Extended Supplementary Controller of UPFC to Improve Damping Inter-Area Oscillations Considering Inertia Coefficient

A. Kazemi and M.R. Shadmesgaran

Abstract— This paper proposed a new control strategy of a unified power flow controller (UPFC) to improve damping inter-area oscillations. Since active loads are continually changed in power systems, considering effects of active load variation on damping of power system oscillations between interconnected areas is very important for the system secure operation. In this paper it is shown that, increasing of active loads in load buses cause increasing the electromechanical oscillations. Also this paper show that increasing inertia coefficient of large generators causes increase electromechanical oscillations in power systems. Simulation results on a two-area 4-generator interconnected system show that the suggested UPFC control strategy can improve damping significantly.

Keywords— Flexible ac transmission system(FACTS), Power flow system oscillation damping, Unified power flow controller (UPFC), Inter-area oscillations.

I. Introduction

A PROBLEM of interest in a power industry in which FACTS controllers could play a major role is the mitigation of low frequency oscillations that often arise between areas in a large interconnected power network. These oscillations are due to the dynamics of inter-area power transfer and often exhibit poor damping when the aggregate power transfer over a corridor is high relative to the transmission strength. The problem of low frequency power swings is a matter of concern for power engineers. The traditional solution to this problem is the use of power system stabilizer(PSS). The addition of PSS in the AVR control loop provides the means to damp these oscillations. Unlike PSS control at a generator location, the speed deviations of the machine of interest are not readily available to a FACTS controller sited in the transmission path [1] , [2]. The added AVRs and PSSs are designed to act upon local measurements such as bus voltage, generator shaft speed, or the rotor angle of the associated machine. This type of feedback control is useful for local and control mode oscillations, but may be unsatisfactory for inter-area oscillations [3]. In [4], demonstrates the superior effectiveness of utilizing the artificial search technique to ascertain parameters optimization of PSS, contemplating proportional-integral derivative controller (PID) for a multi-machine power system, compared to the customary Ziegler-Nichols method. FACTS devices give more flexibility of control for secure and economic operation of power systems [5]. In recent years, new type of FACTS devices have been investigated that may be used to increase power system operations flexibility and controllability, to enhance system stability and to achieve better utilization of existing power systems [6]. The unified power flow controller (UPFC) is member of the FACTS family with very attractive features [7]. The UPFC is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line (voltage, impedance, and phase angle). UPFC which consists of a series and a shunt converter connected by a common dc link capacitor can simultaneously perform the function of transmission line real/active power flow control in addition to UPFC bus voltage/shunt reactive power control [8]. The shunt converter of the UPFC controls the UPFC bus voltage/shunt reactive power and the dc link capacitor voltage. The series converter of the UPFC controls the transmission line real/active power flows by injecting a series voltage of adjustable magnitude and phase angle [9]. on the other hand the series part known as static synchronous series compensator (SSSC) can be controlled without restrictions. The phase angle of series voltage can be chosen independently from line current between 0 to 2π, and its magnitude is variable between zero and a defined maximum value. The parallel part known as STATic synchronous COMpensator (STATCOM), injects an almost sinusoidal current of variable magnitude at the point of connection. In [10], a power injection model was used to study the effect of UPFC for improving damping of oscillations with an energy function-based control strategy. The power injection model is derived from the power balance equations at the UPFC network interface nodes. Most researches have emphasized the effect of UPFCs on stability improvement and power flow control . However, a little literature has been published on dynamic performance and transient behavior of UPFC [11].

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In this paper a new control strategy for unified power flow controller is proposed. The next section describes the inter-area oscillations in the interconnected power systems. Structure of the control system of the series part of the UPFC as described in [12] has been given in section V. In order to focus on the series part for its effectiveness for damping, we consider only controlling series injected voltage for damping control. PI-type regulators control the series injected voltage. It is assumed that the control system has two supplementary inputs. Further damping enhancement can be accomplished by adjusting the proportional gain or adding a supplementary damping signal. The proposed control strategy has been demonstrated a on two area 4-generator interconnected test system. . The simulation results show the effect of active load change on oscillations. Also It has been shown that the UPFC with supplementary controller has a significant impact in damping inter-area system oscillations.

