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TRANSIENT STABILITY IMPROVING OF POWER SYSTEM INCLUDING DFIG BASED WIND FARM BY USING FUZZY LOGIC CONTROLLER

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Abstract- With increased penetration of wind power on power Systems, the influences of wind power penetration on an existing interconnected large power system dynamic behavior, especially the transient stability analysis, must be considered carefully. Among the rest, Inter-area oscillations can be deteriorating the power system condition. These oscillations are as a result of the dynamics of inter-area power transfer in a large interconnected power network, which can seriously limit the system operation. To provide a safe operation for power system stability, damping of these oscillations have become one of the main problems. In this paper, a fuzzy logic controller is developed for a Doubly-Fed Induction Generator (DFIG) based wind farm in order to damp the inter-area oscillations. The auxiliary fuzzy damping controller modulates the reactive power in rotor side converter to accomplish the best damping of oscillations. In order to validate the claims the well-known two-area four-machine power system aggregated with DFIG is simulated using Matlab/Simulink. Simulation results disclose that, the DFIG enhanced with fuzzy damping controller is more robust and effective for damping the electromechanical oscillations. Also a comparison between proposed controller and conventional PI controller is performed that exhibits the superior performance of Fuzzy logic controller toward its conventional PI controller.

Keywords: Inter-Area Oscillation Damping, Doubly Fed Induction Generator (DFIG), Fuzzy Logic Controller, Reactive Power Modulation.

I. INTRODUCTION

The developing rate of large scale wind-farm installations in numerous countries around the world has put wind energy at the lead of the renewable energy revolution. Large penetration of wind power in to electric power system will decrease amount of electric power supply from conventional power plants, which required the development of larger and more robust wind energy conversion systems (WECS) [1-3]. The DFIG based wind farm has been popular among numerous other methods of wind power generation due to variable speed operation, four quadrant active and reactive power Capabilities [4, 5], higher efficiency, and extracting maximum electric power at various wind speeds via rotor speed adjustment [6].

Considering these salient considerable capabilities, in the recent years researches have been motivated to utilize the DFIG for additional functions. One topic is transient stability enhancement and the other is low frequency oscillation damping in power system with DFIG that has been discussed in literature [7, 8 and 9]. Damping of oscillations via an auxiliary power system stabilizer (PSS) loop through DFIG based wind farm is pointed out in [10, 11]. Investigators usually divide the electromechanical oscillations in two types: Inter-area mode and Local mode. Local mode includes two sets of generators that swing against one another. Inter-area mode involves large number of generators and areas with complex features. The control of inter-area oscillation in power systems is more difficult than local oscillation. Inter-area oscillation problem is an essential subject in power system stability and control investigation [10, 11].

Many methods have been used in the design of auxiliary damping controllers in the literature. In [12], it is shown that Flux Magnitude and Angle Control (FMAC) with the PSSs provide the DFIG-based wind generation with much greater capability of contributing to network damping. In [13], a classic phase compensator is investigated for inter-area oscillation damping. Since the inter-area oscillation is a fact related to the rotor angle (active power) and voltage magnitude (reactive power). Therefore, active and reactive power modulations are effective methods for damping oscillations in power system.

In [15] Controllers are supplemented in both active and reactive power control loops of the DFIG to improve electromechanical oscillation damping, that investigates active and reactive power modulation methods for damping the inter-area oscillation in DFIG-based wind farm. Reactive power modulation is better for damping because it has no negative effects on electromechanical torque, but active power modulation has negative effects on electromechanical torque. The main obstacle with these methods which are cited above is that the control principle is based on a linearized machine model and the control parameters are tuned to some nominal operation states.

In the matter of large disturbances, the system conditions will change in an extremely nonlinear behavior and controllers entirely are not capable of damping the oscillations, even controller may supplement a destabilizing impact to the disturbance by for example inserting negative damping. To prevail over these, the control design technique should consider nonlinear dynamics of power system. In this base some stabilizing control method for power system has been suggested [16].

