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AVR and PSS Coordinated Based Fuzzy Approach for Transient Stability Enhancement

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Abstract—This paper deals with transient stability augmentation using fuzzy coordinator in power systems with high penetration of wind turbines. The wind turbines are disconnected from the grid by their protection systems in severe fault situations. The disconnection may strike the power system by jeopardizing its transient stability due to reduction of active power. In this paper a fuzzy-based controller has been designed, that works as a coordinator between Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS). A salient feature of this work is that, the transient stability of power system is improved without any disconnection of wind turbines at the time of fault. Simulation results demonstrate that, the fuzzy coordinator ensures the transient stability of 11-bus power system with 20% penetration of wind turbines after outage of generator number 3.

Keywords—transient stability; high wind turbine penetration; fuzzy coordinator; AVR; PSS

I. INTRODUCTION

Installation of wind turbines as one of the most significant renewable energy sources is increasing quickly around the world; so wind energy is playing a vital role in the energy generation of the world recently [1]. When the contribution of wind turbines in power system is in small scale, the stability of power system is effected minimally; on the contrary, with high penetration of wind turbines, the dynamic performance of the power system can be more effected [2, 3]. Although the variable speed Doubly Fed Induction Generators (DFIGs) constitute a major part of the newly installed wind turbines, but on the other hand, the Fixed Speed Wind Turbines (FSWTs) still organize an unavoidably percentage of 15% of the operating wind turbines in Europe in 2010 [4].

The considered wind turbines in this research employ Squirrel Cage Induction Generator (SCIG) that is directly connected to the grid without any control capability and operate at a substantially constant speed that normally referred as Fixed Speed Induction Generators (FSIGs). The significant features of the induction generator are lower cost and operational simplicity. On the other hand, the induction generators require an external source of reactive power for excitation in all conditions. In the system nominal operating condition the required reactive power can be supplied by the ac power system and through a bank of capacitors installed in its terminal. The reactive power is required to create the rotating magnetic field and it is independent of the generator load [5]. Furthermore, the induction generators require more reactive power in higher penetration levels. On the other hand, FSIGs may be disconnected from power system if the reactive power is not supplied; this threats the power system stability.

Many authors have investigated different methods to enhance the fault ride through capability and the transient stability of power systems in penetration of the FSWTs [6- 10]. Reference [6] advocates that, the transient instability in FSWT appears with instability in the generator slip. It is established in [7] that with connection of FSIGs either series or parallel to the terminal of a DFIG, the dynamic operation of the system can be improved. Also highlighted in [8] that DFIG can contribute to network unbalance compensation, thereby it can improve the performance of FSIG wind farms in its terminal. Reference [9] focuses on the stability of the FSWT in an islanded distributed system. In [10], the stability of power system with FSIG-based wind turbines penetration is enhanced using Static Var Compensator (SVC).

The novel contribution of this paper is to design a fuzzy controller as a coordinator between Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS) in high penetration level of FSIG-based wind turbines in multi-machine power systems to enhance the transient stability at the severe fault conditions, such as generator outage. In a multi-machine power system at fault conditions, while a high-gain fast-response AVR improves the transient stability, it also has detrimental effect on oscillation stability and has a converse effect about the PSS operation for the transient stability [11]. The approach taken is to ensure the transient stability of the well-known 11-bus power system with 20% penetration of FSIG-based wind turbines. The proposed fuzzy controller has two inputs and two outputs: normalized deviation of terminal voltage and rotor phase as the input signals and gains of AVR and PSS as the output signals.

The rest of this paper is organized in seven sections. Section II illustrates the considered power system with wind turbines penetration. The detail about FSWT with induction generator is described in section III. The tradeoffs between investigated controllers are discussed in section IV. Section V presents the fuzzy coordinated control design for AVR and PSS. Simulation results after severe disturbance occurrence in the system, with and without fuzzy coordinator is shown in section VI and a conclusion in section VII closes the paper.