II. INFLUENCE OF INERTIA COEFFICIENT ON INTER-AREA OSCILLATIONS

A. Inter-area Oscillations

A problem of interest in the power system is the mitigation of inter-area oscillations that often arise between areas in a large interconnecting power network [13],[14]. These oscillations are due to the dynamics of inter-area power transfer and often exhibit poor damping when the aggregate power transfer over a corridor is high relative to the transmission strength [15],[16]. The oscillation of one or more generators associated with groups of generators in different areas oscillating against each other are called inter-area modes. The frequencies of the oscillations depend on the strength of the system and on the moment of inertia of the generator rotors. These frequencies are in the range of 0.1-1.0 Hz, in most practical system. The inter-area oscillation limits the amount of power transfer on the tie-lines between the regions containing the groups of coherent generators.

B. Generator Equations

The dynamic behaviour of generators within a power system is of fundamental importance to the overall quality of the power supply. the mechanical equations of a rotating machine are very well established and they are based on the swing equations of the rotating inertia. Generator dynamics is described by [17].

$$M\,\frac{d\Delta\omega}{dt} = P_m - P_g(\delta) - D\,\frac{d\delta}{dt} \qquad (1)$$

where M is the inertia coefficient; D is the damping coefficient; P_m is the mechanical power; P_g is the electrical real power; δ is the rotor angle and $\Delta\omega = d\delta/dt$ is the rotor speed deviation.

The swing equation relates the machine's rotor torque angle to the accelerating torque, which is the difference between the shaft torque and electromechanical torque. When there is an equilibrium between the mechanical shaft and braking electrical torques, the shaft speed will be constant. Any imbalances between the torques will cause the acceleration or deceleration of the machine according to the lows of motion of a rotating body [17].

$$T_{acc} = J\,\frac{d^2\delta_m}{dt^2} = T_{mech} - T_{elec} \qquad (2)$$

where

T_{acc} : Accelerating torque.
J : Combine moment of inertia of the generator and turbine.
δ_m : Mechanical torque angle of the rotor.
t : time.
T_{mech} : Mechanical torque.
T_{elec} : Electrical torque.

An increasing in the machine inertia constant decreases both the natural frequency and the damping ratio. Therefore the synchronous generators with small coefficient of inertia are preferred for large interconnected power systems.

III. UNIFIED POWER FLOW CONTROLLER PRINCIPLE OPERATION

The UPFC is made out of two voltage-source converters VSCs with semiconductor devices having turn-off capability, sharing a common dc capacitor and connected to a power system through coupling transformers. The basic UPFC structure is depicted in Fig. 1.

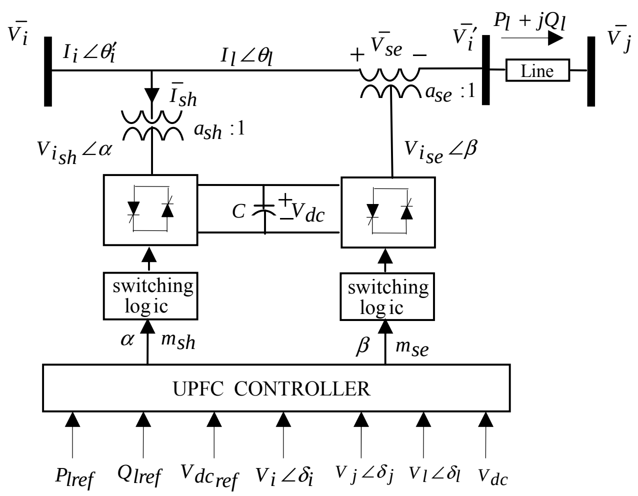

Fig. 1. UPFC functional model.

The shunt converter is primarily used to provide the real power demand of the series converter at the common dc link terminal from the ac power system. It can also generate or absorb reactive power at its ac terminal, which is independent of the active power transfer to (or from) the dc terminal. Therefore, with proper control, it can also fulfill the function of an independent advanced static VAR compensator providing reactive power compensation for the transmission line and thus executing indirect voltage regulation at the input terminal of the UPFC.

The series converter is used to generate a voltage source at the fundamental frequency with variable amplitude and phase angle, which is added to the ac transmission line by the series-connected boosting transformer. The inverter output voltage injected in series with the line can be used for direct voltage control, series compensation, phase shifter, and their combinations. This voltage source can internally generate or absorb all the reactive power required by the different type of controls applied and transfers active power at its dc terminal. The reactive power is generated/absorbed independently by each converter and does not flow through the dc link [18], [19]. The DC link provides a path to exchange active power between the converters. The series converter injects a voltage in series with the system voltage through a series transformer. The power flow through the line can be regulated by controlling the magnitude and angle of the series-injected voltage. The injected voltage and line current determine the active and reactive power injected by the series converter. The converter has a capability of electronically generating or absorbing the reactive power. However, both the series and shunt converters can independently exchange reactive power with the AC system. However, the injected active power must be supplied by the DC link, in turn taken from the AC system through the shunt converter. When the losses of the converters and the associated transformers are neglected, the overall active power exchange between the UPFC and the AC system becomes zero[20].