Recently, Fuzzy Logic Controllers (FLCs) have appeared as an efficient tool to stabilize the power system with various devices for example FACTS devices [16, 17]. However, to author's best knowledge, there is no research to study using of FLC in DFIG based PSS. The aim of this paper is to utilize fuzzy logic supplementary damping controller in DFIG for inter-area oscillation damping.

Two supplemental signals include $\Delta\omega_{13}$, $\Delta\delta_{13}$ that exhibit the inter-area oscillation information, will be inserted as the FLC input signals then output signal of supplementary FLC controller is used to modulate reactive power in DFIG for effective inter-area oscillation damping. This paper also compares the proposed fuzzy logic controller with conventional PI controller for alleviating the inter-area oscillation. The results reveal the superior performance of suggested FLC toward conventional PI controller.

II. MATHEMATICAL MODEL OF THE DFIG

The construction of a grid-tide system with DFIG and wind turbine is shown in Figure 1. The DFIG wind turbine control usually contains of two parts, the mechanical control on the wind turbine bladepitch angle, and the electrical control on the power converters [18].

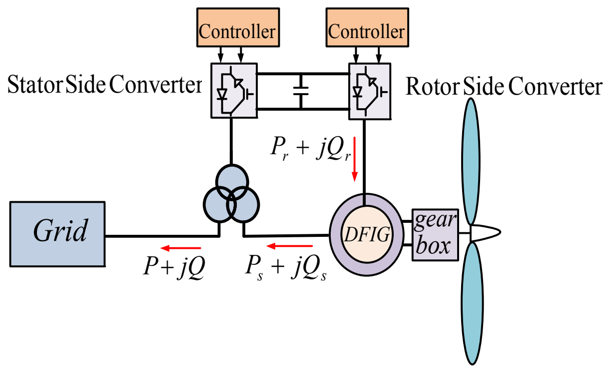

Figure 1. Grid-tied DFIG wind turbine system

A detailed modeling approach of DFIG is pointed out in [19, 9]. The electromechanical dynamic equation is given by [20].

$$n_p j \frac{d_{\omega m}}{d_t} + \omega_m = T_m - T_e \quad (1)$$

where T_e is the electromagnetic torque and T_m is the mechanical torque provided to the machine that is in the reverse direction from T_e, ω_m is rotational angular speed of the lumped-mass shaft system and $\omega_m = n_p \omega_r$, where n_p is the number of pole pair and D_m is the damping of the shaft system.

The induction machine analyzed in this paper is a wound rotor induction machine fed by two back-to-back Converters. The rotor and stator voltage equation in the stationary frame can be written in matrix form as follows [20, 11]:

$$V_{sabc} = R_s i_{Sabc} + j\omega_{sabc}\lambda_{sabc} + \frac{d_{\lambda_{sabc}}}{d_t} \quad (2)$$

$$V_{rabc} = R_r i_{Rabc} + j(\omega_s - \omega_r)\lambda_{rabc} + \frac{d_{\lambda_{rabc}}}{d_t} \quad (3)$$

where, R_s and R_r are, respectively the stator and rotor resistances (Ω), ω_s is the rotational angular speed of the synchronous d-q reference frame, ω_r is the rotational angular speed of the rotor, v is the voltage (V), i is the current (A),and λ is the flux linkage (Wb) in the DFIG. Neglecting the power losses in the stator and rotor resistances, the active and reactive powers from the stator in (d-q) coordinate are given by:

$$p_S = -\frac{3}{2}(i_{sd}v_{Sd} + i_{sq}v_{sq}) \quad (4)$$

$$Q_S = -\frac{3}{2}(i_{sd}v_{Sq} - i_{sq}v_{sd}) \quad (5)$$

and the active and reactive powers from the rotor (d-q) coordinate are given by:

$$P_r = \frac{3}{2}(i_{rd}v_{rd} + i_{rq}v_{rq}) \quad (6)$$

$$Q_r = \frac{3}{2}(i_{rd}v_{rq} - i_{rq}v_{rd}) \quad (7)$$

III. DFIG BASED WIND POWER CONTROL

DFIG is equipped with a decoupled active (P) and reactive (Q) power controller in rotor and grid side converter. The rotor converter allows decoupled control of active and reactive power of the generator. Decoupled control of the active and reactive power is obtained from formulating the control algorithm of the converters in synchronously rotating frame. The block diagram of the overall system including the controllers and the DFIG with rotor-side converter is shown in Figure 2.