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II. POWER SYSTEM STRUCTURE WITH WIND FARMS

The well-known 11-bus power system has been selected as the test case. Fig. 1 shows the single line diagram of this 11-bus power system with wind farms penetration. The detailed data about the system is given in [12]. Each of the synchronous generators in this multi-machine power system has been simulated as a seven-order model in SimPower environment of MATLAB software. The rating of each generator is 900 MVA, 20 KV and it is connected through a 20/230 KV transformer to the transmission line. The total load of the nominal system is 2734 MW and the generation is about 2819 MW. The nominal system is operating with 413 MW exporting from area I to area II.

Wind farms 1 and 2 are considered to be connected to the multi-machine power system through transmission lines and step-up transformers in terminals 7 and 9. Induction generators are used as wind generators in the both of wind farms. Each wind farm consists of three FSIG-based wind turbines and it is assumed that several fixed-speed wind generators are lumped together to obtain each one of them. The bank capacitors are added to the terminals of wind farms to compensate the reactive power requirement of FSIGs in steady-state.

III. FSIG-BASED WIND TURBINE MODEL

Using Squirrel-Cage Induction Generator (SCIG), the FSWT provides a simple and cost effective solution for wind farm integration. A schematic structure of the wind turbine with induction generator is depicted in Fig. 2. The wind turbine model in this study is based on steady-state power characteristics of the turbine. This part of FSWT converts the kinetic energy of wind into mechanical energy. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine. The mechanical power output of a wind turbine, under smooth wind flow conditions is given by (1):

$$P_m = c_p(\lambda, \beta) \frac{\rho A}{2} \upsilon_{wind}^3 \qquad (1)$$

Where Pm is the mechanical output power of the turbine (w), ρ is the air density (kg/m3), A is the turbine swept area (m2), v wind is the speed of wind and Cp is the power coefficient which is a function of both tip speed ratio, λ, and blade pitch angle, β (deg).

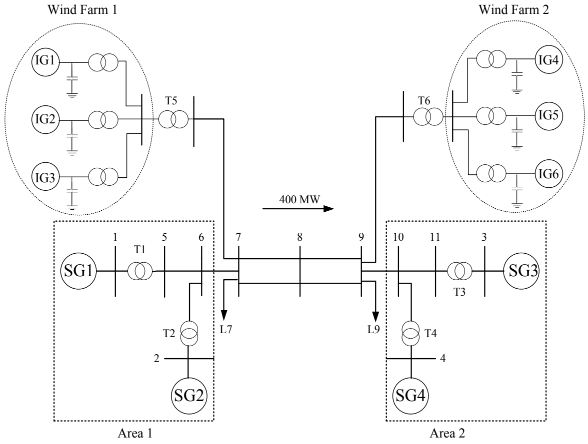


Fig. 1. Two-area power system with wind farms penetration

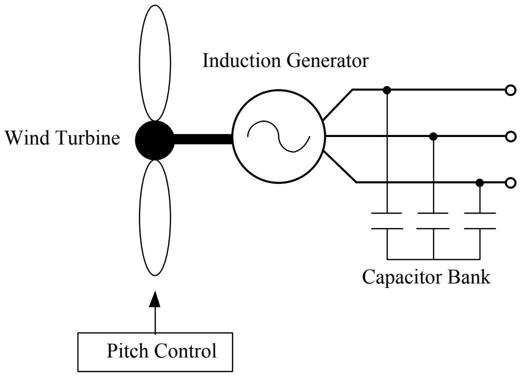


Fig. 2. FSIG-based wind turbine model

The stator winding of induction generator is directly connected to the grid and the rotor is driven by the wind turbine. The pitch angle is controlled by a PI controller in order to limit the generator output power to its nominal value for high wind speeds. In order to generate power, the induction generator speed must be slightly above the synchronous speed. But the speed variation is typically so small that the wind turbine with induction generator is considered to be an FSWT [13].

