed wind system is enhanced using fuzzy logic based damping controller implemented in the system. Three modes of operation namely sub-synchronous (wind speed around 7 m/s), synchronous (8 m/s) and super-synchronous (around 9 m/s) modes are taken for analysis. The fuzzy logic based PSS performance is compared with the results of conventional PSS implemented in the system.

2. Modeling of DFIG

The grid-connected single machine infinite bus system is taken for modeling and simulation and is shown in **Figure 1**. The stator and rotor voltages of the DFIG are supplied by grid and the power converters respectively. The components involved in the modeling include turbine, drive train, generator, and back-to-back converter system.

The mechanical input to the wind turbine is taken as constant, *i.e.*, no change in blade pitch angle during the analysis. In this paper, the two-mass drive train model [13] [14] is considered and the dynamic differential equations are given as follows:

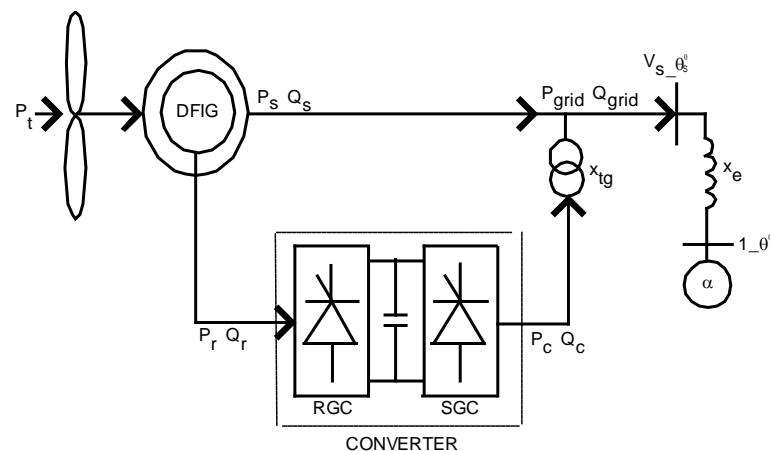


Figure 1. Single machine infinite bus with DFIG wind power system.

$$2H_t \frac{d\omega_t}{dt} = T_m - T_{sh} \quad (1)$$

$$\frac{1}{\omega_{elb}} \frac{d\theta_{tw}}{dt} = \omega_t - \omega_r \quad (2)$$

$$2H_g \frac{d\omega_r}{dt} = T_{sh} - T_e \quad (3)$$

where $T_e = P_s/\omega_s$ is the electrical torque, $T_{sh} = K_{sh}\theta_{tw}$ is the shaft torque, H_t is inertia constant of turbine, H_g is generator inertia constant, θ_{tw} is shaft twist angle, ω_t is wind turbine angular speed, ω_r is generator angular speed, ω_{elb} is the electrical base speed, and K_{sh} is the shaft stiffness and ω_s is synchronous speed.

The DFIG system is represented in terms of direct and quadrature axes quantities, which form a reference frame that rotates synchronously with the stator flux vector. The variables are defined as [15] [16]:

$$e'_{qs} = K_{mrr} \omega_s \psi_{dr} \quad (4)$$

$$e'_{ds} = -K_{mrr} \omega_s \psi_{qr} \quad (5)$$

$$L'_s = L_{ss} - \frac{L_m^2}{L_{rr}} \quad (6)$$

$$T_r = \frac{L_{rr}}{R_r}$$

DFIG model can be expressed as follows.

$$\frac{\omega_s L'_s}{\omega_e} \frac{di'_{qs}}{dt} = -R_1 i'_{qs} + \omega_s L'_s i'_{ds} + \frac{\omega_r}{\omega_s} e'_{qs} - \frac{1}{T_r \omega_s} e'_{ds} + \dots - v_{qs} + K_{mrr} v_{qr} \quad (7)$$

$$\frac{\omega_s L'_s}{\omega_e} \frac{di'_{ds}}{dt} = -R_1 i'_{ds} - \omega_s L'_s i'_{qs} + \frac{\omega_r}{\omega_s} e'_{ds} + \frac{1}{T_r \omega_s} e'_{qs} + \dots - v_{ds} + K_{mrr} v_{dr} \quad (8)$$

$$\frac{1}{\omega_e} \frac{de'_{qs}}{dt} = R_2 i'_{ds} - \frac{1}{T_r \omega_s} e'_{qs} + \left(1 - \frac{\omega_r}{\omega_s}\right) e'_{ds} - K_{mrr} v_{qr} \quad (9)$$

$$\frac{1}{\omega_e} \frac{de'_{ds}}{dt} = -R_2 i'_{qs} - \frac{1}{T_r \omega_s} e'_{ds} - \left(1 - \frac{\omega_r}{\omega_s}\right) e'_{qs} - K_{mrr} v_{dr} \quad (10)$$

where $R_2 = K_{mrr}^2 R_r$, $R_1 = R_s + R_2$.

