Eigenvalue Analysis for Stability Improvement of Wind Turbine by Using UPQC Based on Fuzzy Controller

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Abstract — the unified power quality conditioner (UPQC) can be utilized to alleviate the fluctuations and improve the stability of the wind turbine. The fuzzy controller is able to handle non-linear and time varying systems. This paper presents application of the fuzzy controller in control system of the UPQC for stability enhancement of wind farm.

A frequency-domain method based on a linearized system model using root locus, eigenvalue technique and a time-domain analysis based on nonlinear system model are both employed to verify the effectiveness of the proposed controller. It is validates the UPQC with proposed controller can enhance the stability margin in tested power system significantly and it has fast response. The proposed controller is robust and powerful for recovery of the bus voltage rather than UPQC with classic controller.

***Index Terms*:** Eigenvalue technique, Fuzzy controller, Power quality, Stability improvement, Unified power quality conditioner (UPQC), Wind turbine

1. INTRODUCTION

Wind energy generation is becoming the most advanced renewable generation technology in the world. After a fault, the instability causes in wind turbine. The wind turbine starts to absorb reactive power from the network. Consequently, rotor slip of wind farm increase during fault occurrence, the consumption of reactive power is increased. It is necessary to methods for improvement of power quality and stability. Flexible AC transmission system (FACTS) devices such as static var compensator (SVC), superconducting magnetic energy storage (SMES), static synchronous compensator (STATCOM), dynamic voltage restorer (DVR) and unified power quality conditioner (UPQC) can be improve the stability of the wind farm [1- 9].

Recently, different control techniques such as sliding mode controller, fuzzy controller [10], [11] and radial basis function neural network (RBFNN) have been applied for stability improvement in a power system [12], [13].

The power system equiped to UPQC is a large-scale nonlinear, indetermination and multivariable system; the structure and parameters of system will change especially when faults create suddenly. Therefore, the traditional classic controller has a limited application in some cases because of its non-adaptive parameters and linearity.

In order to solve this problem, fuzzy controller has been proposed for the UPQC in this paper. The controller system with the proposed strategy is adaptive and robust. This paper compares the effects of the UPQC with classic and fuzzy controller in frequency and time domains in a wind farm interconnected to the power system.

This paper is organized as follows. Section 2 introduces the tested power system, wind turbine and UPQC compensator. The UPQC based on classic controller has been designed in Section 3. Section 4 introduces UPQC based on fuzzy controller. Simulation results and characteristics of the proposed controller have been shown in section 5. Specific conclusion of this paper has been illustrated in section 6.

2. THE TESTED POWER SYSTEM

Fig. 1 shows the configuration of the power system for stability analysis. The model system consists of a wind turbine coupled through a transformer to the power grid and double circuit transmission line. CB in this figure represents a circuit breaker. The wind turbine interconnected to the power system is squirrel cage induction generator (SCIG). A 9MW wind turbine interconnected to 25kV distribution system transmits energy to the grid.

In the normal operation of the wind turbine, the electric power is equal to the mechanical power. When fault occurs in the system, a sudden sag in the AC voltage is created and it causes the transmitted power of wind turbines to reduce. The mechanical and electrical power is unbalanced due to the fixed mechanical torque in this condition; rotor accelerates so the rotor slip increases to a new slip. When the system fault is cleared, the AC voltage will return to pre- fault amount.

Because the rotor slip cannot change instantaneously due to mechanical limitations, a large amount of reactive power is absorbed by wind turbine and the electric torque will be more than the mechanical torque. It causes the rotor acceleration to decrease. The deceleration of the wind turbine and reduction of rotor slip lead to reduction of reactive power absorbed by the wind turbine and it causes AC voltage to increase. Consequently, the reactive power and electrical torque come back to their steady state condition [13].

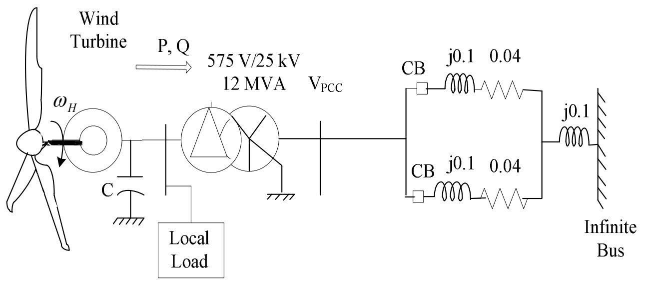
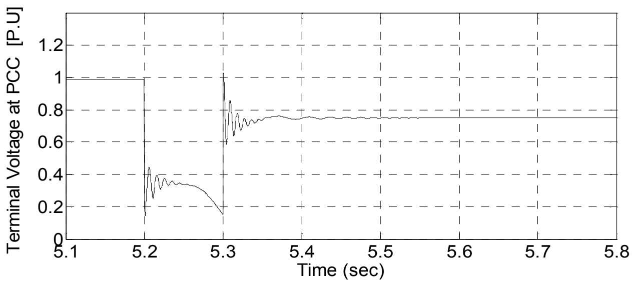


