GPS BASED DIGITAL CONTROL FOR POWER SYSTEMS WITH UPFC EFFECT COSIDERATIONS

Alireza Sanai Sabzevary

Mashhad Institute of Technology, Mashhad P.O. Box,91735-171,Iran
alirezasanai@yahoo.com

Abstract — **In this paper for a multi-machine power system equipped with Unified Power Flow Controller (UPFC) an observer based digital control is designed. The Unified Power Flow allocation in the system is determined by minimization of a performance index which is calculated by offline simulations. Global Positioning System (GPS) data transmission facilities are used to synchronize global data of the system to produce an observer based digital control input for the UPFC.**

Index Terms **— Power Systems, UPFC Allocation, GPS, Digital Control.**

I. INTRODUCTION

With the development of modern power systems and the ever increasing demand for electric energy, the electric power industry is facing great challenges to meet the load demand with high reliability and minimum cost. Power system stability analysis and control are among the most important issues studied by many researchers. The ability of power systems to maintain stability and to provide high quality power supply depends on the controls and application of new technologies to the existing power systems. One of these new technologies is application of GPS data synchronization facilities to the power system. Application of GPS data facilities to the power systems results in integration and coordination of control schemes, protective relaying and state estimation with high accuracy [1]-[5]. Furthermore, application of these technologies results in smart substations with self recovery characteristics and less maintenance cost and space needed. On the other hand with the advancement of power electronics FACTS devices are introduced to the power systems. Upon the application of FACTS devices the transmission lines could be loaded up to their thermal limits [6]-[9]. Therefore the gap between stability limits and thermal limits of transmission lines are considerably reduced. Among FACTS devices it said that UPFC is one of the most powerful and user friend to the power systems. However, optimal allocation of UPFC is one of the main issues in the application of FACTS devices, which has been studied by many researchers [10]-[12]. In this paper for a multi-machine power system an observer based digital control is designed [13]-[14], GPS data facilities are used to synchronize instantaneous data of each generating unit, transmission facilities etc.. The UPFC allocation is determined based on the dynamic behavior of the overall system. For this purpose an index which is directly related to the UPFC control effort under sever fault conditions is introduced. Through numerical simulations the most severe fault condition for the system is found. Then the UPFC is allocated in different places of the system and the index is calculated. The UPFC allocation is determined based on the minimization of the index. It is shown that the proposed method can stabilize the system using global information of the system under sever fault conditions. Since the control is observer based there is no need to measure all the states.

II. UNIFIED POWER FLOW CONTROLLER

Unified Power Flow Controller (UPFC) is a FACTS device which can control the power transmission line reactance and phase angle. Fig. 1 shows the one line diagram of UPFC. It consists of a parallel and a series transformer plus a self-excited inverter and GTO (Gate Turn Off Thyristor) control. The secondary voltage of the series transformer is controlled by using the voltage generated with the self-excited inverter. The output of UPFC, $V_U \angle \delta_U$ can influence the voltage and phase angle of the bus near which it is installed.

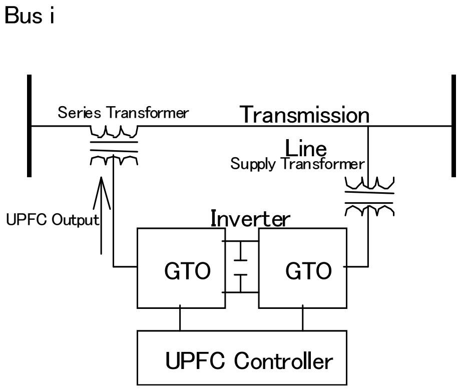

Fig.1. one line diagram of UPFC

The output of UPFC here is modeled as a voltage influencing the bus voltage near at which it is installed.

