International Journal of Robotics and Automation (IJRA)
Vol. 8, No. 3, September 2019, pp. 164~173
ISSN: 2089-4856, DOI: 10.11591/ijra.v8i3.pp164-173

Design of POD controller using linear quadratic regulator tecniques for SMIB power system stability enhancement installed with UPFC

Brijesh Kumar Dubey[1], N. K. Singh[2]
[1]Electrical & Electronics Engineering, Pranveer Singh Institute of Technology, Kanpur, India
[2]Electrical Engineering, RVIT Bijnor, Bijnor, India

Article Info

Article history:

Received Apr 30, 2018
Revised Jun 1, 2019
Accepted Jun 15, 2019

Keywords:

FACTs
LQR
Power oscillation damping controller
Small signal stability
UPFC

ABSTRACT

In the field of the power system stability, this paper presents the current research status and developments. This paper presents a systematic approach for designing Power Oscillation Damping Controller (POD) based Linear Quadratic Regulator Techniques for SMIB power system stability installed with UPFC to damp out low frequency oscillations in a power system. The impacts of control strategy on power system single machine infinite bus installed with UPFC, without UPFC and with UPFC and POD controller at different operating conditions are discussed. The accuracy of the developed models is verified through comparing the study results with those obtained from detailed MATLAB programming.

Corresponding Author:

Brijesh Kumar Dubey,
Electrical & Electronics Engineering,
Pranveer Singh Institute of Technology,
Kanpur, India.
Email: brijesh80d@rediffmail.com

1. INTRODUCTION

Today's power system, comprising of generator, transmission lines and different types of loads is a complex network. As the power demand increase some transmission line is more loaded than was planned. In order to meet the growing power demand, utilities have an interest in better utilization of available power system capacities, existing generation and existing power transmission network, instead of building new transmission lines and expanding substations. The main drawback of the power system is deteriorating voltage profiles and decreasing system stability and security; the main cause of this drawbacks are due to the overloaded of the power flow in transmission lines of power system. In addition, existing ancient transmission facilities, in most cases, are not designed to handle the control requirements of complex and highly interconnected power systems. This overall scenario force us to review of ancient transmission methods and practices, and the creation of new concepts, which might allow the use of existing generation and transmission lines up to their full capabilities without reduction in system stability and security [1]. The main parameters which are responsible to determine the transmitted electrical power over a line are line impedance, the receiving and sending ends voltages, and phase angle between the voltages. Therefore, by controlling, one or more of the transmitted power factors; it is possible to control the active as well as the reactive power flow over a line. Small-signal stability is the ability of the system to return in a normal.

Operating state following a small disturbance. Investigations involving this stability concept usually involve the analysis of the linearized state space equations that define the power system dynamics. To damp out the low power oscillation frequency and increase system oscillations stability, the installation of Power

System Stabilizer (PSS) is both economical and effective [2]. Recently appeared FACTS (Flexible AC Transmission System)-based stabilizer offer an alternative way in damping power system oscillation. The primary function of the FACTS controllers is not only it Damping Duty, but also to increase the overall power system oscillation damping characteristics [3].

Many researchers have presented dynamic models of UPFC [4, 5-14]. A modified linearised Phillips-Heffron model of a power system installed with UPFC have presented by Wang [4, 13-14]. The objective of this paper is to design a UPFC based Power Oscillation Damping (POD) controller to damp the low frequency electromechanical oscillations over wide range of operating conditions [4]. The procedure to achieve the paper objective is as follows:

- The model (Phillips–Heffron) of the single machine infinite bus (SMIB) power system installed with UPFC is obtained by linearising the non-linear equations around a nominal operating point [4].
- To present systematic approach for designing UPFC based power oscillation damping controller.
- Design a POD controller using LQR technique which places the eigenvalue corresponding to mode of oscillation at desired location such that eigenvalues get placed within a vertical degree of stability.
- To demonstrate the effectiveness of the designed POD controller under different controlling parameter.

2. INVESTIGATED SYSTEM

Figure 1 shows a single machine infinite bus power system installed with unified power flow controller between bus A and bus B on the transmission line, which consists of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSC's), a dc link capacitor and based on pulse width modulation converters (assumed). The system parameters are given in Appendix-A.