Fig. 1. The configuration of tested power system

If the fault does not clear on suitable time, the rotor slip may increase extensively and the system will be unstable. Fig.2 indicates this phenomenon. The fault is occurred at t= 5.2sec to t= 5.3sec and the terminal voltage at point of common coupling (PCC) is decreased suddenly. The stator current and electromagnetic torque is changed significantly.



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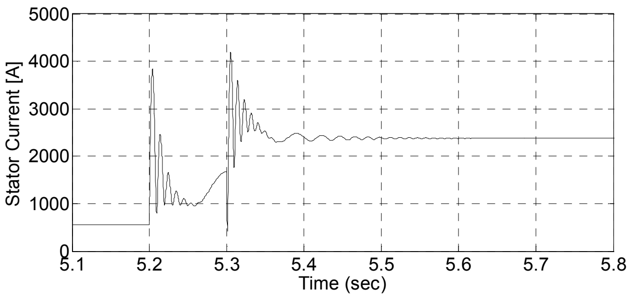

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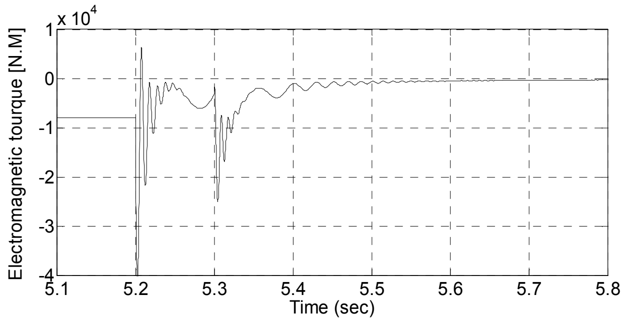

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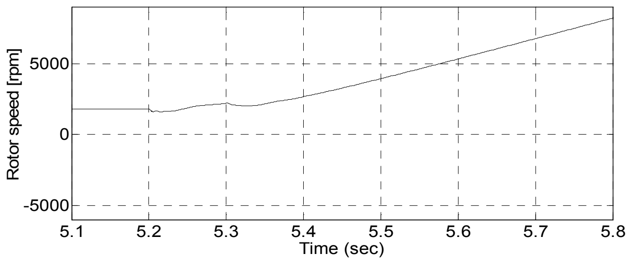


d)

Fig. 2. a) The terminal voltage at the PCC, b) the stator current, c) the electromagnetic torque and d) the rotor speed of the wind turbine during fault occurrence

A. THE WIND TURBINE

The power generated by wind turbine is P and it is presented into following form:

$$P = \frac{1}{2} C_p . \rho . \pi . R^2 . V^3 \qquad (1)$$

Where ρ is air density, R is radius of the swept area, V is wind speed, and C_p is the power coefficient. In this study, these values are $R = 31.2m$, $\rho = 1.225 \frac{kg}{m^3}$ and C_p values are taken from a widely used classical model [13], [14].

The autoregressive moving average with exogenous variable (ARMAX) estimator can be estimate the parameters of ARX model from input and output data in Simulink enviroment. The ARX block uses least-squares analysis to estimate the parameters of an ARX model [15], [16].

The basic transient characteristic of a system related to the location of the poles. The root locus is a very powerful graphical technique for investigating the effects of the variation of a system parameter on location of the closed loop poles. In most cases, the system parameter is the loop gain K, although the parameter can be any other variable of the system [17].

If the value of gain K enters the right-half's plane, the system can become unstable [17]. The linearized model of tested system has been obtained based on ARMAX estimator. The input data are samples data from variations of the PCC voltage (Δv_t) and output data are samples data from the variations of the rotor speed ($\Delta \omega$). Fig. 3 shows pole-zero of the power system and corresponding root locus. Therefore, this linearized- power system is unstable in a wide range.

