http://dx.doi.org/10.11142/jicems.2013.2.1.111
Journal of International Conference on Electrical Machines and Systems Vol.2 , No.1 , pp. 111 ~119 , 2013

Stabilization of Fixed Speed Wind Generator by using Variable Speed PM Wind Generator in Multi-Machine Power System

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Abstract – This paper present stabilization control of fixed speed wind generator by using variable speed permanent magnet wind generator in a wind farm connected with multi-machine power system. A novel direct-current based d-q vector control technique of back to back converter integrated with Fuzzy Logic Controller for optimal control configuration is proposed, in which both active and reactive powers delivered to a power grid system are controlled effectively. Simulation analyses have been performed using PSCAD/EMTDC. Simulation results show that the proposed control scheme is very effective to enhance the voltage stability of the wind farm during fault condition.

Keywords: Voltage stability, PMSG controls system, AC/DC/AC converter, Fuzzy logic controller

1. Introduction

Since last decade, penetration of wind farms into electrical power system has been increasing significantly. In the near future, large numbers of wind generators are going to be connected with grid power system. Global Wind Energy Council (GWEC) predicted that the total capacity of global wind power generation will be 493.33 GW at the end of 2016 [1]. However, the penetration of the wind power into the grid system has significant effect on stability and power quality of the overall system [2]–[5]. The interaction between wind farm and power system such as transient and steady state characteristics has been becoming an important issue to be analyzed.

The wind turbine can be Fixed Speed Wind Turbine with Induction Generator (FSWT-IG) or Variable Speed Wind Turbine with Permanent Magnet Synchronous Generator (VSWT-PMSG). The FSWT-IG has the advantages such as mechanical simplicity, low specific mass, robust construction, and cost efficiency [6]. However, its disadvantages are limited ability of power quality control and terminal voltage fluctuation under steady state condition due to the uncontrollable reactive power consumption [6]. Moreover, the FSWT-IG does not have low voltage ride thought (LVRT) capability when short circuit occurs in the grid system.

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Received 28 January 2013; Accepted 15 February 2013

The VSWT-PMSG is a promising and attractive type of wind turbine concept, in which PMSG can be directly driven by a wind turbine and is connected to the power grid system through the AC/DC/AC power converter. The advantages of VSWT-PMSG are: 1) No gearbox and no brushes, and thus higher reliability 2) The power converter totally decouples the generator from the grid, and hence grid disturbances have no direct effect on the generator 3) No additional power supply for excitation 4) The converter can control active and reactive powers in cases of normal and disturbed conditions and hence the VSWT-PMSG has strong LVRT capability [7]-[8]. However, the disadvantage of these technologies is expensiveness because of the additional costs coming from the power converter and the specific generator. Therefore, consideration of combining the VSWT-PMSG with FSWT-IG in a wind farm can be efficient because it reduces the total wind farm system investment cost. The VSWT-PMSG system with power converter can recover network voltage drop preventing instability of FSWT-IG when a fault occurs.

The AC/DC/AC converter of PMSG consists of stator side converter and grid side converter linked by DC circuit. The grid side converter has important role to ensure the active and reactive power delivered to the network effectively. Parameter change in the grid system can lead significant impact on the stability of the control system performance especially under fault condition. The deviation of grid system impedances can cause change in the stability margin of the grid side controller system. Therefore, the design and analysis of the converter controller system still need to be improved.

In converter control design, PI controllers are most widely used because of their simple structure and good performances in a normal operating condition. However, the PI controllers cannot always effectively control systems with changing parameters or strong nonlinearities and thus, they may need frequent online retuning of their parameters [9]. To solve this problem, fuzzy logic controller is proposed in this paper. The fuzzy logic control is used to adjust the gain parameters of PI controller according to grid system parameter change. By using the PI controller with flexible gain, the dynamic performance of the converter can be improved.

