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European Journal of Advances in Engineering and Technology, 2018, 5(2): 122-127

Research Article ISSN: 2394 - 658X

Dynamic Mathematical Modeling of Unified Power Flow Controller Integrated into Single Machine Power System for Dynamic State Estimation

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ABSTRACT

Flexible AC Transmission System (FACTS) is a progressive technology that has allowed power system utilities to make the most out of the existing grid and control the governing parameters that affect the power flow and/or stability of the transmission and power system broadly. One of the most important FACTS devices is Unified Power Flow Controller (UPFC) which provides fast-acting reactive power compensation on high-voltage electricity transmission networks. The aim of this paper is to discuss in detail the dynamic model of UPFC. It is integrated to a Single Machine Infinite Bus system (SMIB) for state estimation. Power system State Estimation is important for efficient control and operation the system. State Estimator is a computer program which processes the available measurements to obtain the best values of state variables. Conventional State Estimation is static in nature. Static state estimation takes system snap-shots and hence the dynamics of system are not captured efficiently. Thus Dynamic State Estimation (DSE) is becoming more appropriate. It efficiently processes the data captured at smaller sampling time to obtain state vectors. Using the information about state vector at time instant k, a Dynamic State Estimator can predict the state vector at next time stamp k+1. In the present work, results for estimation of system dynamic states as well as UPFC dynamic states are presented using the Extended Kalman filter method.

Keywords: Dynamic State estimation, FACTS, UPFC, Extended Kalman filter, Power system operation

INTRODUCTION

State estimation is an essential tool used by power system operators for real time analysis. State estimation can provide flexibility to operators in decision-making if an emergency occurs. Accurate knowledge of system state is necessary to avoid system failures and blackouts. State estimation results are used as inputs to various power system operations. State estimator is a computer program which processes the available power system measurements to obtain the best values of state variables. Measurements such as voltage, frequency, megawatt, Mvar, breaker status are available from conventional SCADA/EMS systems. State estimator uses these data to compute load angles of different power system buses. A Conventional SCADA has been used to monitor the power grid. However, there are limitations to it like lack of time stamped data, lack of synchronization, modeling errors, communication failures, random noise etc. Additionally, its measurement update rates are 2-10 seconds as reported in [1]. This leads to state estimation carried out considering snap-shots of the system. For the duration of measurement update system is assumed to be static. Thus conventional state estimation is static. Static State estimation does not incorporate the system dynamics which arises due to load changes and/or transients. Load variations are compensated by changing the generation which results into change in power flows through line and injections at buses. The time constants for transient are faster than the rate at which conventional SCADA captures data/measurements. The dispatching and controlling centre cannot know the dynamic operating states of the system from the Static State estimation results. Thus a change in the available estimation process is required. This requirement is met by Dynamic State Estimators (DSE).

A Dynamic State Estimator estimates the dynamics system states like generator rotor angle, speed or generator internal voltages unlike conventional states like bus voltage and angle as in [2]. Such parameters can be helpful to take predictive actions using generator controls in case of incipient emergencies. DSEs use the dynamic mathematical modeling of the system to include true system dynamics. The algorithms used in DSE are feasible to estimate state variables at much higher measurement sampling rates than conventional SCADA measurement update rate. The availability of this fast data is from the Phasor Measurement Units (PMUs) which are the backbone of DSE implementation. PMU data update rate is as high as 240 frames per second [3].

DSE techniques are broadly classified into Kalman filter-based, Robust dynamic techniques, Square root filter-based and Artificial Intelligence-based techniques as reported in [4]. Readers are encouraged to read [4-5] for more insight on these techniques. Kalman filter based are most widely used due to easier mathematical implementation and added prediction ability at next time stamp along with filtration of noise. In this paper the non-linear extension of Kalman filter; Extended Kalman filter is used and is subsequently described.

Present work provides an insight into the Dynamic State Estimation (DSE) with inclusion of Flexible AC Transmission Systems; in particular, Unified Power Flow Controller (UPFC). With growing importance of FACTS devices, it needs to be integrated with the process of power system state estimation for accurate operation and control. Inclusion of FACTS device increases the practical relevance of state estimation and also provides parameters for controller setting for the FACTS device connected. This paper deals with dynamic modeling of UPFC into an SMIB system and application of Extended Kalman filter for DSE. The following section discusses the state estimation for a power system with UPFC. Subsequent sections detail the dynamic model of UPFC which is typically needed for DSE.

CONVENTIONAL STATE ESTIMATION OF POWER SYSTEM WITH UPFC

One of the most important FACTS devices being used in power systems is Unified Power Flow Controller (UPFC). A Unified Power Flow Controller (or UPFC) is an electrical device for providing fast-acting reactive power compensation on high-voltage electricity transmission networks. The controller can control active and reactive power flows in a transmission line. The UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system. This device apparently is a universal controller for flexible, reliable and stable transmission system.

