ENHANCEMENT OF ROTOR ANGLE STABILITY OF POWER SYSTEM BY CONTROLLING RSC OF DFIG

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Abstract: *With the increasing demand of power and due to environmental and economical considerations, conventional methods of generation of electric power have been replaced by the renewable energy sources. Among renewable energy sources Wind Energy Conversion System is the emerging source of power. This paper presents the enhancement of rotor angle stability of the power system which contains both synchronous generators and double fed induction generators (DFIG). A Power System Stabilizer (PSS) is included in the reactive power control loop of Rotor Side Converter (RSC) of DFIG which damps out the rotor angle oscillations which is controlled by a fuzzy logic controller. The proposed control technique is implemented in MATLAB/Simulink software.*

Key words: **Doubly fed induction generator (DFIG), Rotor angle stability, Power system stabilizer (PSS).**

1. INTRODUCTION

In recent years the generation of electric power through renewable energy sources has been increasing gradually because of the negative impacts caused by the production of electric power through non-renewable energy sources both on environment and economy. Among the renewable energy sources, Wind Energy is the most prominent source of electric power generation. As power generation from wind energy has been increasing, it is necessary to study the control and operation of wind energy conversion system. A wind energy conversion system uses a variable speed wind turbines. A doubly fed induction generator (DFIG) is used on wind turbine because of its high energy transfer capability, low investment and flexible control [2]. A doubly fed induction generator is a wound rotor induction generator with back to back power converters which are controlled by pulse width modulation technique. DFIG feds power to grid through both stator and rotor. The Rotor Side Converter (RSC) is able to regulate stator side active and reactive power independently [1]. The Grid Side Converter (GSC) controls the voltage of a DC-link to maintain it within a certain limit and can be used as a reactive power support [1].

With the integration of conventional power generation with the wind energy conversion system, some problems may arise which will affect the total power system stability [2]. Because of its flexible control DFIG is able to control its own reactive power to operate at a given power factor. By proper controlling of DFIG converters, DFIG can reduce the problems associated with the integration of conventional power generation. The main problem arises in such cases is rotor angle oscillations which in turn affects the rotor angle stability of the system, which is a dynamic phenomenon. The rotor angle stability is the major concern with a system with both synchronous generators and wind energy conversion system. When a fault occurs, the rotor angle of a synchronous generator oscillates with a larger angular swing. By implementing a Power System Stabilizer (PSS) in the reactive power control loop of Rotor Side Converter of DFIG the rotor angle oscillations can be damped out quickly without affecting the rotor angle stability during fault conditions [3].

This paper presents a implementation of auxiliary Power System Stabilizer (PSS) using a fuzzy logic controller in the reactive power loop of DFIG-RSC and significant enhancement of rotor angle stability of the power system that the PSS can provide. A test system is used to analyze the effect of proposed control technique which consists of three synchronous generators with three step-up transformers, six transmission lines and three loads totaling 315 MW and 115 MVar. To investigate the effect of DFIG, generator G_2 is replaced by a DFIG-based wind farm. The overall control scheme of RSC is achieved by regulating the rotor current in a stator-flux oriented synchronously rotating reference frame [4]. The entire control scheme is implemented in MATLAB/Simulink software and the results are shown.

2. METHODOLOGY

This section describes the method of modeling and controlling of RSC, implementing the Power System Stabilizer (PSS) and its control technique using a fuzzy logic controller. The overall control and operation is conducted on a test system shown in the fig.1.