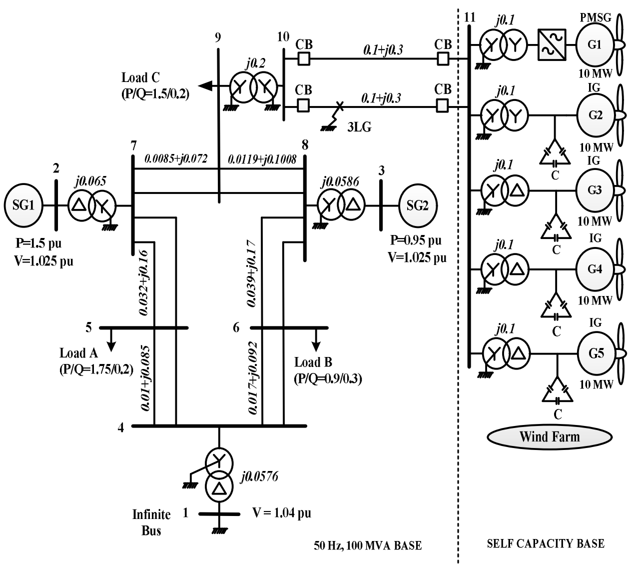


Fig. 1. Power system model

Table 1. Power system model

	Synchronous Generators		IG		PMSG	
	SG1	SG2				
MVA	200	150	MVA	10	MVA	10
ra (pu)	0.003	0.004	R1 (pu)	0.01	Rs (pu)	0.01
Xa (pu)	0.102	0.078	X1 (pu)	0.1	Ls (pu)	0.064
Xd (pu)	1.651	1.22	Xm (pu)	3.5	Xd (pu)	0.9
Xq (pu)	1.59	1.16	R21 (pu)	0.035	Xq (pu)	0.7
X'd (pu)	0.232	0.174	R22 (pu)	0.014	Flux (pu)	1.4
X'q (pu)	0.38	0.25	X21 (pu)	0.03	H	4.5 s
X"d (pu)	0.171	0.134	X22 (pu)	0.089		
X"q (pu)	0.171	0.134	H	3.0 s		
T'do (sec)	5.9	8.97				
T'qo (sec)	0.535	1.5				
T"do (sec)	0.033	0.033				
T"qo (sec)	0.078	0.141				
H	6.2 s	6.0 s				

According to the above point of view, in this work, voltage stability of wind farm connected to a multi-machine power system is investigated by considering combination of VSWT-PMSG and FSWT-IG. A suitable control scheme for power converter of the PMSG is developed to improve the voltage stability as well as reactive power compensation of the FSWT-IG in case of disturbed conditions. In order to improve the dynamic performance of the controller system, integration of conventional PI and fuzzy logic controller is proposed to control the d-q axis current of the grid side converter of the PMSG.

2. Power System Model

Fig. 1 shows a model system composed of 9-bus main system and a wind farm. Steam turbine generator (SG1) and hydro turbine generator (SG2) are connected with the main system. Automatic Voltage Regulator (AVR) and governor models in PSCAD/EMTDC package [10] are used in this paper. The IEEE type SCRX solid state exciter is considered for all synchronous generators as exciter model. In SG1, the generic steam turbine model equipped with approximate mechanical-hydraulic controls of governor is used. In SG2, the hydro turbine with non-elastic water column without surge tank model and the hydro governor with PID controls including pilot and servo dynamics model are used.

Wind farm is considered to be connected to Bus 9 through double circuit transmission lines. Practically, a wind farms is composed of many generators, however, in this paper, aggregate wind generator with capacity of 10 MW is considered for each generator. The wind farm power capacity is 50 MVA composed of one VSWT-PMSG and four FSWT-IGs. A capacitor bank, C, is used for reactive power compensation of IGs. The value of capacitor C is chosen so that the power factor of the wind farm becomes unity at rated condition. The wind generator models in PSCAD/EMTDC package are also adopted in this study. The grid system frequency is 50 Hz and the system base is 100 MVA. Parameters of generators are shown in Table 1.

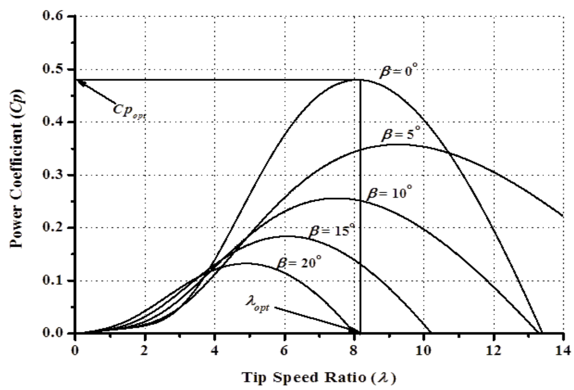


Fig. 2. Cp - λ characteristic for different pitch angle

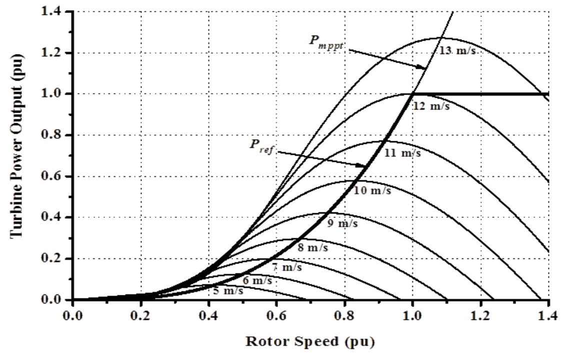


Fig. 3. Turbine power characteristic ($\beta = 0^0$)

