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Fuzzy Logic Controller Design for a DFIG-Based Wind Farm to Damp Interarea Oscillations

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Abstract: In this study, a fuzzy logic controller scheme is developed for a Doubly Fed Induction Generator (DFIG) based wind farm to damp interarea oscillations. These oscillations are due to the dynamics of interarea power transfer in a large interconnected power network that can severely limits the system operations. To provide a safe operation for power networks, damping of these oscillations have become one of the main problems in the power system stability and have received a great deal of attentions. DFIG based wind energy system is the popular type of variable-speed generator used in wind power generation. It is very important to assess the role of DFIG on overall system transient stability. The auxiliary fuzzy damping controller, modulate reactive power in rotor side converter to damp interarea oscillations. Well-known two-area four-machine power system that has low interarea oscillation damping are investigated. Also, a comparison between proposed controller and conventional PI controller is performed. Simulation results in MATLAB/Simulink validate that fuzzy damping controller is more robust and effective for damping electromechanical oscillations.

Key words: Fuzzy logic controller, interarea oscillation damping, Doubly Fed Induction Generator (DFIG), reactive power modulation, Iran

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. Based on the electrical topology in wind farm, wind turbine generators can be classified into the following 4 categories (Zavadil *et al*., 2007):

- Fixed-speed squirrel-cage induction generators
- Variable-slip (wound rotor) induction generators with variable rotor resistance
- Variable-speed generators with full converter interface
- Variable-speed doubly fed asynchronous generators

The Doubly Fed Induction Generator (DFIG) based wind farm has been popular among numerous other methods of wind power generation because variable speed wind turbines utilizing DFIG has higher efficiency and its ability to extract maximum electric power at various wind speeds via rotor speed adjustment.

Also in comparison with the wind turbines based on synchronous machines, the (DFIG) based wind power generation technology has superior characteristics, such as lower converter costs and lower power losses and flexible active and reactive power control capability through its Rotor Side Converter (RSC) (Muller *et al*., 2002; Datta and Rangenathan, 2002).

Thanks to these salient capabilities considerable researches have been developed to the DFIG in the recent years. One of topic is transient stability enhancement and low frequency oscillation damping in power system with DFIG. That has been discussed in literature. To damping oscillations in power system via an axillary Power System Stabilizer (PSS) loop wind turbine employing DFIG is pointed out in CIGRE (1996). Investigators usually divide the electromechanical oscillation into 2 types:

- Interarea mode
- Local mode

Interarea mode includes 2 sets of generators that swing against one another. Interarea mode involves large number of generators and areas with complex features, typically it is more difficult to control Interarea oscillation than local oscillation in actual power systems. Interarea oscillation problem is an essential subject in power system stability and control investigation (CIGRE, 1996; Kundur, 2002).

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Mishra *et al.* (2009), it is shown that Flux Magnitude and Angle Control (FMAC) control with the PSS_s provides DFIG-based wind generation with much greater capability of contributing to network damping. In Fan *et al.* (2011) controllers to improve electromechanical oscillation damping are supplemented in both active and reactive power control loops of the DFIG that investigates active and reactive power modulation methods for damping the interarea oscillation in DFIG-based wind farm. Since, the interarea oscillation is a fact related to the rotor angle (active power), voltage magnitude (reactive power), therefore active and reactive power modulation are effective methods for damping oscillations in power system. Reactive modulation is better for damping because it has not negative effects on electromechanical torque but active modulation has a negative effects on electromechanical torque. Thus in order to achieve better performance, the auxiliary fuzzy damping controller, modulates reactive power in rotor side converter to damp interarea oscillations. Many methods have been used in the design of auxiliary damping controllers in the earlier reference. Like Tsourakis *et al.* (2009) that use a classic phase compensator or reference, Yang *et al.* (2010) that uses pole placement technique for auxiliary controller design. The main obstacle with these methods 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 controller are not entirely acceptable. In this simulation, the controller may even 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 (Krohling and Rey, 2001).

Recently, Fuzzy Logic Controllers (FLC_s) have appear, as an efficient tool to stabilizer power system with various devices for example FACTS devices (Krohling and Rey, 2001) or PSS (Zarghami *et al.*, 2010). However to researchers best knowledge, there is no research to study using of FLC in DFIG based PSS.

The aim of this study is to utilize fuzzy logic supplementary damping controller in DFIG for interarea oscillation damping.

The fuzzy logic controller is varied widely by a suitable choice of membership function and parameters in the rule base. The 2 supplemental signal include $\Delta\omega_{13}$, $\Delta\delta_{13}$ that exhibit the interarea oscillation information will be insert as the FLC input signals then output signal of supplementary FLC controller are used to modulate reactive power in DFIG for effective interarea oscillation damping. Hughes *et al.* (2006), it is shown that an appropriate designed fuzzy controller can give better performance in interarea oscillation damping compare with conventional PI controller.

