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POD controller for UPFC for damping low frequency oscillations in power system stability

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Abstract:
In this paper, a new POD controller is proposed for the UPFC to damp power system low frequency oscillations. The parameters of the POD controller are obtained using the phase compensation technique. The effectiveness of the new proposed POD controller is evaluated under different operating conditions in comparison with the classical controllers to demonstrate its robust performance through time simulation studies.

Keywords: UPFC, POD controller, FACTS devices, Power System Stability.

I.INTRODUCTION

In a stability-constrained power system scenario, there has been a continuous effort to develop new techniques and tools to get better insight into the system behavior for sudden disturbances. With the development of Flexible AC Transmission Systems (FACTS) which is an umbrella title used for incorporating the emerging power engineering technologies [1,2], the search for an accurate and reliable analyzing tool has gained importance. Oscillation Stability analysis and control has been an important subject in power system research and applications. However, a Flexible AC Transmission System (FACTS) device provides solution for this problem. These devices further improve the dynamic performance of the power system in coordination with damping controllers. These can improve system operation because they allow for more accurate control of the power flow, and better and faster control of voltage and system stability. As a result one of their applications is the damping of power system oscillations, which recently has been attracting the interest of many researchers [1-5]. Power System Stabilizers are added to excitation systems to enhance the damping of an electric power system during low frequency oscillation. However, low frequency oscillation will occur on a heavy loaded tie lines after a large or small disturbances. Sometimes the Power System Stabilizer (PSS) installed on a specific generator cannot provide effective damping for that kind of oscillations. In [4, 6], it is shown that the addition of a conventional supplementary controller to the UPFC is an effective solution to the problem. But due to the large model order of power systems the order resulting controller will be very large in general, which is not feasible because of the computational economical difficulties in implementing. this paper presents Power Oscillation Damping controller (POD) for damping of power system low frequency oscillations with UPFC. The Unified Power Flow Controller (UPFC) is a FACTS device whose primary function is to control real and reactive power flow in the line, voltage and current at the UPFC bus. This is achieved by regulating the controllable parameters of the system: line impedance, phase angle and voltage magnitude. Its secondary function is to improve transient stability and the damping of oscillations etc. Recently, several researchers have developed steady state and dynamic models of UPFC. Wang [3] have proposed a control strategy in which the relative effectiveness of UPFC control signals in damping low frequency oscillations has been examined by using a controllability index.

This paper proposes, a new POD controller for the UPFC to damp power system low frequency oscillations. The parameters of the POD are obtained using phase compensation technique.

II.POWER SYSTEM MODEL WITH UPFC

Fig.1 shows a SMIB system equipped with a UPFC. The UPFC consists of an Excitation Transformer, a Boosting Transformer, two three-phase GTO based Voltage Source Converters (VSCs), and a DC link capacitors. The four input control signals to the UPFC are m_E, m_B, δ_E, and δ_B. Where, m_E is the excitation amplitude modulation ratio, m_B is the boosting amplitude modulation ratio, δ_E is the excitation phase angle and δ_B is the boosting phase angle. By applying Park's transformation and neglecting the resistance and transients of the ET and BT transformers, the UPFC can be modelled as [7-8]:

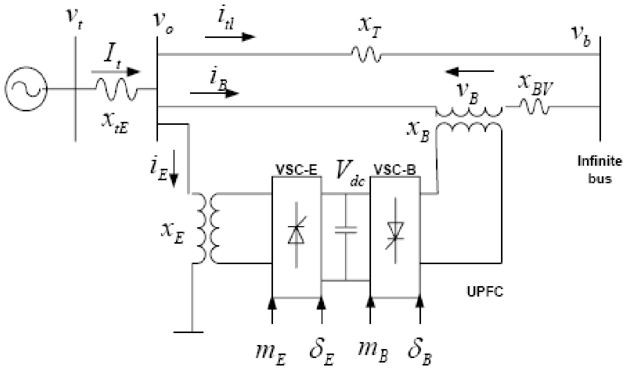

Fig.1. SMIB power system equipped with UPFC

$$\begin{bmatrix} V_{Etd} \\ V_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -X_E \\ X_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E \cos(\delta_E) V_{dc}}{2} \\ \dfrac{m_E \sin(\delta_E) V_{dc}}{2} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{Btd} \\ V_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -X_B \\ X_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B \cos(\delta_B) V_{dc}}{2} \\ \dfrac{m_B \sin(\delta_B) V_{dc}}{2} \end{bmatrix} \quad (2)$$

$$\frac{dV_{dc}}{dt} = \frac{3m_E}{4c_{dc}} [\cos\delta_E \quad \sin\delta_E] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4c_{dc}} [\cos\delta_B \quad \sin\delta_B] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \quad (3)$$