3. Wind Turbine Model

The mechanical power output of wind turbine captured from the wind power can be calculated as follows [11]:

$$P_W = 0.5\rho\pi R^2 V_W^3 C_p(\lambda,\beta) \tag{1}$$

where Pw is the captured wind power (W), ρ is the air density (Kg/m[3]), R is the radius of rotor blade (m), V_w is wind speed (m/s), and Cp is the power coefficient. The value of C_p is depended on tip speed ratio (λ) and blade pitch angle (β) based on the turbine characteristics as follows:

$$C_p(\lambda,\beta) = c_1\left(\frac{C_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{2}$$

with

$$\lambda = \frac{\omega_r R}{V_w} \tag{3}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda - 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

where c_1 to c_6 denote characteristic coefficients of wind turbine (c_1=0.5176, c_2=116, c_3=0.4, c_4=5, c_5=21, and c_6=0.0068[12]) and ω_r is rotor speed of the wind turbine.

The Cp-λ characteristic for different values of β is shown in Fig. 2. It is seen that the optimum value of Cp (Cpopt =0.48) is achieved at λ = 8.1 with β = 00. This value of λ is set as the optimal value (λopt). Fig. 3 depicts the characteristic between the turbine power output and the rotor speed for different wind speeds where the blade pitch angle is set at 0 deg. The maximum power output (1 pu) of wind turbine is obtained at 12 m/sec of wind speed and 1 pu of rotational speed.

In variable speed wind turbine, the rotor speed of wind turbine is measured in order to determine the Maximum Power Point Tracking (MPPT). In general, it is not so easy to measure the wind speed, and hence the maximum power (Pmppt) should be calculated without measuring the wind speed as expressed in eq. (5) [13]. The reference power (Pref) is limited within the rated power of generator.

$$P_{mppt} = 0.5\rho\pi R^2\left(\frac{\omega_r R}{\lambda_{opt}}\right)^3 Cp_{opt} \tag{5}$$

4. PMSG Control System

Block diagram of the control system for VSWT-PMSG proposed in this paper is shown in Fig. 4. The VSWT-PMSG system consists of the following components: a direct drive PMSG, AC/DC/AC converters based on two levels of IGBT which are composed of stator side converter (SSC) and grid side converter (GSC), a DC-link circuit composed of a chopper with a resistance (Rc), a capacitor (Cdc), and two voltage source converter controllers (stator side controller and grid side controller).

The SSC is connected to the stator of PMSG, and it converts the three phase AC voltage generated by PMSG to DC voltage. The three phase voltage and current are detected on the stator terminal of PMSG. The rotor speed of PMSG is measured from the rotor of wind turbine.

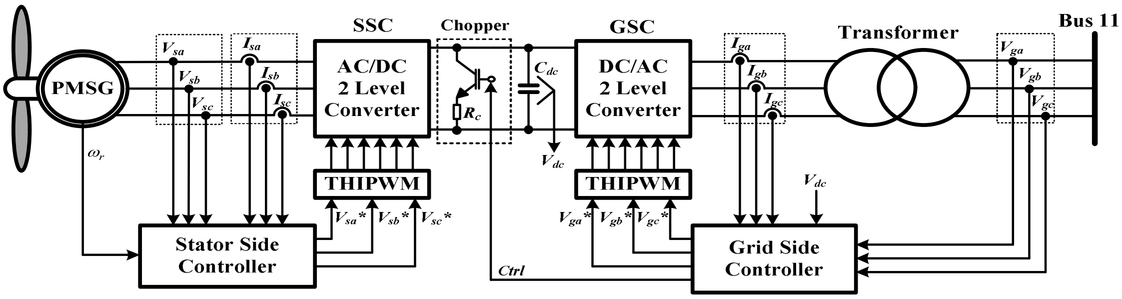


Fig. 4. Control Strategy for VSWT-PMSG

In the GSC, the converter converts the DC voltage into three phase AC voltage of the grid frequency. The converter is connected to the grid system through a step up transformer. The grid current and voltage are detected on the converter output and the high voltage side of the transformer, respectively. The DC voltage (Vdc) is detected on the DC capacitor. When a fault occurs in the grid, the Vdc increases significantly due to power unbalance between SSC and GSC. In order to protect the DC-link circuit, the controller triggers the chopper by a control command (ctrl).