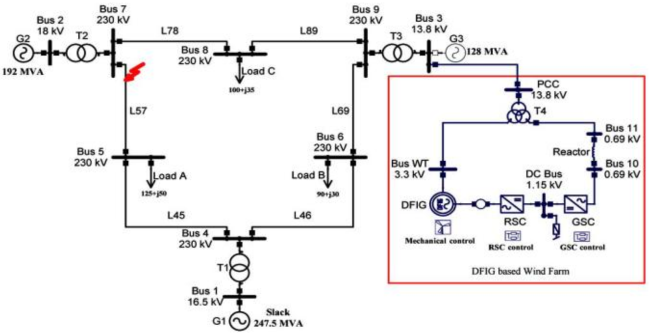

Fig.1. Single line diagram of a test system with DFIG

2.1. DFIG Modeling

The induction generator stator and rotor differential equations are

$$V_{sabc} = r_s i_{sabc} + \frac{d}{dt}\psi_{sabc} \tag{1}$$

$$V_{rabc} = r_r i_{rabc} + \frac{d}{dt}\psi_{rabc} \tag{2}$$

Applying synchronous reference frame transformation rotating by angular speed ω_s to the above equations, the differential equations of the DFIG induction machine in d-q are

$$V_{ds} = r_s i_{ds} - \omega_s \psi_{qs} + \frac{d}{dt}\psi_{ds} \tag{3}$$

$$V_{qs} = r_s i_{qs} + \omega_s \psi_{ds} + \frac{d}{dt}\psi_{qs} \tag{4}$$

$$V_{dr} = r_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{d}{dt}\psi_{dr} \tag{5}$$

$$V_{qr} = r_r i_{qr} + (\omega_s - \omega_r)\psi_{dr} + \frac{d}{dt}\psi_{qr} \tag{6}$$

Where V_{qs}, i_{qs}, ψ_{qs} are respectively the stator voltage, current and flux linkage in the q-axis, and V_{qr}, i_{qr}, ψ_{qr} are respectively the rotor voltage, current and flux linkage in the q-axis. V_{ds}, i_{ds}, ψ_{ds} ar respectively the stator voltage, current and flux linkage in the d-axis, and V_{dr}, i_{dr}, ψ_{dr} are respectively the rotor voltage, current and flux linkage in the d-axis. ω_s and ω_r are rotational speed of the synchronous reference frame and rotor speed.

Flux linkage equations in d-q axis:

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \tag{7}$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \tag{8}$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{9}$$

$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{10}$$

Where the stator L_s and rotor L_r inductance are defined by

$$L_s = L_{ls} + L_m, \; L_r = L_{lr} + L_m \tag{11}$$

Where L_m is the mutual inductance and L_{ls}, L_{lr} are the stator and rotor leakage inductance.

2.2 Rotor Side Converter Control

The RSC of DFIG can be modeled as current controlled voltage source converter. The overall vector control scheme of the RSC is attained by regulating the rotor current in a stator-flux oriented synchronously rotating reference frame to control the stator active power P_s and reactive power Q_s independently [4]. The control scheme of RSC is shown in fig.2. To achieve the independent control of stator active power and reactive power, the instantaneous three phase rotor currents i_{rabc} are transformed to dq components i_{dr} and i_{qr} in the stator flux oriented synchronously rotating reference frame. The reference values for i_{dr} and i_{qr} are determined directly from Q_S and P_S respectively. The actual d-q current signals i_{dr} and i_{qr} are then compared with their reference signals i_{dr}^* and i_{qr}^* to generate error signals, which are passed through two PI controllers to form the voltage signals v_{dr1} and v_{qr1}. The two voltage signals are compensated by the corresponding cross coupling terms (v_{dr2} and v_{qr2}) to form d-q voltage signals v_{dr} and v_{qr}. These are used by the Pulse width modulation (PWM) module to generate IGBT gate control signals to drive rotor-side IGBT converter. The reactive power control using the RSC can be applied to control the stator voltage V_s within the desired range, when the DFIG feeds in to a weak power system without reactive compensation [5].

In the stator flux oriented reference frame, the stator flux linkage ψ_s is aligned to d axis [6]. Therefore, stator flux linkage in d-q will be $\psi_s = \psi_{ds}$ and $\psi_{qs} = 0$.