The i_{qr} and i_{dr} can control active and reactive power of DFIG respectively. The control scheme for rotor-side converter is demonstrated in Figure 2.

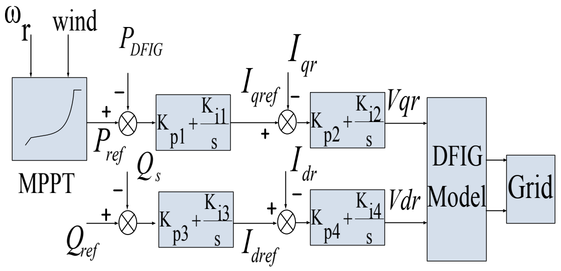

Figure 2. The control structure of the DFIG with rotor-side converter

The reference value of the rotor real power (P_{ref}) is obtained through the Maximum Power Point Tracking (MPPT) lookup table, which enables the optimal power tracking for maximum energy capturing from the wind then PI controllers provide i_{qref} from Δp_s and d-axis loop is used to regulate reactive power of DFIG stator Q_s.

A. Control of Rotor Side Converter (RSC)

The rotor- side converter control scheme consists of two cascaded control loops. The outer control loop manages the active and reactive power in machine. The active power can be controlled by V_{qr} while the reactive power can be controlled by V_{dr}. The inner current control loop manages separately the d-axis and q-axis rotor current components, i_{dr} and i_{qr} according to a synchronously rotating reference frame which is not included in our investigation [21].

B. Control of Grid Side Converter (GSC)

The objective of GSC is to keep DC-link voltage constant with ignoring the magnitude and direction of the rotor power, maintaining the input current sinusoidal and controlling the input power factor. The active power via the GSC represents a shunt power converter as RSC can supply reactive power control, GSC may offer more voltage support capacity in condition of transient operations or excessive speed ranges [19].

C. Electro Mechanical Oscillations

Electromechanical oscillations are due to the dynamic of inter-area power transfer in a large inter connected power network that can seriously limits the operation of system and in some condition induce stress in the mechanical shaft of synchronous generators. Usually the electromechanical oscillations divide in 2 types [11, 21]:

- Local mode: the local mode oscillations are due to swing of one synchronous generator against another generator in same area, they usually have frequencies from 1 to 3 Hz.
- Inter-area mode: the inter-area oscillation involves oscillations of a group of generators in one area against a group of generators in another area. They are in range of less than 1 Hz.

Typically it is more difficult to control inter-area oscillation than local oscillation in actual power systems [10, 11].

IV. CONTROL SCHEME DESCRIPTION

A. Case 1: PI Controller Design

In order to obtain decoupled control of active and reactive power of the DFIG, vector control scheme based on proportional integral (PI) controllers was suggested and has been widely used in the industry due to their simple structure, robust performance, easy to design and low cost [13]. To achieve for better damping of inter-area oscillation in DFIG based-wind farm, many methods have been used in design of auxiliary damping controllers [13, 14]. The DFIG control in [10] is based on FMAC. An auxiliary damping control is added to improve the flux angle reference, which is acquired from a PI controller to follow the active power reference.

In [12], an auxiliary signal extracted from the rotor speed is added to the rotor phase angle control to improve the low frequency damping of the system. It has been recommended and verified in the literature that for inter-area oscillation, the best control signals are the rotor angle difference ($\Delta\delta_{13}$, $\Delta\delta_{14}$) and difference between speeds of generators 3 and 1 or generators 4 and 1 ($\Delta\omega_{13}, \Delta\omega_{14}$) [22, 23]. Two supplemental signals include $\Delta\omega_{13}$ or $\Delta\delta_{13}$ exhibit the inter-area oscillation data will be inserted as the PI controller signals. Output signal of supplementary PI controller is used to adjust reactive power in the DFIG for effective inter-area oscillation damping.

