DAMPING ABILITY STUDY FOR UPFC

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ABSTRACT

This paper using the state space theory deduces the mathematical model for the single-machine infinite-bus systems with UPFC. And the eigenvalue method is employed to analyze the damping ability of UPFC. Based on the eigenvalue method analyzes conclusions, the oscillation frequency of the controlled power system is introduced to the conventional UPFC controller to change the fixed active power reference values. Then, based on the conventional UPFC controller, which adapting four independent PI controller, employs the principle of the PSS, this paper proposes a supplement controller for damping the low oscillation in the controlled power system. The detailed realization processing is stated in this paper. The simulations on the controlled power system without UPFC, with UPFC only and with UPFC integrated with the supplement controller by using PSCAD/EMTDC are made. The results reveal that the UPFC has the function of damping low frequency oscillation of the controlled power system itself, while the supplement controller may strengthen this effect dramatically.

1. INTRODUCTION

There is usually the low frequency power oscillations happened in the long-distance high-voltage transmission tie-line, especially when there is a disturbance, even the small disturbance. Power system stabilization (PSS) is an effective device for damping low frequency oscillation, but in the system with multi-machines, the parameters tuning and the whole system coordinating of PSS is a quite complex problem. Severely, it is very hard to damp the power oscillation in the tie-line through one generator with PSS [1]. With the adventure of the technology of FACTS, a new approach to damp low frequency oscillation, especially the oscillation between regions is come to true[1]-[3]. UPFC is one of the most versatile FACTS devices. It not only can regulate the bus voltage and the transmission power but also can damp the power oscillation for the controlled power systems. Conventionally, the fixed

active power reference is adopted in the UPFC controller [4, 5, 6, 7]. But the magnitude of the active power of the controlled line is variated frequently during the disturbance processing. However, when the system suffers huge disturbance, due to the distance of failure point is unpredictable, the optimal reference transmission power quantity and the corresponding time for the controller are not easy to determine and the conventional controller with the fixed active power reference maybe can not function properly. So in this paper, the eigenvalue method is employed to analyze the damping characteristics of UPFC deeply. based on the four independent PI controller of the conventional UPFC as stated in [4] , uses the controlled power system oscillation frequency as the feedback signal ,adopts the principle of the PSS[1], [3], [8], this paper proposes an complement controller in addition to the UPFC conventional PI controller to damping the low oscillations in the controlled power system. The

output signal of the supplement controller is connected into the fixed reference values of the series side controller of the UPFC to regulate the active power reference values.

To further enhance the function of damping low frequency oscillation, this paper deduces the mathematical model of UPFC connected into the single-machine infinite-bus systems firstly, and using eigenvlue method analyze the damping characteristics of UPFC deeply. Based on the PI controller of UPFC mentioned in [4], adopts the principle of PSS, proposes a supplement controller of UPFC on the basis of proportional control and uses PSCAD/EMTDC to compare and analyze the operation characteristics in three situations. The situations are without UPFC, with UPFC in addition to supplement controller and with UPFC but without supplement controller.

2. MATHEMATICAL MODEL

Fig.1 is the diagram of UPFC connected into the single-machine infinite-bus system, providing the two lines is completely the same, the reactor $X_{L1} = X_{L2} = X$,the sending end voltage is $\dot{V}_s = V_s \angle 0°$,the receiving end is infinite-bus system, the voltage is $\dot{V}_j$,and conforms to $\left|\dot{V}_s\right| = \left|\dot{V}_j\right| = V$ and the phrase angle difference between the sending end and the receiving end voltage is δ_{no} . When the UPFC is connected into the line L_1 , as show in Fig1, suppose the sending end voltage is kept at the constant, $\left|\dot{V}_s\right| = V$, the voltage injected from the series side is $\dot{V}_{se} = V_{se} \angle \theta_{se}$, and the phrase angle difference between the sending end and the receiving end voltage becomes δ .
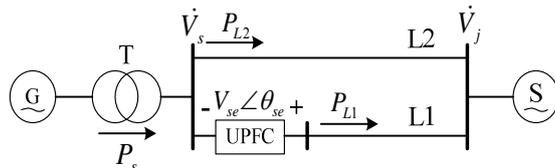