From equation (8) $i_{qs} = -\frac{L_m}{L_s} i_{qr}$ (12)

From equation (3),(4) and (7)

$$i_{ds} = \frac{L_m}{L_s}\left(\frac{v_{qs} - R_s i_{qs}}{\omega_s L_m} - i_{dr}\right) = \frac{L_m}{L_s}\left(i_{ms} - i_{dr}\right) \tag{13}$$

Where $i_{ms} = \frac{v_{qs} - R_s i_{qs}}{\omega_s L_m}$

Neglecting stator and rotor power losses, the stator active and reactive power are

$$P_s = \frac{3}{2}\left(v_{ds} i_{ds} + v_{qs} i_{qs}\right) \tag{14}$$

$$Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \qquad (15)$$

Equation (14) can be written as

$$P_s = -\frac{3}{2}\left(\omega_s \frac{L_m^2}{L_s} i_{ms} i_{qr}\right) \qquad (16)$$

$$Q_s = \frac{3}{2}\left(\omega_s \frac{L_m^2}{L_s} i_{ms}(i_{ms} - i_{dr})\right) \qquad (17)$$

By substituting equations (9), (10), (12) and (13) into (5), (6)

$$V_{dr} = r_r i_{dr} + \sigma L_r \frac{d}{dt} i_{dr} - (\omega_s - \omega_r)\sigma L_r i_{qr} \qquad (18)$$

$$V_{qr} = r_r i_{qr} + \sigma L_r \frac{d}{dt} i_{qr} - (\omega_s - \omega_r)[\sigma L_r i_{dr} + \frac{L_m^2}{L_s} i_{ms} \qquad (19)$$

$$\text{Where } \sigma = 1 - \frac{L_m^2}{L_s L_r} \qquad (20)$$

Equations (16) and (17) shows that DFIG stator active and reactive powers can be controlled independently by the d-q axis rotor current i_{qr} and i_{dr} respectively.The reference values of rotor currents can be determined directly from P_s and Q_s by the outer power control loops [6].

By rewriting the equations (18), (19)

$$\mathrm{v}_{dr} = \mathrm{v}_{dr1} - \mathrm{v}_{dr2} \qquad (21)$$

$$V_{qr} = V_{qr1} + V_{qr2} \qquad (22)$$

Where

$$V_{dr1} = r_r i_{dr} + \sigma L_r \frac{d}{dt} i_{dr} \qquad (23)$$

$$V_{qr1} = r_r i_{qr} + \sigma L_r \frac{d}{dt} i_{qr} \qquad (24)$$

$$V_{dr2} = (\omega_s - \omega_r)\sigma L_r i_{qr} \qquad (25)$$

$$V_{qr2} = (\omega_s - \omega_r)[\sigma L_r i_{dr} + \frac{L_m^2}{L_s} i_{ms}] \qquad (26)$$

The rotor currents i_{dr} and i_{qr} of equations (23) and (24) in terms of v_{dr1} and v_{qr1} can be written as:

$$\frac{d}{dt} i_{dr} = -\frac{r_r i_{dr}}{\sigma L_r} + \frac{1}{\sigma L_r} V_{dr1} \qquad (27)$$

$$\frac{d}{dt} i_{qr} = -\frac{r_r i_{dr}}{\sigma L_r} + \frac{1}{\sigma L_r} V_{qr1} \qquad (28)$$

Equations (27) and (28) indicate that i_{dr} and i_{qr} respond to V_{dr1} and V_{qr1} respectively.