An important operating characteristic about the SCIG is that, this type of generator consumes reactive power which is undesirable for the transmission systems, particularly in the case of high penetration. As the active power generation of induction generator increases, the reactive power consumption rises as well. This reactive power is provided by the grid or by some devices like capacitor banks and FACTS. When severe faults occur in the power system, if sufficient reactive power is not supplied, the electromagnetic torque and electric-power output of the wind generator decrease significantly. However, the mechanical-input torque is almost constant during the fault situations. By this, the difference between mechanical and electromagnetic torques becomes elder and the wind generator and turbine speeds increase rapidly. As a result, the induction generator becomes unstable and it requires to be disconnected from the grid by protection system [14]. This type of instability that occurs with the induction generators can be classified as rotor speed instability [15]. A shut down of large wind farm may strike the transient stability of multi-machine power system. In this paper, the SVC device is used to provide the necessary reactive power in high penetration level. Also, the wind turbine is equipped with a protection system. Preserving the FSWT from under-over AC voltage, AC current and speed is the main reason to using the protection system. By this, if each of the protection indices egresses from the predefined ranges the FSWT will be separated from the power system.

IV. FUZZY-BASED COORDINATOR DESIGN FOR AVR-PSS

A. AVR and PSS Controllers

In this research all of the generators are equipped with AVR and PSS. A first order model of a static type is used for

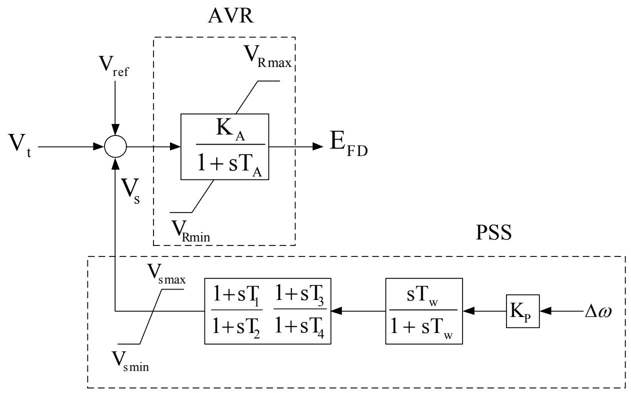


Fig. 3. AVR and PSS structure

the AVR and the conventional form with two lead-lag transfer functions model is also used for the PSS. The AVR provides controllability for the terminal voltage of the generator to which it is attached and the operating function of a PSS is to produce a proper torque on the rotor of the generator that involved in such a way that the phase lag between the exciter input and the machine electrical torque is compensated. An AVR-PSS control system is shown in Fig. 3. In a multi-machine power system at fault conditions, while a high-gain fast-response AVR improves the transient stability, it also has detrimental effect on oscillation stability. On the other hand a PSS can reduce the transient stability by overriding the voltage signal for exciter. Furthermore, it is highlighted in Fig. 3 that, the AVR and PSS controllers enhance the stability of the multi-machine power system including transient-oscillation stability and regulate the terminal voltage, through a unit signal (EFD). This is the major reason to create coordination between AVR and PSS. The parameters of the AVR and PSS controllers also are given in [12].

B. Fuzzy Coordinator

The fuzzy logic approach is an artificial method in decision making and it is able to compensate the inability of the classic control theory for covering the complexity and nonlinearity of physical systems with their uncertainties and inaccuracies. Because of that, fuzzy logic can be considered as a powerful tool for solving the stability problems of the power systems [16]. Typically to design a controller based on fuzzy approach for dynamic systems the following steps should be considered [17]:

Step 1) Understanding of the system dynamic behavior characteristics. Define the states and input/output control variables and their variation ranges.

Step 2) Identify appropriate fuzzy sets and membership functions. Create the degree of fuzzy membership function for each input/output variable and complete fuzzification.

Step 3) Define a suitable inference engine. Construct the fuzzy rule base, using the control rules that the system will operate under. Decide how the action will be executed by assigning strengths to the rules.

Step 4) Determine defuzzification method. Combine the rules and defuzzify the output.