IV. UPFC MODELING

UPFC modeling depends on the range of frequency of concern. The model required for studying low frequency oscillations should faithfully exhibit phenomena of 0.1-3 Hz.

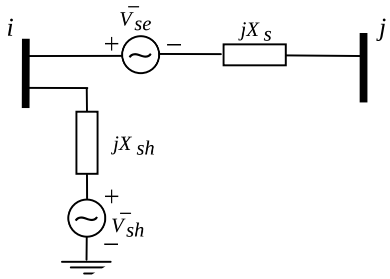

Fig. 2. Equivalent model of UPFC.

UPFC injects a voltage in series with a line through a series transformer. The active power involved in the series injection is taken from the line through a shunt transformer. UPFC generates or absorbs the needed reactive power locally by the switching operation of its converters.

Fig. 2 shows the equivalent circuit of Fig. 1 where the converters are replaced by synchronous voltage sources in series with the associated transformer leakage reactance. The shunt converter voltage and the associated transformer leakage reactance can be replaced by a shunt current source as shown in Fig. 3. The value of the shunt current I_{sh} , is given by

$$I_{sh} = \frac{(V_{sh} - V_i)}{jX_{sh}} \tag{3}$$

Fig. 3 shows a general equivalent diagram of a series-shunt-connected device (like UPFC).

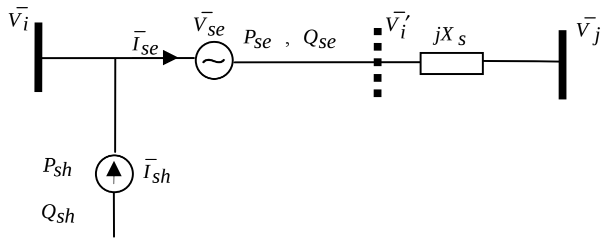

Fig. 3: Equivalent circuit diagram of UPFC

In fig. 3, $X_s = X_{series}$ is the effective reactance seen from the line side of the series transformer, where

X_{series} is the reactance of the series transformer;
$\bar{V}_{se}$ is the induct series voltage;
$\bar{I}_{shunt}$ is the current source.

The series voltage source inverter can be modeled with an ideal injection voltage $\bar{V}_s$ in series with a reactance X_s .The series voltage source $\bar{V}_s$ is controllable in magnitude and phase, i.e.

$$V_{se} = r\bar{V}_i e^{j\gamma} \tag{4}$$

Here r and γ are respectively the relative magnitude and angle, of $\bar{V}_{se}$, with respect to the complex voltage $\bar{V}_i$ of bus i. The control ranges of r and γ are :

$0 \le r \le r_{\max}$ and $0 \le \gamma \le 2\pi$

The injected voltage $\bar{V}_{se}$ consists of in-phase component V_p and quadrature component V_q with respect to the UPFC input voltage $\bar{V}_i$.
$\bar{V}_i'$ is a fictitious voltage behind the series reactance X_s .

$$\bar{V}_i' = \bar{V}_i + \bar{V}_{se} \tag{5}$$

The equivalent circuit vector diagram is shown in Fig. 4. voltage of bus i, $\bar{V}_i$, is assumed to be the reference vector, i.e., $\bar{V}_i = V_i \angle 0^{\circ}$.

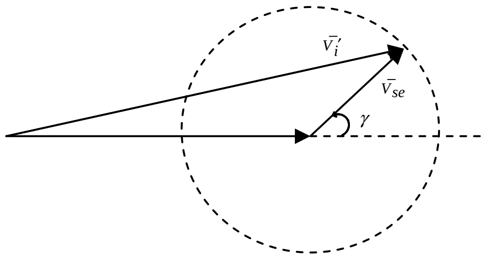

Fig. 4: Vector diagram of the equivalent circuit of series voltage source

To obtain an injection model for UPFC, it is first necessary to consider the series voltage source, Figure 5.

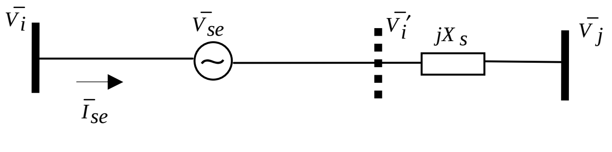

Fig. 5: Representation of the series connected voltage source

The power injection model can be obtained by replacing the voltage source V_{se} by a current source I_{inj} in parallel with the transmission line as shown in fig. 6.