Fig.1 Diagram of UPFC connected into the single-machine infinite-bus system

2.1 MATHEMATICAL MODEL OF SINGLE-MACHINE INFINITE-BUS SYSTEM

When the UPFC is not connected into the system, the generated active power in fig1 is

$$P_e = P_S = P_{L1} + P_{L2} = \frac{2V^2 \sin\delta_{no}}{X}$$

(1)

Taking into account of the system damping, the armature equation of the generator is

$$\frac{d\delta}{dt} = \omega - \omega_N = \Delta\omega$$

$$\frac{T_J}{\omega_N}\frac{d^2\delta}{dt^2} = P_T - (P_e + P_D) = P_T - (P_e + D\Delta\omega)$$

(2)

Where, D is the inherent damping, T_J is the inertia time-constant of the generator, ω_N is the synchronous speed.

Linearization the electric power equation Eqn (1) and the rotor motion equation Eqn (2) at the stabilized operating point can get

$$\frac{T_J}{\omega_N}\frac{d^2\Delta\delta}{dt^2} + D\frac{d\Delta\delta}{dt} + \frac{2V^2\cos\delta_{no\_0}}{X}\Delta\delta = 0$$

(3)

This can be written in the form of space state equation as followings. These equations indicate that in the case that UPFC is not connected into the system, the state equation in coefficient matrix form can be represented as

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \end{bmatrix} = A_{noUPFC} \cdot \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \dfrac{-2\omega_N V^2 \cos\delta_{no\_0}}{T_J X} & \dfrac{-D\omega_N}{T_J} \end{bmatrix} \cdot \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix}$$

(4)

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$$A_{noUPFC} = \begin{bmatrix} 0 & 1 \\ \dfrac{-2\omega_N V^2 \cos\delta_{no\_0}}{T_J X} & \dfrac{-D\omega_N}{T_J} \end{bmatrix} \quad (5)$$

2.2 MATHEMATICAL MODEL WITH UPFC

When UPFC is available in the system, the active and reactive power on line L_1 is deduced as following [4]:

$$P_{L1} = \frac{1}{X}(V^2 \sin\delta + V_{se}V\sin(\delta + \theta_{se})) \quad (6)$$

$$Q_{L1} = \frac{1}{X_{L1}}[V_s^2 + V_{se}^2 + 2VV_{se}\cos\theta_{se} - V_sV_j\cos\theta_j - V_{se}V_j\cos(\theta_j + \theta_{se})] \quad (7)$$

From [4], we can split the voltage $\dot{V}_{se}$ into the quadrate $\dot{V}_f$ and in phase $\dot{V}_e$, Eqn (6), Eqn (7) can be expressed as follows

$$P_{L1} = \frac{1}{X}(V^2 \sin\delta + VV_e \sin\delta + VV_f \cos\delta) \quad (8)$$

$$Q_{L1} = \frac{1}{X}(V^2 + V_e^2 + V_f^2 + 2VV_e - V^2\cos\delta - VV_e\cos\delta + VV_f\sin\delta) \quad (9)$$

The electric power of the generator is

$$P_e = P_S = P_{L1} + P_{L2} = P_{L1} + \frac{V^2 \sin\delta}{X} \quad (10)$$

Linearization Eqn (8), Eqn (9), and Eqn (10) around the stabilized point obtains

$$\Delta P_{L1} = a_1\Delta\delta + b_1\Delta V_e + c_1\Delta V_f$$
$$\Delta Q_{L1} = a_2\Delta\delta + b_2\Delta V_e + c_2\Delta V_f \quad (11)$$

$$\Delta P_e = \Delta P_{L1} + \frac{V^2\cos\delta}{X}\Delta\delta = (\frac{V^2\cos\delta_0}{X} + a_1)\Delta\delta + b_1\Delta V_e + c_1\Delta V_f \quad (12)$$

Where

$$a_1 = \frac{1}{X}(V^2\cos\delta_0 + VV_e\cos\delta_0 - VV_f\sin\delta_0)$$

$$b_1 = \frac{V\sin\delta_0}{X}, \quad c_1 = \frac{V\cos\delta_0}{X} \quad (13)$$

$$a_2 = \frac{1}{X}(V^2\sin\delta_0 + VV_e\sin\delta_0 + VV_f\cos\delta_0)$$

$$b_2 = \frac{2V_e - V\cos\delta + 2V}{X}, \quad c_2 = \frac{2V_f + V\sin\delta_0}{X} \quad (14)$$