In modulation technique, Third Harmonic Injection Pulse Wave Modulation (THIPWM) is used in this work. In both converters, the triangle signal is used as the carrier wave for modulation. The frequency switching (fs) is set to 3 KHz for both SSC and GSC. The DC-link capacitor is 25000 μF. The rated DC-link voltage is 2.0 kV (1 pu).

Fig. 6 shows a block diagram of the grid side controller system. In this control strategy, the control system based on the d-q rotating reference frame is implemented which has same rotational speed as the grid voltage. The Phase Locked Loop (PLL) in [14] is used to extract the grid side phase angle (θg). The controller is divided into two cascades.

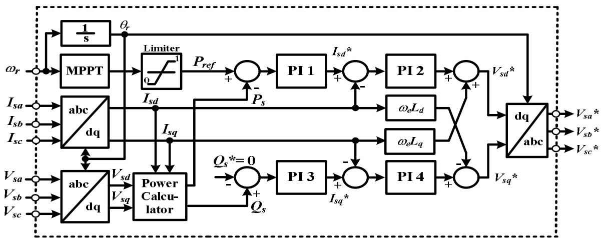


Fig. 5. Stator Side Controller

Fig. 5 shows a block diagram of the stator side controller system. The aim of the stator side controller is to control active and reactive power outputs of the PMSG. The rotor angle position (θe) used in the transformation between abc and dq variables is obtained from the rotor speed of generator. The active power (Ps) and reactive power (Qs) of the generator are controlled by the d-axis current (Isd) and the q-axis current (Isq), respectively. The value of active power reference (Pref) is determined by MPPT method. For unity power factor operation, the reactive power reference (Qs*) is set to zero.

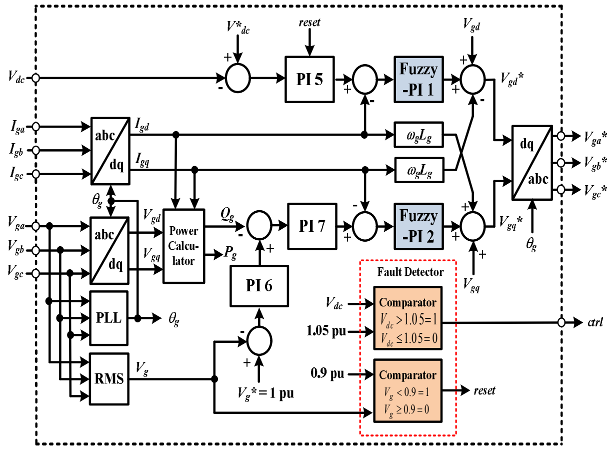


Fig. 6. Grid Side Controller

loop control; one for active power and the other is for the reactive power. The active and reactive power delivered to the grid is controlled by the d-axis current (I_{gd}) and the q-axis current (I_{gq}), respectively. For d-axis and q-axis current components regulation, combination PI and fuzzy logic (Fuzzy-PI) controller is proposed in this paper. The DC-link protection controller is also included in the grid side control system. When a fault condition, the active power transfer to the grid is set to zero by triggering reset command to PI 5. By using this way, supplying reactive power to the grid can be maximized. At the same time, the detector sends the control signal command (*ctrl*) to trigger the DC link protection. The *reset* command is activated when the grid voltage decreases under 0.9 pu. The *ctrl* command is activated when the DC link voltage exceeds the predefine limit (2.1 kV, 1.05 pu).

5. Fuzzy Logic Control Design

In grid side current loop controller, the d-axis and q-axis current controllers are assumed identical, and hence both of the current control can be similarly designed. Block diagram of current loop controller of the GSC is shown in Fig. 7. The controller system is composed of Fuzzy-PI controller, sampling time transfer function, inverter transfer function and plant transfer function, $1/(sL_t+R_t)$, where L_t

and R_t are inductance and resistance of transformer, respectively.