The converter model in DFIG system comprises of two pulse width modulation inverters connected back-to-back via a dc link. The rotor converter is a controlled voltage source and it injects ac voltage to the rotor. The grid side converter generates an ac voltage at power frequency, acting as a controlled voltage source. The power balance equation for the converter model can be given as

$$P_r = P_g + P_{dc} \quad (11)$$

where P_r , P_g , P_{dc} represent the active power at RSC, GSC, and dc link respectively.

The mathematical modeling of the DFIG system without controller and also including the damping controller have been carried out in this work. The Appendix section gives the state matrices developed for open loop and closed loop system.

3. Controllers for DFIG

The controllers for DFIG system play a vital role in enhancing the stability of the wind power system. In DFIG system, there are two back-to-back converters and there is a need to control these two converter sides. To enhance damping, a new auxiliary control signal is added to the angle control in the RSC to enhance the damping. This is known as damping control scheme for DFIG.

The damping controller model consists of the washout block, gain block and cascaded phase compensation block. The rotor speed deviation $\Delta\omega$ is the controller input and output is the damping control signal (ΔU_E) given to generator- excitation system feedback loop [17] [18].

The transfer function of the damping controller is given by

$$\left[\frac{\Delta U_E}{\Delta\omega} \right] = K_s \left[\frac{sT_w}{1+sT_w} \right] \cdot \left[\frac{1+sT_1}{1+sT_2} \right] \cdot \left[\frac{1+sT_3}{1+sT_4} \right] \quad (12)$$

Here K_s represents the controller gain and (T_1 to T_4) represent the time constants of the controller. The washout time constant (T_w) will be around 20 seconds.

The fuzzy logic control, which implements uncertainty and fuzziness in the decision-making process, offers good performance for various power system problems. The main idea behind fuzzy logic control is to incorporate the expert experience of human operator in designing a controller whose input-output relationship is explained by set of fuzzy rules involving linguistic variables. The fuzzy controller consists of the four basic components namely fuzzification interface, fuzzy rule base, inference engine and defuzzification [19] [20].

In this paper, the rotor speed and power angle deviations are taken as fuzzy inputs to the controller. These inputs have significant effects on mitigating electromechanical oscillations experienced in the test DFIG wind power system taken. A membership function in fuzzy logic represents the degree of truth of the taken input signals [21]-[24]. The seven set up normalized cosine Gaussian membership function is defined for the proposed control as given in **Figure 2**.

The proposed fuzzy controller is characterized as follows.

1. Seven fuzzy sets for each input and outputs: NB, NM, NS, ZE, PS, PM, PB (negative big, medium and small, zero, positive small, medium and big).
2. Gaussian membership functions for simple action.
3. Fuzzification using continuous universe of discourse.
4. Mamdani's "min" operator based implication.
5. Centroid method for defuzzification.

A set of 49 fuzzy rules has been implemented in this control. **Table 1** provides the fuzzy rules implemented in the fuzzy controller. Finally, the aggregated output is defuzzified to represent a real number which is the fuzzy logic output.

For stable operation of power system, all the computed system eigen values should lie on better stable locations in left half of complex s-plane. Time domain simulation analysis involves minimizing the overshoots and settling time of the rotor speed, power angle, real power flow and reactive power flow at the earliest possible, to enhance stability.

4. Simulation Results and Analysis

In case of single machine DFIG power system simulation, wind turbine connected to infinite bus is taken as the test system model. For all the simulation, computation and analysis, MATLAB tool has been implemented using the data as given in Appendix. Time domain simulation experiments involving various modes of operation based on wind speed and load change disturbances have been implemented.