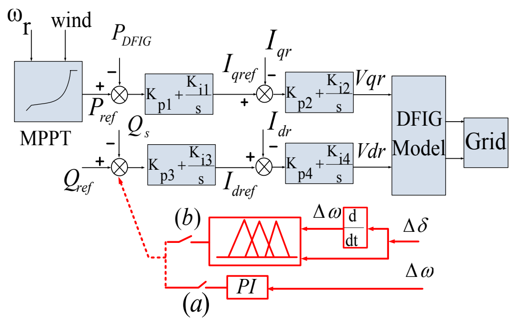

Figure 3. Proposed control structure of the DFIG with rotor-side converter

The dynamic response of reactive power modulation on the electromagnetic torque T_e is less harmful than active power modulation case, and also the reactive power modulation has not negative effects on the shaft mode [15]. Thus in this paper for the study system, the reactive power modulation investigated and its construction is shown in Figure 3.

As shown in Figure 3 there are two cases in order to switch between control loops. The PI controller loop acts when switch (a) operates, furthermore, the Fuzzy controller loop acts when switch (b) operates which is precisely clarified in next section. The damping loop is added to reactive power control loop of the DFIG RCS. The PI controllers are utilized in the control loops such that the measured power follows the modulated reference power values.

Traditional methods of design, based on some characteristics of the output curves for particular inputs applied on the system, were used to acquire initial values for the PI gains of the controllers. Then, the gains were exactingly regulated for trying and error through various simulations, in order to obtain least difference for the controlled variables include in design. After this long operation of adjusting, the values acquired for the PI controller gain are shown in Table 2 of Appendices. The block diagram of proposed PI controller is demonstrated in Figure 4.

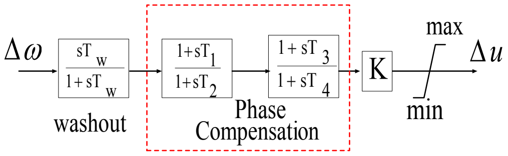

Figure 4. Transfer function for PI controller

B. Case2: Fuzzy Controller Design

Although PI controller can play an important role in stability of the power system and especially for damping of inter-area oscillation, the best performance of the PI controller and accordingly, the performance of the DFIG depend on a suitable choice of the PI gains. Tuning the PI gains to make optimal operation is difficult task, especially, when the process is nonlinear and may change during operation. Because of the fuzzy control robustness about to many nonlinear procedures, this paper suggests the design of the fuzzy controller to control the reactive power modulation.

As earlier depicted in Figure 3, the fuzzy controller acts when the switch (b) operates. Fuzzy controller introduces a systematic method to control a nonlinear procedure based on human experience. This can be regarded as a heuristic method that can enhance the operation of closed loop system. The fuzzy controller operation is based on its capability to simulate several role implications at the same time procedure, and the output results are significantly comprehensive.

A correctly designed fuzzy controller can provide higher operation in presence of variations in parameters, external perturbations, and load existence than conventional PI controllers.

The basic formation of a fuzzy controller is consisted of four parts: fuzzifications block, fuzzy knowledge based block, a fuzzy inference engine and a defuzzification block. Figure 5 shows the block diagram of the fuzzy control for $\Delta\omega_{13}$ or $\Delta\delta_{13}$ (difference between speeds of generators 3 and 1 or the rotor angle differences) [23].

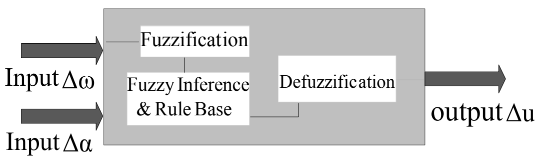

Figure 5. Block diagram of the fuzzy controller

Standard triangular membership's functions were employed for the inputs and output fuzzy sets of the fuzzy controller. The schemed fuzzy sets for $\Delta\omega_{13}$ or $\Delta\delta_{13}$ are shown in Figure 6. The control roles of the fuzzy controllers are demonstrated by set of heuristically selected fuzzy rules. The schemed fuzzy rules employed in this paper for controller are stated in Table 1.