MATHHEMATICAL MODEL OF THE DFIG

In this part, the dynamic model of the DFIG is exhibited by a set of mathematical equations. The construction of a grid-tide system with DFIG and wind turbine is shown in Fig. 1. The DFIG wind turbine control usually contain of 2 parts, the mechanical control on the wind turbine, blade pitch angle and the electrical control on the power converters. The electrical part of the DFIG includes the rotor-side current control, the power control, dc link dynamics, the grid-side current control and pulse wide modulation scheme. A detailed modeling approach of DFIGs pointed out in Tapia *et al.* (2003), Mei and Pal (2008) and Muller *et al.* (2002). The electromechanical dynamic equation is given by:

$$n_p J \frac{d\omega_m}{dt} + D_m \omega_m = T_m - T_s \tag{1}$$

Where:

T_s = The electromagnetic torque

T_m = The mechanical torque provided to the machine that T_s is in the reverse direction of mechanical torque

ω_m = The rotational angular speed of the lumped-mass shaft system and $\omega_m = n_p\omega_r$

n_p = The number of pole pair

D_m = The damping of the shaft system

The rotor and stator magne to-motive force have to be in synchronism, than slip frequency, ω_{slip} or frequency of the rotor currents is given by:

$$\omega_{slip} = \omega_s - \omega_r =_s \omega_s \tag{2}$$

The induction machine analyzed in this study is a wound rotor induction machine fed by 2 back-to-back converters. The following foundation equations are used to model the DFIG generator. The rotor and stator voltage equation in the stationary frame can be written in matrix form as follows (Krause, 1986; Kundur, 2002):

$$v_{sabc} = R_s i_{sabc} + \frac{d\lambda_{sabc}}{dt} \tag{3}$$

$$v_{rabc} = R_r i_{rabc} + \frac{d\lambda_{rabc}}{dt} \tag{4}$$

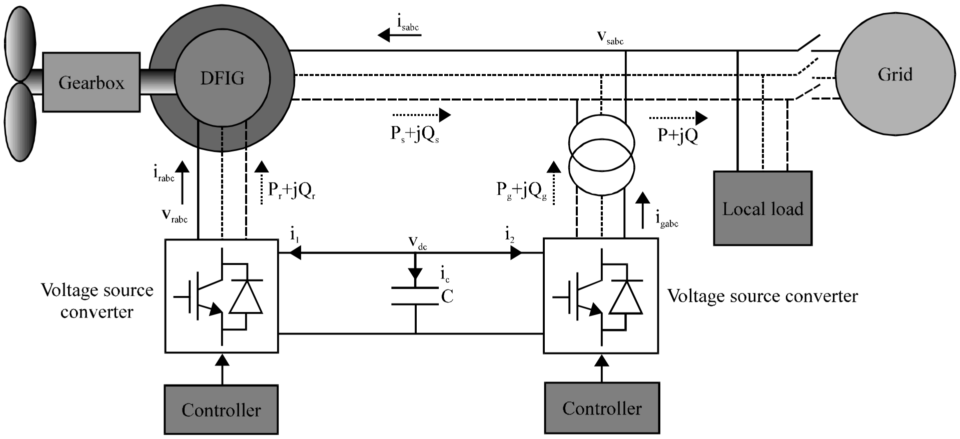

Fig. 1: Grid-tied DFIG wind turbine system

These 2 equations in the arbitrary references frame (d-q) can be written in terms of the currents as:

$$v_{sd} = R_s i_{sd} - \omega_s \lambda_{sq} + \frac{d\lambda_{sd}}{dt} \tag{5}$$

$$v_{sq} = R_s i_{sq} - \omega_s \lambda_{sd} + \frac{d\lambda_{sq}}{dt} \tag{6}$$

$$v_{rd} = R_r i_{rd} - (\omega_s - \omega_r)\lambda_{rq} + \frac{d\lambda_{rd}}{dt} \tag{7}$$

$$v_{rq} = R_r i_{rq} + (\omega_s - \omega_r)\lambda_{rd} + \frac{d\lambda_{rq}}{dt} \tag{8}$$

Where:

R_s and R_r = The stator and rotor resistances (Ω)
ω_s = The rotational angular speed of the synchronous d-q reference frame
ω_r = The rotational angular speed of the rotor
v = The voltage (v)
ι = The current (A)
λ = The flux linkage (Wb)

In the DFIG, v_{qr} and v_{dr} are not zero and are controllable via the rotor-side converter. Also, the stator and rotor flux linkages are given by:

$$\lambda_{sd} = L_{ls} i_{sd} + L_m (i_{sd} + i_{rd}) = L_s i_{sd} + L_m i_{rd} \tag{9}$$

$$\lambda_{sq} = L_{ls} i_{sq} + L_m (i_{sq} + i_{rq}) = L_s i_{sq} + L_m i_{rq} \tag{10}$$

$$\lambda_{rd} = L_{lr} i_{rd} + L_m (i_{sd} + i_{rd}) = L_r i_{rd} + L_m i_{sd} \tag{11}$$

$$\lambda_{rq} = L_{lr} i_{rq} + L_m (i_{sq} + i_{rq}) = L_r i_{rq} + L_m i_{sq} \tag{12}$$

Where:

L_s, L_r = The stator and rotor inductance
L_m = The mutual inductance

The electromagnetic torque manufactured by generator can be expressed as:

$$T_e = n_p L_m (i_{sd} i_{rq} - i_{sq} i_{rd}) \tag{13}$$

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:

$$P_S = -\frac{3}{2}(i_{sd} v_{sd} + i_{sq} v_{sq}) \tag{14}$$

$$Q_S = -\frac{3}{2}(i_{sd} v_{sq} - i_{sq} v_{sd}) \tag{15}$$

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

$$P_r = \frac{3}{2}(i_{rd} v_{rd} - i_{rq} v_{rq}) \tag{16}$$

$$Q_r = \frac{3}{2}(i_{rd} v_{rq} - i_{rq} v_{rd}) \tag{17}$$

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 converter allows decoupled control of active and reactive power of the generator in addition reactive power control can be implemented at lower cost due to the DFIG system (4-quadrant converter and induction machine) in reality operates similar to a synchronous generator. The converter has to provide only excitation energy (Petersson, 2003; Peresada *et al.*, 2004).