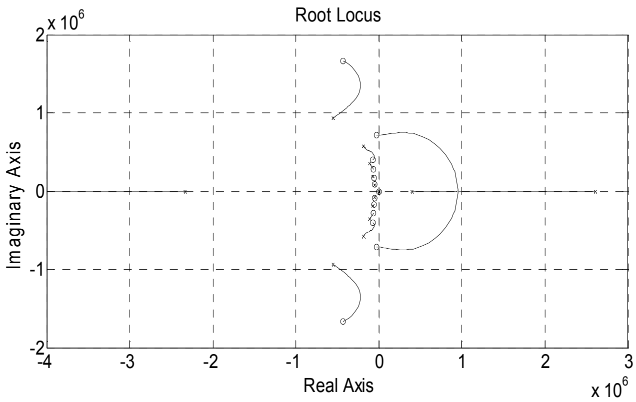


Fig. 3. Pole-zero configuration of the linearized system and corresponding root locus

The system eigenvalues (rad/s), damping of the studied IG with the power system has been shown in Table I. The eigenvalues $\lambda_1 - \lambda_{14}$ listed in Table I are related to the mechanical modes of the tested system.

Table I demonstrates that the system eigenvalues aren't placed on the desired locations of the complex plane.

TABLE I
SYSTEM EIGENVALUES (rad/s), DAMPING OF THE STUDIED IG

	IG	
	Eigen value	Damping
λ_1	$2.61*10^6$	-1
λ_2	$(-5.50 + j9.35)* 10^5$	1
λ_3	$(-5.50 + j9.35)* 10^5$	0.507
λ_4	$(-5.50 - j9.35)* 10^5$	0.507
λ_5	$(-1.87 + j5.79)* 10^5$	0.307
λ_6	$(-1.87 - j5.79)* 10^5$	0.307
λ_7	$4*10^5$	-1
λ_8	$(-1.07 + j3.51)* 10^5$	0.292
λ_9	$(-1.07 - j3.51)* 10^5$	0.292
λ_{10}	$(-0.707 + j1.93)* 10^5$	0.344
λ_{11}	$-0.707 - j1.93)* 10^5$	0.344
λ_{12}	$(-4.90 + j7.41)* 10^4$	0.551
λ_{13}	$(-4.90 - j7.41)* 10^4$	0.551
λ_{14}	3.64	-1

B. UPQC MODEL

Fig. 4 indicates a model of the UPQC installed with the SCIG wind turbine in the distribution system.

The UPQC consists of a number of static synchronous compensators; static synchronous compensator (STATCOM) and dynamic voltage restorer (DVR) that they are connected together via a common DC link. The DVR is connected in series while the STATCOM is connected in shunt with the AC line. The STATCOM acts such as synchronous current source and it charges the voltage of the common DC link. The DVR operate as a synchronous voltage source which can be regarded as series reactive and active power compensation scheme producing a controllable voltage. By controlling of amplitude, phase angle and frequency of injected voltage, DVR restore the quality of the voltage at the load side (or wind farm side) when the quality of the supply voltage is distorted.

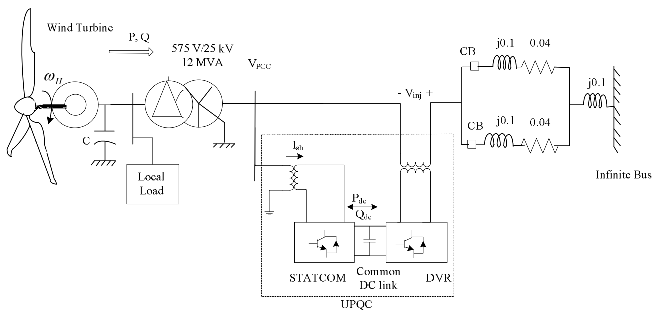
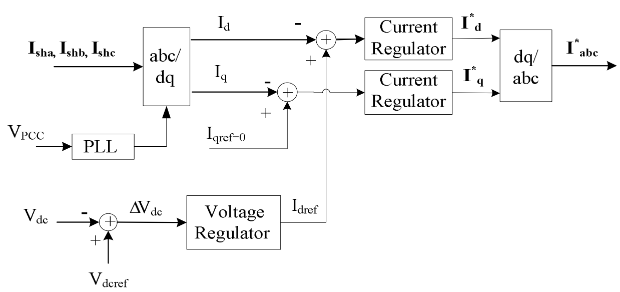


Fig. 4. The tested system with UPQC

3. THE CONTROL STRATEGY OF THE UPQC

The control strategy of the UPQC based on conventional controller (PI controller) has been presented in the literatures [18], [19]. Fig. 5 shows the control strategy of the UPQC. The STATCOM regulates the voltage of common DC link and acts as active filter, suppresses the current harmonics. The DVR regulates the bus voltage (the PCC voltage) through stored energy in DC link by STATCOM.

In control strategy of the DVR, the injected three voltages by phase locked loop (PLL) track the phase of load voltage. The load voltage is transformed to V_d, V_q and V_0 based on Park's transform. For regulation of load voltage, they are compared with reference voltages V_{dref}, V_{qref} and produce error. High quality voltage only include d- component. For efficient sag compensation, $V_{dref} = 1$ and $V_{qref} = 0$ are chosen.