Table 1. The fuzzy rule bases

$d\delta$ \ $d\omega$	PL	P	ZE	N	NL
PL	PL	PL	PL	ZE	ZE
P	PL	PL	P	N	N
ZE	PL	PL	ZE	NL	NL
N	P	P	N	NL	NL
NL	ZE	ZE	NL	NL	NL

The fuzzy sets have been determined as: NL, negative large, NM, negative medium, NS, negative small and ZE, zero, PS, Positive small, PM positive medium, PL, positive large, respectively.

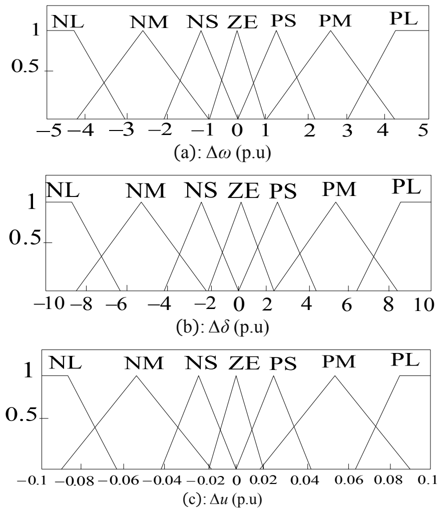

Figure 6. Triangular membership functions for inputs and output fuzzy sets of the fuzzy controllers

V. SIMULATION RESULTS

A. System under Study

In this section, the well-known two-area four-machine power system that developed in [11] is investigated, and is shown in Figure 7. In steady state, approximately 400 MW flows from area 1 to area 2. Both areas have two synchronous generators, both with 835 MW rated power. All four synchronous generators are the same and are enhanced with turbine governors.Detailed parameters of the synchronous generators [20] and other control block parameters are included in appendices. As cited above, a power system is aggregated with DFIG based wind farm which is linked to the grid in bus 7. The wind farm is transferring 150 MW to power system.

The scope of this simulation is to study the operations of both PI and fuzzy controllers respecting the damping of inter-area oscillation in the power system with DFIG-based wind farm when there is disturbance in the power systems.

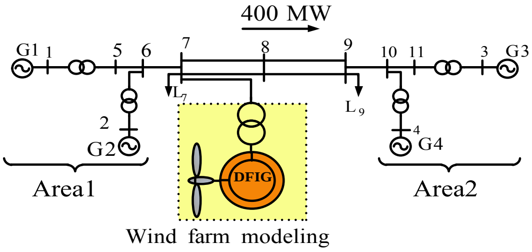

Figure 7. One-line diagram of two-area system with a wind generator

The regarded control scheme is tested in the power system shown in Figure 7 [11]. The power transfer between the two areas is about 400 MW. During the simulation, the wind speed is constant (11.85 m/s), A short-term three-phase fault happens at bus 8 under steady state at t=1 sec and is cleared after 12 cycle (12/60 sec). It is essential to note that, the time scale in this simulation is smaller than wind variation, and in fact the speed of wind considered constant during this simulation. Simulation results in Matlab/Simulink confirm the analysis precisely.

B. Simulation Results without any Controller

Figure 8 (a-e) shows the dynamic response of the DFIG and synchronous generator responses without any controller for reactive power modulation.