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

The reference value of the stator real Power (P_{ref}) is obtained though the Maximum Power Point Tracking (MPPT) lookup table which enable 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 the DFIG stator Q_s. The dynamics of DC link between the rotor side converter and grid side converter are ignored.

Control of Rotor-Side Converter (RSC): The rotor-side converter control scheme consists of 2 cascaded control loops. The outer control loops manage the active power and reactive power output from the machine stator independently. The inner current control loops manage separately the d-axis and q-axis rotor current components, i_{rd} and i_{rq}, according to a synchronously rotating reference frame. Where the voltage directed vector control is used.

Control of Grid-Side Converter (GSC): The objective of control of the GSC is to keep DC-link voltage constant with ignoring the magnitude and direction of the rotor power. Hence, 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 in transient operations or excessive speed ranges. In this study, only the control of RSC is considered.

Dynamical model of the aggregated wind farm based DFIG: The objective of the stability and behaviour studies of the DFIG wind turbine system are present better comprehensible of the system inherent dynamics which can be valuable for robust control design of such system.

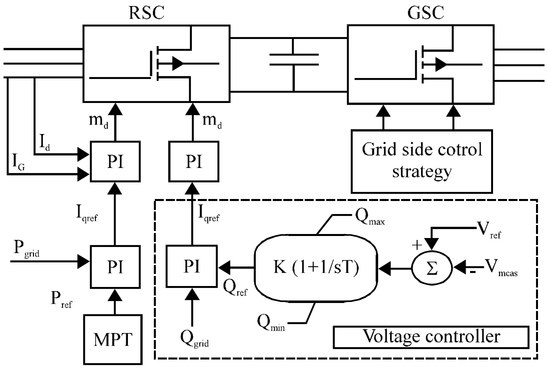

Fig. 2: Rotor-side converter control loops

The dynamic model of DFIG based on time-domain simulations have been analyzed to explore the operation of the DFIG system and its effect on power system dynamics (Akhmatov, 2003; Nunes *et al.*, 2004). Regarding that electrical dynamics is faster than the steady state of the system (Ledesma and Usaola, 2004, 2005). So, the corresponding mechanical behavior can be approximated for the dynamical aggregated wind farm. The simplified mathematical model of aggregated wind turbine is considered because the main goal of investigation is to evaluate the effects of wind farm an electromechanical oscillation of power grid. So, single lumped mass mathematical model of the aggregated wind turbine can be expressed:

$$\begin{gathered}\left(J_g + \frac{J_t}{\left(n_{gb}\right)^2}\right)K_{sh} = \left(J_g + \frac{J_t}{\left(n_{gb}\right)^2}\right) \\ n_{gb}.K_{sh} = \frac{T_t}{N}T_e\end{gathered} \tag{18}$$

This equation shows the generator shaft K_{sh} via the gearbox n_{gb}, J_t and J_g being the intertias of the aggregated wind turbine model and the generator plus the gearbox one, respectively.

ELECTROMACHENICAL OSCILLATION

In this part, electromechanical oscillations are described. Also, a nonlinear control scheme with DFIG-based wind farm (active and reactive power modulation) to damp interarea oscillations is proposed. Electromechanical oscillations are due to the dynamic of interarea 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 synchronous generators. Usually the electromechanical oscillations divide in to 2 types

(Kundur, 2002; Sauer and Pai, 1998): Local mode, the local mode oscillations are due to swinging of one synchronous generator against another generator in same area, they usually have frequencies from 1-3 Hz.

The interarea mode, the interarea oscillation due to swinging of area 1 against area 2. They are in range of <1 Hz.

Typically it is more difficult to control interarea oscillation than local oscillation in actual power systems. In active and reactive power modulation for interarea oscillations damping have been investigated and its shown that both methods are effective (Fan *et al*., 2011). And demonstrated that active power modulation is better for damping oscillations, however wind farm with active power modulation effects on the wind turbine's shaft. (Damping of the shaft mode decreases) because in wind turbine, the torsional oscillation frequency is pretty low. While reactive power modulation has not negative effects on the wind turbine's shaft and electromechanical torque because reactive power is not straightly associated with the wind turbine's shaft and electromagnetic torque. Therefore in order to achieve better performance, the auxiliary control loop supplemented for modulate reactive power in rotor side converter of DFIG's.

SYSTEM UNDER STUDY

In this study, well-known two-area four-machine power system that has low interarea oscillation damping, developed in Kundur (2002) are investigated. And is shown in Fig. 3. In steady state, approximately 400 MW flows from area 1-2.

Both areas have 2 synchronous generators, both with 835 MW rated power. All 4 synchronous generators are the same and enhance with turbine governors. Detailed parameters of the synchronous generators and other control block parameters are included in Appendix. As cited before, a power system in aggregated with wind farm based a DFIG which is linked to the grid in area one. The wind farm is transferring 200 MW to power system.