Substituting Eqn (12) into Eqn (2) can get

$$\begin{cases} \dfrac{d\Delta\delta}{dt} = \Delta\omega \\ \dfrac{T_J}{\omega_N}\dfrac{d^2\Delta\delta}{dt^2} + D\dfrac{d\Delta\delta}{dt} + (\dfrac{V^2\cos\delta_0}{X} + a_1)\Delta\delta + b_1\Delta V_e + c_1\Delta V_f = 0 \end{cases} \quad (15)$$

When there is no the frequency feedback signal in the UPFC control system, we can get

$$\begin{cases} V_q = (P_{L1ref} - P_{L1}) \cdot (K_{p3} + \dfrac{K_{i3}}{S}) \\ V_d = (Q_{L1ref} - Q_{L1}) \cdot (K_{p4} + \dfrac{K_{i4}}{S}) \end{cases} \quad (16)$$

Linearization the above equations at the stabilized point can obtain

$$\begin{cases} \Delta\dot{V}_f = -K_{p3}\Delta\dot{P}_{L1} - K_{i3}\Delta P_{L1} \\ \Delta\dot{V}_e = -K_{p4}\Delta\dot{Q}_{L1} - K_{i4}\Delta Q_{L1} \end{cases} \quad (17)$$

Substituting Eqn (11) and derivative of its first order into Eqn (17) yields:

$$\begin{cases} (1+K_{p3}c_1)\Delta\dot{V}_f = -K_{p3}a_1\Delta\omega - K_{p3}b_1\Delta\dot{V}_e - K_{i3}a_1\Delta\delta - K_{i3}b_1\Delta V_e - K_{i3}c_1\Delta V_f \\ (1+K_{p4}b_2)\Delta\dot{V}_e = -K_{p4}a_2\Delta\omega - K_{p4}c_2\Delta\dot{V}_f - K_{i4}a_2\Delta\delta - K_{i4}b_2\Delta V_e - K_{i4}c_2\Delta V_f \end{cases} \quad (18)$$

Combining Eqn (18) and Eqn (15), we can obtain the state equation as below:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{V}_f \\ \Delta\dot{V}_e \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \dfrac{-\omega_N}{T_J}(\dfrac{V^2\cos\delta}{X} + a_1) & \dfrac{-\omega_N D}{T_J} & \dfrac{-\omega_N b_1}{T_J} & \dfrac{-\omega_N c_1}{T_J} \\ \dfrac{-K_{i3}a_1}{1+K_{p3}c_1} & \dfrac{-K_{p3}a_1}{1+K_{p3}c_1} & \dfrac{-K_{i3}c_1}{1+K_{p3}c_1} & \dfrac{-K_{i3}b_1}{1+K_{p3}c_1} \\ \dfrac{-K_{i4}a_2}{1+K_{p4}b_2} & \dfrac{-K_{p4}a_2}{1+K_{p4}b_2} & \dfrac{-K_{i4}c_2}{1+K_{p4}b_2} & \dfrac{-K_{i4}b_2}{1+K_{p4}b_2} \end{bmatrix} \cdot \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta V_f \\ \Delta V_e \end{bmatrix}$$
$$+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \dfrac{-K_{p3}b_1}{1+K_{p3}c_1} \\ 0 & 0 & \dfrac{-K_{p4}c_2}{1+K_{p4}b_2} & 0 \end{bmatrix} \begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{V}_f \\ \Delta\dot{V}_e \end{bmatrix} \quad (19)$$

If we introduce the frequency oscillation

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feedback signal and exact it directly on the referenced value of active power flow as described in [4], we can get

$$
\begin{cases}
V_f = (P_{L1ref} + K_D\omega - P_{L1}) \cdot (K_{p3} + \dfrac{K_{i3}}{S}) \\[2mm]
V_e = (Q_{L1ref} - Q_{L1}) \cdot (K_{p4} + \dfrac{K_{i4}}{S})
\end{cases}
\tag{20}
$$

As the same theory, we can get the UPFC state equation after introducing the frequency feedback signal as follows.