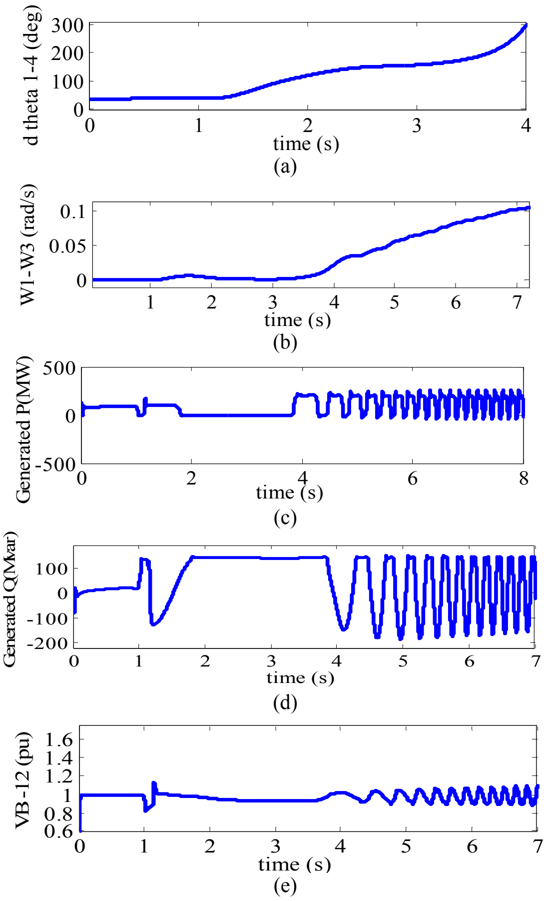

Figure 8. Simulation results for the system dynamic responses without any controller (a) Relative rotor angles (δ_{14}, δ_{24}, δ_{34}) (b) Speed deviation between generator 1 and 3 (c) Output active power generated by the DFIG (d) Output reactive power generated by DFIG (e) the voltage at bus 12 [p.u]

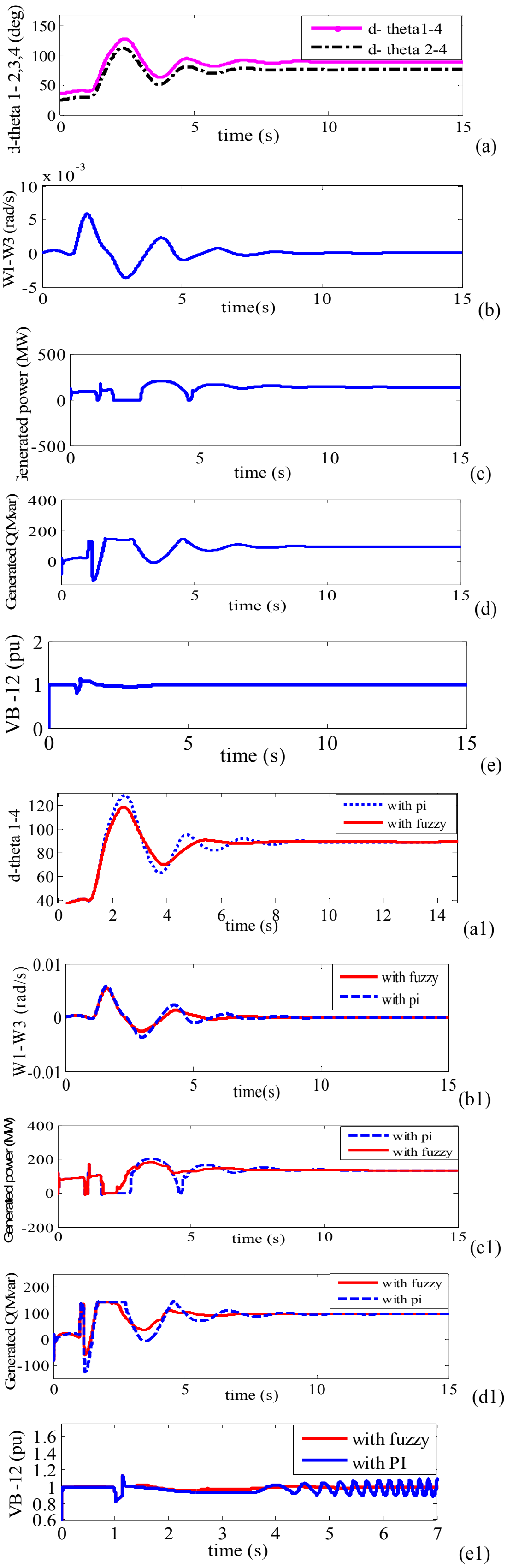

Figure 9. Simulation results for the system dynamic responses enhanced with fuzzy controller in comparison with PI controller (a and a1) - Relative rotor angle (δ_{14}) (b and b1) - Speed deviation between generator 1 and 3 (c and c1). Output power generated by the DFIG (d and d1) - Output reactive power generated by DFIG (e and e1) the voltage at bus 12 [p.u]