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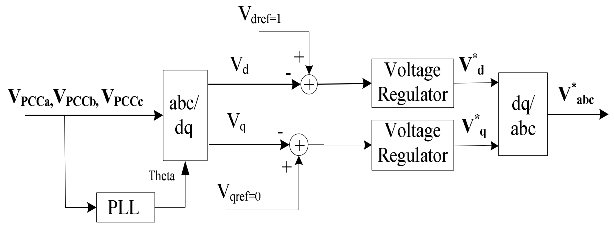


Fig. 5. The conventional strategy of the UPQC; a) STATCOM, b) DVR control system

The linearized model of tested system with UPQC compensator has been obtained based on ARMAX estimator. The root locus method has been applied to draw the pole-zero configuration of the system with UPQC compensator. Fig. 6 shows the pole-zero configuration of this system, the root locus placement has been moved to the left- half's plane. Therefore, the stability of tested system has been enhanced to some extent.

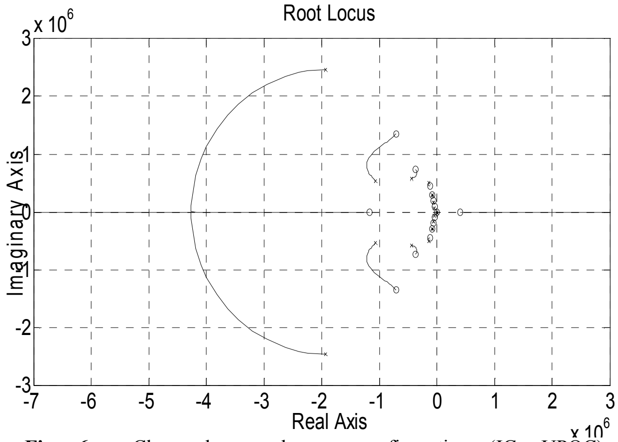


Fig. 6. Close- loop pole-zero configuration (IG, UPQC) and corresponding root locus

The system eigenvalues (rad/s), damping of the tested system with the UPQC compensator has been shown in Table II. It shows the system eigenvalues are assigned on the desired locations of the complex plane rather than the power system without any compensator.

TABLE II
SYSTEM EIGENVALUES (rad/s), DAMPING OF THE STUDIED IG AND UPQC

IG with UPQC based on classic controller		
	Eigen value	Damping
λ_1	(-1.93e + j2.47)* 10^6	6.15e-001
λ_2	(-1.93e - j2.47)* 10^6	6.15e-001
λ_3	(-0.106 + j5.42)* 10^5	8.90e-001
λ_4	(-1.06 - j5.42)* 10^5	8.90e-001
λ_5	(-4.37 + j5.81)* 10^5	6.01e-001
λ_6	(-4.37 - j5.81)* 10^5	6.01e-001
λ_7	(-1.44 + j5.02)* 10^5	2.75e-001
λ_8	(-1.44 - j5.02)* 10^5	2.75e-001
λ_9	(-8.22 + j0.296)* 10^4	2.68e-001
λ_{10}	(-8.22 – j0.296))* 10^4	2.68e-001
λ_{11}	(-5.95 + j0.17)*)* 10^4	3.30e-001
λ_{12}	(-5.95e+004 – j0.17)*)* 10^4	3.30e-001
λ_{13}	(-4.14 + j6.78)*)* 10^4	5.21e-001
λ_{14}	(-4.14 - j6.78)*)* 10^4	5.21e-001
λ_{15}	-4.26	1.00e+000

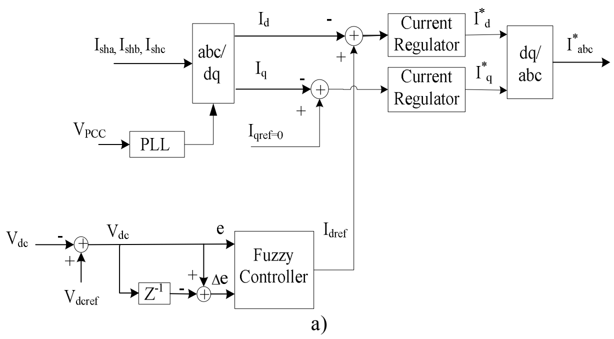
4. THE PROPOSED CONTROL SYSTEM OF THE UPQC

A. Fuzzy logic Controller

Recently, fuzzy logic controllers have generated a great deal of interest in various applications and have been applied in the power electronics and FACTS devices [20], [21]. The advantages of fuzzy logic controllers over the classic (PI) controller are that they do not require an accurate mathematical model; they can work with imprecise inputs, can handle nonlinearity, and may be more robust than the classic controller [22].