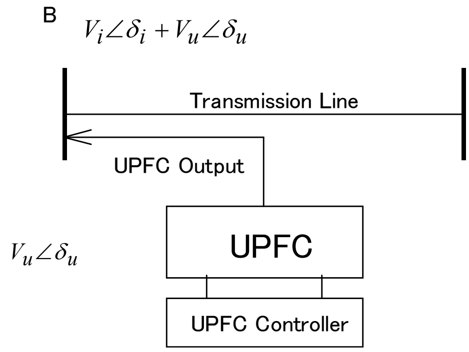

Fig.2. UPFC equivalent model

III. POWER SYSTEM WITH UPFC

A four machine 11-bus power system model shown in Fig. 3, is considered. The system is equipped with UPFC. The UPFC consists of a shunt and a series branch which can absorb or generate active and reactive power. The main role of UPFC is controlling the reactance and power flow of the system, which in turn increases the damping of system oscillations, transmission line capabilities and overall system stability margins.

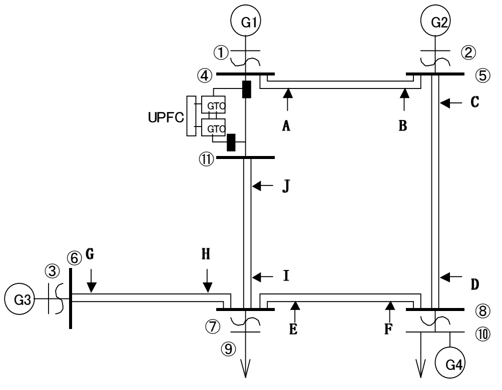

Fig.3. Four machine power system with UPFC

The differential equations describing the dynamics of the *i* th. generator are given by eqs. (1)-(8) , see [12] for more details.

$$\dot{\delta}_{(i)} = \omega_0(\omega_{(i)} - 1) \tag{1}$$

$$\dot{\omega}_{(i)} = \frac{P_{m(i)} - P_{e(i)} - D_{(i)}(\omega_{(i)} - 1)}{M_{(i)}} \tag{2}$$

$$\dot{E}'_{q(i)} = \frac{E_{fd(i)} - E'_{q(i)} - (X_{d(i)} - X'_{d(i)})I_{d(i)}}{\tau'_{do(i)}} \tag{3}$$

$$\dot{E}_{fd(i)} = -\frac{E_{fd(i)} - E_{fd0(i)} + K_{a(i)}(V_{t(i)} - V_{t0(i)})}{\tau_{a(i)}} \tag{4}$$

$$V_{d(i)} = X_{q(i)}I_{q(i)} \tag{5}$$

$$V_{q(i)} = E'_{q(i)} - X'_{d(i)}I_{d(i)} \tag{6}$$

$$V_{t(i)} = \sqrt{V_{d(i)}{}^2 + V_{q(i)}{}^2} \tag{7}$$

$$P_{e(i)} = V_{d(i)}I_{d(i)} + V_{q(i)}I_{q(i)} \tag{8}$$

It is clear from these equations that the $\delta_{(i)}$, $\omega_{(i)}$, $E'_{q(i)}$, and $E_{fd(i)}$ are dependent on $I_{d(i)}$ and $I_{q(i)}$. The terminal voltage of the i th machine is given by.

$$\overline{V} = e^{j\delta}E'_q - jX'_d\overline{I} + (X_q - X'_d)e^{-j(\frac{\pi}{2}-\delta)}I_q \tag{9}$$

where

$\overline{V}$: terminal voltage (row vector, phasor)
$\overline{I}$: generator current (row vector, phasor)
E'_q, I_q : row vector, phasor
$e^{j\delta}$, X'_d, $(X_q - X'_d)$, $e^{j(\pi/2-\delta)}$: diagonal matrix

As it is shown in Fig. 3. the UPFC is located near the p th generator, The UPFC output $V_U\angle\delta_U$ influences the terminal voltage of the p th generator. Therefore, the generator terminal voltage considering UPFC effects can be written as below

$$\overline{V} + \overline{V}_U = e^{j\delta}E'_q - jX'_d\overline{I} + (X_q - X'_d)e^{-j(\frac{\pi}{2}-\delta)}I_q + \overline{V}_U$$

$$\overline{V}_U \equiv \begin{bmatrix} 0 & \cdots & 0 & \underset{(i=p)}{V_U e^{j\delta_U}} & 0 & \cdots & 0 \end{bmatrix}^T \tag{10}$$