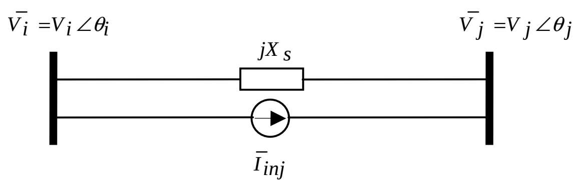

Fig. 6: Transformed series voltage source

where

$$\bar{I}_{inj} = -jb_s \bar{V}_{se} = -jb_s (rV_i \angle 0 e^{\gamma}) = -jrb_s V_i e^{j\gamma} \tag{6}$$

and $b_s = 1/X_s$

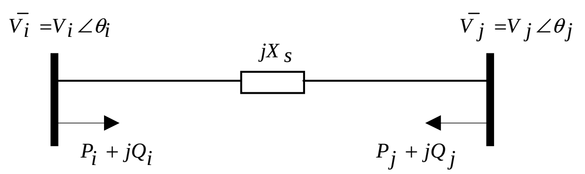

Fig. 7: Injection model of the series part of the UPFC

Then, the complex powers injected into each bus become:

$$\bar{S}_{is} = -rb_s V_i^2 \sin(\gamma) - jrb_s V_i^2 \cos(\gamma) \tag{7}$$

$$\bar{S}_{js} = rb_s V_i V_j \sin(\theta_{ij} + \gamma) + jrb_s V_i V_j \cos(\theta_{ij} + \gamma) \tag{8}$$

where $\theta_{ij} = \theta_i - \theta_j$

and the real and reactive powers can be obtained by

$$P_{si} = -\mathrm{Real}(\bar{S}_i) \qquad Q_{si} = -\mathrm{Imag}(\bar{Q}_i) \tag{9}$$

$$P_{sj} = -\mathrm{Real}(\bar{S}_j) \qquad Q_{sj} = -\mathrm{Imag}(\bar{S}_j) \tag{10}$$

Therefore we have

$$P_{si} = rb_s V_i^2 \sin(\gamma) \tag{11}$$

$$Q_{si} = rb_s V_i^2 \cos(\gamma) \tag{12}$$

$$P_{sj} = -rb_s V_i V_j \sin(\theta_{ij} + \gamma) \tag{13}$$

$$Q_{sj} = -jrb_s V_i V_j \cos(\theta_{ij} + \gamma) \tag{14}$$

The parallel branch provides only the active power that is injected to the network via the series branch. Having the UPFC losses neglected,

$$P_{parallel} = P_{series}$$

The apparent power supplied by the series converter is calculated from:

$$\bar{S}_{series} = \bar{V}_{se} \bar{I}_{se}^{*} = re^{j\gamma} \bar{V}_i \left(\frac{\bar{V}_i' - \bar{V}_j}{jX_s} \right)^{*} \tag{15}$$

Therefore active power and reactive power supplied by parallel inverter is:

$$P_{series} = rb_s V_i V_j \sin(\theta_{ij} + \gamma) - rb_s V_i^2 \sin(\gamma) \tag{16}$$

$$Q_{series} = -rb_s V_i V_j \cos(\theta_{ij} + \gamma) + rb_s V_i^2 \cos(\gamma) + r^2 b_s V_i^2 \tag{17}$$

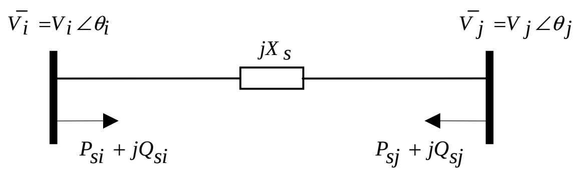

Fig. 8: Injection model of the UPFC

The injection model for UPFC can be achieved by equations (9) and (14). The injected powers for UPFC are then given by

$$P_{si} = rb_s V_i V_j \sin(\theta_{ij} + \gamma) \tag{18}$$

$$Q_{si} = rb_s V_i^2 \cos(\gamma) \tag{19}$$

$$P_{sj} = -P_{si} = -rb_s V_i V_j \sin(\theta_{ij} + \gamma) \tag{20}$$

$$Q_{sj} = -jrb_s V_i V_j \cos(\theta_{ij} + \gamma) \tag{21}$$

If there is a control objective to be achieved, the bus power injections are modified through changes of the UPFC parameters r, γ, and Q_{series}.