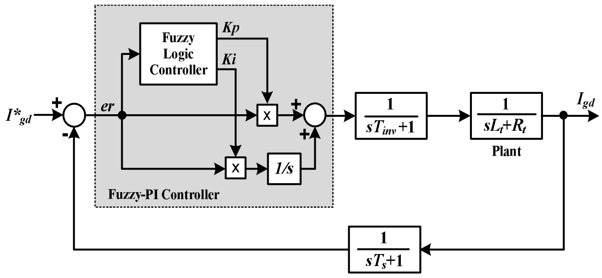


Fig.7. Current Loop Controller of GSC

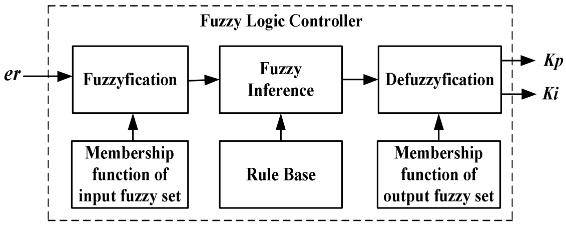


Fig.8. Fuzzy Logic Controller

The fuzzy logic controller adjusts the PI parameters according to the error (*er*) of the input signals. To determine control signal for proportional gain (*Kp*) and integration gain (*Ki*), inference engine with rule base having if-then rules in form of "If *er*, then *Kp* and *Ki*" is used.

The general structure of the Fuzzy Logic Controller is shown in Fig 8. The Fuzzy Logic Controller is composed of fuzzification, membership function, rule base, fuzzy inference and defuzzification. The fuzzification comprises the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term. For fuzzification of the three variables of the fuzzy logic controller, the error (er) have seven membership functions and the gain outputs of Kp and Ki, have four triangle membership functions. The variables of fuzzy subsets for input are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). The variables of fuzzy subsets for output are Small (S), Medium (M), Big (B), and Very Big (VB). Fig. 9 shows the membership function for input *er*. The interval input of the membership function is set at [-1 to 1] due to the variation of the d-axis or q-axis current between -1 to 1 pu.

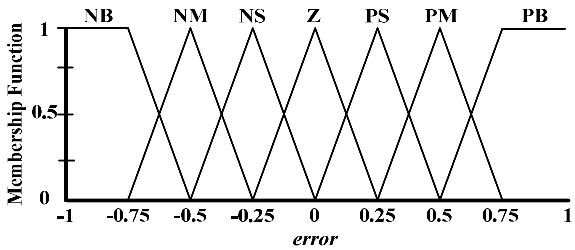


Fig.9. Membership function of error

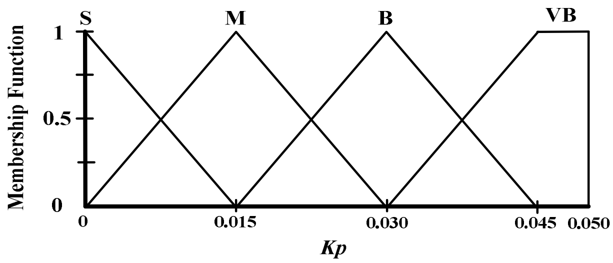


Fig.10. Membership function of *Kp*

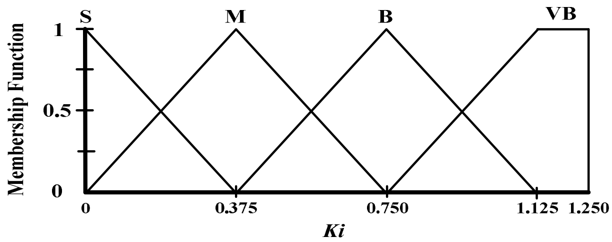


Fig.11. Membership function of *Kp*

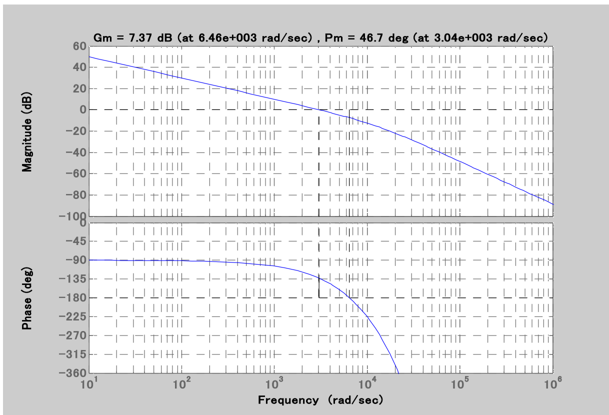


Fig.12. Bode diagram of current loop controller of GSC with K_p =0.05 and K_i = 1.25

The membership functions of output for *Kp* and *Ki* are designed based on frequency response of the bode diagram of the current control loop. To stabilize the controller system, the requirement of Gain Margin (Gm) and Phase Margin (Pm) should be larger than 6 dB and 45 deg, respectively. The initial gain K_p is obtained by using optimum modulus criterion. The maximum gain margins are obtained with K_p= 0.05 and K_i =1.25 such as depicted on the bode diagram in Fig. 12. Therefore, the interval of membership function for output *Kp* and *Ki* can be set at [0.0 to 0.05] and [0.00 to 1.25] as shown in Figs. 10 and 11, respectively.