Generator current considering UPFC effect is

$$\overline{I} = \overline{Y}_R(\overline{V} + \overline{V}_U) \tag{11}$$

where

$\overline{Y}_R$: reduced scale admittance matrix

with some mathematical manipulation from eq. (10) and (11) the equation for the current of the i th generator can be derived as follows

$$\overline{I} = \overline{Y}e^{j\delta}E'_q + \overline{Y}(X_q - X'_d)e^{j(\frac{\pi}{2}-\delta)}I_q + \overline{Y}\overline{V}_U \tag{12}$$

$$\overline{Y} \equiv \left(\overline{Y}_R^{-1} + jX'_d\right)^{-1}$$

$$\begin{aligned} \overline{I}_{(i)} = &\sum_{\substack{k=1\\(k\neq p)}}^{n} \overline{Y}_{(i,k)}\left\{e^{j\delta_{(k)}}E'_{q(k)} + (X_{q(k)} - X'_{d(k)})e^{-j(\frac{\pi}{2}-\delta_{(k)})}I_{q(k)}\right\} \\ &+ \overline{Y}_{(i,p)}\left\{e^{j\delta_{(p)}}E'_{q(p)} + (X_{q(p)} - X'_{d(p)})e^{-j(\frac{\pi}{2}-\delta_{(p)})}I_{q(p)} + \overline{V}_{U(i)}\right\} \end{aligned} \tag{13}$$

$$I_{d(i)} = \mathrm{Re}\left(\bar{I}_{(i)} e^{j(\frac{\pi}{2}-\delta_{(i)})} \right)$$

$$= \sum_{\substack{k=1 \\ (k\neq p)}}^{n} Y_{(i,k)}\left[-S_{(i,k)}E'_{q(k)} + (X_{q(k)} - X'_{d(k)})C_{(i,k)}I_{q(k)} \right]$$
$$+ Y_{(i,p)}\left[-S_{i(p)}E'_{q(p)} + (X_{q(p)} - X'_{d(p)})C_{(i,p)}I_{q(p)} + V_{U(i)}S_{U(i)} \right] \tag{14}$$

$$I_{q(i)} = \mathrm{Im}\left(\bar{I}_{(i)} e^{j(\frac{\pi}{2}-\delta_{(i)})} \right)$$

$$= \sum_{\substack{k=1 \\ (k\neq p)}}^{n} Y_{(i,k)}\left[C_{(i,k)}E'_{q(k)} + (X_{q(k)} - X'_{d(k)})S_{(i,k)}I_{q(k)} \right]$$
$$+ Y_{(i,p)}\left[C_{(i,p)}E'_{q(p)} + (X_{q(p)} - X'_{d(p)})S_{(i,p)}I_{q(p)} + V_{U(i)}C_{U(i)} \right] \tag{15}$$

$$\begin{aligned}
\bar{Y}_{(i,k)} &\equiv Y_{(i,k)}e^{j\phi_{(i,k)}} \\
S_{(i,k)} &\equiv \sin\left(-\delta_{(i)} + \delta_{(k)} + \phi_{(i,k)} \right) \\
C_{(i,k)} &\equiv \cos\left(-\delta_{(i)} + \delta_{(k)} + \phi_{(i,k)} \right) \\
S_{U(i)} &\equiv \sin\left(-\delta_{(i)} + \phi_{(i,p)} + \delta_{u(i)} \right) \\
C_{U(i)} &\equiv \cos\left(-\delta_{(i)} + \phi_{(i,p)} + \delta_{u(i)} \right)
\end{aligned}$$