Where V_{Et}, i_E, V_{Bt}, and i_B are the excitation voltage, excitation current, boosting voltage, and boosting current, respectively; C_{dc} and V_{dc} are the DC link capacitance and voltage, respectively. The nonlinear model of the SMIB system as shown in Fig.1 is described by:

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \qquad (4)$$

$$\dot{\delta} = \omega_o(\omega - 1) \qquad (5)$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \qquad (6)$$

$$\dot{E}_{fd} = (-E_{fd} + K_A(V_{ref} - V_t))/T_A \qquad (7)$$

Where

$P_e = V_{td}I_{td} + V_{tq}I_{tq}$; $E_q = E'_{qe} + (X_d - X_d')I_{td}$

$V_t = V_{td} + jV_{tq}$; $V_{td} = X_q I_{tq}$; $V_{tq} = E_q' - X_d' I_{td}$

$I_{td} = I_{tld} + I_{Ed} + I_{Bd}$; $I_{tq} = I_{tlq} + I_{Eq} + I_{Bq}$

$$I_{tld} = \frac{X_E}{X_T} I_{Ed} + \frac{1}{X_T}\frac{m_E V_{dc}\cos(\delta_E)}{2} - \frac{1}{X_T} V_b \cos\delta \quad I_{tlq} = \frac{X_E}{X_T} I_{Eq} - \frac{1}{X_T}\frac{m_E V_{dc}\sin(\delta_E)}{2} + \frac{1}{X_T} V_b \sin\delta$$

$$I_{Ed} = \left[\frac{X_{dt} - X_{BB}X_{b3}}{X_{dE}}\right] V_b \cos\delta - \left[\frac{X_{dt} m_B V_{dc}\cos\delta_B}{2X_{dE}}\right] + \frac{X_{BB}}{X_{dE}} E_q' - \left[\frac{X_{dt} + X_{BB}X_{b2}}{X_{dE}}\right]\frac{m_E V_{dc}\cos\delta_E}{2}$$

$$I_{Eq} = \left[\frac{X_{dt} + X_{BB}X_{a3}}{X_{qE}}\right] V_b \sin\delta - \left[\frac{X_{qt} m_B V_{dc}\sin\delta_B}{2X_{qE}}\right] - \left[\frac{X_{qt} + X_{BB}X_{a2}}{X_{qE}}\right]\frac{m_E V_{dc}\sin\delta_E}{2}$$

$$I_{Bd} = \left[\frac{X_{b3}X_E - X_{b1}}{X_{dE}}\right] V_b \cos\delta + \frac{X_{b1} m_B V_{dc}\cos\delta_B}{2X_{dE}} + \frac{X_E}{X_{dE}} E_q' + \left[\frac{X_{b1} - X_E X_{b2}}{X_{dE}}\right]\frac{m_E V_{dc}\cos\delta_E}{2}$$

$$I_{Bq} = -\left[\frac{X_{a3}X_E + X_{b1}}{X_{qE}}\right] V_b \sin\delta + \frac{X_{a1} m_B V_{dc}\sin\delta_B}{2X_{qE}} + \left[\frac{X_{a1} - X_E X_{a2}}{X_{qE}}\right]\frac{m_E V_{dc}\sin\delta_E}{2}$$

$X_{dt} = X_{tE} + X_d'$; $X_{qt} = X_q + X_{tE}$; $X_{ds} = X_E + X_{dt}$; $X_{qs} = X_E + X_{qt}$;