The rules are set based upon the knowledge and working of the system. A rule in the rule base can be expressed in the form:

If (*er* is NB) then (K_p and K_i is VB).
If (*er* is NM) then (K_p and K_i is B).
If (*er* is NS) then (K_p and K_i is M).
If (*er* is Z) then (K_p and K_i is S).
If (*er* is PS) then (K_p and K_i is M).
If (*er* is PM) then (K_p and K_i is B).
If (*er* is PB) then (K_p and K_i is VB).

In this work, Mamdani's max-min method is used for inference mechanism [15]. The center of gravity method is used for defuzzification to obtain Kp and Ki, which is given by following equation:

$$K_p \text{ and } K_i = \frac{\sum_{i=1}^{n} \mu_i C_i}{\sum_{i=1}^{n} \mu_i} \tag{6}$$

where, n is the total number of rules, μ_i is the membership grade for the i-th rule and C_i is the coordinate corresponding to respective output or consequent membership function.

6. Simulation Results

The model system shown in Fig. 1 is analyzed in this paper, which includes a wind farm connected with multi-machine power system. The wind farm is composed of VSWT-PMSG and FSWT-IG. Symmetrical three-line-to-ground fault (3LG) is considered as network disturbance. The fault occurs at 0.1 sec, the circuit breakers (CBs) on the faulted line are opened at 0.2 sec and the CBs are reclosed at 1.0 sec.

Table 2. Cases Study

Case	Generator Type				
	G1	**G2**	**G3**	**G4**	**G5**
Case 1	IG	IG	IG	IG	IG
Case 2	PMSG with PI	IG	IG	IG	IG
Case 3	PMSG with Fuzzy-PI	IG	IG	IG	IG

Three cases shown in Table 3 are considered in the simulation study to verify the stabilization effect of the proposed controller for the VSWT-PMSG. In Case 1, all of wind generators in the wind farm are IG. In Case 2 and Case 3 the generator number 1 (G1) is PMSG where the current control of the grid side converter is performed by PI and Fuzzy-PI controller, respectively. In Case 2 and 3, when the fault occurs in the grid system, the full-rating power converter of VSWT-PMSG wind turbine system is controlled in such a way to maintain the grid voltage (voltage at Bus 11) at desired reference level. To maximize the reactive power support to the grid system, the active power reference is set to zero during the fault. Simulations were performed by using PSCAD/EMTDC

Fig. 14 shows the wind speed data for each wind generator considered in the simulation analysis. Responses of reactive power outputs of the generators in Case 1, Case 2 and Case 3 are shown in Figs. 14 (a), (b) and (c), respectively. From these figures it is seen that the grid side converter of G1 can support necessary reactive power during fault condition in Case 2 and Case 3.

The terminal voltage at Bus 11 can return back to the rated value quickly in Case 2 and Case 3 as depicted in Fig. 15. The rotor speeds of all wind generators become stable in Case 2 and Case 3 as shown in Fig. 16. It is seen that the wind farm voltage can be stabilized to the nominal value more effectively in the case of the Fuzzy-PI controller than in the case of the PI controller.