V. UPFC CONTROL SYSTEM

A. Controller Design

The control system of the series part of the UPFC is shown in Fig. 9 [15]. In order to focus on the series part for its effectiveness for damping, only controlling series injected voltage for damping is considered. The series injected voltage is controlled by PI-type regulator. As shown in Fig. 9 the control system has two supplementary inputs. The series injected voltage $\bar{V}_{se}$ is decomposed into the in-phase component $\bar{V}_p$ and quadrature component $\bar{V}_q$ in the UPFC control system. Then the injected voltage of the series inverter $\bar{V}_{se} = V_{se}\measuredangle\gamma$ is computed as follows:

$$V_{se} = \sqrt{V_p^2 + V_q^2} \tag{22}$$

$$\gamma = \arctan\left(\frac{V_q}{V_p}\right) \tag{23}$$

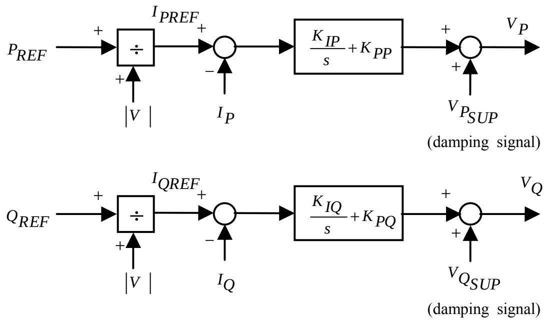

Figure 9: the series part of the control system of UPFC

The UPFC plays two important controlling roles as a power flow controller in order to achieve steady state objectives (slow control) and as a device to improve transient performance (requiring fast control).

B. Damping Controller Design

Supplementary controller plays major roles on increasing system damping. Since UPFC is located in transmission systems, local input signals are always prefered, usually the active or reactive flow through UPFC.

In this paper the supplementary controller consists of an amplification block, a wash-out and a lead-lag block. The transfer function of the supplementary controller is given by:

$$H(s) = K\frac{sT_W}{1+sT_W}\frac{1+sT_{lead}}{1+sT_{lag}} \tag{24}$$

VI. CASE STUDY

A simple four machine two area test system (Fig. 10) is used in this study. Case study is conducted to evaluate the performance of UPFC and its controller on damping of power oscillations. The system has one inter-area mode with a very poor damping.

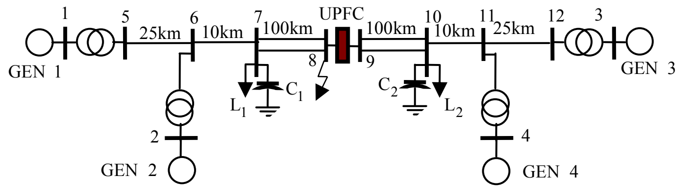

Fig. 10. A simple two-area power system model.

It is assumed that a UPFC is installed on the middle of the 200 km tie-line. All generators are fourth-order two-axis models equipped with 1st order fast exciters. All the exciter parameters are the same as: $K_A = 200\ (pu)$ and $T_A = 0.02\ (s)$.

VII. TIME SIMULATION RESULTS

To test the effectiveness of the proposed UPFC controller, a three-phase six-cycle fault applied to the load bus of area 1.

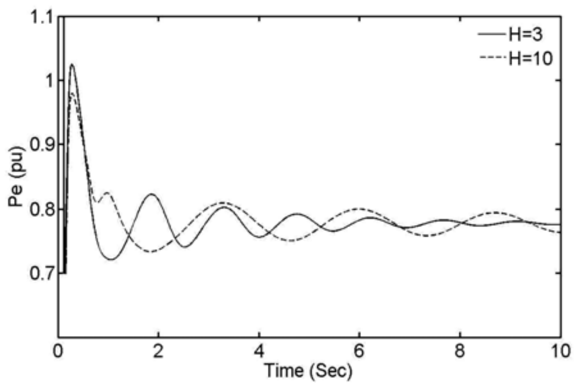

Fig. 11: Response of test power system to changes of inertia coefficient of generators.

In order to show the impact of coefficient of inertia on inter-area oscillations, two cases (H=3 , H=10) based on test system are carried out. In Fig. 11 the simulation result is shown. Solid line shows the active power oscillation with H=3 for all synchronous machines. Dashed line shows the active power oscillation with H=10 for all synchronous machines.