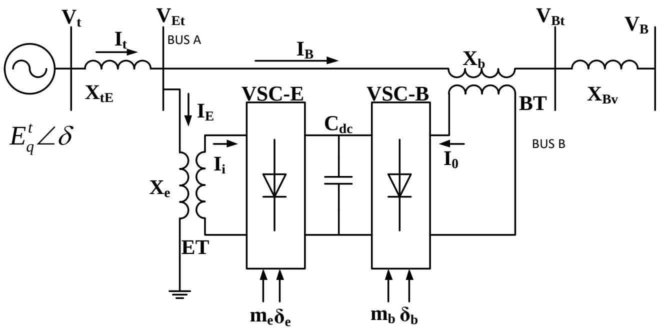

Figure 1. UPFC installed in SMIB power system

3. UNIFIED POWER FLOW CONTROLLER

The dc link provides a bi-directional path to exchange active power between the converters, coupled a static synchronous compensator and static synchronous series compensator. me, mb , δe, δb are the input control parameter of the UPFC. Here me is amplitude modulation ratio of shunt VSC-E, δe is phase angle of shunt VSC-E, mb is amplitude modulation ratio of series VSC-B and δb represents phase angle of series VSC-B [15, 16]. Power system which comprises a synchronous generator connected to an infinite bus through a transmission line and stepping up transformer. The generator is assumed to have Automatic Voltage Regulator (AVR) controlling its terminal voltage. The UPFC is used in this study to just analyze the purpose of power system stability and its characteristics. The UPFC can fulfill multiple control objectives.

4. MODIFIED PHILLIPS-HEFFRON MODEL OF A SMIB SYSTEM WITH UPFC

Figure 2 shows the Modified Phillips-Heffron model of power system installed with UPFC, developed by Wang [4] with the modification of the basic Phillips-Heffron model including UPFC. Around a nominal operating point, by linearising the nonlinear model, this model has been developed.

The parameters of the model depend on the system parameters and the operating condition. In this model [Δu] is the column vector while [W_{pu}], [W_{qu}], [W_{vu}] and [W_{cu}] are the row vectors.

Where,

$[\Delta u] = [\Delta m_e\ \Delta\delta_e\ \Delta m_b\ \Delta\delta_b]^T$

$[W_{pu}] = [W_{pe}\ W_{pde}\ W_{pb}\ W_{pdb}]$

$W_{qu}] = [W_{qe}\ W_{qde}\ W_{qb}\ W_{qdb}]$

$[W_{vu}] = [W_{ve}\ W_{vde}\ W_{vb}\ W_{vdb}]$

$[W_{cu}] = [W_{ce}\ W_{cde}\ W_{cb}\ W_{cdb}]$

The control parameters of the UPFC are,

- m_b–pulse width modulation index of series inverter. The magnitude of series injected voltage can be controlled by controlling m_b.
- δb–Phase angle of series inverter. δb when controlled results in the real power exchange.
- me–pulse width modulation index of shunt inverter. By controlling me, the voltage at a bus where UPFC is installed, is controlled through reactive power compensation.
- δe–Phase angle of the shunt inverter, which regulates the dc voltage at dc link.

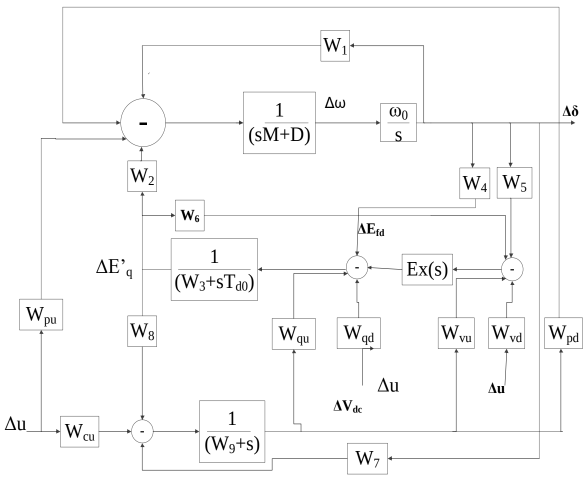

Figure 2. Modified Phillips-Heffron model of power system installed with UPFC

5. MODEL ANALYSIS

The constant parameters of the model computed for nominal operating condition and system parameters are.