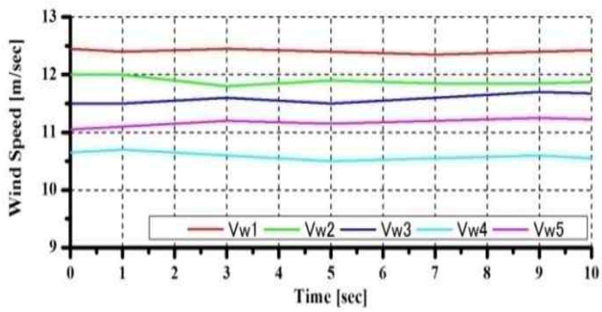
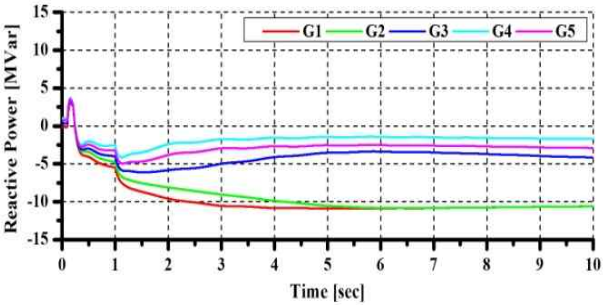
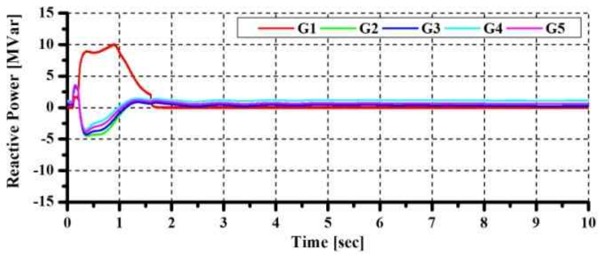


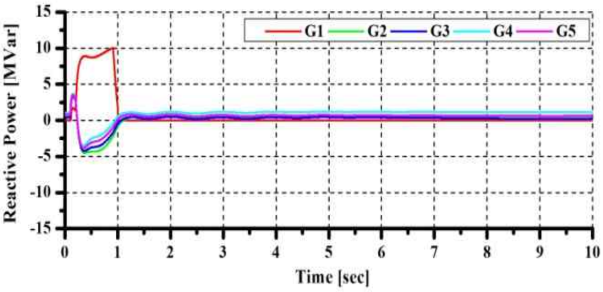
Fig. 13. Wind speed data



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 14. Reactive power output of wind generators

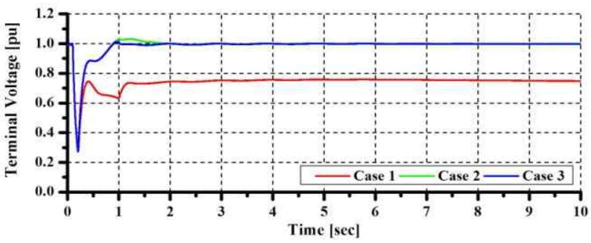
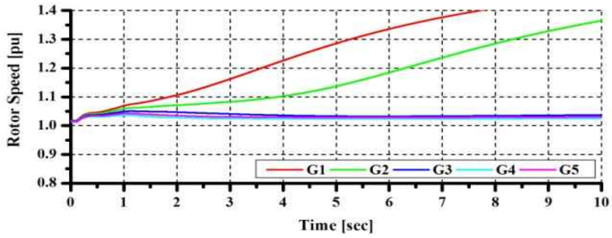
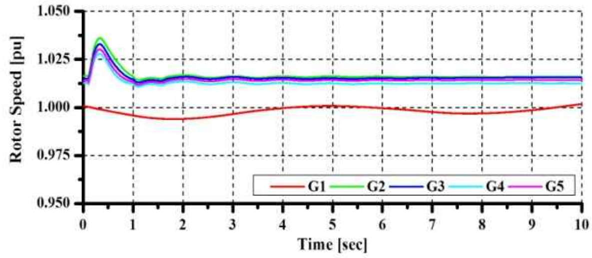


Fig. 15. Terminal voltage at Bus 11

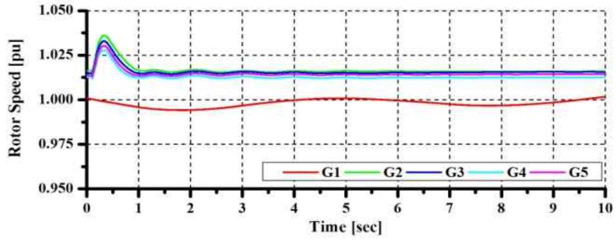
The active power output of wind generators are shown in Fig. 17. It is seen that, the active power of PMSG is controlled to be decreased to zero during the fault effectively in Case 2 and 3 and then to be recovered after the reactive power compensation returns to the initial level. From Figs. 14 through 17, it is seen that the proposed Fuzzy-PI controller is very effective in improving the voltage stability of wind farm during a fault condition.



