Improving of Transient Stability of Power Systems By supplementary Controllers of UPFC Using Different Fault Conditions

A. KAZEMI and F. MAHAMNIA
Department of Electrical Engineering
Iran University of Science and Technology (IUST)
Tehran
IRAN
kazemi@iust.ac.ir farrokh.mahamnia@ee.iust.ac.ir

Abstract-- Long distance AC transmission is often subject to stability problems , which limits the transmission capability.Large interconnected power systems often suffer from weakly damped swings between synchronous generators and subsystems.This paper presents two methods , based on the use of nonlinear system model , to improve transient stability and damping of power swings using UPFC. A state- variable control strategy has been derived using local available signals of real and reactive power. The results of simulation tests of two control methods, undertaken using a small multi-machine system model, have been presented. The simulations show that the methods make good results in different fault places and clearing time. The results present that controlling series part of UPFC can improve transient stability by state-variable control method, but simultaneous control of shunt and series part of UPFC can damp voltage oscillations by direct Lyapunov method.

Key-Words: Transient stability, Local measurement, Flexible ac transmission systems (FACTS) , UPFC , Power oscillations damping.

1 Introduction

Transient stability is the ability of the system to return to a normal operating state and generators remaining in synchoronism , following a large disturbance , such as multi-phase short-circuit or switching of lines.

Power systems exhibit various modes of oscillation due to interactions among system components. Most of the oscillations are due to synchronous generator rotors swinging relative to each other. Stressed power systems are known to exhibit nonlinear behaviour. Load changes or faults are the main causes of power oscillations.

If the oscillation is not controlled properly , it may lead to a total or partial system outage. If no adequate damping is possible, the oscillations may be sustained for minutes affecting power flows and grow to cause loss of synchronism between systems.

Application of power system stabilizer (PSS) has been one of the first measures to enhance the damping of power swings. With increasing transmission line loading over long distances, the use of conventional PSS might in some cases, not provide sufficient damping for power swings. PSS increases damping torque of a generator by affecting the generator excitation control, while FACTS devices improve damping by modulating the equivalent power-angle characteristic of the power system[1].To increase power system oscillation stability, the installation of supplementary excitation control, PSS, is a simple, effective and economical method.

By using power electronics controllers a Flexible AC Transmission System which offers greater control of power flow, secure operation and damping of power system oscillations. FACTS devices are used in power systems to improve both the steady state and dynamic performances of the systems [2].

Damping can be improved by using one of the flexible AC transmission systems (FACTS) devices, which offers an alternative means to mitigate power system oscillation. Thus, a question of great importance is the selection of the input signals and a control strategy for these devices in order to damp power oscillation in an effective and robust manner.

The work reported here was to derive a state-variable control using a nonlinear system model in order to take into account the influence of changing operating conditions and changes in the network parameters. To achieve this goal, the direct Lyapunov method was used [3].

Unlike the PSS at a generator location, the speed deviations of the machines are not readily available to a FACTS controller located on a transmission line. For a UPFC based damping controller, we want to use an input signal to the damping controller from the locally measurable quantities at the UPFC location. The electrical active and reactive power flows can be easily measured at the UPFC location and hence may be used as an input signal to the damping controller.

The paper [6] used the rate of dissipation of transient energy as an index to determine and compare the additional damping provided by a STATCOM and SSSC. The SSSC can be operated in many different modes and the final outcome is such that the SSSC injects a voltage in series with transmission line [7].

Since a fault appears in any point of a power system with different clearing times, the ability of damping controllers in different fault conditions is important. Stability of the system depends on operating point before faults and strength of disturbance [8].

The UPFC parameters can be controlled in order to achieve maximal desired effect where transient stability problems appear when bulk power is transmitted by long transmission lines [9].

In this paper we consider the stabilizing control of the UPFC by two methods [3,10] , and their effects for different fault places and clearing delay times. Ability of two control methods were studied in the presense of three-phase short circuit with different durations (100, 150, 200 msec) placed in different locations.The voltage oscillations are well damped with direct Lyapunov method. This method gives better power oscillations damping results.

2 Power System Oscillations

The dynamic equations of the single-machine-to-infinite-bus system are given in Fig.1 as below [1]:

$$\begin{cases} \dfrac{d\,\Delta\omega_r}{dt} = \dfrac{1}{2H}[\Delta\tau_m - \Delta\tau_e - D\Delta\omega_r] \\ \dfrac{d\,\Delta\delta}{dt} = \omega_0\Delta\omega_r \end{cases} \tag{1}$$

The state equation of above relations is given by:

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega_r \\ \Delta\delta\end{bmatrix} = \begin{pmatrix} -\dfrac{D}{2H} & -\dfrac{K_S}{2H} \\ \omega_0 & 0 \end{pmatrix}\begin{bmatrix}\Delta\omega_r \\ \Delta\delta\end{bmatrix} + \begin{bmatrix}\dfrac{1}{2H} \\ 0\end{bmatrix}.\Delta\tau_m \tag{2}$$

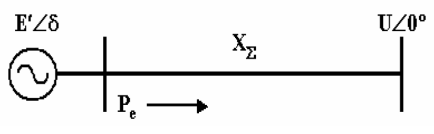

Fig. 1 Single-machine-to-infinite-bus.

The equations (1) and (2) make the base of most stability and low frequency oscillations studies in power systems.

The eigenvalues of the system are calculated from the following equation:

$$|A - \lambda I| = 0 \tag{3}$$

The standard form of the characterstic equations is given by:

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0 \tag{4}$$

$$s_{p1,p2} = -\xi\omega_n \pm j\omega_d$$

The damping coefficient (D) is very small in synchronous generators, so they are working in oscillatory and underdamped states $(0 < \xi < 1)$.