Essentially the AVR and PSS controllers are designed for the nominal operating point of the system and for fault conditions it needs to have coordination between these two controllers. In this research, the fuzzy unit works as a coordinator between AVR and PSS controllers. A general scheme of this fuzzy coordinator is illustrated in Fig. 4. A fuzzy system is composed of four main sections: fuzzification, fuzzy rule base, inference system and deffuzzification. The proposed control framework for application of fuzzy controller has two inputs and two outputs. Of particular interest is the input signal for fuzzy unit. The terminal voltage deviation and rotor phase difference can be selected as the input signals. But it is noteworthy that, after severe disturbances the terminal voltage and rotor phase of the generators change unlimited. A normalization method is applied to limit these deviations. The normalization method has been illustrated in the normalization block of Fig. 4 for voltage deviation and phase difference of the generators. $\Delta\delta'i$ and $\Delta V'i$ demonstrate the normalized phase difference and terminal voltage deviation. The $\Delta\delta'i$ and $\Delta V'i$ can change in range of [-1, 1] for all generators.

In this paper, in order to reach fast response from the controller system, all membership functions considered as triangular with the mathematical definitions as follows:

$$\mu_x(x_i) = \max(0, 1 - \left|\frac{x - x_i}{c}\right|) \tag{2}$$

Where x and c are the mean and spread of the fuzzy set X, respectively, and xi is a crisp variable. The membership functions corresponding to the input variables are arranged as Negative Large (NL), Negative Small (NS), Zero (ZR), Positive Small (PS) and Positive Large (PL), and for the output variables they are arranged as Very Small (VS), Small (S), Medium (M), Large (L). In the present investigation, five membership functions are defined for the input signals and four membership functions are defined for output signals. The

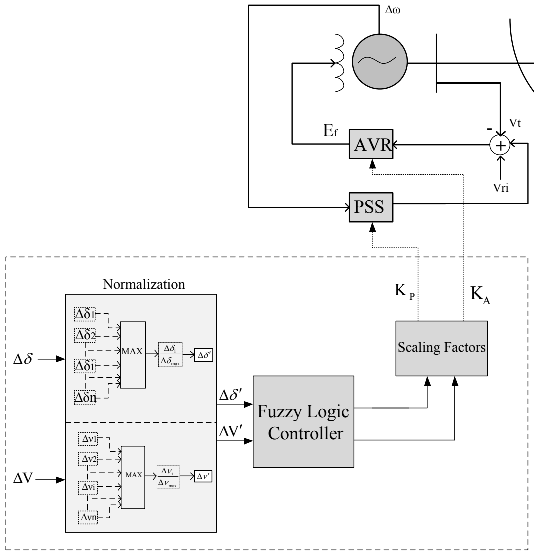


Fig. 4. A general scheme of the fuzzy coordinator

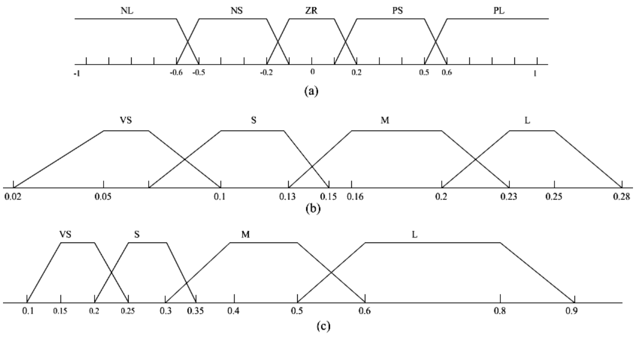


Fig. 5. Membership functions; a) input signals, b) output signal KA , c) output signal KP

membership functions for input and output variables are demonstrated in Fig. 5. The Mamdani inference system is also used for the proposed fuzzy. The performed fuzzy rules are given in Table I. Using Table I, fuzzy rules can be expressed in the form of IF-THEN statements such as:

IF Δδ'i is NL AND ΔV'i is PL, THEN KP is S and KA is M.