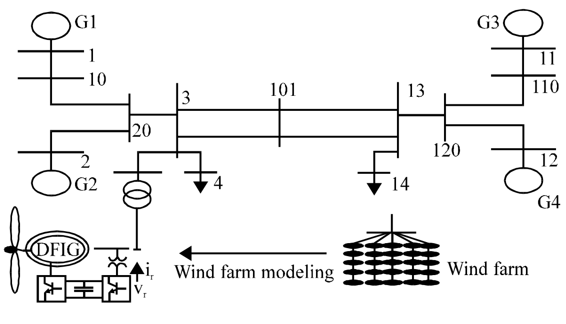

Fig. 3: One-line diagram of two-area system with a wind generator

CONTROL SCHEME DESCRIPTION

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 (Tsourakis *et al*., 2009). The decoupled control of DFIG has several different PI controllers. Suitable controller parameters are needed to achieve better up until now, the PI controller design is most broadly adopted in industrial application due to their simple structure and robust performance, easy to design and low cost. To achieve for better damping the interarea oscillation in DFIG based-wind farm, many methods have been used in design of auxiliary damping controllers, as suggested by Tsourakis *et al*. (2009) that used a classic phase compensator and PI controller or reference of Yang *et al*. (2010) that uses pole placement technique for auxiliary controller design. The DFIG control in CIGRE (1996) is based Flux Magnitude and Angle Control (FMAC). An auxiliary damping control is added to improve the flux angle reference which is acquired from a Proportional-Integral (PI) controller to follow the active power reference. Mishra *et al*. (2009), 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 interarea oscillation, the best control signals are the rotor angle difference ($\Delta\delta_{13}$ or $\Delta\delta_{14}$) and difference between speeds of generators 3 and 1 or generator 4 and 1 (Fan *et al*., 2002; Larsen *et al*., 1995). The 2 supplemental signals include $\Delta\omega_{13}$ or $\Delta\delta_{13}$ that exhibit the interarea oscillation data will be insert as the PI controller signals. Output signal of supplementary PI controller are used to modulation active and reactive power in the DFIG for effective interarea oscillation damping, the active power modulation will modulate the active power reference value because the dynamic response of reactive power modulation on the electromagnetic torque T_e is harmless than active power modulation case and also the reactive power modulation has not negative effects on the shaft mode. Thus in this study for the study system, the reactive power modulation investigated and its construction is shown in Fig. 4. As shown in Fig. 4, the damping loop is added to reactive power control loop of the DFIG RCS.

PI controllers are utilized in the control loops such power values. Traditional methods of design, based on that the measured power follows the modulated reference

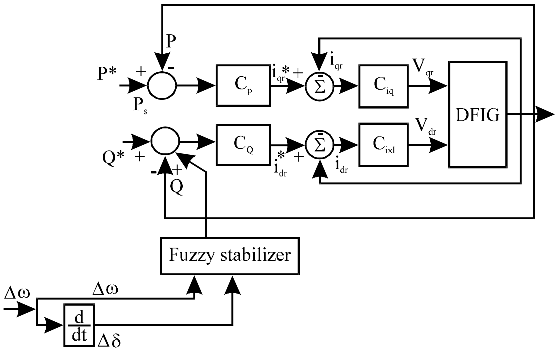

Fig. 4: The overall control structure of the DFIG with rotor-side converter

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 Appendix.

Case 2; fuzzy controller design: Although, PI controller could play an important role in stability of the power system and especially for damping of interred oscillation, however 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 study, suggests the design of the fuzzy controller to control the reactive power modulation. 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 simulation at the same time procedure several rule implication giving a better complete output. A correctly designed fuzzy controller can provide higher operation in presence of variations in parameters, external perturbations and load than conventional PI controllers. The basic formation of a fuzzy controller is consisted of 4 parts: Fuzzifications block, fuzzy knowledge-base block, a fuzzy inference engine can 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 he rotor angle difference). The tasks of the blocks and working fundamental law of the fuzzy system are briefly explained, as follow as (Lee, 1990):

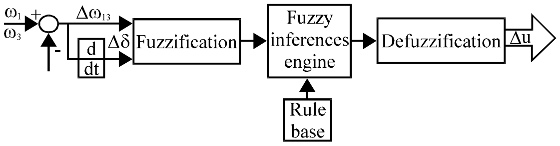

Fig. 5: Block diagram of the fuzzy controller

Fuzzificaton: Fuzzification is the procedure of finding suitable membership function to illustrate crisp information. The input signals to Fuzzy Logic Controller (FLC) are scaled utilizing suitable component factors. These scaled input information are then transformed into linguistic variables which can be observed as labels of fuzzy sets. Fuzzy sets may be categorized by membership functions. The membership functions can be classified into the various types for example triangular function, linear function, trapezoidal function and exponential function.

Fuzzy knowledge-base: The knowledge-base is the heart of a fuzzy controller that is consisted of 2 parts namely called fuzzy sets (data base) and fuzzy control rule base. These concepts are subjectively explained and based on experience. So, the exact choice of the membership function of a term set plays a necessary role in the prosperity of an application.

Fuzzy inference: The basic performance of the inference engine is that it deduces, i.e., it infers from evidence or information a logical deduction. This means that the fuzzy inference engine handles rules inference where human experience can simply be inserted through linguistic rules.

Defuzzification: The fuzzy conclusion of the inference engine is defizzified, i.e., it is transformed in to a continuous (crisp) signals. The cited signal is last result of the FLC which is the crisp control signal to the procedure.