The most commonly used method for state estimation of power system with UPFC is Weighted Least Square as in [6-7]. Authors in [8] extended the analysis considering different coordinate systems like rectangular and polar. Recursive Least Squares iterative method is proposed in [9]. The sequential solution approach in [10] uses matrix reduction which gives mathematical advantage but it does not include the constraints which appear in presence of the FACTS device connected. Other methods such as Predictor-Corrector and Weighted Least Average are used in [11-12].

For all the discussed methods a defined set of measurements is taken considering a snap-shot of power system which shows that the estimation is static in nature. Thus if these methods are applied for dynamic state estimation it could take large time as well as memory. These methods also do not consider the dynamic modeling of the UPFC. In-order to perform dynamic state estimation of the system with UPFC, dynamic modeling of UPFC is the primary requirement. Conventional state estimation with UPFC is based on a static model of UPFC as described in the following subsection.

UPFC Static Model

UPFC is modeled as two voltage sources synchronized in such a way that one is connected in series and other in shunt. This model is sufficient for a steady-state or static analysis. Figure 1 shows a UPFC equivalent circuit commonly used for static state estimation.

The estimation process is modified to include the additional states of UPFC which are represented by the magnitude and angle of equivalent voltage nodes as shown in Figure 1. This means the dimension of the state vectors increases. Additional algebraic constraints are added by the real and reactive power flow through the UPFC controller as shown by Eqs (1-4).

$$P_{km}= V_k^2G_{kk}+V_kV_m\left(G_{km}\cos\left(\theta_k-\theta_m\right)+B_{km}\sin\left(\theta_k-\theta_m\right)\right)+V_kV_{cR}\left(G_{km}\cos\left(\theta_k-\theta_{cR}\right)+B_{km}\sin\left(\theta_k-\theta_{cR}\right)\right) +V_kV_{vR}(G_{km}\cos(\theta_k-\theta_{vR})+B_{km}\sin(\theta_k-\theta_{vR})) \quad (1)$$

$$Q_{km}=-V_k^2B_{kk}+V_kV_m\left(G_{km}\sin\left(\theta_k-\theta_m\right)-B_{km}\cos\left(\theta_k-\theta_m\right)\right)+V_kV_{cR}\left(G_{km}\sin\left(\theta_k-\theta_{cR}\right)-B_{km}\cos\left(\theta_k-\theta_{cR}\right)\right) + V_kV_{vR}\left(G_{km}\sin\left(\theta_k-\theta_{vR}\right)-B_{km}\cos\left(\theta_k-\theta_{vR}\right)\right) \quad (2)$$

$$P_{mk}=V_m^2G_{mm}+V_kV_m\left(G_{mk}\cos\left(\theta_m-\theta_k\right)+B_{mk}\sin\left(\theta_m-\theta_k\right)\right)+V_mV_{cR}\left(G_{mm}\cos\left(\theta_m-\theta_{cR}\right)+B_{mm}\sin\left(\theta_m-\theta_{cR}\right)\right) \quad (3)$$

$$Q_{mk}=-V_m^2B_{mm}+V_kV_m\left(G_{mk}\sin\left(\theta_m-\theta_k\right)-B_{mk}\cos\left(\theta_m-\theta_k\right)\right)+V_mV_{cR}\left(G_{mm}\sin\left(\theta_m-\theta_{cR}\right)-B_{mm}\cos\left(\theta_m-\theta_{cR}\right)\right) \quad (4)$$

Under steady-state conditions UPFC converters neither absorb real power nor supply with respect to each other. A loss-less converter operation is constrained by the Eqs (5-7).

$$P_{cR}=V_{cR}^2 G_{mm}+V_k V_{cR}\left(G_{km}\cos(\theta_{cR}-\theta_k)+B_{km}\sin(\theta_{cR}-\theta_k)\right)+VmV_{cR}\left(G_{mm}\cos(\theta_{cR}-\theta_m)+B_{mm}\sin(\theta_{cR}-\theta_m)\right) \quad (5)$$

$$P_{vR} = -V_{VR}^2 G_{vR} + V_k V_{vR}\left(G_{vR}\cos(\theta_{vR}-\theta_k) + B_{vR}\sin(\theta_{vR}-\theta_k)\right) \quad (6)$$