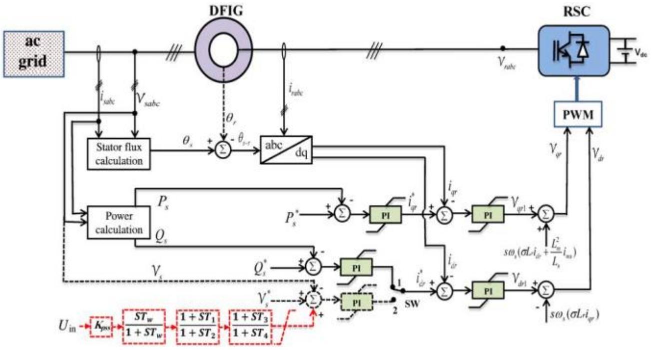

Fig.2. Overall vector control scheme of DFIG-RSC and power system stabilizer (dashed red lines)

2.3 Power System Stabilizer

As discussed earlier, the stator active and reactive power (P_s and Q_s) of DFIG can be controlled independently by regulating the rotor current i_{qr} and i_{dr} respectively. These control loops can be used to improve the power system stability by adding additional signals. Therefore, a robust control strategy could improve the damping of the power system oscillations by adding an additional signal to the active or reactive power control loops [6]. In this paper, an auxiliary power system stabilizer (PSS) is implemented in the reactive power control loop.

The main function of PSS is to damp low-frequency oscillations in the range of 0.1 to 2 Hz, which are known as inter area oscillations. PSS enhances the test system stability and damp out the rotor angle oscillations [1]. The input of the PSS is any signal that can affect by the oscillation such as terminal voltage, frequency and oscillating power. The input signal is provided with a constant gain [6]. In this paper, terminal voltage is chosen as input to the proposed power system stabilizer. The conventional PSS with lead-lag controllers is represented by the following equation [7].

$$u_{pss} = K_{pss}\left(\frac{ST_w}{1+ST_w}\right)\left(\frac{1+ST_1}{1+ST_2}\right)\left(\frac{1+ST_3}{1+ST_4}\right)u_{in}$$

Where u_{in} and u_{pss} are control input and output signals, respectively, K_{pss} is the controller gain, T_w is a washout time constant (s), and $T_1 - T_4$ are lead-lag time constants (s). The PSS output signal is added to the reference voltage signal in the RSC as shown in fig.1. with red dashed lines. The amount of damping is determined by the PSS gain (K_{pss}). Washout block is a high pass filter that allows a selected input frequency range and expected to act only during transient period. The dynamic phase compensator can produce a a lead-lag phase in order to reduce rotor angle oscillations [1]. Parameters of the PSS used in this paper are given in the following equation.

$$u_{pss} = 170\left(\frac{5S}{1+5S}\right)\left(\frac{1+0.06308S}{1+0.26497S}\right)\left(\frac{1+0.06308S}{1+0.26497S}\right)u_{in}$$

2.4 Fuzzy Logic Controller

In this paper, PSS is controlled using fuzzy logic controller. Fuzzy logic controller contains four steps knowledge base, fuzzification, interface mechanism and defuzzification as shown in fig.3. Knowledge base is composed of database and rule base. Data base consists of input and output data. The rule base consists of rules of linguistic variables to get the desired output. Fuzzification converts input values to membership functions. Interface mechanism executes all rules in the rule base to compute the fuzzy output functions. Finally, defuzzification process converts the fuzzy output functions to crisp output values.

In this paper, mamdani fuzzy interface system is used for fuzzification and centroid method is used for defuzzification. The linguistic variables used are nb (negative big), ns (negative small), ze (zero), ps (positive small), pb (positive big). The rules used in fuzzy logic controller are shown in table.1.

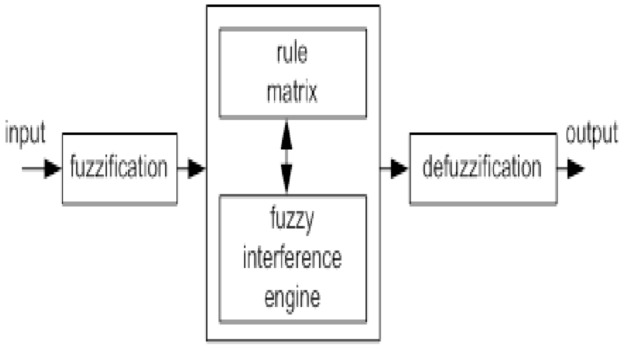

Fig.3. Fuzzy logic controller

Change In error	Error				
	nb	Ns	ze	Ps	pb
nb	Pb	Pb	pb	Pb	Pb
ns	Pb	Pb	ps	Ps	Pb
ze	Ze	Ze	ze	Ns	Pb
ps	Ns	Ns	ns	Ns	Pb
pb	Nb	Nb	nb	Nb	Pb