In this study, the inputs and the output are normalized for the base values explained to the system and described in the Appendix. The frame and number of the memberships functions explaining the fuzzy value of controller (for the inputs and output) were described off-line and the universes of discourse for each variable were normalized to discrete values corresponding with the manner of the variables perceived during simulations. Standard triangular membership's functions were employed for the inputs and output fuzzy sets of the fuzzy

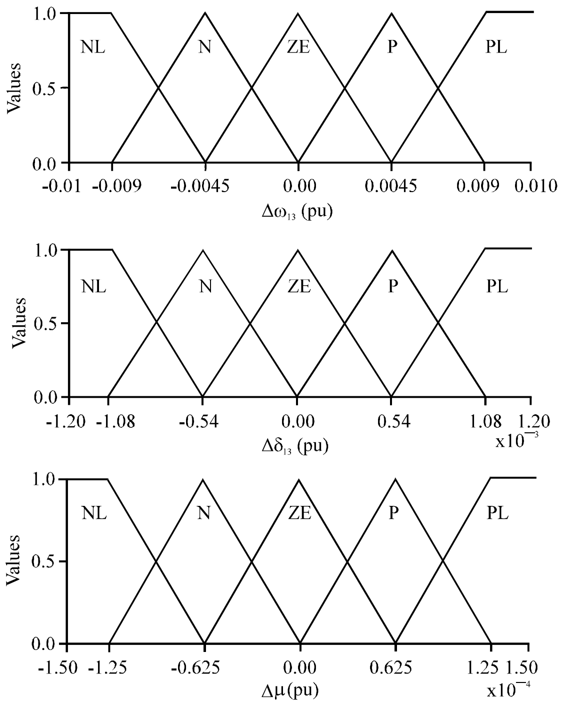

Fig. 6: Triangular memberships functions for inputs and output fuzzy sets of the fuzzy controller

Table 1: Rule base

	$\omega\Delta_{1\text{-}3}$				
$d\Delta\omega_{1\text{-}3}$	NB	NM	Z	PM	PB
P	NB	NM	Z	PM	PB
N	NB	NM	Z	PM	PB

controller. The schemed fuzzy sets for $\Delta\omega_{13}$ or $\Delta\delta_{13}$ are shown in Fig. 6. The control roles of the fuzzy controllers are demonstrated by set of heuristically selected fuzzy rules. The schemed fuzzy rules employed in this study for controller are stated in Table 1. The fuzzy sets have been determined as: NL (Negative Large), N (Negative), P (Positive), PL (Positive Large) and ZE (Zero), respectively.

SIMULATION RESULTS

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

The regarded control scheme is tested in the power system shown in Fig. 3. The power transfer between the 2 areas is about 400 MW (Kundur, 2002). During the simulation, the wind speed is constant (11.85 m sec^{-1}), a short-term three-phase fault happens at bus 3 under steady state for τ = 0.10 sec and is cleared at τ = 0.2 sec. It is essential to not that the time scale in this simulation is smaller than wind variation in fact the speed of wind considered constant during this simulation. A simulation result in MATLAB/Simulink more confirms the analyses.

Simulation results with PI controller: Figure 7 and 8 display the dynamic response of the DFIG and synchronous generator without interarea oscillation control. In Fig. 7, the rotor speeds and the rotor angle differences and electric Power (P_e) exporting levels are shown. In Fig. 8, the rotor speed, mechanical torque, electric torque and terminal voltage of the DFIG are plotted. It was observed that the system performance under test without any damping controller would be considerable poor and as time passed, the oscillation increase and the system can be unstable. Figure 9 and 10 shows the dynamic response of the DFIG and synchronous generator with the PI controller for reactive power modulation.

Figure 11 shows the dynamic response of the rotor angles (synchronous generator) where the dashed lines correspond to without PI controller and solid lines show the system with PI controller. It is deduced that reactive power modulation can impressively improve the damping of the interarea oscillation. Simulation results illustrate the effectiveness of PI damping controller by choosing the PI gains correctly.

Simulation results with fuzzy controller: The purpose of this research is to study the operations of PI and fuzzy controllers considering the dynamic stability of the power system that includes an evolution of the rotor speeds and the rotor angle difference and electric power exporting levels behaviors when there is disturbance in the connected networks. Figure 12 and 13 show the dynamic response of the DFIG and synchronous generator with fuzzy controller for reactive power modulation.

The results of simulation obviously show that fuzzy controller performance is better than the PI counterpart. The results of simulation obviously show that fuzzy controller performance is better than the PI counterpart. Figure 14 shows the dynamic response of the rotor angles (synchronous generator) where the dashed lines correspond to PI controller an solid lines correspond to fuzzy controller. As shown the plots, it is clear that the damping controller is effective for interarea oscillation damping out the 0.7 Hz. When the fault occurs in the system, the damper PI controller performance would be remarkably weak that is due to nonlinear and coupling terms and a new adjusting of the gains would be essential. During the fault occurs, the fuzzy controller performs more robustly, essential. During the fault occurs, the fuzzy controller performs more robustly, despite the reality that