$X_{a1} = \dfrac{(X_{qs}X_T + X_{qt}X_E)}{X_T}$; $X_{a2} = 1 + \dfrac{X_{qt}}{X_T}$

$$X_{b1} = \frac{(X_{ds}X_T + X_{dt}X_E)}{X_T}\;;\; X_{b2} = 1 + \frac{X_{dt}}{X_T}$$

$$X_{BB} = X_B + X_{BV}\,;\, X_{a3} = -\frac{X_{qt}}{X_T}\,;\, X_{b3} = \frac{X_{dt}}{X_T}$$

$$X_{qE} = -(\frac{X_{BB}X_{qt}X_E}{X_T} + X_E X_{qt} + X_{BB}X_{qs})$$

$$X_{dE} = (\frac{X_{BB}X_{dt}X_E}{X_T} + X_E X_{dt} + X_{BB}X_{ds})$$

The equation for real power balance between the series and shunt converters is given by:

$$\mathrm{Re}\left(V_B I_B^* - V_E I_E^*\right) = 0 \qquad (8)$$

A. Power system linearised model

The linear dynamic model is obtained by linearizing the nonlinear model around an operating condition. The linearized model of the power system as shown in fig.1 is given as follows:

$$\Delta\dot{\delta} = \omega_o \Delta\omega \qquad (9)$$

$$\Delta\dot{\omega} = \frac{\Delta P_m - \Delta P_e - D\Delta\omega}{M} \qquad (10)$$

$$\Delta\dot{E}_{fd} = -\frac{\Delta E_{fd}}{T_A} - \frac{K_A \Delta V}{T_A} \qquad (11)$$

$$\Delta E_q = (X_d - X_d')\Delta i_d - \Delta E_q' \qquad (12)$$

$$\Delta\dot{V}_{dc} = K_7\Delta\delta + K_8\Delta E_q' - K_9\Delta V_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \qquad (13)$$

where

$$\Delta\dot{E}_q' = (-\Delta E_q + \Delta E_{fd}) / T_{do}'$$

$$E_q = (X_d - X_d')i_d - E_q'$$

$$\Delta V = \Delta V_{ref} - \Delta V_t$$

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q' + K_{pd}\Delta V_{dc} + K_{pe}\Delta m_E + K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B$$

$$\Delta E_q' = K_4\Delta\delta + K_3\Delta E_q' + K_{qd}\Delta V_{dc} + K_{qe}\Delta m_E + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_q' + K_{vd}\Delta V_{dc} + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B$$

K_1, K_2 … K_9, K_{pu}, K_{qu} and K_{vu} are the linearization constants. The 28 constants of the model depend on the system parameters and the operating condition. The state space model of power system is given by:

$$\dot{X} = AX + BU \qquad (14)$$

Where the state vector X, control vector U, A and B are

$$X = \begin{bmatrix} \Delta\delta & \Delta\omega & \Delta E_q' & \Delta E_{fd} & \Delta V_{dc} \end{bmatrix}^T$$

$$U = \begin{bmatrix} \Delta m_E & \Delta\delta_E & \Delta m_B & \Delta\delta_B \end{bmatrix}^T$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & 0 & \frac{-K_2}{M} & 0 & \frac{-K_{pd}}{M} \\ \frac{-K_4}{T_{do}'} & 0 & \frac{-K_3}{T_{do}'} & \frac{1}{T_{do}'} & \frac{-K_{qd}}{T_{do}'} \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & \frac{-1}{T_A} & \frac{-K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-K_{pe}}{M} & \frac{-K_{p\delta e}}{M} & \frac{-K_{pb}}{M} & \frac{-K_{p\delta b}}{M} \\ \frac{-K_{qe}}{T_{do}'} & \frac{-K_{q\delta e}}{T_{do}'} & \frac{-K_{qb}}{T_{do}'} & \frac{-K_{q\delta b}}{T_{do}'} \\ \frac{-K_A K_{ve}}{T_A} & \frac{-K_A K_{v\delta e}}{T_A} & \frac{-K_A K_{vb}}{T_A} & \frac{-K_A K_{v\delta b}}{T_A} \\ K_{ce} & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix}$$

The block diagram of a linearized model of the SMIB power system with UPFC is shown in fig.2.