C. Simulation Results with Fuzzy and PI Controller

The purpose of this section is to study the operations of PI and fuzzy controllers considering the dynamic stability of the power system for reactive power modulation when there is disturbance in the connected networks. Figure 9 (a-e) shows the dynamic response of the DFIG and synchronous generator only with PI controller and Figure 9 (a1-e1) shows the same response with PI and fuzzy controller, where the dashed lines correspond to PI controller and solid lines correspond to fuzzy controller.

The results of simulation obviously show that, fuzzy controller performance is better than the PI counterpart since the system with Fuzzy controller has less overshoot and less settling time, compared with the conventional PI controller. When the fault occurs in the system, the damper PI controller performance would be remarkably weak that is due to nonlinear and coupling terms, so a new adjusting of the gains would be essential. During the fault, the fuzzy controller performs robustly, despite the reality that membership functions and the rules were not carefully regulated as in the PI controller scheme. In this paper, although in fuzzy controller not used any optimization methods, however, fuzzy stabilizer provides a better choice of performance for damping of low frequency oscillations when large distortions exist in power system.

VI. CONCLUSIONS

In this paper, a fuzzy logic controller design is investigated for DFIG based wind power penetration in inter connected system oscillation damping. The fuzzy damping control loop for DFIG modulates reactive power in rotor side converter to damp the inter-area oscillations. Comparative experiments between the PI controller and proposed fuzzy controller scheme have been accomplished using dynamic simulation in Matlab/ Simulink. As it was demonstrated, although PI controller can perform a key role in DFIG to damp the inter-area oscillations, but its better performance is required to meet the suitable range of gains that, is possible with much amount of simulations, while the proposed fuzzy controller scheme were regulated in only a few simulations. Simulation results reveal that, since the system includes nonlinear and coupling terms, the DFIG with proposed fuzzy controller is more effective and has robust control, than the DFIG with the conventional PI controller in damping of inter-area oscillations.

APPENDICES

Table 2. Parameters of the Shaft System of DFIG

H_t (s)	0.09955
H_g (s)	3.95279
D_t (pu)	0
D_g (pu)	0
D_{tg} (pu)	.09231
K_{tg} (pu)	0.22

Table 3. Gains for PI controller

Gains	Values
k	100
T_W	20
T_1	0.3
T_2	1
T_3	.7
T_4	.35

- Induction Machine and Turbine Data
Rated rotor voltage = 1945 V;
Rated DC-link voltage = 1200 V;
Rated stator power = 1270 kW;
Rated stator voltage = 690 V;

- Parameters of Synchronous Generator
Synchronous Generators Data
Rating: 835 MVA
Line to line voltage: 26 kV
Power factor: 0.85
Poles: 2, Speed: 3600 r/min

NOMENCLATURES

ω_s , ω_r: Stator and rotor rotating speed.
T_m: Mechanical torque
T_e: Electromagnetic torque
n_p: Number of pole pairs
j: Inertia constant
ω_m: Rotational angular speed
v_{sabc}: Stator voltage
v_r: Rotor voltage
i_{sabc}: Stator current
i_r: Rotor current
R_s , R_r : Stator and rotor resistances
λ_{sabc}: Stator flux linkage
λ_{rabc}: Rotor flux linkage
v_{sd} , v_{sq}: Stator voltages in d and q axis
i_{sd} , i_{sq}: Stator currents in d and q axis
λ_{sd} , λ_{sq}: d and q axis stator flux linkages
v_{rd} , v_{rq}: Rotor voltages in d and q axis
i_{rd} , i_{rq}: Rotor currents in d and q axis
$\Delta\delta$: Rotor angle difference
$\Delta\omega$: Difference between speeds
Q_{ref}: Refrence value for reactive power
P_{ref}: Refrence value for active power

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BIOGRAPHIES

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