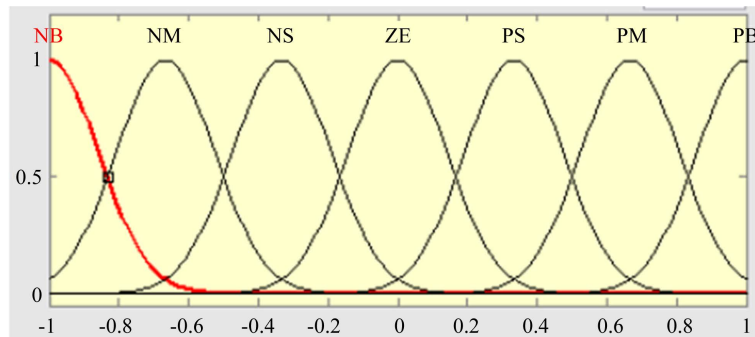


Figure 2. Gaussian membership function.

Table 1. Fuzzy rules for FPSS controller.

		ERROR (e)						
		NB	NM	NS	ZE	PS	PM	PB
Change in Error Δe	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

Figure 3 shows the simulation model for the proposed system without and with controller (CPSS and FPSS). Here, there are three modes of control available namely MODE 0, MODE 1 and MODE 2. In MODE 0, the system will be an open loop system without controller. In MODE 1, the system is implemented with CPSS and in MODE 2, the FPSS will be included in the system model.

The time domain simulations and eigen value analysis are carried out for the system with these three modes separately for three modes of operation namely sub-synchronous/synchronous/super-synchronous modes.

The steady-state operation of DFIG based wind power system has to be analyzed under different modes of operation. The open loop and closed loop state matrices developed for the DFIG system model is given in Appendix. These state matrices help in computing the eigen values of the system.

Table 2 provides the open loop and closed loop eigen values calculated for various operating conditions. The location of real part of eigen values is at unstable locations for the system without controller. The low frequency values of the oscillations are also computed for various wind speeds.

Also non linear time domain simulations have been performed for the system without any controller. The observed electromechanical oscillations are analyzed in terms of rotor speed, power angle, terminal voltage and electrical torque deviations in this work. **Figure 4** represents the speed deviation response of wind system under $P = 0.8$ and $Q = 0.2$ p.u. at wind speed of 7 m/s and load change disturbance of 0.01 p.u. condition. The rotor speed deviations are continuously growing in magnitude, thus making DFIG power system unstable. The DFIG system is in need of damping controller to be equipped in the system so that these oscillations are damped out, thus enhancing the DFIG system stability.

Need of Damping Controller

The modeling and simulations of the DFIG system with fuzzy controller have been performed to compute the closed loop eigen values of the DFIG system.

The closed loop eigen values are computed for the system for wind speeds of 7 m/s, 7.5 m/s, 8 m/s , 8.5 m/s and 9 m/s as shown in **Table 2**. The magnitude of system damping is represented in terms of its damping ratio. A threshold damping ratio of 0.1 is taken in this work for analysis. The damping ratio ζ can be computed from the system eigen value. From **Table 2**, it is clear that the closed loop eigen values are well placed in stable locations in left half of complex s-plane. The damping ratios are calculated only for the weakly damped eigen values for all wind speed conditions. The proposed controller provide better damping to the system, with its damping ratios more than threshold level of 0.1 for all the operating conditions involved. The eigen values and damping ratios computed for the system with controller confirm that the DFIG wind system is stable for all wind speeds and load change disturbances.

Figure 5 and **Figure 6** represent the simulated speed deviation and power angle deviation responses obtained by implementing the damping controller in the DFIG system for $P = 0.8$, $Q = 0.2$ p.u. and wind speeds of 7 m/s and 8 m/s respectively. The fuzzy logic controller minimizes the deviation overshoots to a better extent and also the deviations settle at a quicker time in comparison with the conventional controller.

For example in **Figure 5**, the rotor speed deviation overshoot obtained for CPSS is 1.4289 p.u and for the