$W1 = 0.1372$	$Wpb = 0.0715$	$W_{pde} = -0.2514$
$W_2 = 0.4350$	$W_{qb} = -0.0223$	$W_{qde} = -\ 0.2243$
$W_3 = 0.4727$	$W_{vb} = 0.0145$	$W_{vde} = 0.0782$
$W_4 = 0.0598$	$W_{pe} = 0.7860$	$W_{cb} = 0.1763$
$W_5 = -0.0159$	$W_{qe} = -0.2451$	$W_{ce} = 0.0018$
$W_6 = 0.5092$	$W_{ve} = 0.1597$	$W_{cdb} = 37.7306$
$W_7 = 80.9318$	$W_{pdb} = -0.0229$	$W_{cde} = 77.2952$
$W_8 = 21.0677$	$W_{qdb} = -\ 0.0204$	$W_{pd} = 0.4287$
$W_9 = 40.6634$	$W_{vdb} = 0.0061$	$W_{qd} = -0.1337$
		$W_{vd} = 0.0871$

6. DESIGN OF POD CONTROLLER (LINEAR QUADRATIC REGULATOR TECHNIQUE)

In Figure 3 is generalized Diagram of POD Controller. The linearized state-space model of SMIB power system is obtained by phillip-heffrons model as expressed by (1),

$$\dot{X} = AX + BU \tag{1}$$

Where A and B are the matrices of the system and input respectively. X is the system state vector, and U is the input state vector. The matrices A and B are constant under the assumption of system linearity. Determine the matrix K of the LQR vector, that is, if we set u(t)= -Kx(t), so in order to determine the performance index (2) [17], [18].

$$J = \int_0^\infty \left(x^T Qx + u^T Ru \right) dt \tag{2}$$

In as shown in (48) the second term on the right side accounts for the expenditure of the energy on the control efforts. The matrix Q and R determine the relative importance of the error and the expenditure of this energy. The as shown in (48) can be rewrite as (3)

$$J = \int_0^\infty \left(x^T Qx + x^T K^T RKx \right) dt = \int_0^\infty x^T (Q + K^T KR) x dt \tag{3}$$

For solving the parameter-optimization problem, set the equation as shown in (4-5)

$$x^T (Q + K^T RK) x = -\frac{d}{dt}(x^T Px) \tag{4}$$

$$\left.\begin{aligned} & x^T (Q + K^T RK) x = -\dot{x}^T Px - x^T P\dot{x} \\ & = -x^T [(A - BK)^T P + P(A - BK)] x \end{aligned}\right\} \tag{5}$$

Comparing both sides of the as shown in (5) and this equation must hold true for any x, (6)

$$(A - BK)^T P + P(A - BK) = -(Q + K^T RK) \tag{6}$$

Since R is a positive-definite Hermitian or real symmetric matrix (assume), then write it, ($R=T^T T$) where T is a nonsingular matrix, and (7)

$$A^T P + PA + [TK - (T^T)^{-1} B^T P] - PBR^{-1} B^T P + Q = 0 \tag{7}$$

The minimization of J with respect to K requires the minimization of (8)

$$x^T [TK - (T^T)^{-1} B^T P]^T [TK - (T^T)^{-1} B^T P] x \tag{8}$$

As shown in (8) is nonnegative, the minimum occurs when it is zero, or when (9-10)

$$TK = (T^T)^{-1} B^T P \tag{9}$$

$$K = T^{-1} (T^T)^{-1} B^T P = R^{-1} B^T P \tag{10}$$

Thus a control law is (11)

$$u(t) = -Kx(t) = -R^{-1} B^T Px(t) \tag{11}$$

In which P must satisfy the reduced Riccati equation (12)

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \tag{12}$$

Steps for controller design
- Required data–A, B, Q, R and N matrix
- Data for calculation-K matrix, P matrix and eigenvalue “e”
- Set N matrix is zero
- Q and R are the positive definite real symmetric matrix.
- Calculate the P matrix with the help of the Riccati equation (12)
- Find the value of K matrix from the equation (10)