$$
\begin{bmatrix} \Delta\dot\delta \\ \Delta\dot\omega \\ \Delta\dot V_f \\ \Delta\dot V_e \end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 \\
\dfrac{-\omega_x}{T_J}(\dfrac{V^2\cos\delta}{X}+a_1) & \dfrac{-\omega_x D}{T_J} & \dfrac{-\omega_x b_1}{T_J} & \dfrac{-\omega_x c_1}{T_J} \\
\dfrac{-K_{i3}a_1}{1+K_{p3}c_1} & \dfrac{-K_{p3}a_1+K_D K_{i3}}{1+K_{p3}c_1} & \dfrac{-K_{i3}c_1}{1+K_{p3}c_1} & \dfrac{-K_{i3}b_1}{1+K_{p3}c_1} \\
\dfrac{-K_{i4}a_2}{1+K_{p4}b_2} & \dfrac{-K_{i4}a_2}{1+K_{p4}b_2} & \dfrac{-K_{i4}c_2}{1+K_{p4}b_2} & \dfrac{-K_{i4}b_2}{1+K_{p4}b_2}
\end{bmatrix}
\begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta V_f \\ \Delta V_e \end{bmatrix}
$$

$$
+ \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & K_D K_{p3} & 0 & \dfrac{-K_{p3}b_1}{1+K_{p3}c_1} \\
0 & 0 & \dfrac{-K_{p4}c_2}{1+K_{p4}b_2} & 0
\end{bmatrix}
\begin{bmatrix} \Delta\dot\delta \\ \Delta\dot\omega \\ \Delta\dot V_f \\ \Delta\dot V_e \end{bmatrix}
\tag{21}
$$

Eqn (4), Eqn (19), Eqn (21) represent the following three situations respectively, i.e. the SMIB system not containing UPFC, UPFC not introducing the frequency feedback signal and UPFC introducing the frequency feedback signal. From Eqn (19), Eqn (21), we know, after introducing UPFC, the state equations can become four-dimension, where the first two-dimension is used for describing the system's state, and the latter is for the control system of UPFC. Comparing the three state equations, we conclude that the introduction of UPFC and the different of its control strategy will result in the different system state equations, which will influence the eigenvalues and the system's damping ability, the more detail difference will be stated in follows.

3. DAMPING ABILITY ANALYZE

In order To analyze the damping characteristics furthermore , we are going to employ a set of typical parameters, nominal values, for the system as shown in

fig1.When UPFC is installed in the system, the RMS of voltage on the sending and receiving end is both $V = 1.0\,p.u.$ .The phrase angle difference is $\delta = 10°$,both the equivalent reactance of the two lines are $X = 1.0\,p.u.$,the initial comprehensive damping coefficient is $D = 0.5$,the inertia time-constant of the generator is $T_J = 1.0$,the voltage injected from the series   is $V_{se} = 0.4\angle -30°\,p.u.$ .Choosing PI coefficients of the controller on the series as $K_{p3} = K_{p4} = 0.5$, $K_{i3} = K_{i4} = 1$. Then can get the eigenvalues distribution of three states as shown in fig2.

As for the system without UPFC, according to the given system parameters, due to the uncertain phrase angle δ_{no} between the first terminal voltage and end voltage, we can get the real part of the eigenvalues, $\dfrac{-D\omega_N}{2T_J} = -0.25$ as the dashed line suggested in Fig. 2 .when the UPFC is installed, the system still adopts the PI parameter above and the frequency feedback signal is not existed, the eigenvalue is $-0.281 \pm 1.234i$ for $K_D = 0$,the rest two eigenvalues reflecting the control characteristics will not be considered. Note that compared to the eigenvalues of the system with UPFC, in terms of two conditions mentioned above, it is obvious that the eigenvalues moved toward left in the system. When UPFC introduces the frequency feedback signal and the coefficient K_D is continuous increasing, the eigenvalues will move to the left gradually. The eigenvalues distribution is shown in Fig.2 with K_D ranging from 0 to 2 and increasing at a length rate of 0.2.

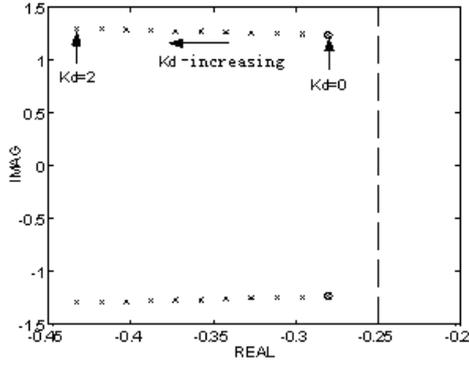*Aihong TANG, Jiaoyu LIU, Youxin YUAN*

Fig.2 The system eigenvalues distribution

As the above analysis indicate, UPFC possesses a positive damping characteristics itself and improves the system damping greatly, meanwhile, through regulating the amplification coefficient K_D , the eigenvalues distribution is moved and the system damping ability is enhanced. Therefore, if the controlling parameter is set correctly, UPFC with the frequency feedback signal can damp the low frequency oscillation quickly. So, in the following, we will propose a supplement controller of UPFC on the basis of the principle of PSS by the controller method stated above.