As can be seen in the above IF-THEN statement, the antecedent part of the rules is composed of two parts, combined with fuzzy “AND” operators; in this paper, the combination is done based on interpreting the “AND” operator by algebraic product operation.

TABLE I. Fuzzy Rule Base for,
a)PSS gain, and b) AVR gain

(a)

KP		ΔV'				
		NL	NS	ZR	PS	PL
Δδ'	NL	VS	VS	VS	VS	S
	NS	S	S	S	M	S
	ZR	S	M	L	L	L
	PS	S	S	M	M	L
	PL	M	M	M	L	L

(b)

KA		ΔV'				
		NL	NS	ZR	PS	PL
Δδ'	NL	VS	S	VS	VS	M
	NS	VS	S	VS	VS	M
	ZR	VS	S	S	S	VS
	PS	VS	S	S	S	M
	PL	VS	S	S	M	L

V. SIMULATION RESULTS

As has been explained, the fuzzy unit works as a coordinator between the AVR and PSS to create trade-off between these two conventional controllers. The main objective of this coordination is preserving transient stability in power system. Considering economic constraints, installing of fuzzy coordinator on all of synchronous generators of multi-machine power system seems irrational. So, the fuzzy controller is added to one of the generators in each area. In the 2-area 4-generator test power system of this paper, all the generators have similar dynamic features. So, each of the generators in the system can be equipped with fuzzy coordinator. On the other hand, generators with maximum capacity can be count as appropriate selection to equip with fuzzy coordinator. Generator number 2 in the area I has more capacity. In area II, generator number 3 is selected as severe fault scenario in the system. So, generator number 2 in area I and generator number 4 in area II are equipped with fuzzy coordinator. The fuzzy control unit is activated in the system following 0.3 second after fault scenario for prevention of

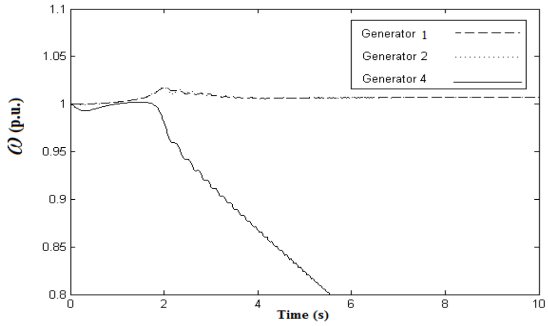
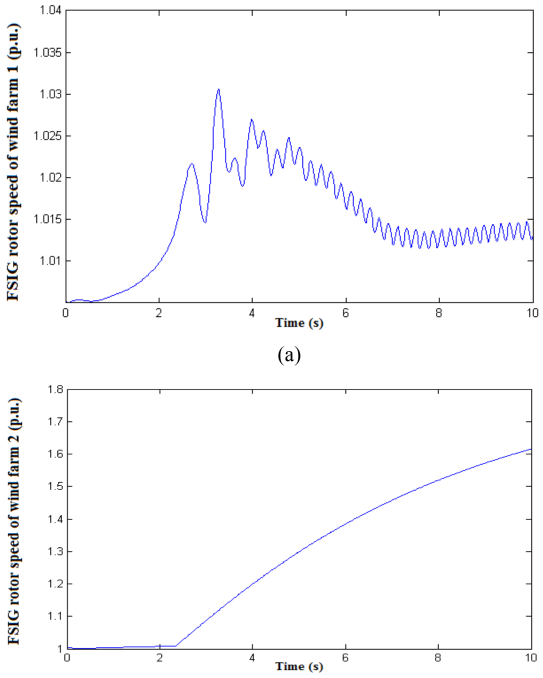


Fig. 6. Generators speed for 20% of penetration without fuzzy coordinator



(a)

(b)

Fig. 7. FSIG rotor speed of wind farms for 20% of penetration without fuzzy coordinator, a) wind farm 1, b) wind farm 2

transient instability and wind farm disconnection. The reason for this selection is that, the time horizon for transient instability is about 3-5 s; but the action of protection system in wind farms to unbalances is too fast.