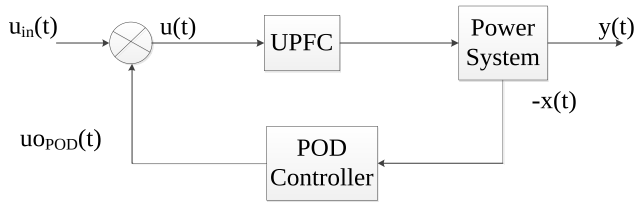

Figure 3. Generalized diagram of POD controller

7. SIMULATION RESULTS UNDER DIFFERENT SYSTEMS AND AT VARIOUS LOADING CONDITIONS

The proposed model of UPFC in single machine infinite bus power system Figure 1 has been used in order to study the damping performance. To study the performance of the proposed controller, simulation results under different system conditions and at various loading conditions i.e. at normal operating point corresponding to line loading of 1.0 pu and at 20 percent decrease and increase in line loading are shown. It can be readily seen that the proposed controller performs better in terms of reduction of overshoot and settling time than system without UPFC and system with UPFC only. Simulation results with variation in system- state, rotor angle (δ) of generator is only considered.

In Figure 4 is variation in delta with UPFC, without UPFC and with POD controller of unstable (D=0) system at nominal loading (1.0 pu). In Figure 5 is variation in delta with UPFC, without UPFC and with POD controller of unstable (D=0) system at 20 percent decrease in loading (0.8 pu). In Figure 6 is variation in delta with UPFC, without UPFC and with POD controller of unstable (D=0) system at 20percent increase line loading (1.2 pu).

In Figure 7 is variation in delta without UPFC, with UPFC and with POD controller of weak (D=4) system at nominal line loading (1.0 pu). In Figure 8 is Variation in delta with UPFC, without UPFC and with POD controller of weak (D=4) system at 20 percent increase line loading (1.2 pu). In Figure 9 is variation in delta with UPFC, without UPFC and with POD controller of stronger (D=8) system at nominal loading (1.0 pu). In Figure 10 is variation in delta with UPFC, without UPFC and with POD controller of strong (D=8) system at 20 percent decrease line loading (0.8 pu).

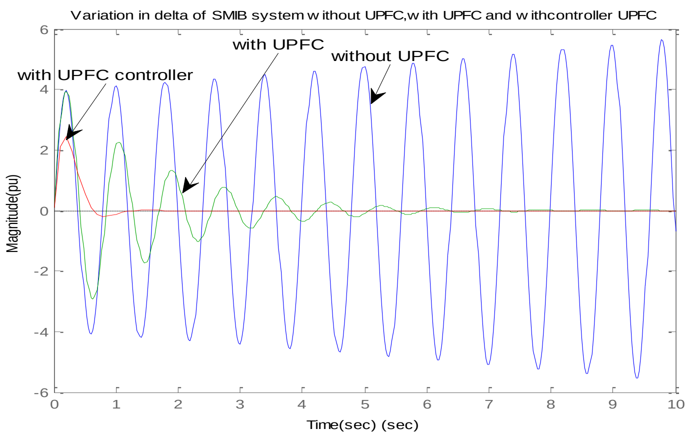

Figure 4. Variation in delta of unstable (D=0) system at nominal loading (1.0 pu)

In Figure 11 is variation in delta with UPFC, without UPFC and with POD controller of strong (D=8) system at 20 percent increase line loading (1.2 pu). In Figure 12 is variation in delta with UPFC, without UPFC and with POD controller of weak (D=4) system without any line loading. In Figure 13 is variation in delta with UPFC, without UPFC and with POD controller for modulation index of both converters 0.6. In Figure 14 is variation in delta with UPFC, without UPFC and with POD controller for both converters phase angle 0.6.