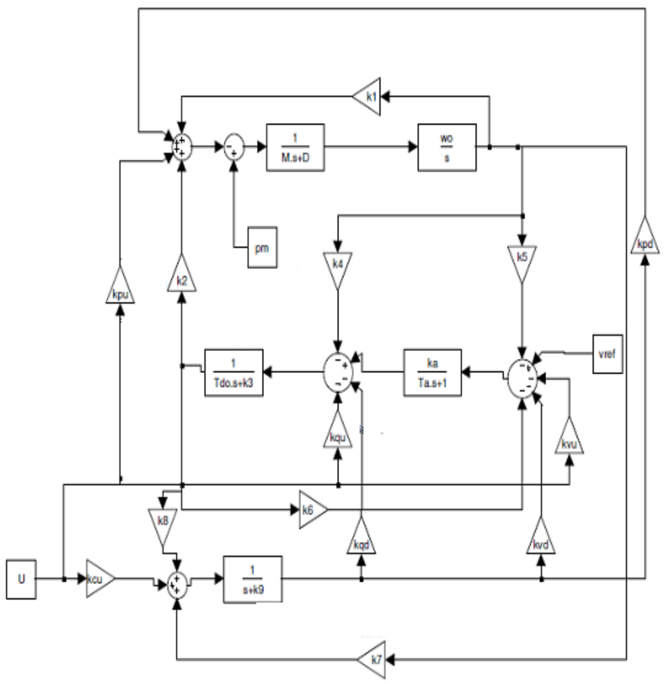

Fig.2 Modified Heffron-Phillips transfer functionModel

III. POD CONTROLLER DESIGN

In this section design of POD controller is suggested for damping of power system low frequency oscillations with UPFC. The POD controller is considered as comprising gain k_{DC}, wash out block and lag-lead compensator. The parameters of the lead-lag compensator are chosen so as to compensate for the phase shift between the control signal and the resulting electrical power deviation. The gain setting of the damping controller is chosen so as to achieve the desired damping ratio of the electromechanical mode. Optimum parameters for the damping controllers are given in Appendix. The structure of the POD controller is shown in Fig.3. The design of the POD controller is based on phase compensation technique. The washout circuit shown in Fig.3 is provided to eliminate the steady-state bias in the output of Power Oscillation Damping controller (POD). T_W must be chosen in the range of 4 to 20.

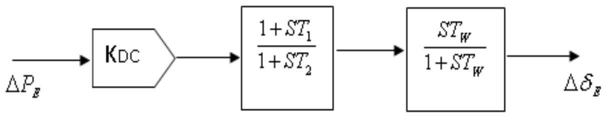

Fig.3. Structure of POD controller

IV.SIMULATION RESULTS

In this section different cases are examined to show the effectiveness of the proposed POD controller in comparison with the conventional UPFC controllers. In this study, the conventional PI type controllers as shown in Fig.4 and 5 are considered for power-flow and DC-voltage regulator. The Conventional Damping Controller (CDC) is designed to produce an electrical torque in phase with the speed deviation according to phase compensation method. The four control parameters of the UPFC (m_E, m_B, δ_E, and δ_B) can be modulated in order to produce the damping torque. In this study, m_B is modulated in order to damping controller design. The speed deviation Δω is considered as the input to the damping controller. The structure of the UPFC based damping controller is shown in Fig.6. It consists of gain, signal washout and phase compensator blocks. The parameters of the CDC are obtained using the phase compensation technique [9] for the nominal operating condition with damping ratio of 0.5 as follows:

$$CDC = 568.968 \frac{S(S+0.5)}{(S+0.25)(S+1.052)} \qquad (15)$$

Using the designed CDC controller optimal parameters of the conventional power-flow controller (K_{PP} and K_{PI}) and DC-voltage regulator (K_{dp} and K_{dI}) are obtained using genetic algorithm [10] for operating condition 1 as given in Appendix. Optimum values of the power-flow controller are obtained as K_{PP}=2 and K_{PI} =10. When the parameter of power-flow controller are set at their optimum values, the parameters of DC-voltage regulator are now optimized and obtained as K_{dp} =0.5985 and K_{dI} =2.

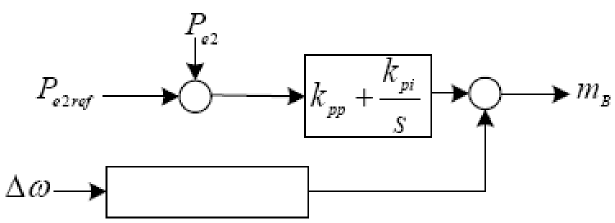

Fig.4. PI-type power flow controller with damping controller

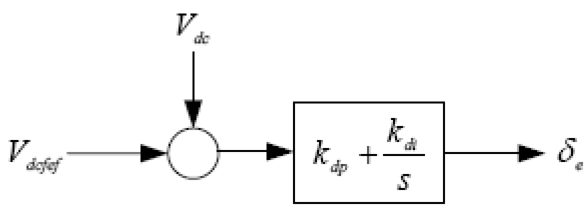

Fig.5. PI-type DC-voltage regulator

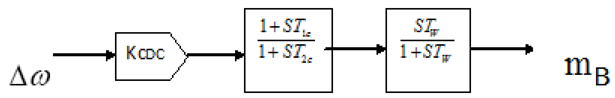

Fig.6. Block diagram of UPFC based conventional damping controller

The performance of the proposed POD controller and CDC damping controllers for 10% step sudden change in reference power on transmission line 2 and mechanical power are shown in Figs.7 to 10 for different load conditions. The loading condition and system parameters are given in Appendix.
It can be seen that the proposed POD controller is very effective, achieve good robust performance and compared to CDC have the best ability to reduce power system low frequency oscillations.