Increasing of D, causes increasing of ξ and so the system oscillations are damping very fast.

3 Unified Power Flow Controller

The unified power flow controller (UPFC) is the most versatile device in the FACTS family which can provide simultaneous control of power system parameters such as transmission voltage, line impedance and phase angle [5]. It has a capability of improving both steady-state and dynamic performances of a power system[11]. It can be connected in series with a transmission line inside a system or in a tie-line connecting subsystems in a large interconnected system.

UPFCs have the capability to control voltage magnitude and phase angle.Besides, UPFC can independently provide either positive or negative reactive power injections[12].

Moreover UPFC further improves the dynamic performance of the power system in coordination with damping controllers[13].

They can improve system operation because they allow for more accurate control of the power flow , 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 [14]-[17].

It consists of two solid-state synchronous voltage-source converters coupled through a common DC link capacitor as shown in Fig. 2.

As shown in Fig. 2, the UPFC consists of a boosting transformer and an excitation transformer linked by back-to-back converters VSC1 and VSC2. First converter (VSC1) is connected in shunt and the second one (VSC2) in series with the line.The shunt converter is primarily used to provide active power demand of the series converter through a common DC link. Converter 1 can also generate or absorb reactive power and thereby provide independent shunt reactive compensation for the line. Converter 2 provides the main function of the UPFC by injecting additional voltage ΔU, with controllable magnitude and phase angle in series with the transmission line through series transformer .

The main task of the UPFC is to control the flow of power in steady-state conditions. In addition, high speed of operation of thyristor devices makes it possible to control real and reactive power flow. The UPFC can be employed to enhance power system damping by modulating the converter voltages.That area of application is the main subject of this paper.

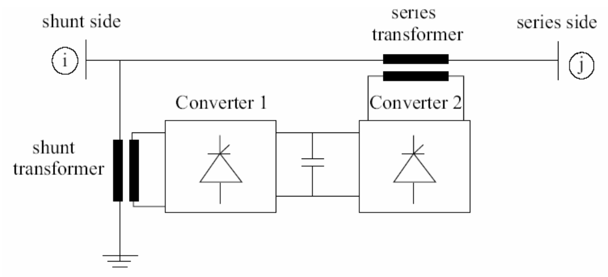

Fig. 2 Schematic diagram of UPFC.

4 Control Strategy Based On State Variables

4.1 UPFC control and modeling

For simplicity a UPFC is connected at the end of the transmission line, near the infinite bus. Fig. 3 shows the single-line diagram of SMIB system with the UPFC. The vector diagram of a UPFC connected to a network (Fig.3) is presented in Fig.4 .

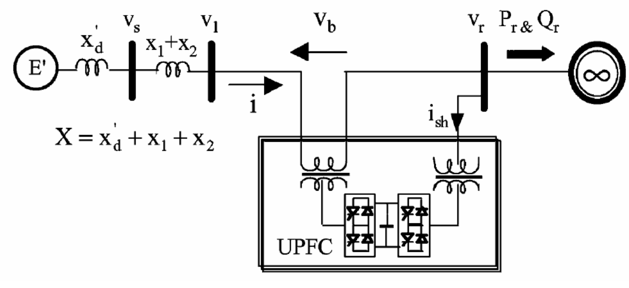

Fig. 3 SMIB system with the UPFC.

According to Fig.4, $V_b p$ and $V_b q$ are the in-phase and quadrature components of the series voltage of UPFC [4].They are proportional to the voltage at the point of connection of UPFC and can be written as:

$$V_b p = V_r \gamma(t) \quad (5)$$

$$V_b q = V_r \beta(t) \quad (6)$$

where $\beta(t)$ and $\gamma(t)$ are the control variables.
The generator swing equation is :

$$M\frac{d^2\delta}{dt^2} = P_m - A.\sin(\delta) - D\frac{d\delta}{dt} - P_{UPFC} \quad (7)$$

where

$$P_{UPFC} = -A\cos(\delta)\gamma(t) + A\sin(\delta)\beta(t) \quad (8)$$

In equations (7) and (8), $(A = E'V_r / X)$ presents amplitude of power-angle characteristic in case of series voltage and is equal zero where P_{UPFC} introduces additional damping to the system if it is positive and proportional to the speed deviation $\Delta\omega = d\delta/dt$.

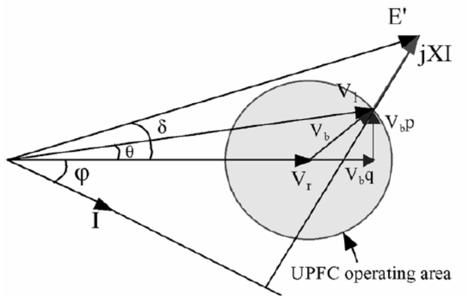

Fig.4 Vector diagram of a UPFC connected to a network.

The control strategy for achieving these aims are given as the following relations:

$$\gamma(t) = -K\cos(\delta)\frac{d\delta}{dt} \quad and \quad \beta(t) = -K\sin(\delta)\frac{d\delta}{dt} \quad (9)$$

The state variables defined by (9) can be executed by using time derivatives of the receiving active and reactive powers. According to Fig. 4, we can calculate the partial derivatives of Pr and Qr as below [4], [10]:

$$\frac{dP_r}{dt} = \frac{(-V_b p)E'}{KX} - \frac{V_r}{X}\frac{d(V_b p)}{dt} \quad (10)$$

$$\frac{dQ_r}{dt} = \frac{(-V_b q)E'}{KX} - \frac{V_r}{X}\frac{d(V_b q)}{dt} \quad (11)$$

Fig. 5 shows the proposed block diagram of a modulation controller for the in-phase component of the series injected voltage of UPFC by using (10). The quadrature component is similar and drived by (11).