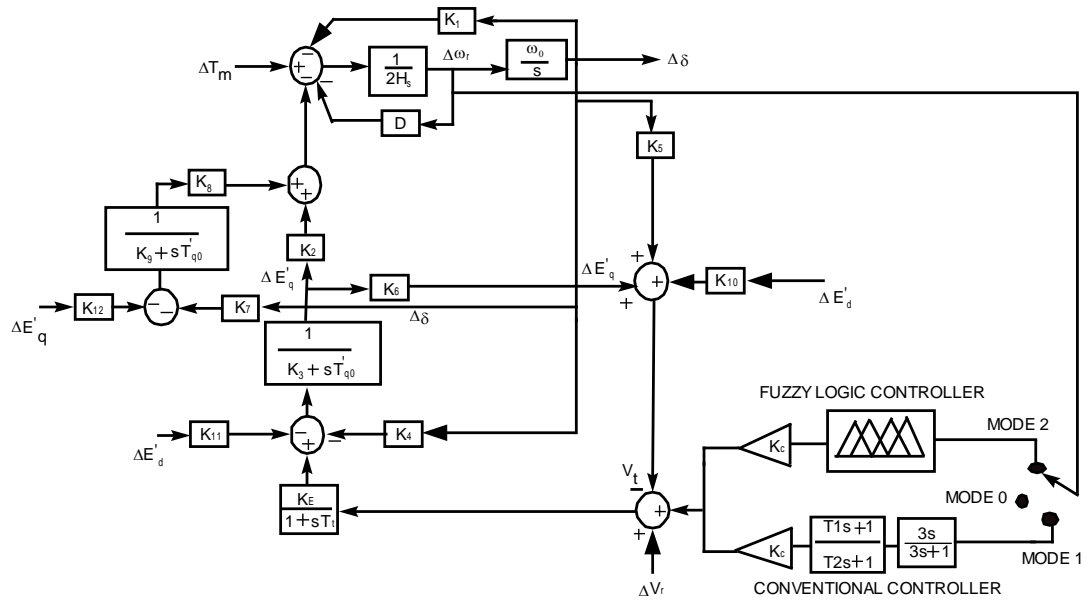


Figure 3. Simulink model of DFIG fourth order linear model with and without controller.

Table 2. Computed eigen values without and with damping controller.

Wind Speed	Without damping controller			With damping controller		
	Eigen value	Freq	Damping ratio ζ	Eigen value	Freq	Damping ratio ζ
7 m/s	$-0.2038 \pm j5.6072$	0.8924	0.0363	$-6.7045 \pm j8.2796$	1.3177	0.6293
	$-0.2744 \pm j10.6985$	1.7027	0.0250	$-7.1012 \pm j11.214$	1.7848	0.3877
7.5 m/s	$-0.1955 \pm j5.4244$	0.8633	0.0360	$-6.7862 \pm j8.3266$	1.3252	0.6317
	$-0.2741 \pm j11.6780$	1.8586	0.0229	$-7.2072 \pm j11.081$	1.7636	0.3303
8 m/s	$-0.1878 \pm j5.2587$	0.8369	0.0356	$-6.8607 \pm j8.3661$	1.3315	0.6341
	$-0.2080 \pm j10.6595$	1.6965	0.0191	$-7.2969 \pm j10.961$	1.7445	0.4056
8.5 m/s	$-0.1807 \pm j5.1075$	0.8128	0.0353	$-6.9218 \pm j8.3999$	1.3368	0.6359
	$-0.2736 \pm j10.6429$	1.6938	0.0268	$-7.3740 \pm j10.852$	1.7272	0.4355
9 m/s	$-0.1741 \pm j4.9688$	0.7908	0.0350	$-6.9747 \pm j8.4291$	1.3415	0.6375
	$-0.2734 \pm j11.9278$	1.8983	0.0224	$-7.4410 \pm j11.753$	1.8706	0.3876

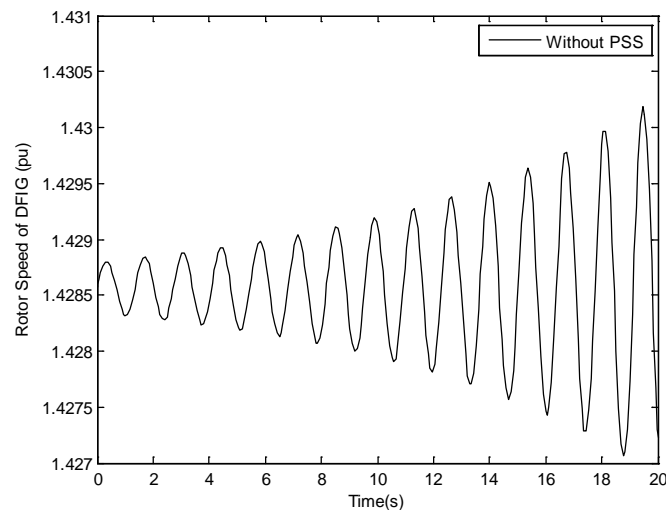


Figure 4. Open loop rotor speed deviation of DFIG system under 0.01 p.u. disturbance with wind speed of 7 m/s.