(a) Case 1

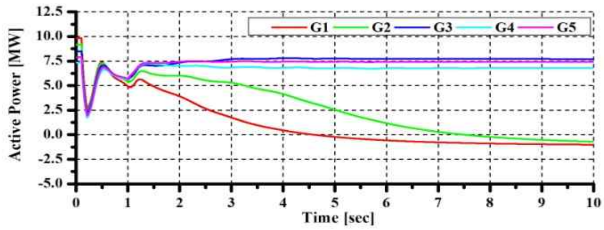


(b) Case 2

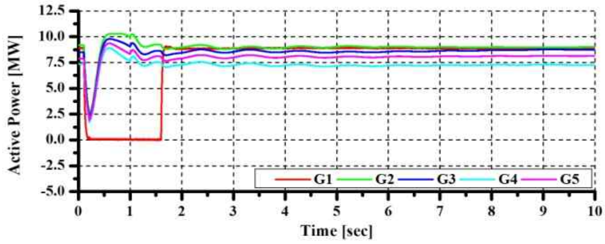


(c) Case 3

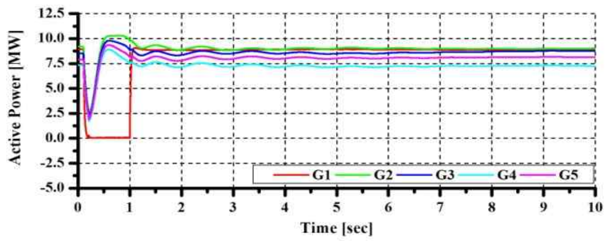
Fig. 16. Rotor speed response of wind generators



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 17. Active power output of wind generators

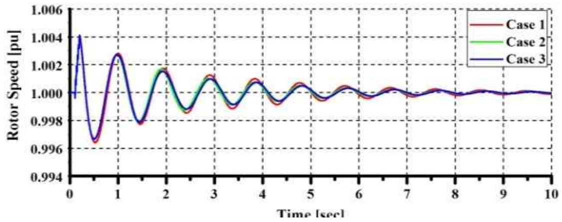


Fig. 18. Rotor speed of SG1

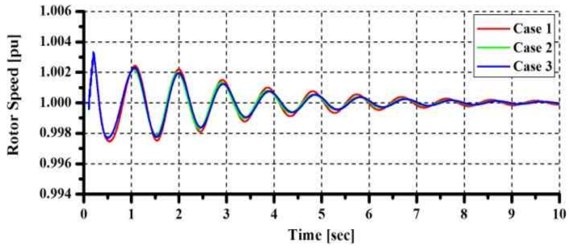


Fig. 19. Rotor speed of SG2

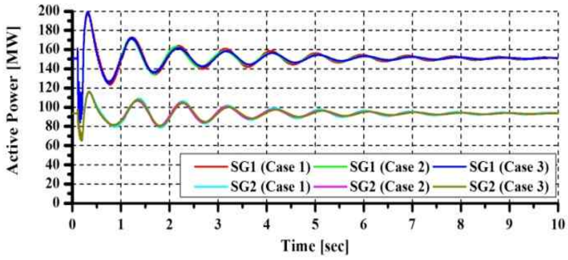


Fig. 20. Active power output of synchronous generators

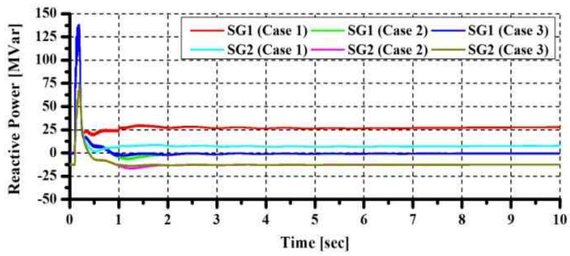


Fig. 21. Reactive power output of synchronous generators

Figs. 18 and 19 show responses of rotor speed of SG1 and SG 2, respectively. Figs. 20 and 21 show the active power and the reactive power output of SG1 and SG2, respectively. It can be seen that participation of VSWT-PMSG can also improve the transient behavior of synchronous generator in some degree.

7. Conclusion

A new control strategy of Variable Speed Wind Turbine with Permanent Magnet Synchronous Generator (VSWT-PMSG) for stabilizing wind farm composed of Fixed Speed Wind Turbine with Induction Generators (FSWT-IG) as well as PMSG and connected to a multi-machine power system is presented. The Fuzzy-PI controller is proposed in the current controlled grid side voltage source converter of PMSG to enhance the performance of the wind farm also composed of FSWT-IGs. The results show that participation of VSWT-PMSG with the proposed Fuzzy-P controller can enhance the transient stability as well as the voltage stability of the wind farm when a severe 3LG fault occurs in the power system.

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