The injected series voltage is calculated as equation (12):

$$V_{bref} = \sqrt{V_b^2 p + V_b^2 q} \qquad \delta_b = \tan^{-1}(\frac{V_b p}{V_b q}) \tag{12}$$

This voltage which is applied to the control system.

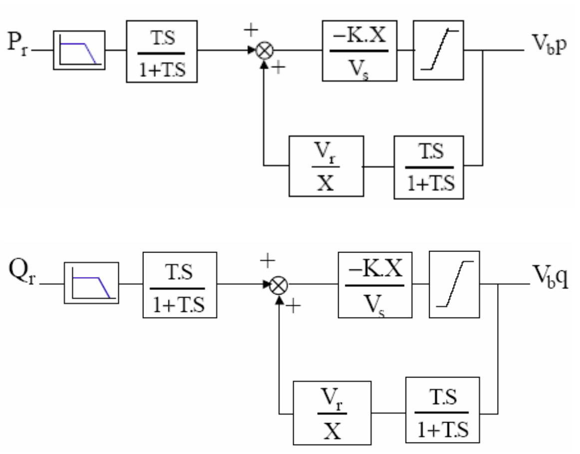

Fig. 5 Modulation controller for $V_b p$ and $V_b q$.

5 Control Strategy Based On Direct Lyapunov Method

5.1 Power system model with UPFC

The thyristor controlled UPFC can be treated as a lag element with a very small time constant or, as a proportional element. Hence the series part of the UPFC can be modeled by the series reactance of the left-hand side of the transmission link X_a and by the ideal complex transformation ratio:

$$\frac{I_b}{I_a} = \eta^* = |\eta| e^{-j\theta} \qquad \eta = \frac{U_a}{U_b} = |\eta| e^{j\theta} \tag{13}$$

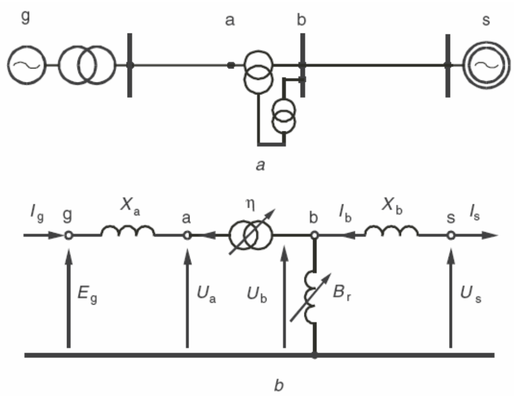

Fig. 6 SMIB with UPFC : (a) Schematic diagram; (b) Single-phasediagram

The shunt part of the UPFC can be modelled as a controlled shunt susceptance B_r (Fig.6b). Voltage ΔU injected by the booster transformer can be resolved into two orthogonal components (Fig. 7): direct ΔU_Q and quadrature ΔU_P.The direct and quadrature components ΔU_Q and ΔU_P influences the reactive and real power flow.

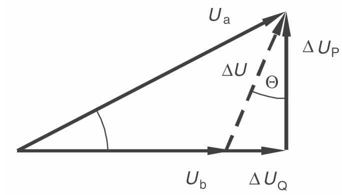

Fig. 7 SMIB with UPFC: Phasor diagram.

5.2 Generator equations

Generator dynamics is described by the swing equation[1]:

$$M\frac{d\Delta\omega}{dt} = P_m - P_g(\delta) - D\frac{d\delta}{dt} \tag{14}$$

Where δ is the power angle and $\Delta\omega$ is the rotor speed deviation, M is the inertia coefficient, P_m is the mechanical power, P_g is the electrical real power, D is the damping coefficient.

$$\begin{cases} \dfrac{d\delta}{dt} = \Delta\omega \\ M\dfrac{d\Delta\omega}{dt} = P_m - b_\Sigma \sin\delta - D\dfrac{d\delta}{dt} + X_{SHC} B_r . b_\Sigma \sin\delta \\ \qquad -(1 - X_{SHC} B_r)[\beta . b_\Sigma \sin\delta - \gamma . b_\Sigma \cos\delta] \end{cases} \tag{15}$$

The above equations form nonlinear state equations of $\dot{x} = f(x,u)$, in which $x = (\delta, \Delta\omega)$ are the state variables, while $u = (\gamma, \beta, B_r)$ are the control variables. $\left(X_{SHC} = X_a X_b B_\Sigma, B_\Sigma = 1/(X_a + |\eta|^2 X_b)\right)$

5.3 Direct Lyapunov method

Let $V(x)$ be a Lyapunov function defined for the power system model described by (15).If $\dot{V} = dV/dt$ is negative, Lyapunov function $V(x)$ decreases with time and tends towards its minimum value.The more negative the value of $V(x)$, the faster the system returns to the equilibrium point $\hat{x}$.