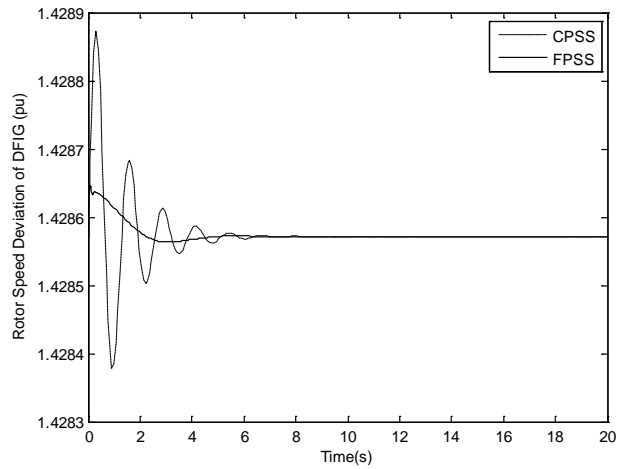


Figure 5. Rotor speed deviation of DFIG at 0.01 p.u. disturbance with wind speed of 7 m/s.

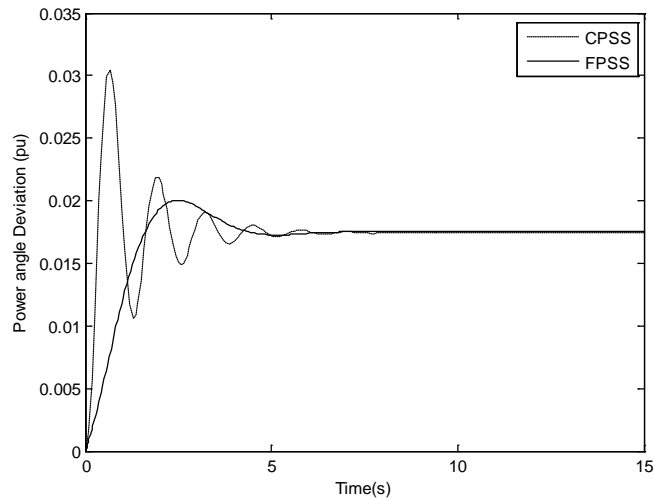


Figure 6. Power angle deviation at 0.02 p.u. disturbance with wind speed of 8 m/s.

FPSS is 1.42865 p.u. The settling time of the rotor speed deviation for CPSS is nearly 6 sec and for FPSS is nearly 4 sec. **Figure 6**, the maximum power angle deviation overshoot obtained for CPSS is 0.03 p.u. and for FPSS, the overshoot is only 0.02 p.u. These responses clearly indicate that the FPSS provide better damping to the system oscillations in comparison with the conventional controller.

Also the terminal voltage, real power and reactive power deviations are simulated for various wind speeds and are presented in **Figures 7-9**, respectively.

Figure 8 shows, the real power deviation at 0.01 p.u. disturbance with wind speed of 8 m/s overshoot obtained for CPSS is 0.81 p.u. and for the FPSS is 0.804 p.u. The settling time of the rotor speed deviation for CPSS is nearly 5.2 sec and for FPSS is nearly 1 sec.

Figure 9 shows, the real power deviation at 0.01 p.u. disturbance with wind speed of 9 m/s the overshoot obtained for CPSS is 0.21 p.u. and for the FPSS is 0.201 p.u. The settling time of the rotor speed deviation for CPSS is nearly 5.2 sec and for FPSS is nearly 1 sec. So the proposed fuzzy controller damp the deviations better in comparison with the conventional lead lag controller for this condition.