B. UPQC Based on Fuzzy Controller

The fuzzy controller configuration incorporates attractive features such as simplicity, fast dynamic response, and automation, while using a low cost hardware and software implementation. Fig. 7 shows the control system of the UPQC controller based on FLC.



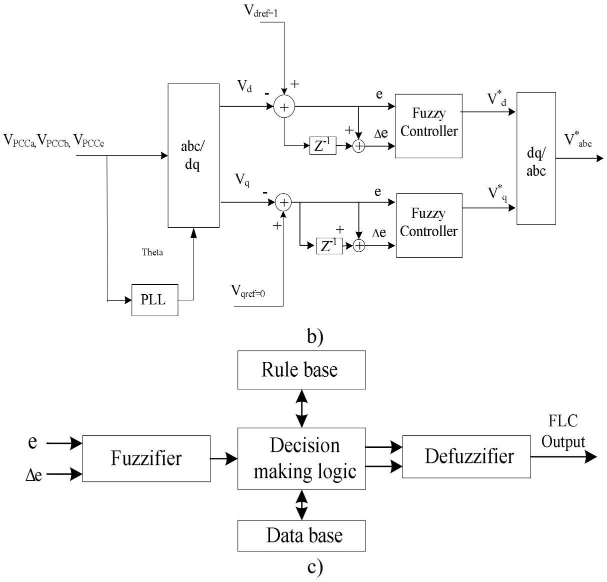


Fig. 7. The control strategy of the UPQC; a) STATCOM, b) DVR control system based on fuzzy controller and c) the block diagram of fuzzy controller

In this case, a two-input, one-output fuzzy logic controller has been considered. The input signals for the FLC are the DC-link voltage variations in the STATCOM controller. Variations of d, q- components of the PCC voltage with the deviations are FLC input signals in the DVR controller.

The fuzzy logic controller consists of fuzzification part, fuzzy inference part and defuzzification part.

The inference part consists of membership functions and rule bases which are obtained from an understanding of the UPQC behavior and using of systematic procedure. They are modified and tuned by simulation performance. A triangular membership function has the advantages of simplicity and easier implementation and is chosen for this application [22].

There are seven linguistic variables for each input and five linguistic variables for output variable, namely, Positive Big (PB), Positive Smal (PS), Positive Medium (PM), Zero (Z), Negative Small (NS), Negative Medium (NM), and Negative Big (NB) has been shown in Fig. 8. Generally, FLC generates the required variable signal to change amplitude modulation ratio and control the magnitude of the injected voltage based on these rules. The centroid defuzzyfication strategy was used in this fuzzy controller.

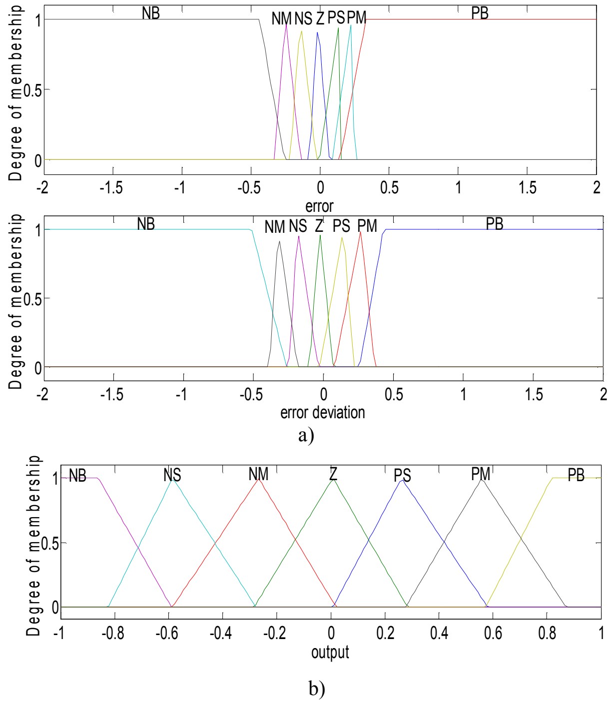


Fig. 8. The membership function of a) error and error deviation, b) output of FLC

Table III shows the utilizing 25 linguistic rules directly processes three phase supply voltages to improve the response time of UPQC.