The penetration level for the wind turbines is about 20% of the nominal generation rating by conventional generators in the system. So, the generation rating for wind farms is about 560 MW. The large disturbance that has been considered in this paper is outage of the generator number 3. Fig. 6 shows that, without fuzzy coordinator there is transient instability in the power system after this fault. The generator number 4 is separated from the other generators in the system and the two areas work separately after fault. The power system has lost its synchronism. It is also seen in Fig. 7 that, rotor speed of the induction generator in the wind farm 2 is being unstable and in wind farm 1 has oscillations. Wind farm 2 is disconnected from the network by its protection system in 1.89 s.

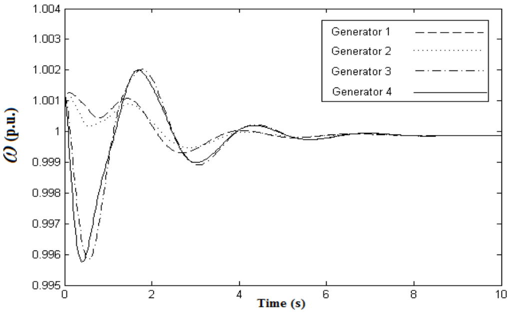
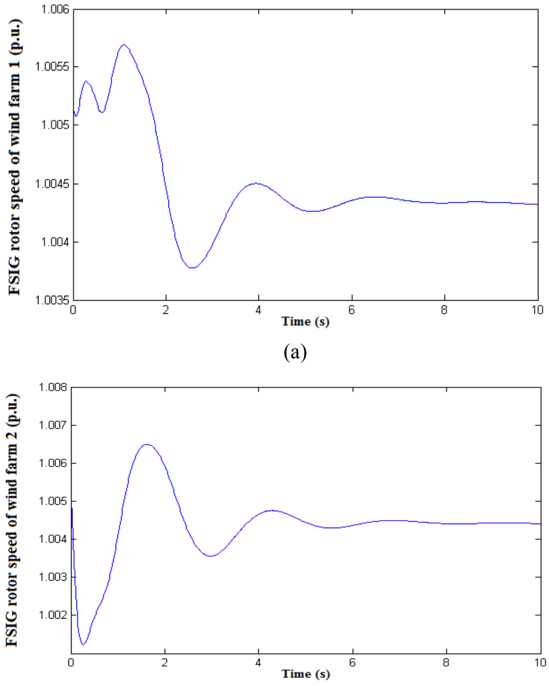


Fig. 8. Generators speed for 20% of penetration with fuzzy coordinator



(a)

(b)

Fig. 9. FSIG rotor speed of wind farms for 20% of penetration with fuzzy coordinator, a) wind farm 1, b) wind farm 2

By adding the fuzzy coordinator units to the generators number 2 and 4, transient stability of the power system has enhanced. This is observable from Fig. 8. The fuzzy coordinator has preserved synchronism of power system. Also, the rotor speed of wind farm 2 is not unstable and the wind farm 1 has not any oscillations in its rotor speed, it is observable from Fig. 9. So, fuzzy coordinator has ensured the transient stability of the multi-machine power system and rotor speed stability of the wind farms 1 and 2.

VI. CONCLUSION

In this paper, the transient stability of multi-machine power system with high penetration of FSIG-based wind turbines has enhanced. The FSIGs may be disconnected from the power system by their protection systems in severe fault situations, if rotor speed of their induction generators is became unstable. A fuzzy coordinated control scheme is proposed for outstanding generators in power system. The fuzzy controller accepted normalized terminal voltage deviation and rotor phase difference signals as inputs and generated the gains of AVR and PSS controllers.

Outage of G3 as a severe fault was applied to 11-bus power system in simulations and the power system and wind farm 2 lost their synchronism with conventional AVR and PSS. By adding the fuzzy coordinator units to generators 2 and 4 in the system, the transient stability of the power system is preserved. Also, the fuzzy coordinator prevented to rotor speed instability of wind turbines and their disconnection from network.

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