Figure 10 represents the electrical torque deviation responses computed for wind speed of 7 m/s the overshoot obtained for CPSS is 0.576 p.u and for the FPSS is 0.5704 p.u. The settling time of the rotor speed deviation for CPSS is nearly 5 sec and for FPSS is nearly 4 sec. In all these simulated responses, the performance of

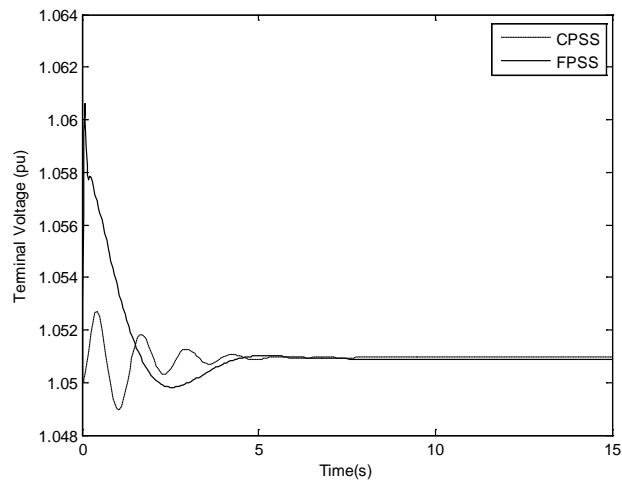


Figure 7. Terminal voltage deviation at 0.02 p.u. disturbance with wind speed of 7.5 m/s.

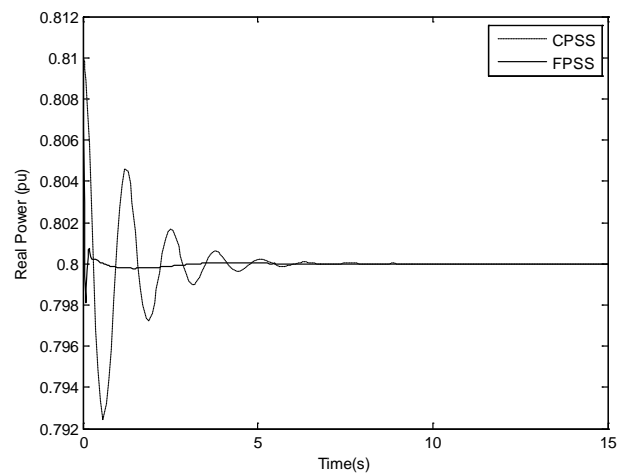


Figure 8. Real power deviation at 0.01 p.u. disturbance with wind speed of 8 m/s.

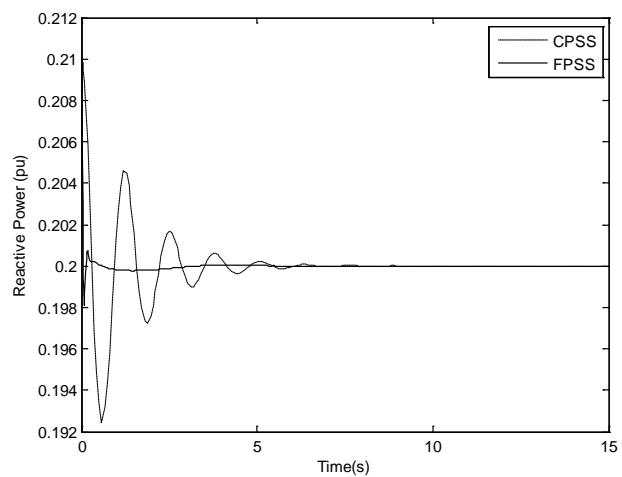


Figure 9. Reactive power deviation at 0.01 p.u. disturbance with wind speed of 9 m/s.

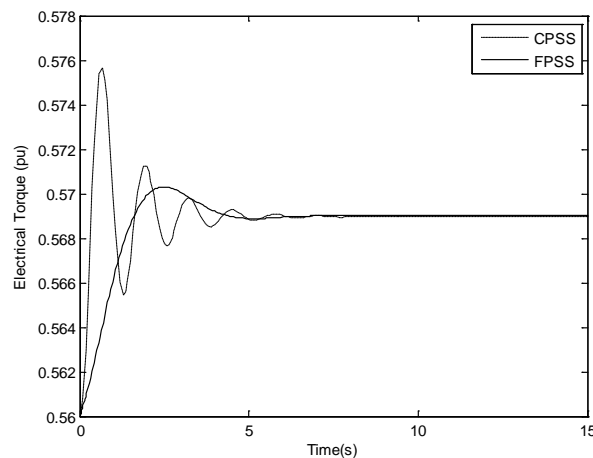


Figure 10. Electrical torque of DFIG at 0.01 p.u. disturbance with wind speed of 7 m/s.

the proposed fuzzy power system stabilizer is better than the conventional controller so that the small signal stability of the test DFIG system is enhanced to a greater extent.