TABLE.1. Rules for fuzzy logic controller

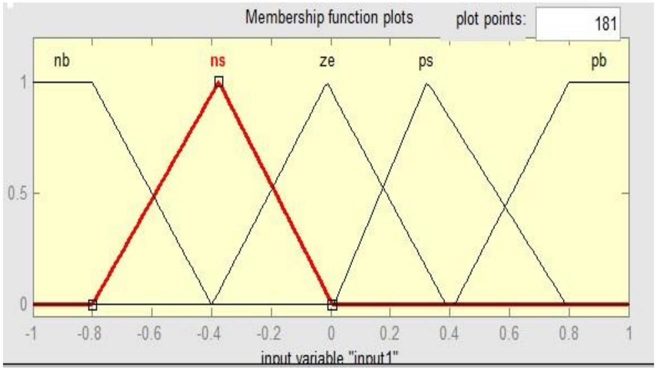

Fig.4. Membership function for input 1 (error)

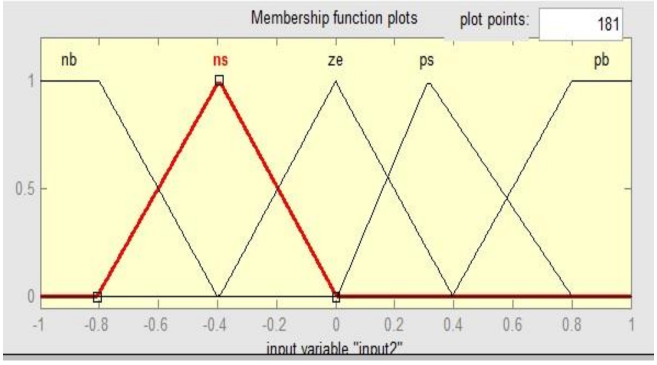

Fig.5. Membership function for input 2 (change in error)

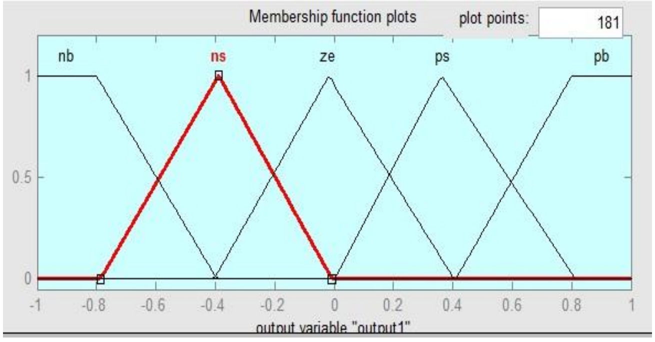

Fig.6. Membership function for output

3. SIMULATION AND RESULTS

A test system which consists of three synchronous generators is used. To show the effect of DFIG with PSS, one synchronous generator is replaced with a DFIG wind system. A disturbance lasting nine cycles of a three phase to ground fault at 60 Hz is imposed near bus 7 on line 5-7. The fault was cleared by opening both sides of the faulted line simultaneously. The reactive power control loop in RSC is used to maintain terminal voltage at 1 p.u. Terminal voltage of G_3 falls to about 0.2 p.u. during the fault and then recovers to nearly 1 p.u. after the fault is cleared as shown in fig.7. During the fault, the reactive power is variable and stabilizes after fault is cleared. In order to assess the rotor angle stability, the rotor angle of G_2 is observed. The rotor angle of G_2 with PSS is shown in fig.10. It is clearly shown that oscillations damps out quickly and the rotor angle steady state value is reached in a time of less than 3 s. Thus, DFIG-based wind farm enhances the rotor angle stability.