This curve indicates that an increasing in the generator inertia constant decreases both the natural frequency and the damping ratio of oscillations.

In order to show the impact of active loads on inter-area oscillations, two cases ($L_{act1}=967MW$ $L_{act2}=1767MW$) and ($L_{act1}=1167MW$ $L_{act2}=2167MW$) based on the test system are carried out. In Fig. 12 the simulation result is shown. Dashed line shows the active power oscillation with ($L_{act1}=967MW$ $L_{act2}=1767MW$). Solid line shows the active power oscillation with ($L_{act1}=1167MW$ $L_{act2}=2167MW$). This curve indicates that an increasing in the active loads increases the oscillations and the decreases damping ratio of oscillations.

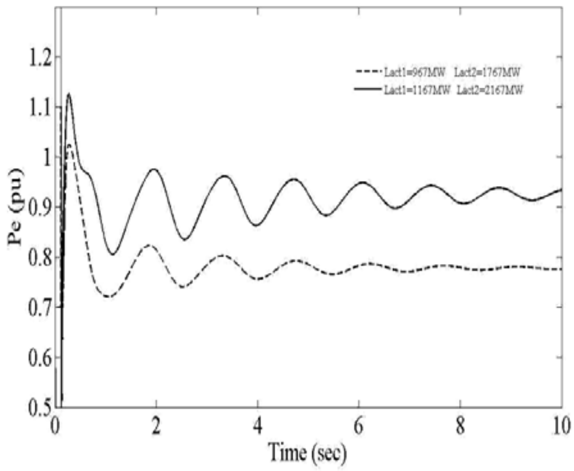

Fig. 12: Response of test power system to changes of active loads

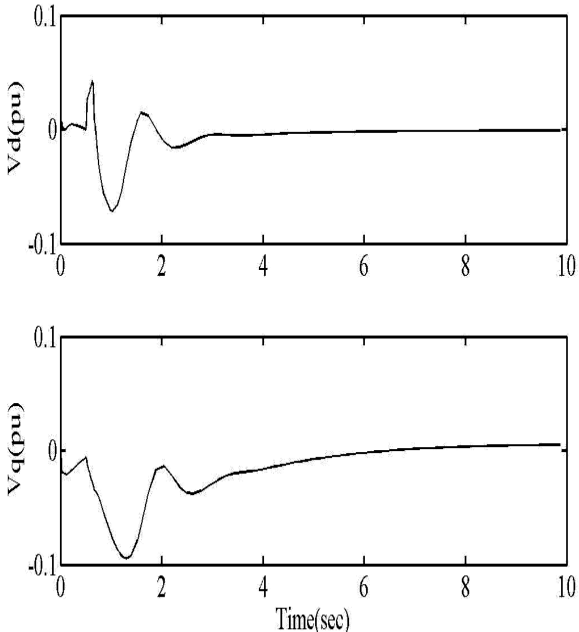

Fig. 13: series injected voltage by UPFC for damping oscillations.

The series injected voltage components with controller for damping oscillation is shown in Fig. 13.

It has been shown that the UPFC with supplementary controller provides an effective means of adding damping to the power system. The dynamic oscillations are well damped.