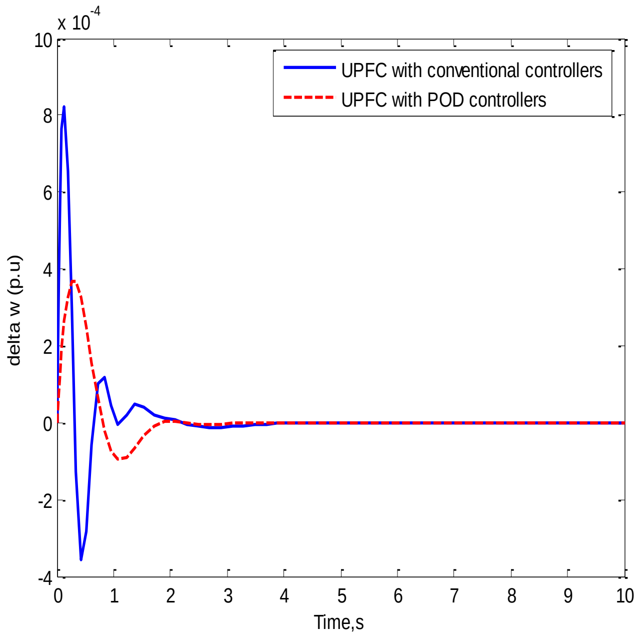

Fig.7. Time response of $\Delta\omega$ with CDC and POD controllers at operating point 1.

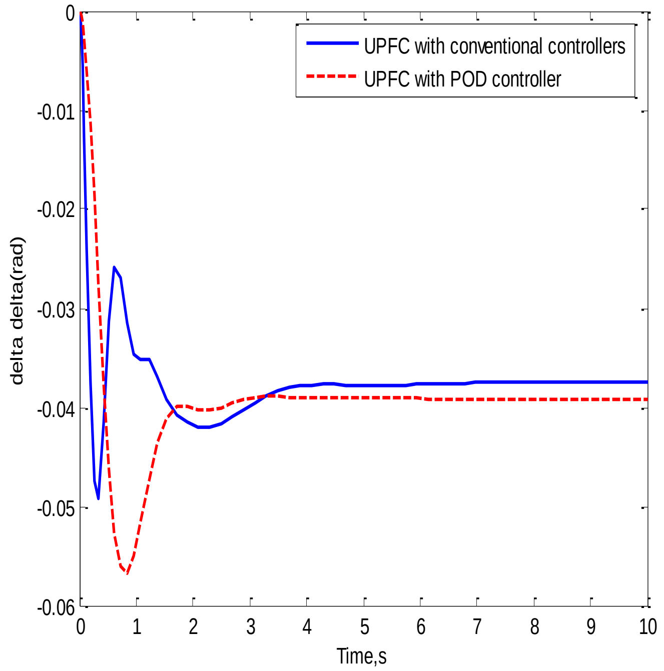

Fig.8. Time response of $\Delta\delta$ with CDC and POD controllers at operating point 1..

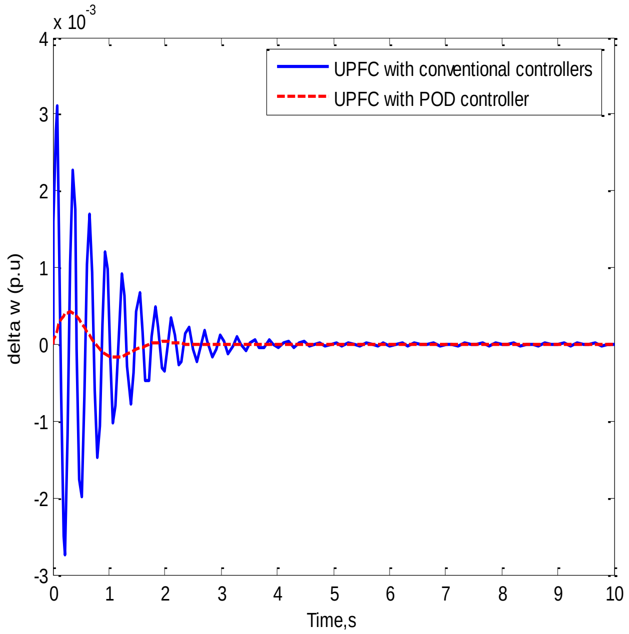

Fig.9. Time response of $\Delta\omega$ with CDC and POD controllers at operating point 7.