TABLE III

THE RULE TABLE OF THE FUZZY LOGIC CONTROLLER (25 LINGUISTIC RULES)

e \ Δ*e*	PB	PM	PS	Z	NS	NM	NB
PB	PB	PB	PB	PM	PM	PS	Z
PM	PB	PB	PM	PM	PS	Z	NS
PS	PB	PM	PM	PS	Z	NS	NM
Z	PM	PM	PS	Z	NS	NM	NM
NS	PM	PS	Z	NS	NM	NM	NB
NM	PS	Z	NS	NM	NM	NB	NB
NM	Z	NS	NM	NM	NB	NB	NB

When the FLC output's magnitude is more than carrier signal's magnitude, the PWM circuit generates high output and when the FLC output's magnitude is less than carrier signal's magnitude, the PWM circuit produces low output. The carrier signal is a saw tooth waveform at 20 kHz taking values between -1 and 1.

The linearized model of tested system with UPQC compensator based on fuzzy controller has been obtained based on ARMAX estimator. The root locus method has been applied to draw the pole-zero configuration of the system with UPQC compensator. Fig. 9 shows the pole-zero configuration of this system, the root locus placement has been moved to the left- half's plane. Therefore, the stability of tested system has been enhanced in a wide range.

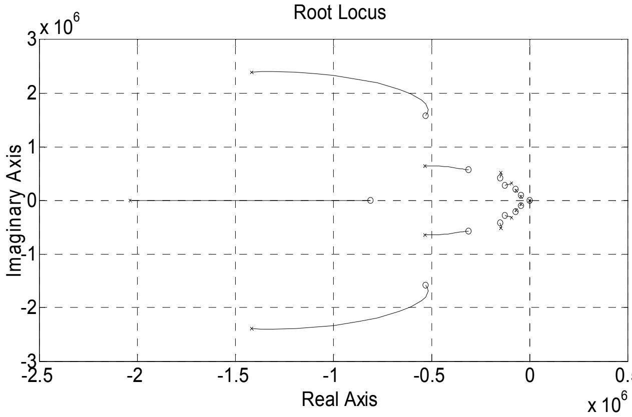


Fig. 9. Close loop pole-zero configuration of tested system with UPQC based on fuzzy controller and corresponding root locus

The system eigenvalues of the tested IG with the UPQC based on fuzzy controller are shown in Table IV. It shows the system eigenvalues are assigned on the desired locations of the complex plane rather than the power system with UPQC based on classic controller.

TABLE IV

SYSTEM EIGENVALUES (rad/s), DAMPING OF THE STUDIED IG AND UPQC FUZZY CONTROLLER

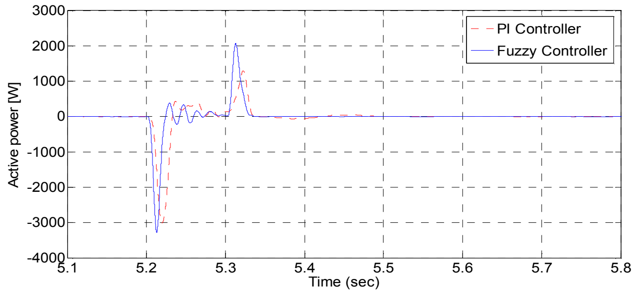
IG with UPQC based on fuzzy controller		
	Eigen value	Damping
λ_1	$(-1.42 + j2.40)* 10^6$	5.09e-001
λ_2	$(-1.42 - j2.40)* 10^6$	5.09e-001
λ_3	$-2.03*10^6$	1.00e+000
λ_4	$(-5.32 + j6.44)* 10^5$	6.37e-001
λ_5	$(-5.32 - j6.44)* 10^5$	6.37e-001
λ_6	$(-1.47 + j5.11)* 10^5$	2.77e-001
λ_7	$(-1.47 - j5.11)* 10^5$	2.77e-001
λ_8	$(-9.19 + j0.316)* 10^4$	2.79e-001
λ_9	$(-9.19 – j0.316)* 10^4$	2.79e-001
λ_{10}	$(-6.72 + j181)* 10^4$	3.48e-001
λ_{11}	$(-6.72 – j0.181)*)* 10^4$	3.48e-001
λ_{12}	$9-4.27 + j7.13)*)* 10^4$	5.14e-001
λ_{13}	$(-4.27 - j7.13)*)* 10^4$	5.14e-001
λ_{14}	-1.36	1.00e+000

5. SIMULATION RESULTS AND DISCUSSION

To evaluate the system performance, the model of the UPQC for wind turbine is simulated using Matlab/Simulink. The parameters of wind farm simulated power system have been shown in Table V in appendix.

Fig. 2 shows the voltage sags which occurred at t= 5.2 sec to t= 5.3 sec. As been stated in Sec. III, the UPQC operate to regulate the terminal voltage of SCIG, rejecte the PCC voltage variations.

Fig. 10 indicates the exchange active and reactive power between STATCOM and DVR (common DC link) by PI and fuzzy controller.