The relation between UPFC output $V_U \angle \delta_U$ and the i th. Generator current is derived as follows

$$V_U \equiv \sqrt{\left(V_{d0(p)} + X_{q(p)}\Delta I_{qU}\right)^2 + \left(V_{q0(p)} - X'_{d(p)}\Delta I_{dU}\right)^2} - V_{t0} \tag{16}$$

$$\delta_U \equiv \Delta\delta_U \tag{17}$$

where $V_{d0(p)}$, $V_{q0(p)}$, V_{t0} represent initial values. The nonlinear differential equations describing the generator dynamics are linearized at an operating point. The continous time linear full state feed back control of the power system in a compact form can be written as follows:

$$\begin{cases} \dot{x}(t) = A_0\, x(t) + B_0\, u(t) \\ y(t) = C_0\, x(t) + D_0\, u(t) \end{cases} \tag{18}$$

where

$$x(t) = \left[\cdots \quad \Delta\delta_{(i)} \quad \Delta\omega_{(i)} \quad \Delta E'_{q(i)} \quad \Delta E_{fd(i)} \quad \cdots \right]^T$$

$$u(t) = \left[\Delta I_{dU} \quad \Delta I_{qU} \quad \Delta\delta_U \right]^T$$

$$y(t) = \left[\cdots \quad \Delta\omega_{(i)} \quad \Delta E_{fd(i)} \quad \Delta P_{e(i)} \quad \Delta V_{t(i)} \quad \Delta I_{t(i)} \quad \cdots \right]^T$$

$I_{t(i)}$: magnitude of Generator current [pu]

A_0 , B_0 , C_0 , D_0 are power system nominal matrices. Eq. (18) is disceretised with a sampling time of 10ms.

$$\begin{cases} x[i+1] = A\,x[i] + B\,u[i] \\ y[i] = C\,x[i] + D\,u[i] \end{cases} \tag{19}$$

IV. DIGITAL CONTROL THEORY

Continous linear system can be approximated by a discrete time linear system provided that the sampling time is considerably small [13]. For power system control in practice the control is designed for a continous time system and then disceretiized with a suitable sampling time.

In equation (18), $u[i]$ is the control input, where for a linear optimal control design it is defined as follows

$$u[i] = -Kx[i] \tag{20}$$

K is the gain matrix. To construct the full state feedback power system control all of the states should be available in real time. However, the delay of global information transmitted to UPFC and the delay for the measurement and transmission of data should be considered in that case. The control input can be calculated as follows.

$$\begin{aligned} u[i] = -KA^L x[i-L] - KA^{L-1}Bu[i-L] - KA^{L-2}Bu[i-1] - \cdots \\ \cdots - KABu[i-2] - KBu[i-1] \end{aligned} \tag{21}$$

where K is the state-feedback gain matrix when there is no delay considered. L is the delay in terms of sampling time.

Design of Estimator- To design a digital power system control all the states should be measured. Among the states describing the power system under study the states $\delta_{(k)}$ and $E'_{q(k)}$ cannot be measured easily. Therefore an estimator is designed to estimate these states using measurable states. The descrete time estimator used here has the following form

$$\begin{bmatrix} x_1[i+1] \\ \hat{x}_2[i+1] \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1[i] \\ \hat{x}_2[i] \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u[i] \tag{22}$$

$$\begin{bmatrix} x_1[i] \\ y_2[i] \end{bmatrix} = \begin{bmatrix} I & 0 \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} x_1[i] \\ \hat{x}_2[i] \end{bmatrix} + \begin{bmatrix} 0 \\ D_2 \end{bmatrix} u[i] \tag{23}$$

Where

$x_1[i]$:synchronized states ($\omega_{(k)}$, $E_{fd(k)}$)
$\hat{x}_2[i]$:estimated states ($\delta_{(k)}$, $E'_{q(k)}$)
$y_2[i]$:measured states ($P_{e(k)}$, $V_{t(k)}$, $I_{t(k)}$)

then we have.