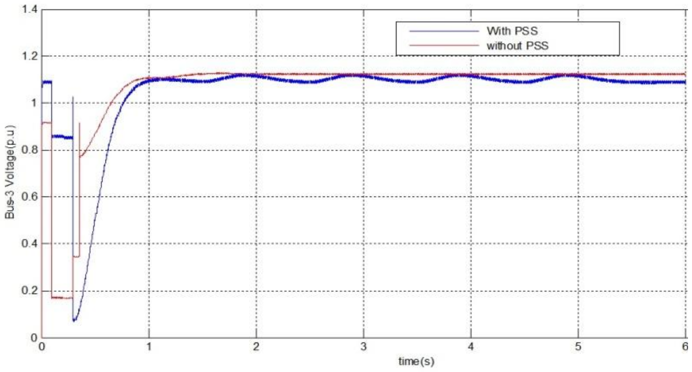

Fig.7 Terminal voltage of Bus 3 Vs time

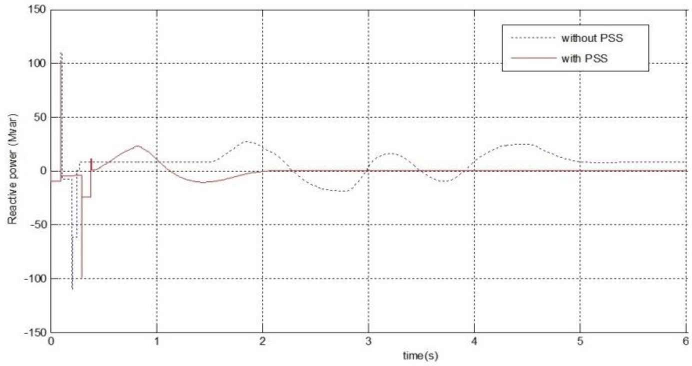

fig.8 DFIG Reactive power Vs time

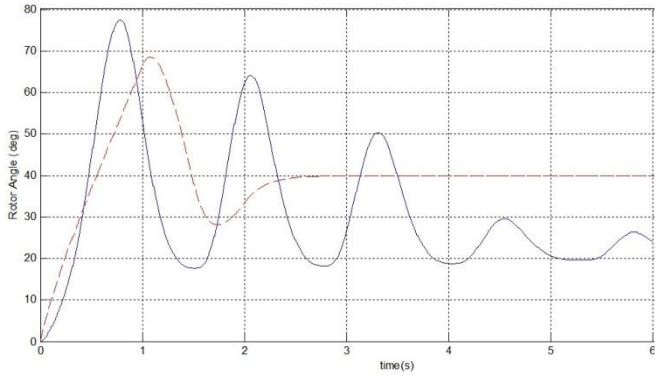

Fig.10. Rotor angle of G_2 Vs time with(dashed lines) and without PSS

Therefore, the high penetration of DFIG-based wind farm has an impact rotor angle stability of a power system with synchronous generators.

4. CONCLUSION

In this paper, impacts of replacing conventional SGs with equivalent DFIG wind farms on rotor angle stability of power systems. The impacts on transient stability of the system would depend on the control strategy used within the DFIG-RSC. An auxiliary power system stabilizer (PSS) is included in the reactive power control loop of DFIG-RSC. The implementation of the proposed PSS within the reactive power control loop of the wind farm can influence the rotor angle of SG and thus damp the power system oscillations effectively. It is shown that the proposed technique is an efficient and effective way to improve the rotor angle stability by utilizing the available DFIG reactive power. As the levels of wind penetration are increased, the benefit of such control scheme is that the DFIG-based wind farms are able to take over the SGs responsibility to support power system stability.

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