5. Conclusion

This work provides an efficient solution to the problem of electromechanical oscillations experienced in DFIG based wind power system, thus enhancing the small signal stability of the system to a greater extent. The mathematical modeling and time domain simulations of the system with and without controller have been performed. The simulation results show that the proposed fuzzy controller damps the electromechanical oscillations better in comparison with the conventional lead lag controller. The simulation under various operating conditions of wind speed and load change disturbances shows that the proposed fuzzy logic controller is robust and effective to improve the small signal stability of the DFIG system.

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Appendix

A1. Nomenclature

- θ_{tw} : Shaft twist angle (rad).
 P_s : Stator active power per unit (p.u.).
 L_{ss} : Stator self induction (p.u.).
 L_{rr} : Rotor self induction (p.u.).
 L_m : Mutual inductance between rotor and stator (p.u.).
 R_r : Rotor resistance (p.u.).
 R_s : Stator resistance (p.u.).
 H_t : Inertia constant of turbine (s).
 H_g : Inertia constant of the generator (s).
 ω_t : Wind turbine angular speed (p.u.).
 ω_r : Generator angular speed (p.u.).
 ω_s : Synchronous speed (p.u.).
 ω_{elb} : Electrical base speed (rad/s).
 T_{sh} : Shaft torque (p.u.).
 T_m : Wind torque (p.u.).
 T_{em} : Electromagnetic torque (p.u.).
 K_{sh} : Shaft stiffness (p.u./el.rad).
 e'_{ds}, e'_{qs} : d and q axis voltages behind-transient reactance (p.u.).
 ψ_{dr}, ψ_{qr} : d and q axis rotor fluxes (p.u.).
 i_{ds}, i_{qs} : d and q axis stator currents (p.u.).
 v_{ds}, v_{qs} : d and q axis stator voltages (p.u.).
 i_{dr}, i_{qr} : d and q axis rotor currents (p.u.).
 i_{dg}, i_{qg} : d and q axis currents of the grid-side converter (p.u.).
 v_{dg}, v_{qg} : d and q axis voltages of the grid-side converter (p.u.).
 v_{dr}, v_{qr} : d and q axis rotor voltages (p.u.).
 v_{dc}, i_{dc} : Voltage and current of dc capacitor (p.u.).
 C : Capacitance of the dc capacitor (μ farad).

A2. Data's for DFIG System Simulation in (p.u.)

$H_t = 4, H_g = 0.4, X_m = 4, L_m = 4, X_{ly} = C = 0.01, X_c = 0.06, L_{ss} = 4.04, L_{rr} = 4.0602, R_s = (X_m/800), R_r = 1.1 * R_s,$
 $M = 9.26, X_d = 0.973, X_{d1} = 0.0190, X_q = 0.550, D = 0, T_{d01} = 7.76, R = 0.034, X = 0.997, K_e = 50, T_e = 0.05, T_f = 1.$

A3. State Matrix

Open Loop

$$A = \begin{bmatrix} 0 & \frac{-K_1}{M} & \frac{-K_2}{M} & 0 \\ \omega_b & 0 & 0 & 0 \\ 0 & \frac{-K_4}{T_{d01}} & \frac{-1}{T_{d01}K_3} & \frac{-1}{T_{d01}} \\ 0 & \frac{-K_e K_5}{T_e} & \frac{-K_e K_6}{T_e} & \frac{-1}{T_e} \end{bmatrix}$$

Closed Loop

$$A_c = \begin{bmatrix} 0 & \frac{-K_1}{M} & \frac{-K_2}{M} & 0 & 0 & 0 \\ \omega_b & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-K_4}{T_{d01}} & \frac{-1}{T_{d01}K_3} & \frac{-1}{T_{d01}} & 0 & 0 \\ 0 & \frac{-K_e K_5}{T_e} & \frac{-K_e K_6}{T_e} & \frac{-1}{T_e} & 0 & \frac{K_e}{T_e} \\ 0 & \frac{-K_1}{M} & \frac{-K_2}{M} & 0 & \frac{-1}{T_e} & 0 \\ 0 & \frac{-K_c K_3 T_1}{MT_2} & \frac{-K_c K_2 T_1}{MT_2} & 0 & \frac{K_c}{T_2 \left(1 - \frac{T_1}{T_2}\right)} & \frac{-1}{T_2} \end{bmatrix}$$