For the considered single machine infinite bus system (Fig. 6) and when the network resistance has been neglected, the Lyapunov function $V(x)$ can be defined [1] as the total system energy:

$$V = E_K + E_P \tag{16}$$

where

$$E_K = \frac{1}{2}M(\Delta\omega - \Delta\hat{\omega})^2 = \frac{1}{2}M\Delta\omega^2$$

$$E_P = -[P_m(\delta - \hat{\delta}) + b_\Sigma(\cos\delta - \cos\hat{\delta})$$

are kinetic and potential energy, respectively, and $(\hat{\delta}, \Delta\hat{\omega} = 0)$ are the coordinates of the post-fault equilibrium point.

$$\dot{V} = \frac{dE_P}{dt} + \frac{dE_K}{dt} = -D\Delta\omega^2 - \beta(1 - X_{SHC}B_r)b_\Sigma \sin\delta.\Delta\omega + \\ + \gamma(1 - X_{SHC}B_r)b_\Sigma \cos\delta.\Delta\omega + B_r b_\Sigma X_{SHC} \sin\delta.\Delta\omega \tag{17}$$

This equation shows that each control variable γ, β, B_r can contribute to the power system damping by increasing the negative value of $\dot{V} = dV/dt$.

5.4 Control Strategy Based on Local Measurements

The control strategy is given by relations(18)-(20):

$$\gamma(t) \approx K_\gamma \frac{dP_b}{dt} \tag{18}$$

$$\beta(t) = \frac{K_\beta}{K_X}\frac{dQ_b}{dt} = K_{\beta(Q)}\frac{dQ_b}{dt} \tag{19}$$

$$B_r(t) \approx -\frac{K_\beta}{K_X}\frac{dQ_b}{dt} = -K_{B(Q)}\frac{dQ_b}{dt} \tag{20}$$

A block diagram of a controller operating on P_b or Q_b and controlling γ or β respectively, is shown in Fig.8. The shunt part of the UPFC can operate as the reactive power compensator controlling the voltage U_b and susceptance B_r.

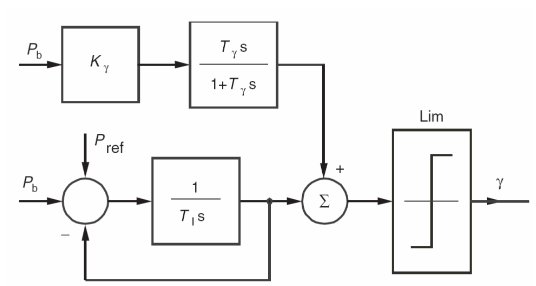

Fig. 8 Block diagram of the controller.

6 Simulation Results

The effectiveness of the two control strategies will be illustrated using two sample systems: a single machine infinite bus system and a three-machine test system.

The following notations are used :

- dotted line: UPFC was not active;
- dashed line: UPFC is controlled by state-variable control with local measured powers (method-1).
- solid line: UPFC is controlled by direct Lyapunov method (method-2).

Damping of rotor and power swings due to both control methods is much stronger than for the uncompensated case.

6.1 Results for SMIB test system

A diagram of a single machine infinite bus sample system is shown in Fig.9 .The parameters of this sample system are shown in reference [4].

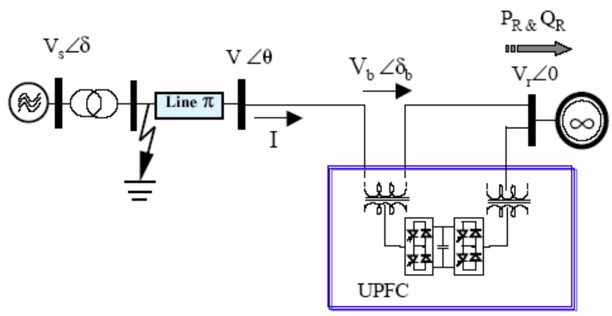

Fig.9 SMIB test system with UPFC.

The control strategies have been tested for different types of disturbances.The considered contingency is a three-phase fault at the sending end of one transmission line while the generator is operating at 95% of its rated capacity.The three-phase short-circuit duration time in all simulations is considered between t=0.15 and 0.35 second.

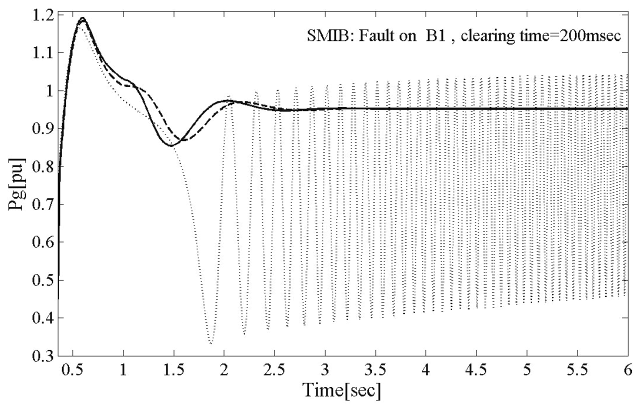

Fig.10 Variation of active power (P_g) in sending end of SMIB system.

The dotted line indicates that the system is unstable and electrical power being sent into undamped oscillation (Fig.10).It is clear that the series compensation effectively damps the power flow oscillation on the transmission line and power swings due to both control methods is similiar.

The references of series injected voltages are calculated and applied to the control system of UPFC by method-1(Fig.11,12).

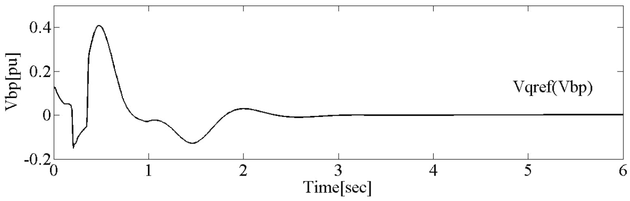

Fig. 11 Reference value of quadrature-axis injected voltage (pu) of UPFC.