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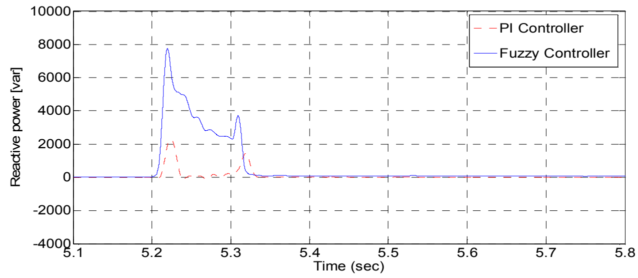

b)

Fig. 10. The exchange active power and reactive power in the common DC link (P_{dc}, Q_{dc})

Fig. 11, 12 shows the efficient of proposed control structure based on fuzzy controller for compensation of the voltage sags. As a result, the UPQC increases and regulated the voltage of DC link through rectifying by the STATCOM. The UPQC injects the series voltage through the DVR. It feeds the local load and protects from wind farm during fault condition. It prevents from disconnection wind farm and causes the SCIG have been continuous operation. The wind farm transmits energy to grid and local load by this combination during disturbance.

Therefore, the PCC voltage is regulated with FLC better than PI controller. The stator current of the SCIG by UPQC based on FLC has fast transient response rather than UPQC based on PI controller.

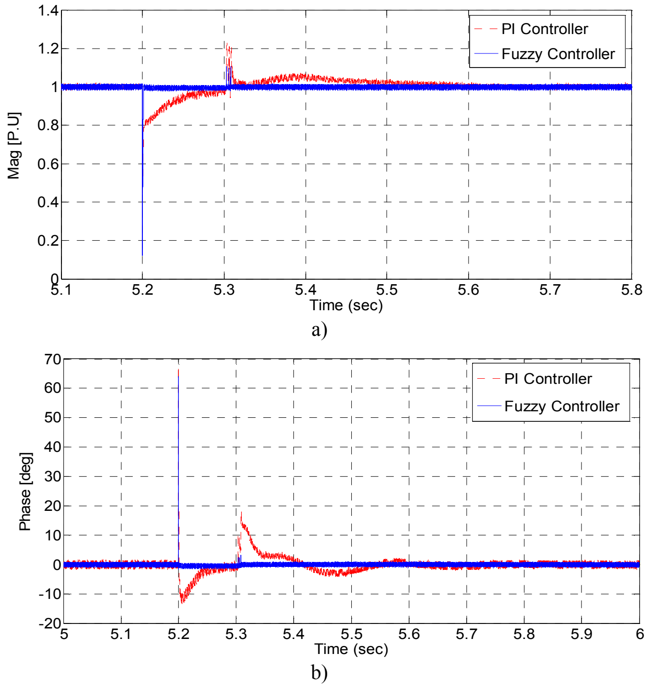

Fig. 11. Comparison a) the magnitude and b) phase compensated of the PCC voltage between conventional controller and fuzzy controller

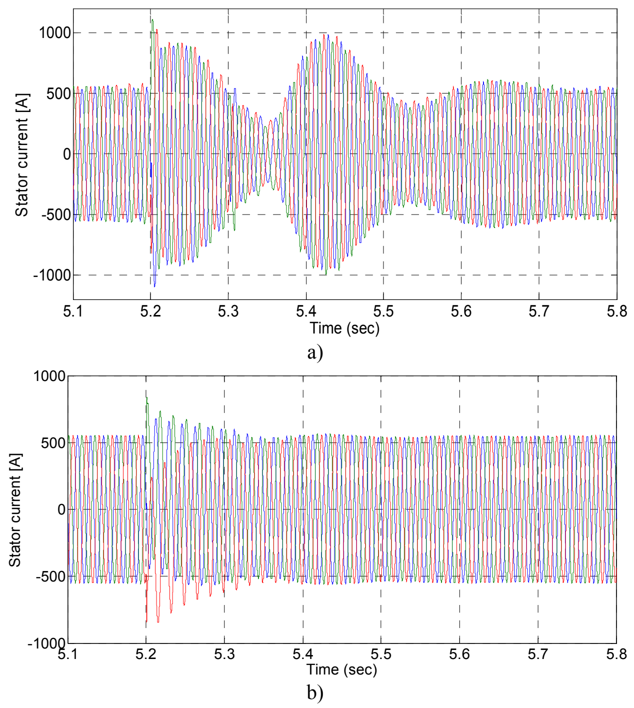

Fig. 12. Comparison the stator current between a) PI controller and b) fuzzy controller

The fluctuations the electromagnetic torque and rotor speed by UPQC based on FLC mitigate, significantly.