4. SUPPLEMENT CONTROLLER S-TUDY

The function of supplement controller is to help the UPFC to enhance damping ability effectively by improving the UPFC control strategy .According to the damping characteristics suggested above, this paper proposes the supplement controller of UPFC on the basis of the principle of PSS as shown in fig3.
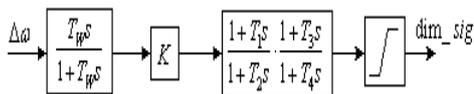

Fig.3 Supplement controller block diagram

Where: T_W is the blocking DC time constant, T_1 , T_3 is the lead compensation time constant, T_2 , T_4 are the lag compensation time constants. The supplement controller applies the PI control method. The oscillation frequency $\Delta\omega$ is

considered as input signal and the output signal is $\dim\_sig$ through several units such as blocking DC, amplification, lead –lag compensation limiting amplitude, which is similar to the ordinary PSS controller.

Superimposing the output signal $\dim\_sig$ of the supplement controller on the reference value of the active flow of the main controller in the series side as shown in fig4, combining with main controller of the shunt side of UPFC stated in [4], the whole control system is constituted with supplement controller.
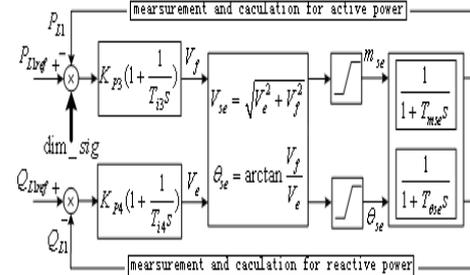

Fig.4 The control block diagram of UPFC with supplement controller in the series side

5. DYNAMIC CHARACTERISTICS SIMULATIONS FOR THE SUPPLE-MENT CONTROLLER

In order to demonstrate the effects of the supplement controller as well as the conclusions of part Ⅲ , the PSCAD/EMTDC software is used, and the damping characteristics will be analyzed detailed in the follow parts.

5.1 PARAMETERS SETTING

The simulation is carried out in the single-machine infinite-bus system in fig1, and UPFC is connected to the sending end of line L_1 .Then, the original system 10kV, 600A is reduced to a simulation system 800V, 10A in proportion. where, the rated power P_N of generator is 12kW ,the power factor $\cos\varphi_N$ is 0.8,

the rated voltage of the generator terminal is 230V,the synchronous reactance, transient reactance

is $X_d = 0.56$, $X'_d = 0.132$,inferior transient reactance, $X''_d = 0.113$, $X''_q = 0.135$,the rated power of the transform T is 15kVA,the voltage ratio is 210V/800V;the equivalent leakage reactance is 13%,ignoring the short-circuit loss and No-loss of the transformer, the equivalent reactance of the two line is $Z_L = (1.69 + j22.7)\Omega$,UPFC is connected into the sending end of the line L_1 . The infinite bus voltage is 800V, the equivalent internal resistance is $Z_s = 0.4188\Omega$.

5.1.1 THE OPERATION PARA MET-ERS OF UPFC

In the shunt side: the rated capacity of the shunt transformer is 10kVA,connected as Y / Δ ,the transformer winding turns ratio is 2.5/1;the switch frequency of shunt converter VSC1 is 1650Hz; in the output filtering unit ,the inductor is $12mH$,the capacitor is $1\mu F$,the equivalent resistance is 0.1Ω .

In the serial side :the rated capacity of the serial transformer T_{se} is 10kVA,three single phase transformers is connected in Y / Δ ,and the Δ side is connected with the UPFC device , the winding turns ratio. is 2.5/1;the switch frequency of the series side converter VSC2 is 5400Hz; in the output filtering unit ,the inductor is $2mH$,the capacitor is $20\mu F$,the equivalent resistance is 0.14Ω .

In the DC side: the capacitor is 9400μF , the rated voltage is 400V.