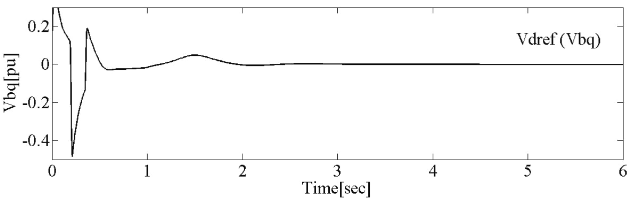

Fig. 12 Reference value of direct-axis injected voltage (pu) of UPFC.

6.2 Results for 3-machine test system

A diagram of a three-machine sample system is shown in Fig.13. The inertia coefficient of generator G1 is much greater than that of generator G2. Therefore, the swings of generator G1 are little slower than that of generator G2. The parameters of this sample system are shown in reference [3].

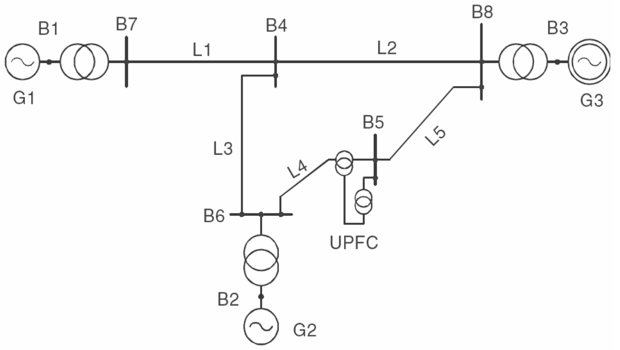

Fig. 13 Three-machine test system.

To illustrate typical results, Figs. 14-23 show real power variations following a temporary three-phase short-circuits on buses B4,B5,B6,B7 and B8 with duration time 200msec.

6.1 Short circuit in bus B4

The method-2 gives slightly weaker damping than method-1 for G1, and an increase in the amplitude of the first and second swings for G2 (Fig. 14, 15).

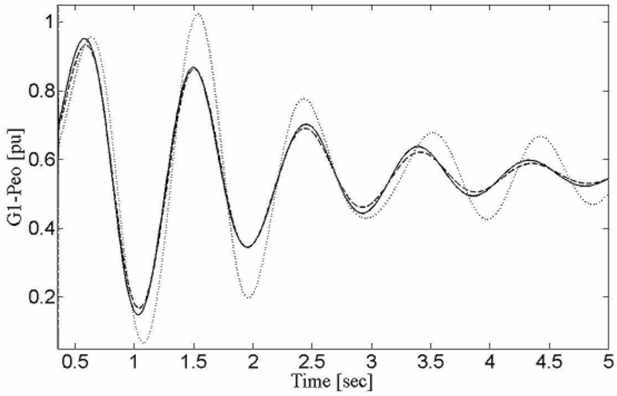

Fig.14 Fault on bus B4 , real power of generator G1.

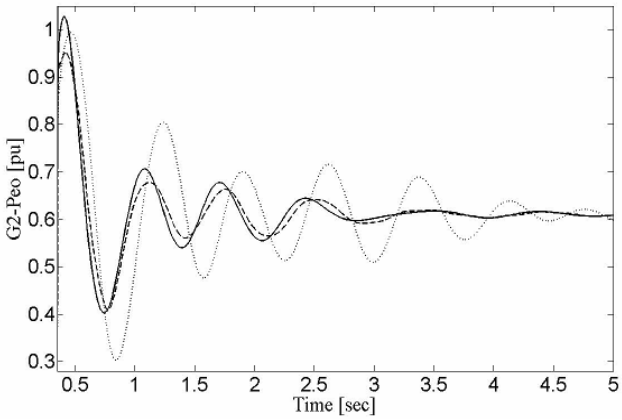

Fig.15 Fault on bus B4 , real power of generator G2.

6.2 Short circuit in bus B5

The method-2 gives stronger damping than method-1 for G1 and G2 (Fig. 16,17).

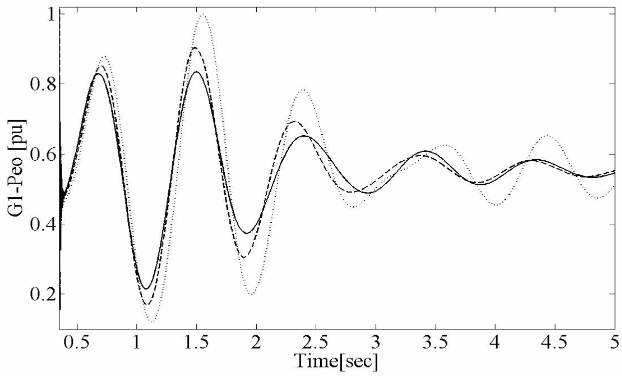

Fig. 16 Fault on bus B5, real power of generator G1.

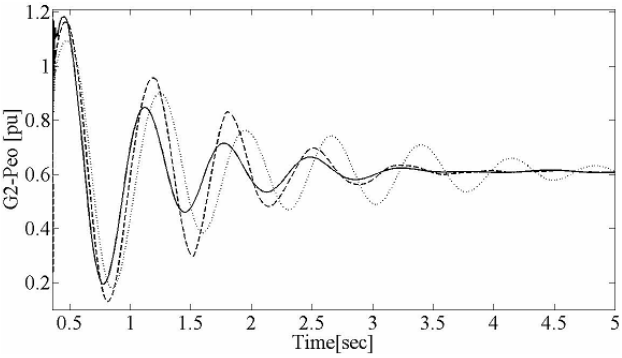

Fig.17 Fault on bus B5, real power of generator G2.

6.3 Short circuit in bus B6

The method-2 gives stronger damping than method-1 for G1, but an considerable increase in the amplitude of the first and second swings for G2 with faster damping (Fig. 18,19).