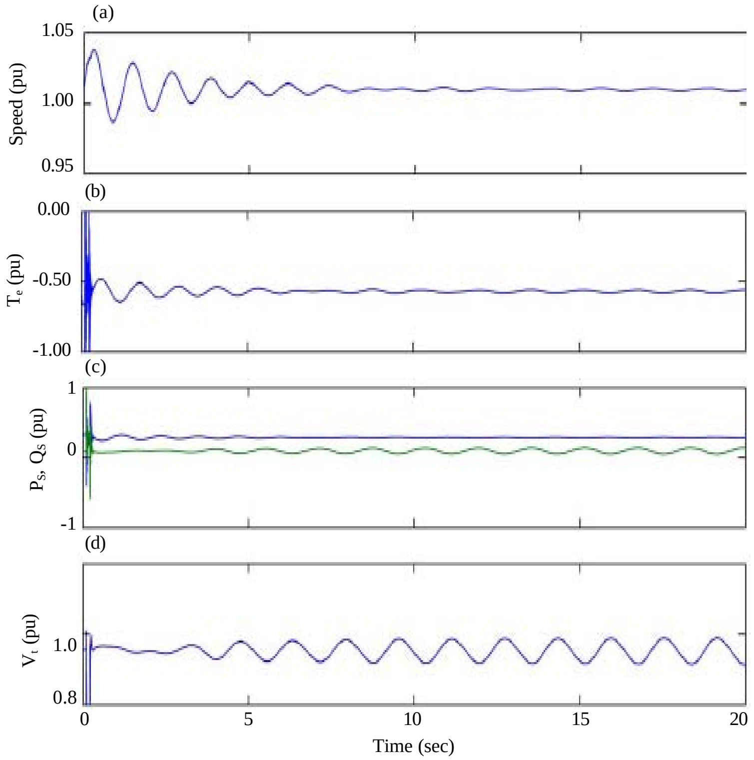

Fig. 7: Experimental results for the wind turbine generation dynamic responses with no supplementary damping control: a) Speed of DFIG rotor; b) Electrical torque; c) Output P and Q of the DFIG (P is above curve Q); d) Terminal voltage magnitude of the DFIG

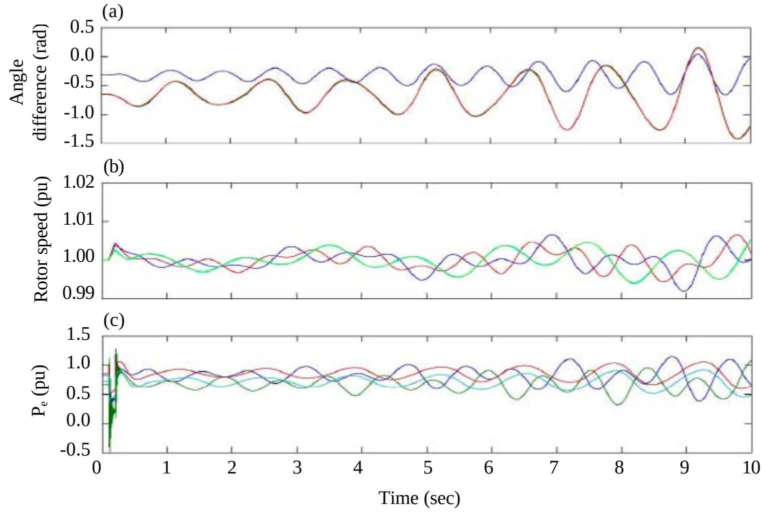

Fig. 8: Experimental results for the synchronous generator dynamic responses without any controller: a) Relative rotor angles δ_{14}, δ_{13} and δ_{12}; b) Speeds of the 4 synchronous generators; c) Output power levels from the 4 synchronous generators

membership functions and the rules were not carefully regulated as in the PI controller scheme. In this study, although in fuzzy controller not used any optimization methods, however fuzzy stabilizer be able have a better performance for damping of Low Frequency Oscillations (LFO) when exist large distortions in power system under test. For the same disturbance, the operation of the proposed stabilizer is shown in plots. As shown

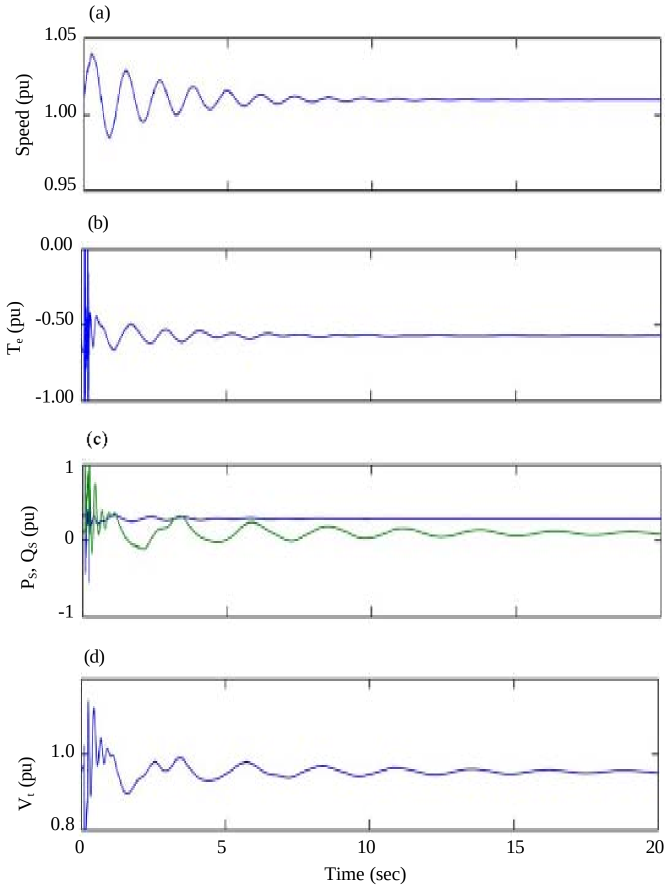

Fig. 9: Simulation results for the DFIG dynamic responses with PI controller: a) Speed of DFIG rotor; b) Electrical torque; c) Output P and Q of the DFIG (P is above curve Q); d) Terminal voltage magnitude of the DFIG