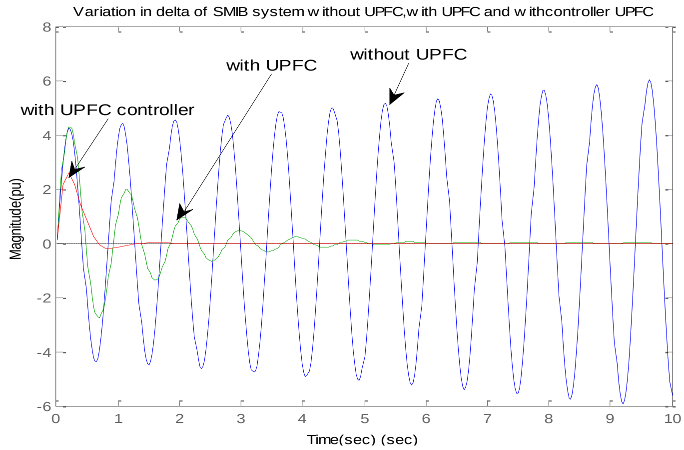

Figure 5. Variation in delta of unstable (D=0) system at 20 percent decrease in loading (0.8 pu)

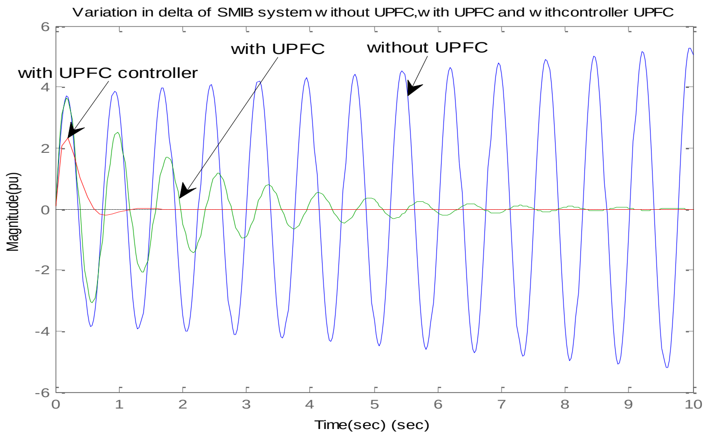

Figure 6. Variation in delta of unstable (D=0) system at 20percent increase line loading (1.2 pu)

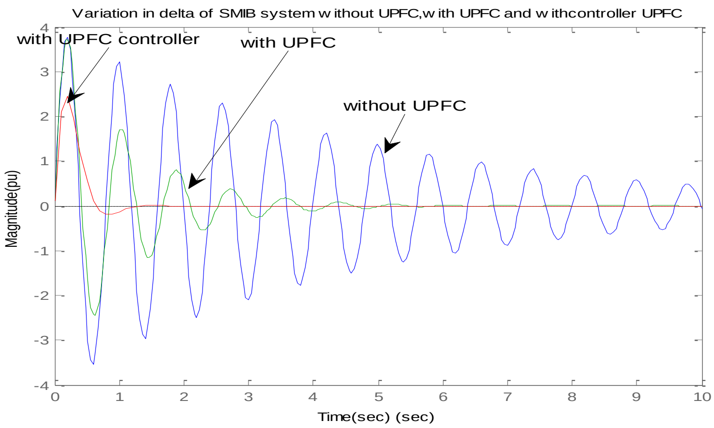

Figure 7. Variation in delta of weak (D=4) system at nominal line loading (1.0 pu)

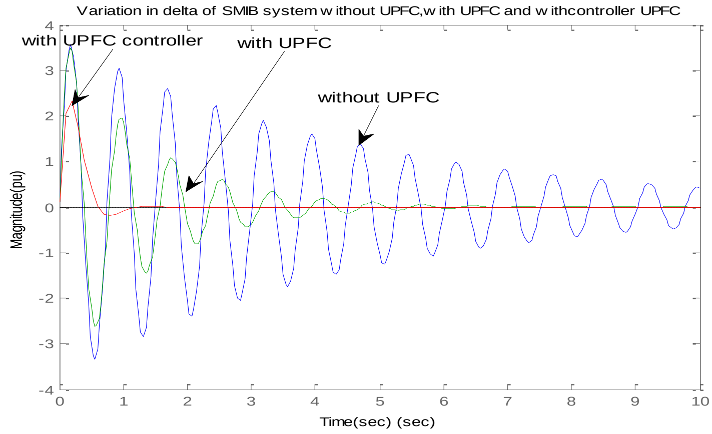

Figure 8. Variation in delta of weak (D=4) system at 20 percent increase line loading (1.2 pu)