5.1.2 CONTROLLER PARAMETERS OF UPFC

The controllers in the shunt side and the serial side both adopt the conventional PI control method as stated in [4].Through many simulations, the following parameters are adopt, $K_{p1} = 0.05$, $T_{i1} = 0.3$, $K_{p2} = 1$, $T_{i2} = 0.2$, $K_{p3} = 1$, $T_{i3} = 0.008$, $K_{p4} = 8$, $T_{i2} = 0.008$.

Parameters for supplement controller are set below, blocking DC time constant $T_W = 0.15$, amplification sector $K = 0.5$, lead–lag compensation unit $T_1 = 0.2$, $T_2 = 0.05$, $T_3 = 0.3$, $T_4 = 1$,output limiting amplitude $[-0.001, 0.001]$.

To produce the low frequency oscillation in the single-machine infinite-bus system, the operating point must be near to the stabilized operation limit, therefore, the initial operation state is set as, the rated power of the generator is 15kVA, whose output active power is $P_s = 12kW$. In this simulation, we don't consider the effect of generator exciting system and regulating speed system. UPFC is installed without affecting the stable operation point. Not only the AC bus voltage $V_s = 800V$ is maintained unchangeable, but also the power flow in line L_1 is still controlled to be the natural distribution flow, i.e. $P_{L1} = 6kW$, $Q_{L1} = 0kVar$. At the moment of 0.5s, a small disturbance is added to the generator to produce a low frequency oscillation in the system, we introduce the disturbance in the way which the output mechanical power of the generator jumps from 0.8p.u. to 1.0p.u.at 0.5s,then reduces to 0.8p.u at 0.51s. At this moment, the output active power increases from 12kW to 15kW, then falls to 12kW instantaneously.

5.2 RESULTS OF SIMULATIONS

Using the software PSCAD/EMTDC and

comparing the following three cases, the system without UPFC, the system including UPFC with supplement controller and the system including UPFC without supplement controller. The results are shown in Fig.5.and Fig.6.

The simulation results indicate that when the small disturbance leads to the low frequency oscillation in the system, more than 5s is spent in the system without UPFC to come to its steady-state, and the oscillation amplitude is very large. The system with UPFC, but without supplement controller can come to steady-state after four adjusting periods. While UPFC with supplement controller can come to its steady-state only after two and half adjusting periods, and the oscillation amplitude is decreased significantly as shown in Fig.5 and Fig.6. In conclusion, UPFC without supplement controller has the capability of damping the oscillation itself to some extent. UPFC with supplement controller can improve the damping ability effectively.
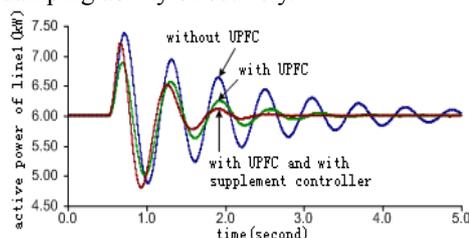

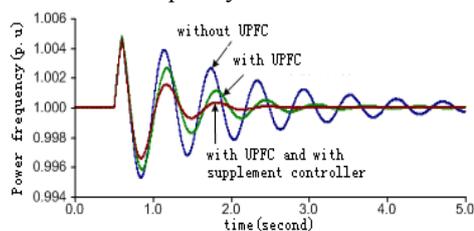**Fig.5** Waveform comparison of active power on line L1 in the case of low frequency oscillation

Fig.6 Waveform comparison of system frequency in the case of low frequency oscillation

6. CONCLUSIONS

Through the eigenvalue method analyzing, we get the conclusion as that UPFC possesses a positive damping characteristics itself and improves the system damping greatly, meanwhile, through regulating the amplification coefficient K_D , the eigenvalues distribution is moved toward to left and the system damping ability is enhanced. The dynamic simulations demonstrate that controlled by the supplement controller studied in this paper, the power systems come to steady-state more quickly and the power oscillation magnitude is decreased effectively.

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BIOGRAPHY

Aihong TANG was born in JIANGXI province of China on December 1, 1969. She received her PH.D for power systems and its automation from Huazhong University in June, 2007, and MS for power systems and its automation from Wuhan University of hydraulic and electric in June, 1997. Her employment experience included the power supply bureau, electric power design institute and university. Now, she engage in the operation and intelligent controlling for power systems and flexibility AC transmission systems.