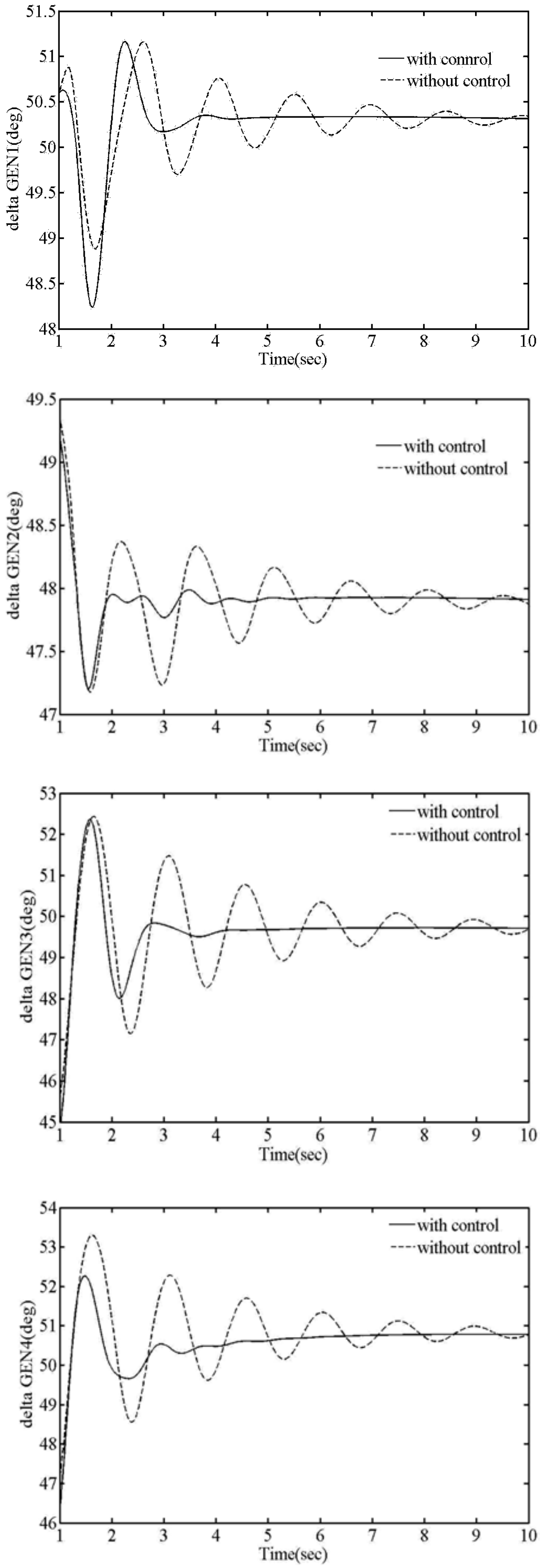

Fig. 14: Machine angle oscillation of generators to three phase fault with and without controller.

shown in Fig. 14. the dashed line corresponds to the case when the UPFC was not active, while the solid line shows the influence of UPFC controlled by the proposed controller based on local measurements and ($K_{IP}=0.1$, $K_{PP}=0.01$, $K_{IQ}=0.4$, $K_{PQ}=0.01$ and the washout time constant $T_W=5\text{sec}$).

Also it is clear from the results that the effect of UPFC is more pronounced when the controller is placed near faulted bus rather than placed at remote locations.

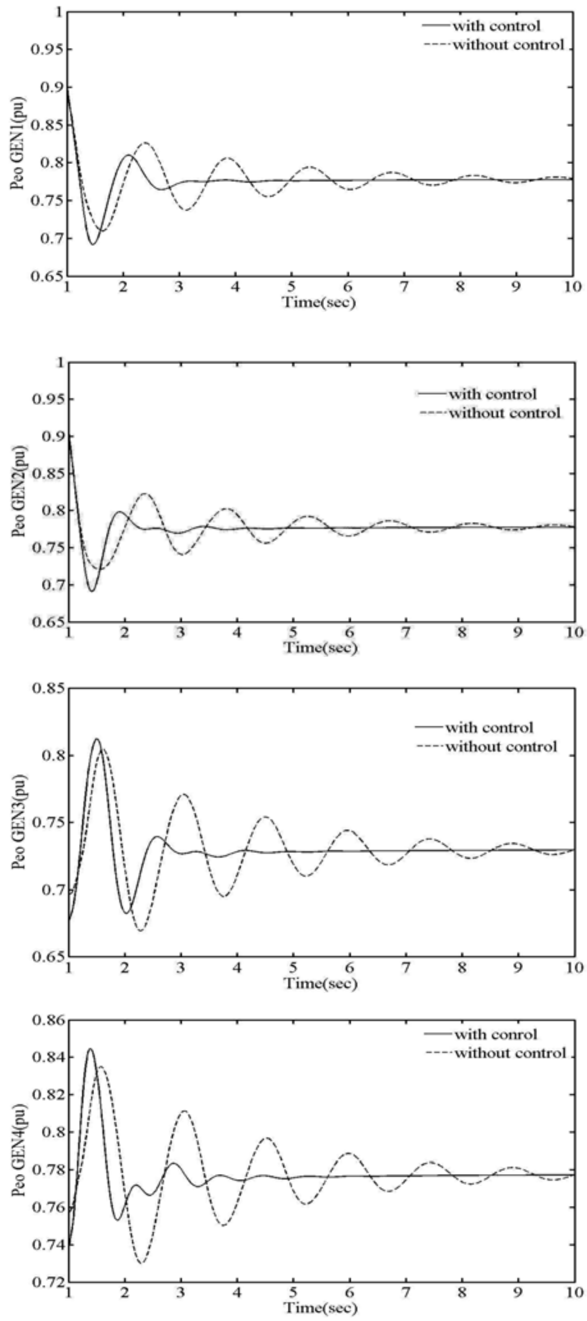

Fig. 15: Active power oscillation of generators to three phase fault with and without controller.