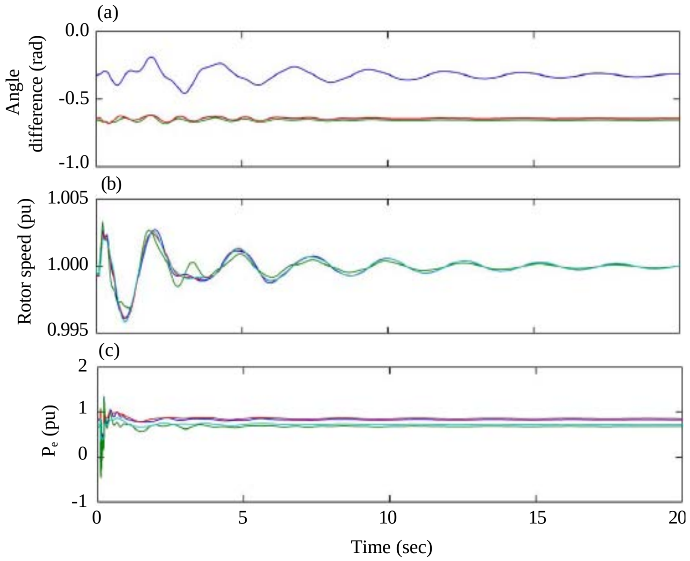

Fig. 10: Experimental results for the synchronous generator dynamic responses with PI controller: a) Relative rotor angles δ_{14}, δ_{13} and δ_{12}; b) Speeds of the 4 synchronous generators; c) Output power levels from the 4 synchronous generators

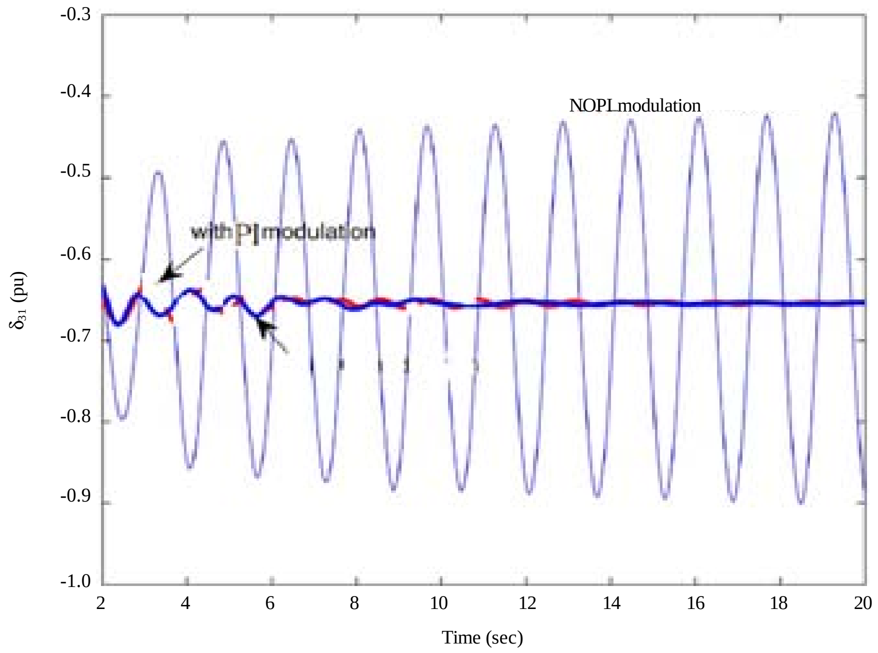

Fig. 11: Dynamic responses of relative rotor angle δ_{31}

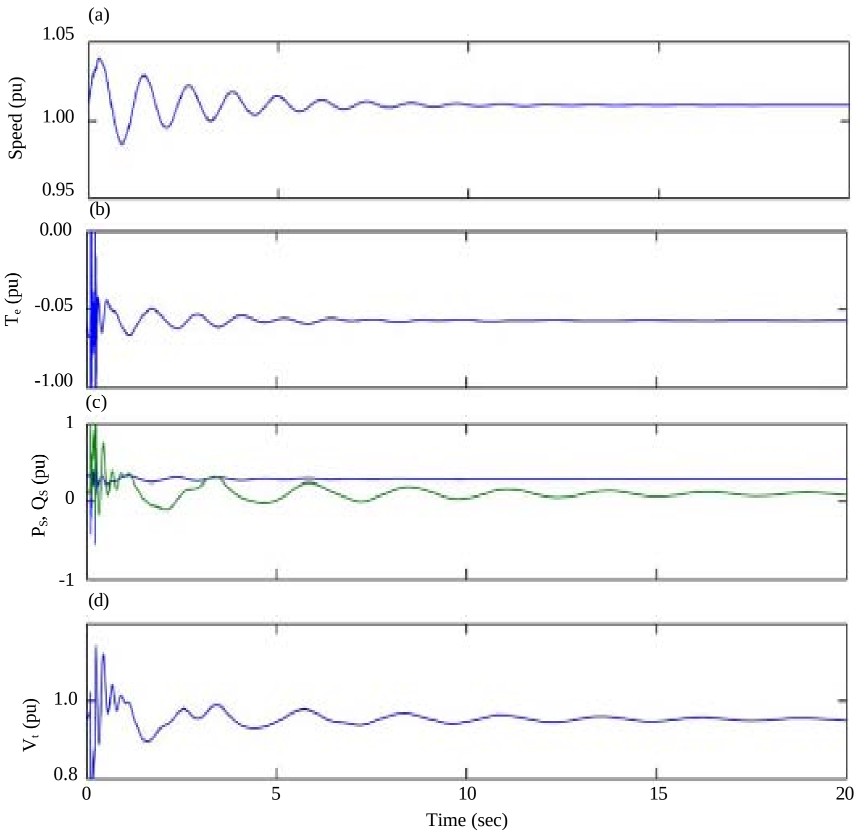

Fig. 12: Simulation results for the DFIG dynamic responses with fuzzy controller: a) Speed of DFIG rotor; b) Electrical torque; c) Output P and Q of the DFIG (P is above curve Q); d) Terminal voltage magnitude of the DFIG