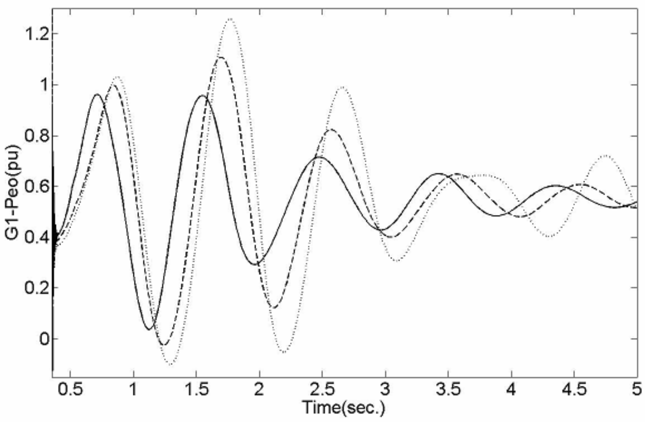

Fig. 18 Fault on bus B6,real power of generator G1.

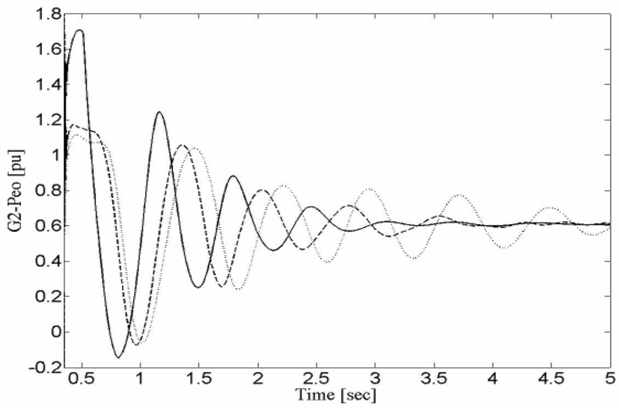

Fig. 19 Fault on bus B6,real power of generator G2.

6.4 Short circuit in bus B7

The method-2 gives slightly weaker damping than method-1 for G1, but weaker first and second swings for G2. (Fig. 20,21)

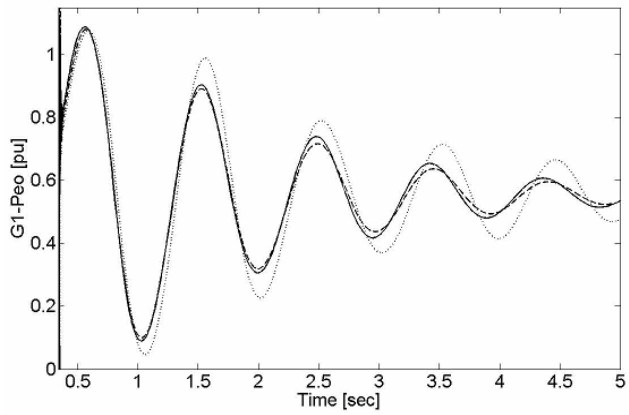

Fig.20 Fault on bus B7 and real power of generator G1.

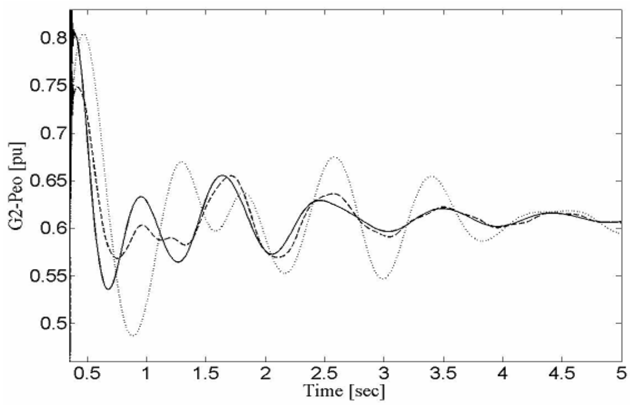

Fig.21 Fault on bus B7 and real power of generator G2.

6.5 Short circuit in bus B8

The method-2 gives stronger damping than method-1 for G1 and G2 (Fig. 22,23)

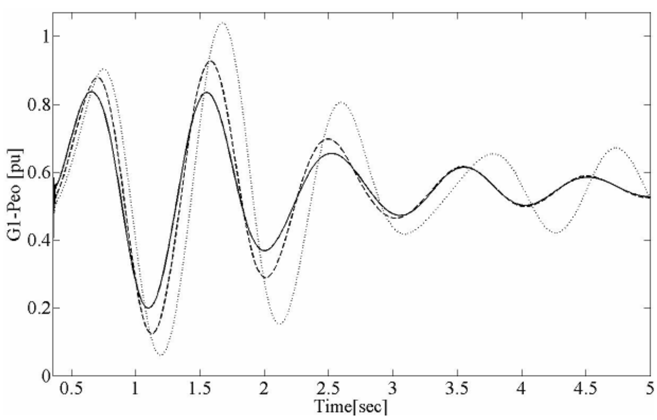

Fig.22 Fault on bus B8 and real power of generator G1.

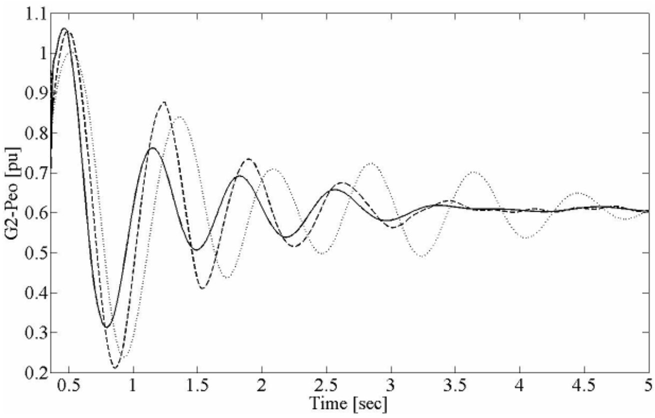

Fig.23 Fault on bus B8 and real power of generator G2.