$$\hat{x}_2[i+1] = A_{22}\hat{x}_2[i] + (A_{21}x_1[i] + B_2u[i]) \tag{24}$$

$$y_2[i] - C_{21}x_1[i] - D_2u[i] = C_{22}\hat{x}_2[i] \tag{25}$$

$$z_2[i] = A_{22}\hat{x}_2[i-1] + (A_{21}x_1[i-1] + B_2u[i-1]) \tag{26}$$

$$\hat{x}_2[i] = z_2[i] + M\left(y_2[i] - C_{21}x_1[i] - D_2u[i] - C_{22}z_2[i]\right) \tag{27}$$

where, M is estimator gain matrix and $z_2[i]$ is temporary estimated states

V. GPS DATA FACILITIES

With the advances in satellite and microprocessor technologies, Phasor Measurement Units, PMUs, with data recording capabilities can be used to assess the impact of disturbances over a wide region of the system. PMUs measure instantaneous voltages and currents at very fast sampling rates (240-10,000 Hz). They are capable of calculating quantities such as the system frequency, RMS values of voltages, apparent impedances, and active reactive power flows from the measured raw data, and storing them at much lower sampling rates (10-50 Hz). The receiver unit of Generator k ($k = 1,\cdots,n$) in each sampling time receives measurement $y_{(k)}(iT) = y_{(k)}[i]$ ($x_1[i]$ and $y_2[i]$) in generator k, which is transmitted to the UPFC controller using a special high-speed telecommunication line by mT [sec](m times the sampling time T [sec]). Therefore, measurement $y[i-m]$ ($x_1[i-m]$ and $y_2[i-m]$) in all Generators of the m sample delay becomes latest already-known information in the UPFC controller at present time (iT [sec]). The control input $u[i-1]$ can be constructed using this information. The nominal system matrices A_0, B_0 and C_0 in (18), are determined by using the states, measurements, GPS receivers outputs and various constants of the electric power system. The UPFC output $V_U[i]\angle\delta_U[i]$ is determined using control input $u[i]$ which the feedback and observer gain matrices have been calculated offline. Fig. 4 shows flow chart of the process. However, application of smart sensors with failure report capabilities, protective coordination and offline contingency simulations could result in security measures to guarantee operation of the system under abnormal conditions

VI. UPFC ALOCATION ALGORITHM

For UPFC allocation different strategies are proposed. The main purpose of these strategies is to improve the system behavior during severe faults. In this paper the optimal UPFC allocation, from stability point of view is proposed as follows:

Step-1: allocate the UPFC to the ith generator

Step-2: for a three phase to ground fault followed by one circuit line opening near each bus integrate the UPFC control input.

Step-3: repeat steps 1-2 for j times

Step-4: find the maximum control input as follows

$$S_{ge} \ \therefore\ \ MAX(i,j) = \int_0^t \Delta\delta_u(i,j)$$

Step-5: repeat step 1-4 for i times(i, is the number of buses).

Step-6: find the minimum control input among all maximum control inputs i.e. find *MIN(MAX(i,j)),* and allocate the UPFC near the ith. bus.