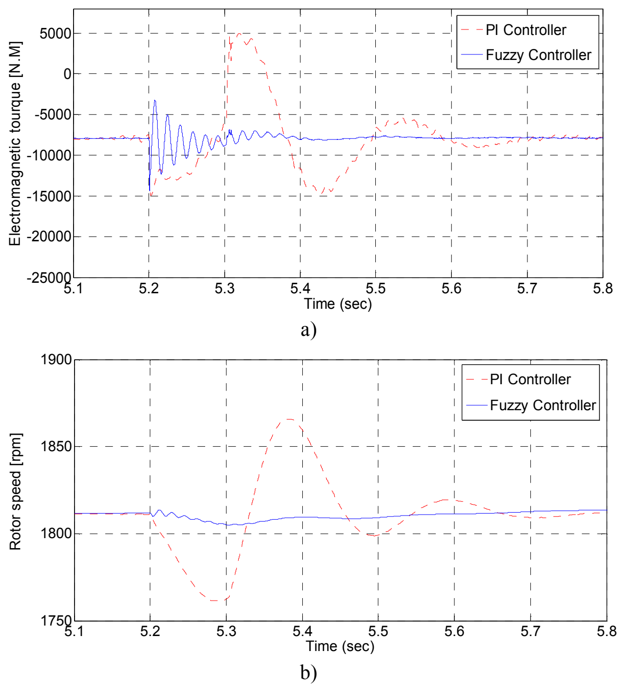

Fig. 13. Comparison a) the electromagnetic torque and b) rotor speed between conventional controller and fuzzy controller

Delay time of recovery is time that the PCC voltage restores to pre-fault voltage, therefore if this time reduces; the dynamic response of UPQC is fast. The tested power system investigated in different conditions. Table V compares delay time of recovery with UPQC based on classic and fuzzy controllers. The fuzzy controller gives a better performance rather than PI controller. The rotor speed deviations and electromagnetic torque oscillations of the wind turbine mitigate with fuzzy controller, rapidly.

TABLE V

COMPARISON BETWEEN DELAY TIME OF RECOVERY WITH PI AND FUZZY CONTROLLERS

Dynamic and transient conditions	Delay time of recovery with PI controller	Delay time of recovery with fuzzy controller
Three phase to ground	65 msec	2.2 msec
Two phase to ground	62 msec	2 msec
Single phase to ground	58 msec	1.8 msec
Voltage sags	40 msec	8 msec
Voltage swell	55 msec	1.7 msec

6. CONCLUSION

This paper presents the effects of UPQC with fuzzy controller on stability of wind turbine. The proposed controller combines the robustness and simplicity designing of fuzzy controller.

Simulation results illustrate that the UPQC controller can effectively increase stability, compared without any compensation. The proposed system effectively compensates the voltage variation caused by voltage sag in the PCC. The proposed controller can restore the magnitude and phase jump of the PCC voltage, rapidly. This control system is applied to assist for continuous operation of the SCIG during faults.

A frequency-analysis based on linearized system model using root locus, Eigen techniques employed to validate the effectiveness of the proposed controller. The root locus placement of the proposed controller moved to the left halt-plane. The locations of the eigenvalues on complex plane with proposed controller desirer than the power system equipped to UPQC with classic controller. Therefore, the stability of the power system with proposed controller has been increased in a wide range.

A time-domain analysis based on a nonlinear system model employed to verify the effectiveness of the proposed controller. The PCC voltage of the wind turbine can be regulated with UPQC based on fuzzy controller, rapidly. The control system smoothen the electromagnetic torque and rotor speed deviations of the SCIG wind turbine.

APPENDIX

Table VI shows the associated parameters in simulation of wind farm and the proposed topology.

TABLE VI

THE APPLIED PARAMETER IN SIMULATION

	parameters
Wind turbine	Nominal power= 9 MW, Voltage (line-line)= 575 V, Stator resistance and inductance [R_s (ohm), L_{ls} (H)]= [0.029, 0.226/377], Rotor resistance and inductance [R_r (Ohm), L_{rs} (H)]= [0.022, 0.226/377], Mutual inductance L_m (H)= 13.04/377, Inertia, friction factor and pole pairs [J (kg.m^2, F (N.m.s), P]=[63.87, 0, 2]
Transformer coupling	575 V/25 kV, 12 MVA
Line section length	10 km
Source frequency	60 Hz
Local load	200 kW
STATCOM controller	The AC voltage regulator: proportional gain K_p= 5, Integral gain K_i= 1000, the DC bus voltage regulator proportional gain K_p= 0.0001, Integral gain K_i= 0.005
Supplementary controller	K_p= 0.5, K_i= 300, K_d= 0.003, limiter [max, min]= [0.35, -0.35]
Infinite Bus	25 kV, 2500 MVA
Fault resistance	R= 2 Ohm

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