6.5 Voltage Oscillations in Bus B6

The Voltage oscillations are well damped with method-2 and voltage drop is fastly reach to steady state value as Fig. 24.

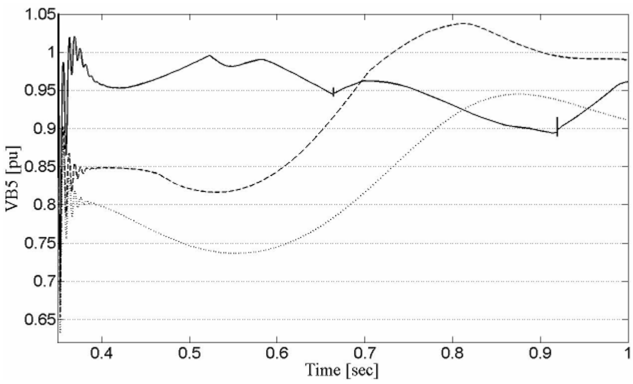

Fig. 24 Fault on bus B6 and voltage at bus B5.

6.6 Manual voltage injection reference

The series converter operates in manual voltage injection mode. The reference values of injected voltages Vdref and Vqref are used to synthesize the converter voltage. The simulations of two method with MATLAB , Vq in-quadrature with U_b controls active power and Vd in-phase with U_b controls reactive power.Whereas, MATLAB uses the model of UPFC with shunt before series part , so the U_b substituted by input voltage U_a, but results are similar. (Fig. 25,26)

The references of series injected voltages and shunt injected current are calculated and applied to the control system of UPFC by method-2.

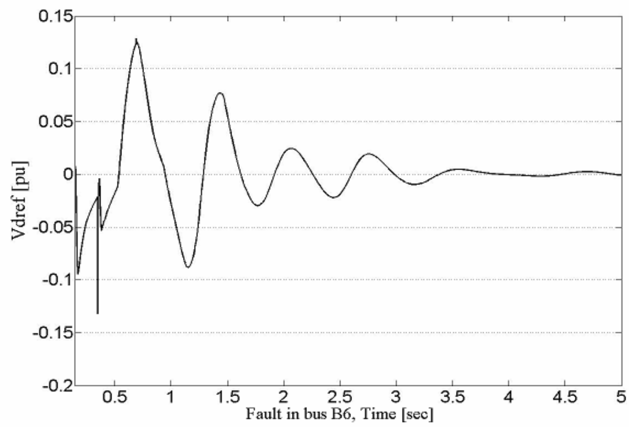

Fig. 25 Reference value of direct-axis injected voltage (pu) of UPFC.

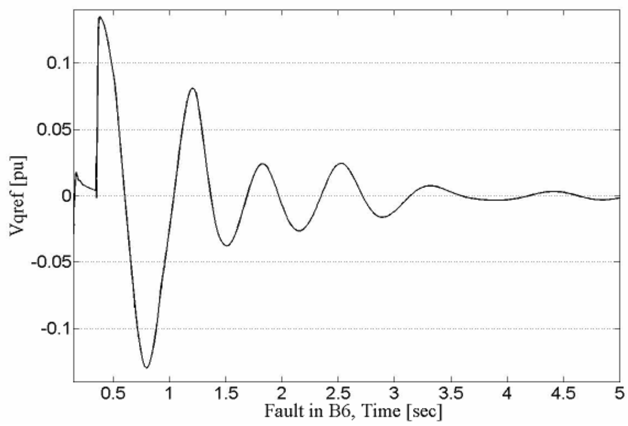

Fig. 26 Reference value of quadrature-axis injected voltage (pu) of UPFC.

6.7 Oscillation Damping in Different Fault Clearing Times

Improving transient stability using different fault duration times (100,150,200msec) by method-2 are given in Figs.27,28.

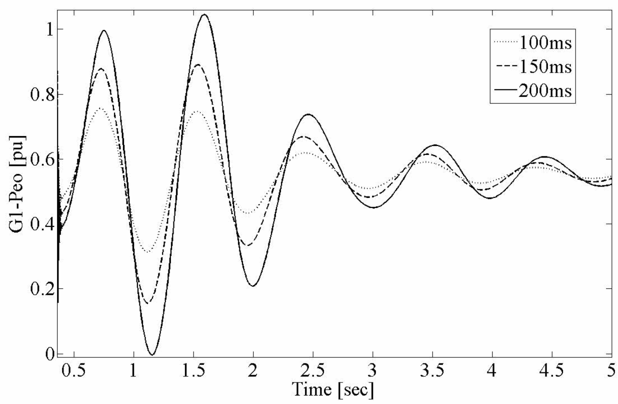

Fig.27 Fault on bus B6 and real power of generator G1.