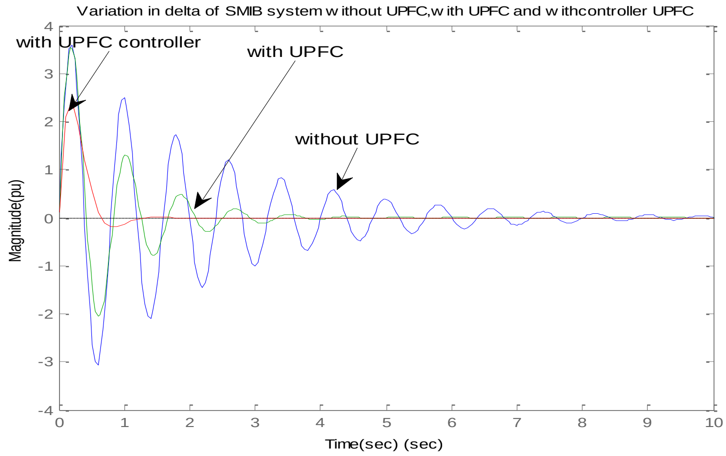

Figure 9. Variation in delta of stronger (D=8) system at nominal loading (1.0 pu)

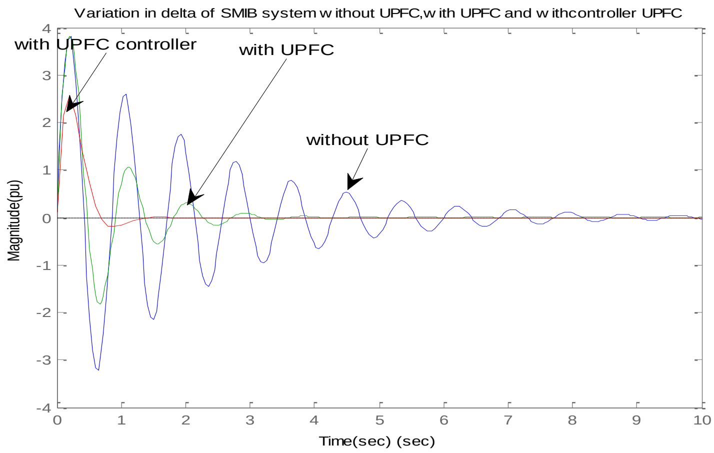

Figure 10. Variation in delta of strong (D=8) system at 20 percent decrease line loading (0.8 pu)

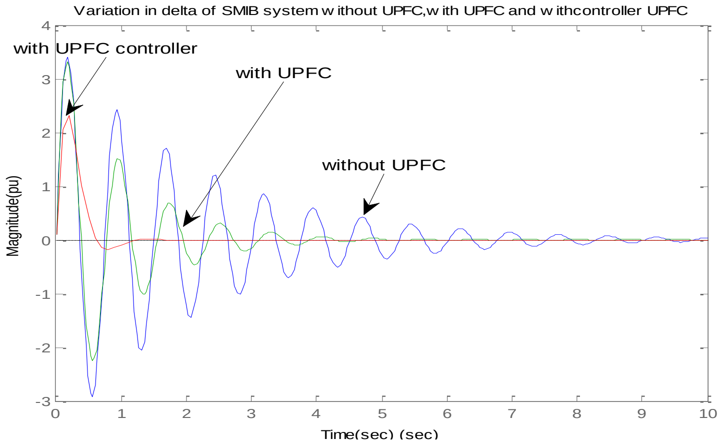

Figure 11. Variation in delta of strong (D=8) system at 20 percent increase line loading (1.2 pu)