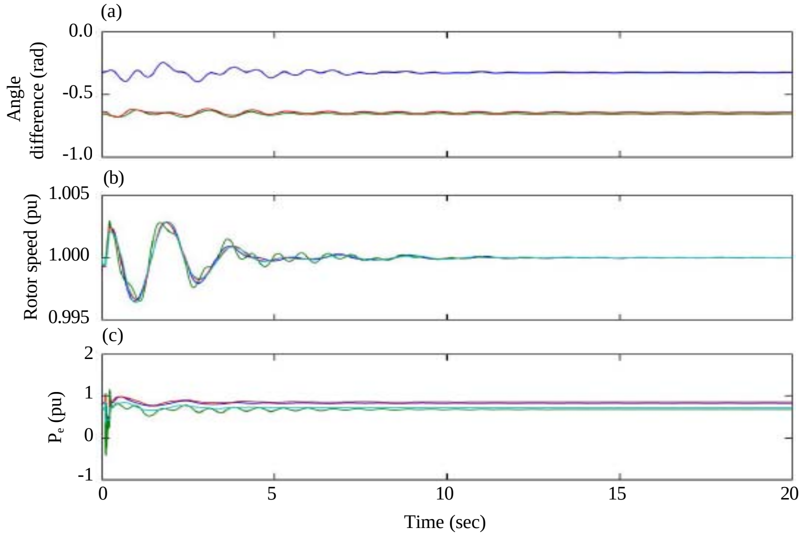

Fig. 13: Experimental results for the synchronous generator dynamic responses with fuzzy controller: a) Relative rotor angles δ_{14}, δ_{13} and δ_{12}; b) Speeds of the 4 synchronous generators; c) Output power levels from the 4 synchronous generators

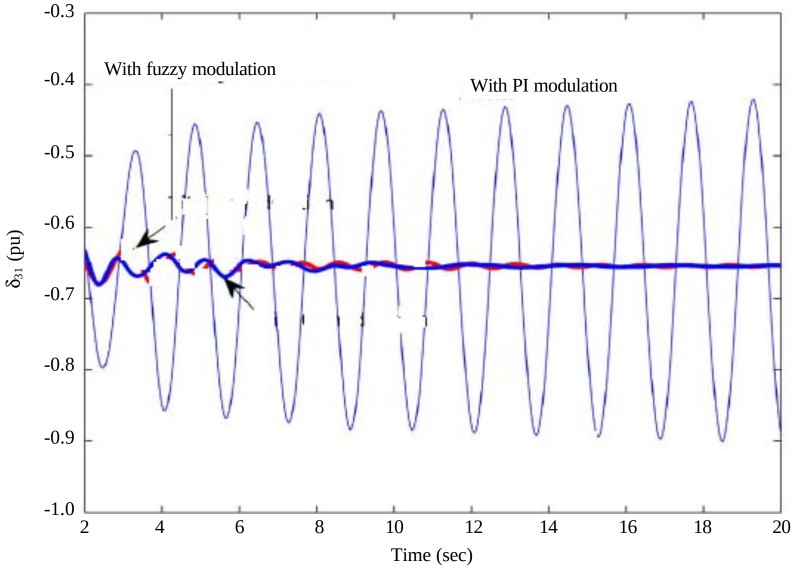

Fig. 14: Dynamic responses of relative rotor angle δ_{31}

obviously, the fuzzy stabilizer is more effective and better performance than conventional stabilizer in damping of interarea oscillations since the system with fuzzy controller has less overshoot and less steeling time, compared with the conventional PI controller.

CONCLUSION

In this study, a fuzzy logic controller design is investigated for DFIG-wind power penetration in inter connected system oscillation damping. The fuzzy damping control loop for DFIG, modulate reactive power in rotor side converter to damp the low frequency oscillations. A 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 controllers could perform a key role in DFIG to damping the interarea oscillations but its better performance is required to meet the suitable range of gains that this is possible with much amount of simulations. While the proposed fuzzy controller scheme were regulated in only a few simulations. Simulation results show that due to 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 LFO.

APPENDIX

Parameters: Base values for the per-unit system conversion.
Base power: 100 MVA.
Base voltages: 0.69 kV for low-voltage bus-bar and 13.8 kV for medium-voltage bus-bar. The parameters of DFIG and the parameters of synchronous generator are listed below:

Parameters of the DFIG

Parameters	Values
r_s (pu)	0.00488
r_r (pu)	0.00549
X_{rs} (pu)	0.09231
X_{rr} (pu)	0.09955
X_M (pu)	3.95279
H (kg. m^2)	3.50000

Parameters of the shaft system of DFIG

Parameters	Values
H_t (s)	0.09955
H_g (s)	3.95279
D_t (pu)	0.00000
D_g (pu)	0.00000
D_{tg} (pu)	0.09231
K_t(tg) (pu)	0.22000

Parameters of synchronous generator

Parameters	Values (pu)
r_s	0.003000
X_q	1.800000
r'_{kq1}	0.001780
X'_{lkq1}	0.812500
r'_{kq2}	0.008410
X'_{lkq2}	0.093900
X_{ls}	0.190000
X_d	1.800000
r'_{fd}	0.000929
X'_{lfd}	0.114140
r'_{kd}	0.013340
X'_{lkd}	0.081250

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