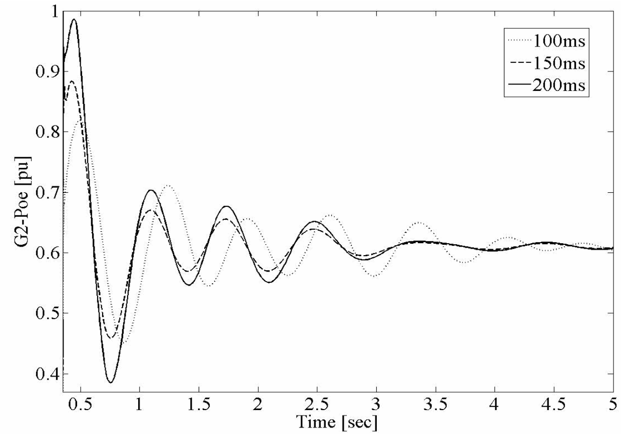

Fig.28 Fault in bus B4 and real power of generator G2.

7 Conclusion

In this paper two control strategies for supplementary stabilizing loop of UPFC has been derived using the nonlinear power system model.
The input signals of controllers, using the local variables of power system. The local control improves transient stability and achieves good damping of power and voltage oscillations if both the series and the shunt branch of UPFC are controlled.
The paper has presented a comparsion between two methods with UPFC for first swing transient stability and oscillations damping. The advantages of these two methods are using the local variables of system and offer better transient stability and fast oscillations damping.
Therefore in most cases ,the direct Lyapunov method gives better stability and damping results than state-variable control method.
In view of voltage oscillations , the Lyapunov method is better the other because of shunt part help for voltage regulation. Single-phase and two-phase to ground faults and increasing of loads have similar results.
Further damping of rotor and power swings due to both control strategies is much stronger than for the uncontrolled case for different fault Conditions (different fault clearing times and different fault locations).

References:

[1] Machowski, J., Bialek, J., Bumby, J.R. : " *Power system dynamics and stability* " (John Wiley ,UK ,1997)

[2] Hingorani N.G., Gyugyi L. :"*Understanding FACTS: Concepts and technology of flexiable AC transmission systems*" , IEEE Press Inc., New York 2000.

[3] M. Januszewski, J. Machowski and J.W. Bialek:"Application of the direct Lyapunov method to improve damping of power swings by control of UPFC ",*IEE Proc. Gener. Transm. Distrib.*,Vol. 151, No. 2 , March 2004,pp.252-260

[4] E. Gholipour and S. Saadate:"Improving of Transient Stability of Power Systems Using UPFC",*IEEE Trans. On Power Delivery*,Vol.20, No.2 , April 2005

[5] Gyugyi, L.," Unified power flow controller concept for flexible AC transmission systems ",*IEE Proc. Gener. Transm. Distrib.*, 1992, No. 139, pp.323-331

[6] M.H. Haque ," Damping improvement by FACTS devices: A comparison between STATCOM and SSSC ", *Elsevier, Elec. Power Systems Research*, No.76, pp.865-872, 2006

[7] K. K. Sen, " Unified Power Flow Controller: Theory, Modeling and Applications ",*IEEE Trans. On Power Delivery*, vol. 13 ,No. 4, pp.1453-1460, October 1998

[8] Kundur, P., " *Power System Stability and Control* ", McGraw-Hill, New York ,1994.

[9] R. Mihalic , "Improvement of transient stability using unified power flow controller ", *IEEE Trans. Power Delivery*, vol.11 , no. 1, pp. 485-492, Jan. 1996

[10] E. Gholipour and S. Saadate:"A new method for improving transient stability of power Systems by using UPFC",*Proc. European Power Electronics*, Toulouse, France , Sep. 2003

[11] A. Nabavi-Niaki and M.R. Iravani:"Steady-state and dynamic models of unified power flow controller (UPFC) for power sytem studies", *IEEE Trans. Power Systems*, vol. 11 ,no. 4, pp.1937-1943, Nov. 1996

[12] Ismail Musirin, Nur D.M. Radzi, M.M. Othman , M.K. Idris and Titak K.A. Rahman: "Voltage Profile Improvement Using Unified Power Flow Controller via Artificial Immune System ", *WSEAS Transactions on Power Systems*, Issue 4,Vol. 3 , pp.194-204 , April 2008

[13] S.N. Dhurvey and V.K. Chandrakar: " Performance Comparsion of UPFC in Coordination with Optimized POD and PSS On Damping of Power System Oscillations ", *WSEAS Transactions on Power Systems* , Issue 5 , Vol. 3 , pp.287-299 , May 2008.
[14] V.K.Chandrakar, A.G.Kothari:" RBFN Based UPFC for Improving transient stability Performance, *WSEAS Transactions on Power Systems,* Issue 1 , Vol. 2 , pp.1-6 , Jan 2007.
[15] K.R. Padiyar , K. Uma Rao : " Modeling and Control of UPFC for Transient Stability " , *Elsevier, Electrical Power Energy Systems* , NO.21, pp. 1- 11, 1999.
[16] M.Ghandhari, "*Control Lyapunov Functions: A Control Strategy For Damping of Power Oscillations in Large Power Systems* , PhD Thesis , Royal Institute of Technology , Sweden , 2000.
[17] N.Tambey and M.L. Kothari: " Damping of power system oscillations with unified power flow controller (UPFC) " , *IEE Proceeding* ,Vol. 150, No. 2, March 2003.

Biographies:

Ahad Kazemi was born in Tehran, Iran, in 1952. He received his M.Sc. degree in electrical engineering from Oklahoma State University, U.S.A in 1979. He is currently an associate professor in electrical engineering department of Iran University of Science and Technology, Tehran, Iran. His research interests are reactive power control, power system dynamics, stability and control and FACTS devices.

Farrokh Mahamnia was born in Tabriz, Iran, in 1969. He is currently a M.Sc. student at the department of electrical engineering at the Iran University of Science and Technology, Tehran, Iran. His research interests are power system dynamics, stability and control and FACTS devices.