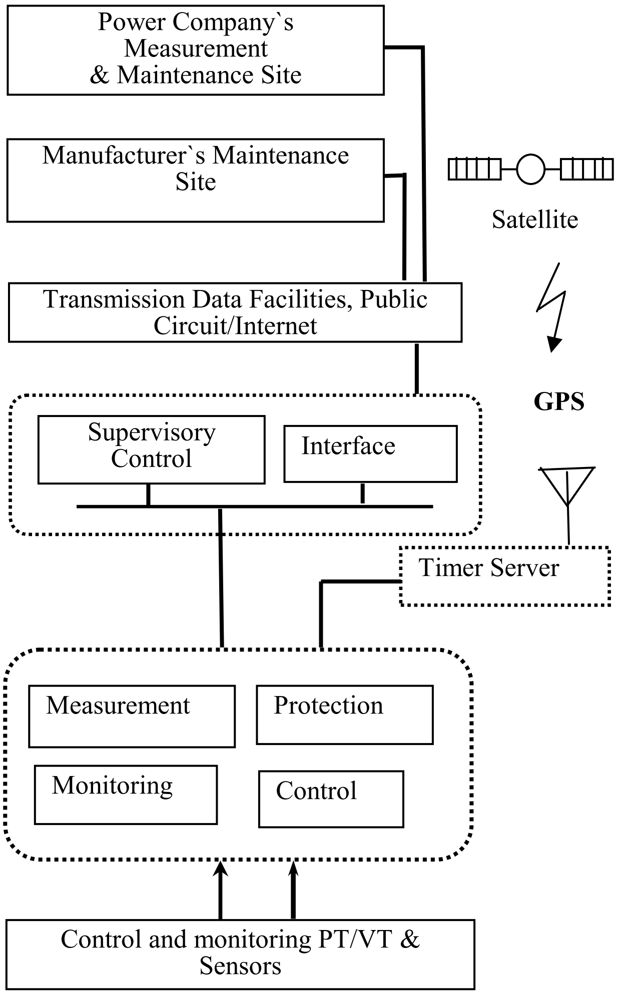

Fig. 4: GPS data facilities

VI. SIMULATIONS

A 4-machine 11-bus power system model equipped with UPFC is used for numerical simulations. The main purpose of simulations is first to show the effectiveness of the proposed method with the application of the GPS data facilities, second to investigate the effects of UPFC location on important system parameters and system transient performance.

Fault scenario

For all simulation cases fault duration of 100 ms after which the faulted line is opened and re-closed after one second is carried out. The simulation is run for different fault locations as shown in Fig. 3 with UPFC allocated near each generator terminal. To show the real system behavior the original nonlinear equations of the system with UPFC are used for numerical simulations.

UPFC allocation

For optimal allocation of UPFC several factors should be considered in practice. However, from stability point of view, the algorithm for UPFC allocation is followed and the results are shown in table-1. It is clear that from control effort point of view for sever fault conditions, the best place for UPFC to be allocated is near terminals of generator 3 for which the maximum performance index S_{ge} (rad) representing UPFC control effort is minimized.

Table 1: index S_{ge} (rad) for A to J fault location

	UPFC installed near terminals of G1	UPFC installed near terminals of G2	UPFC installed near terminals of G3	UPFC installed near terminals of G4
A	21.2053	22.2170	21.6832	21.7356
B	20.9979	22.6901	21.6255	21.6566
C	24.6523	23.5649	24.3145	24.1232
D	24.5693	23.3941	24.3476	24.3475
E	20.3455	23.4954	21.5676	21.4923
F	20.3788	24.1173	21.5788	21.5089
G	20.8119	24.8677	22.4345	22.6213
H	20.8365	25.2165	22.7660	22.8856
I	23.7134	26.1183	23.7518	25.1378
J	24.2107	26.7787	23.8743	24.1299