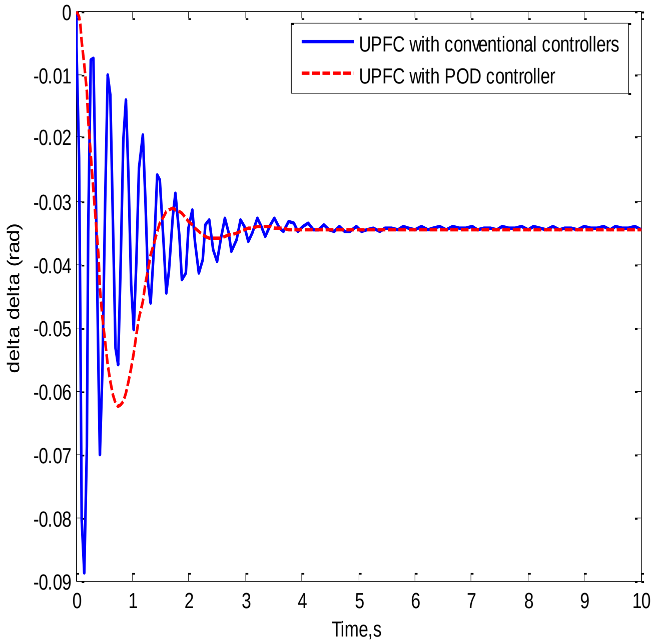

Fig.10.Time response of $\Delta\delta$ with CDC and POD controllers at operating point 7.

V.CONCLUSIONS

In this paper, a new Power Oscillation damping controller is proposed for the UPFC for damping power system low frequency oscillations.The construction and implementation of proposed controller is fairly easy and economical,which can be useful in real world power system.The proposed controller has been tested on a SMIB power system in comparision with the conventional damping controllers under different operating conditions.

Appendix

System data: M=8 MJ/MVA, D=0, T'_{do} =5.044s,

X_d =1pu, X_q =0.6pu, X'_d =0.3pu, K_A =10, T_A =0.05s,
$X_T = X_B = X_E$ =0.1pu, $X_{T1} = X_{T2}$ =1pu,

UPFC parameters: V_{DC} =2pu, C_{DC} =1pu, m_E =0.4
δ_E = -85.35^o, m_B =0.08, δ_B = -78.21^o.

K-constants: K_1 =2.5026, K_2 =1.7465, K_3 =2.4464
K_4 =1.0505, K_5 = -0.1239, K_6 =0.3510, K_7 = -0.083
K_8 =0.0441, K_9 =0.1464, K_{Pd} =0.1978, K_{qd} = -0.0188

K_{Vd} =0.0625, K_{pe} =0.1397, $K_{p\delta e}$ =1.5509, K_{pb} =0.2757, $K_{p\delta b}$ =0.0018, K_{qe} =0.0226, $K_{q\delta e}$ =0.4842, k_{qb} =0.0985, $K_{q\delta b}$ =0.0086,

K_{ve} = -0.013, $K_{v\delta e}$ = -0.3101, K_{vb} = -0.1828,

$K_{v\delta b}$ =-0.0038, K_{ce} =0.4210, $K_{c\delta e}$ =1.3736, K_{cb} =0.4479, $K_{c\delta b}$ =0.0138.

POD controller parameters:

K_{DC} =22, T_W =4, T_1 =0.2283, T_2 =0.5.

Operating conditions:

1)Nominal load V_t =1.032	P=0.8	Q=0.15
2) V_t =1.032	P=0.9	Q=0.17
3) V_t =1.032	P=1.0	Q=0.20
4) V_t =1.032	P=1.1	Q=0.28
5)Heavy load V_t =1.032	P=1.125	Q=0.285
6) V_t =1.032	P=0.7	Q=0.10
7)Very heavy load V_t =1.032	P=1.15	Q=0.3

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