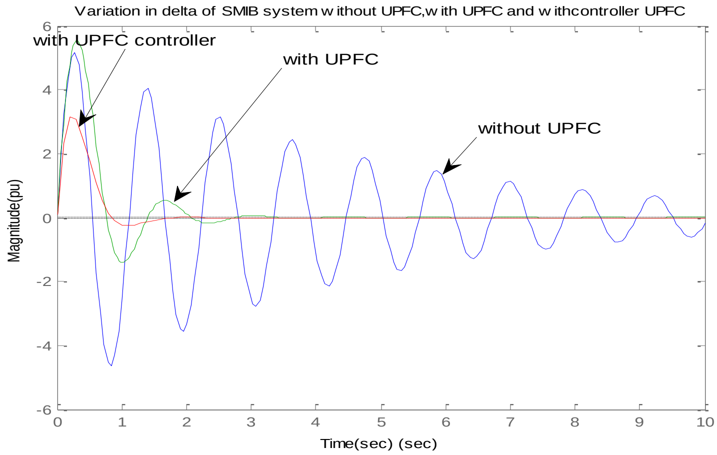

Figure 12. Variation in delta of weak (D=4) system without any line loading

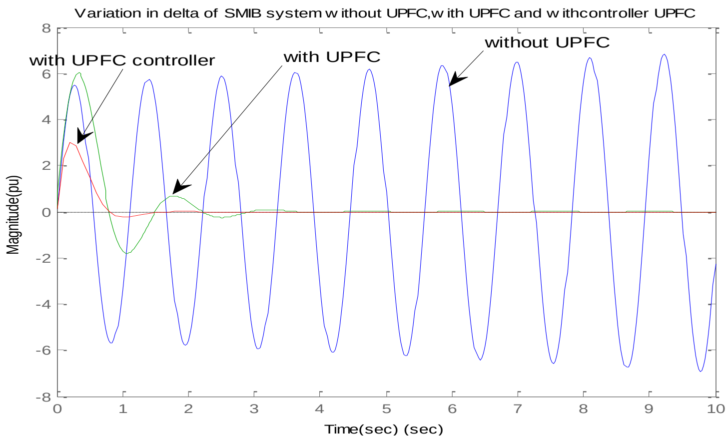

Figure 13. Variation in delta for modulation index of both converters 0.6

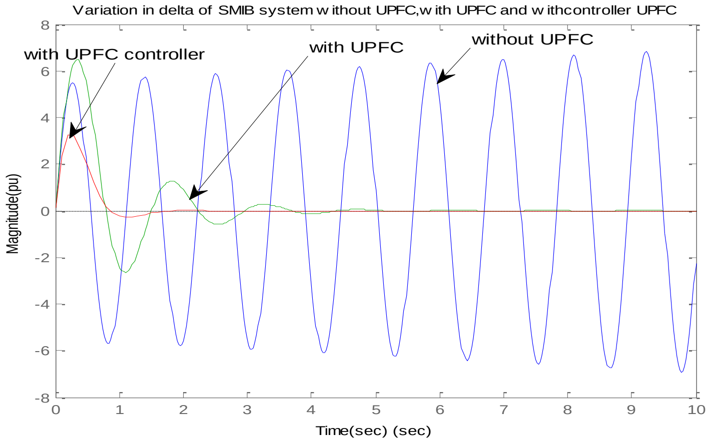

Figure 14. Variation in delta for both converters phase angle 0.6

8. EIGEN VALUE ANALYSIS

Eigen values with UPFC POD controller for weak stable SMIB system as shown in Table 1.

Table 1. Eigen values with UPFC POD controller for weak stable SMIB system (PF=.85, ME =.5, ΔE =.5, MB =.5, ΔB =.5)

Controller Damping constant (D)	System without UPFC	System with UPFC only	System with UPFC controller
	-98.7309	-102.18	-102.18
	0.0224 + 5.6180i	-33.02	-33.02
D = 0	0.0224 - 5.6180i	-1.26 + 4.63i	-3.79 + 4.63i
	-1.6663	-1.26 – 4.63i	-3.79 – 4.63i
	0	-3.35	-3.35
	-98.7309	-102.18	-102.18
	-0.2270 + 5.6116i	-33.04	-33.04
D = 4	-0.2270 - 5.6116i	-1.62 + 4.70i	-4.86 + 4.70i
	-1.6674	-1.62 – 4.70i	-4.86 – 4.70i
	0	-3.12	-3.12
	-98.7309	-102.18	-10218
	-0.4765+5939i	-33.05	-33.05
D = 8	-0.4765-5.5939i	-1.98 + 4.78i	-5.95 + 4.78i
	-1.6686	-1.98 – 4.78i	-5.95 – 4.78i
	0	-0.0289	-2.89

9. CONCLUSION

In this paper, the power system low frequency electromechanical oscillations was damped via LQR technique (using MATLAB tool) based POD controller when applied independently with UPFC and investigated for a SMIB power system. For the proposed controller design problem, an eigenvalue-based objective function to maximize the system damping ratio among all complex eigenvalues was developed. The effectiveness of the proposed controller in damping the low frequency EM mode of oscillations and hence improving power system dynamic stability have been verified.