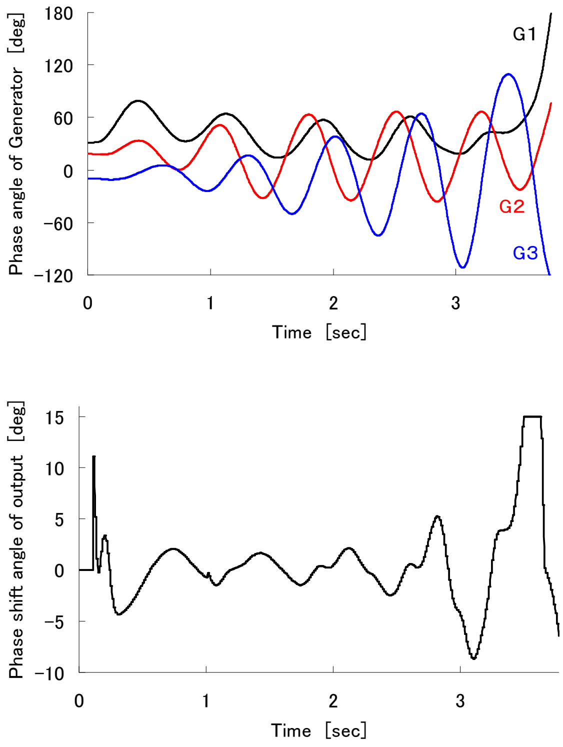

Fig. 5: System with UPFC control input based on local data

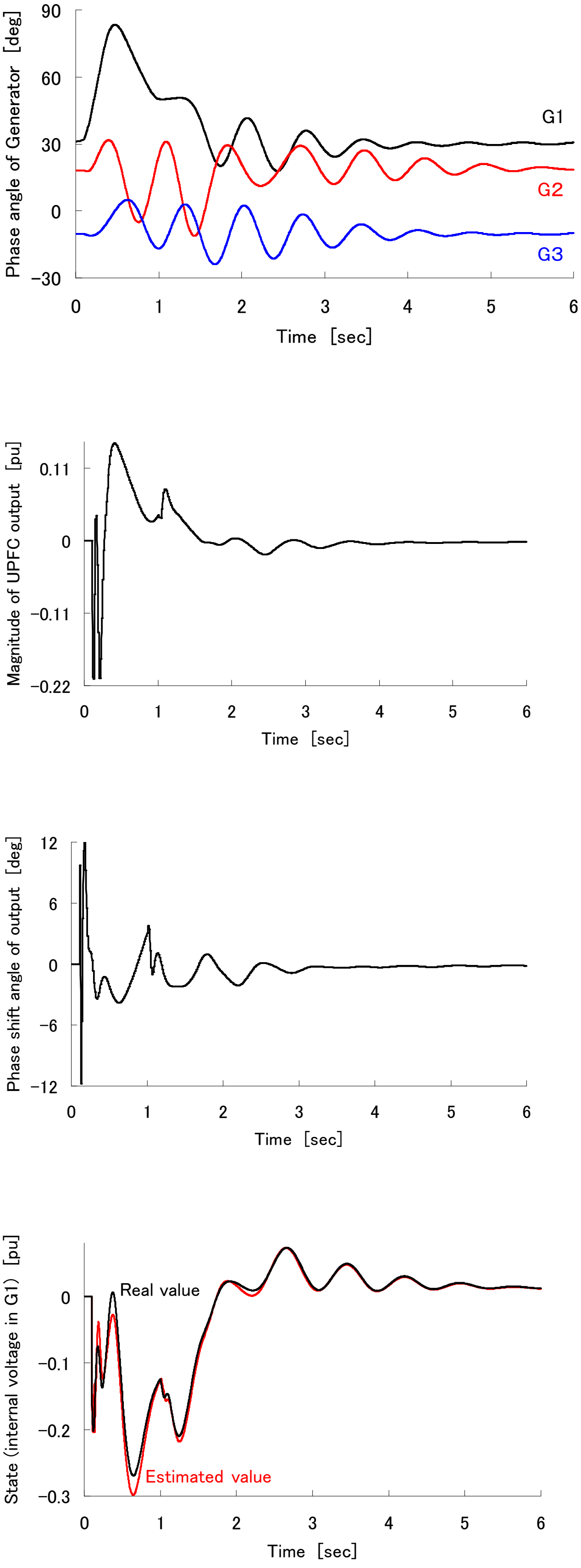

Fig. 6: System with UPFC control input based on GPS global data

VI. CONCLUSIONS

In this paper, GPS data facilities have been used to design a digital control for power systems with UPFC. An UPFC allocation method with transient stability consideration is introduced. The optimal UPFC allocation is carried out offline. Since the control is observer based there is no need all states to be measured. The effectiveness of the proposed control method is verified by nonlinear simulations using a 4- machine 11-bus electric power system model with UPFC for different fault conditions. It is shown that UPFC control input calculated based on global data of the system can stabilize the system under sever fault conditions. While application of local data for UPFC control input calculation fails to stabilize the system. Data transmission delay is considered during the simulations. Fig. 5-6 shows numerical simulation results. With the advancement of synchronous measurement technology using GPS, the calculation speed of the computer and telecommunication technology it is expected that UPFC's power flow control can provide the power systems with a promising conditions, which in turn will enlarge the stability margins of the existing power systems and in this way some part of ever increasing electric power demand will be covered.

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ALIREZA SANAI SABZEVARY

Was born in Iran on June 1953. He received the B.E, M.E. and PhD in Electrical Engineering from Tabriz University, Iran and Waseda University, Tokyo, Japan in 1973, 1993 and 1997 respectively. Presently he is an associate professor at Mashhad Institute of Technology, Iran and a visiting researcher at Waseda University Department of Electrical Engineering and Bioscience. His research interests include power system stability, control, protection, GPS application to power systems and e-learning.