Fig. 15 shows the damping of active power oscillations with UPFC and compares improving of damping oscillations with and without supplementary controller.

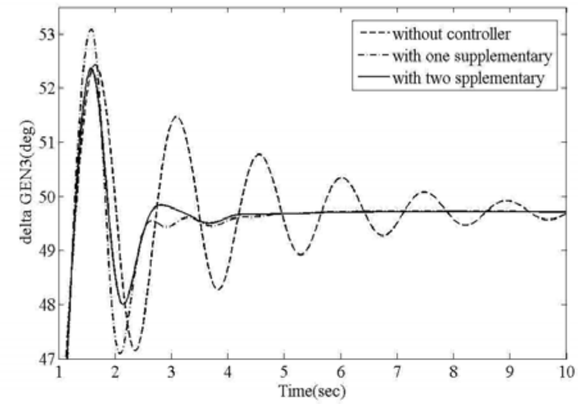

Fig. 16: Machine angle oscillation of GEN3 to three phase fault with one and two supplementary damping signals

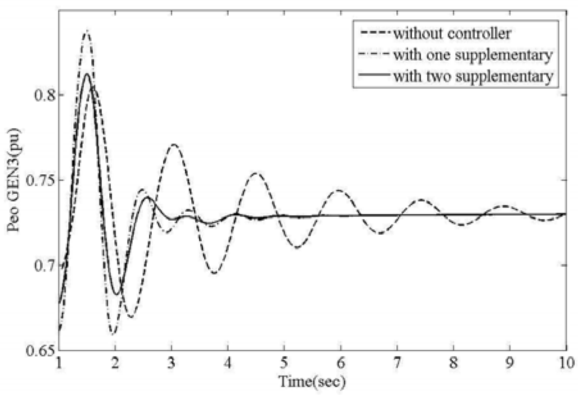

Fig. 17: Active power oscillation of GEN3 to three phase fault with one and two supplementary damping signals

Fig. 16 and fig. 17 show the effects of extended controller on damping of Machine angle oscillation and active power oscillations and compares improving of damping oscillations with and without extended supplementary controller.

VIII. CONCLUSION

In this paper, the inter-area oscillations on interconnected power systems when certain local signals are used for FACTS-based damping controllers, have been investigated. A new control strategy of a unified power flow controller (UPFC) is proposed to improve damping of oscillations. The UPFC with very attractive features is able to control all the parameters affecting power flow in the transmission line (voltage, impedance and phase angle). The proposed control strategy has been demonstrated on a two area four machine interconnected power system.

In this paper, a current injection model of UPFC, which is suitable for using in power system stability studies, has been presented. The paper shows that supplementary controller plays major role on increasing system damping. More damping can be achieved by using local measurements of real and reactive power and by carefully choosing gains in the supplementary control loops. The simulation results for a case study also indicate that an increasing in the active loads increases power oscillations and decreases the damping ratio.

The paper also presents that an increasing in the machine inertia constant decreases both the natural frequency and the damping ratio. The proposed control can significantly improve damping of inter-area oscillations.

APPENDIX

System Parameters:

The transmission system nominal voltage is 230 kV. The line lengths are shown in Fig. 11. The parameters of the lines in pu on 100 MVA, 230 kV base are $r = 0.0001\ \text{pu/km}$, $xL = 0.001\ \text{pu/km}$, $bC = 0.00175\ \text{pu/km}$.

Each step-up transformer has an impedance of $j0.15$ pu on 900 MVA and 20/230 kV base. Each generator has a rating of 900 MVA and 20 kV and the parameters in pu are as follows: $H = 6.5\ (G1, G2),\ 6.175(G3, G4)$, $D = 0$, $T'_{do} = 8.0$, $T'_{qo} = 0.4$, $X_d = 0.2$, $X'_d = 0.033$, $X_q = 0.18$, $X'_q = 0.033$.

The limit of the UPFC for damping control is assumed to be ± 0.09 pu each for the v_P and v_Q around the operating point. The shunt converter just provides the real power needed by the series inverter. Their limits are far below its steady-state capability in order not to make the system unstable due to the UPFC's action. It is assumed that the steady-state control limit is 600 MVA with injected voltage 1.2 pu, current 5 pu, shunt converter current 6 pu on 100 MVA, 230 kV base. The steady state ratings, however, does not matter in this paper because this paper deals with small-signal problem that are associated with low-frequency oscillations.

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