REFERENCES

[1] Yu Y. N., “Electric Power System Dynamics,” Academic Press., (1983)

[2] P. M. Anderson and Fouad A. “*Power System Control and Stability*,” IEEE Press.

[3] Larsen E. V., Gasca J. S., and Chow J. H (1995), “*Concepts for Design of FACTS Controllers to Damp Power Swings*,” IEEE Trans. On Power System, Vol. 10, No. 2, pp. 948-955, 1994.

[4] Sauer P. W. and Pai P. W., “Power system Dynamics and Stability,” Prentice Hall, 1998.

[5] R K Pandey and N K Singh. “Analysis of Unified Power Flow Controller in Damping Power System Oscillations,” Proceeding of 13th National Power System Conference, vol II, pp. 884-889, in press, 2004.

[6] Wang H. F., “*Damping Function of Unified Power Flow Controller*,” IEE Proceedings Generation Transmission and Distribution, 146(1), pp. 81–87, 1999.

[7] Shieh L. S., Dib H. M. and McInnis B. C., “Linear Quadratic Regulators with Eigenvalue Placement in a Vertical Strip”, IEEE Trans. on Automatic Control, Vol. AC-31, pp. 241-243, (1986).

[8] Patel R. V., Munro Neil, “Multivariable System Theory and Design,” Int. Series on System and Control, Vol. 4, Pergamon Press, New York.

[9] Saxena, Akash, Bhanu Pratap Soni, and Vikas Gupta, "*Minimax approximation synthesis in PSS design by embedding gravitational search algorithm," Advanced Communication Control and Computing Technologies (ICACCCT),*” 2014 International Conference on, IEEE, 2014.

[10] Saxena, Akash, Bhanu Pratap Soni, and Vikas Gupta, "A Chronological Review and Comparison of Four Evolutionary Based Algorithms," European Journal of Advances in Engineering and Technology 2.1 (2015): 35-41.

[11] Arun Kumar, G. Priya, “Power System Stability Enhancement using FACTS Controllers,” Mehta et al./Electrical Power and Energy Systems 70 (2015), 70–82.

[12] Aritra Mitra, Mriganka Mukherjee, Kishankumar Naik, “*Enhancement of Power System Transient Stability Using a Novel Adaptive Backstepping control law*,” IEEE Trans 978-1-4799-4445-3/15 2015.

[13] A Nabavi-Niaki and M. R. Iravani, “Steady-state and dynamic models of Unified power flow controller (UPFC) for power system studies”, IEEE Trans. on Power Systems, Vol. 11, No. 4, pp. 1937-1943, November 1996.

[14] K. S. Smith, L. Ran, J. Penman, “Dynamic modeling of a Unified power flow controller,” IEE Proceedings-C, Vol. 144, No. 1, pp. 7-12, January 1997.

[15] T. Makombe and N. Jenkins, “*Investigation of a Unified power flow controller,*” IEE Proceedings-C, Vol. 146, No. 4, pp. 400-408, July 1999.

[16] Papic, P. Zunko et al., “*Basic control of Unified Power Flow controller,*” IEEE Trans. on Power Systems, Vol. 12, No. 4, pp. 1734- 1739, November 1997.

[17] H. F. Wang, “*A unified model for the analysis of FACTS devices in damping power system oscillations–Part III: Unified power flow controller,*” IEEE Trans. on Power Delivery, Vol. 15, No. 3, pp. 978-983, July 2000.

[18] H. F. Wang, “*Applications of modeling UPFC into multi-machine power systems,*” IEE Proceedings-C, Vol. 146, No. 3, pp. 306-312, May 1999.