$$P_{vR} + P_{cR} = 0 \quad (7)$$

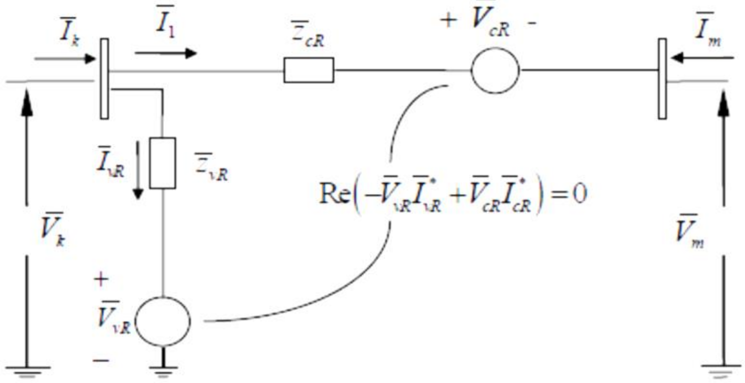

Fig.1 UPFC steady-state model

Since conventional state estimation is static in nature hence a steady-state equivalent voltage based model it sufficient. The duration at which measurement samples are taken does not consider the changes that a UPFC undergoes during transients. Hence state variables to be estimated are simplified to added voltage magnitude and angle. However, this model is not suitable at higher sampling rates used in DSEs. Fast changing dynamics of UPFC should be identified to represent actual power system dynamics. It is thus important to understand the difference in the steady-state model of UPFC and dynamic model of UPFC so it can be extended to carry out studies like dynamic state estimation, stability studies, etc.

UPFC DYNAMIC MODEL INTEGRATED TO SMIB FOR DSE

Basics of dynamic model of UPFC are given in [13-16]. There is no exchange of real power with the system if system losses are neglected under steady-state. This function is done by voltage control of DC link capacitor, which remains constant under steady-state. In case any transient or disturbance conditions; there is an exchange of energy with system which causes the DC link voltage to vary depending on the control signals of converters.

The dynamic model of UPFC which is a non-linear differential equation which describes variation of DC link voltage with the input control signals. If the resistance of transformers is neglected, the basic set of DAE equations that describes the UPFC dynamic state is represented by Eq (8):

$$\frac{dv_{DC}}{dt} = \frac{3m_{SH}}{4C_{DC}}\begin{bmatrix}\cos\delta_{SH} & \sin\delta_{SH}\end{bmatrix}\begin{bmatrix}i_{SH_d}\\ i_{SH_q}\end{bmatrix} + \frac{3m_{SE}}{4C_{DC}}\begin{bmatrix}\cos\delta_{SE} & \sin\delta_{SE}\end{bmatrix}\begin{bmatrix}i_{SE_d}\\ i_{SE_q}\end{bmatrix} \quad (8)$$

where, v_{DC} is the DC link voltage, m_{SH}, m_{SE} are amplitude modulation ratios of voltage source converters(VSCs) and δ_{SH}, δ_{SE} are phase angles of control signal of VSCs. Eq (8) along with modeling of other components of power system; like generator, transmission lines, etc can be utilized for formulating a dynamic estimator.

In the present paper, a single machine (generator) connected to an infinite machine is modelled integrated with UPFC to perform dynamic state estimation as shown in Figure 2.

Three generator variables; generator rotor angle (δ), generator speed (ω) and q-axis synchronous voltage (E_q') are estimated and one UPFC variable (v_{DC}). Eqs (9-11) represent the generator dynamics [17]. Eqs (9-12) to show the complete dynamics of an SMIB system with UPFC.

$$\frac{d\delta}{dt} = \omega - \omega_0 \quad (9)$$

$$\frac{d\omega}{dt} = \frac{\omega_0}{2H}\left[Pm - Pe - D\left(\frac{\omega-\omega_0}{\omega_0}\right)\right] \quad (10)$$

$$\frac{dE_q'}{dt} = \frac{1}{T_{d0}'}\left[E_{fd} - (X_d - X_d')I_d - E_q'\right] \quad (11)$$

$$\frac{dV_{DC}}{dt} = \frac{3m_{SH}}{4C_{DC}}\left[\cos\delta_{SH}\, I_{SH_d} \quad \sin\delta_{SH} I_{SH_q}\right] + \frac{3m_{SE}}{4C_{DC}}\left[\cos\delta_{SE}\, I_{SE_d} \quad \sin\delta_{SE}\, I_{SE_q}\right] \quad (12)$$

Here, V_T and V_I are the generator terminal voltage and the voltage of infinite bus. Current I is the line current, P_e is the power injected by the generator at the bus of connection. Eqs. (13-15) show algebraic equations to model the system [18].

$$P_e = V_{Td}I_d + V_{Tq}I_q \quad (13)$$

where, $V_{Td} = X_q I_q$; $V_{Tq} = E_q{}' - X_d{}' I_q$; $I_d = I_{SH_d} + I_{SE_d}$; $I_q = I_{SH_q} + I_{SE_q}$; $V_T = \sqrt{(V_{Td}{}^2) + (V_{Tq}{}^2)}$.

$I_{SH_d}, I_{SE_d}, I_{SH_q}, I_{SE_q}$ are the d-q components of generator current injection. Current injections can be obtained from the voltage injected by the UPFC in shunt and series; V_{SH} and V_{SE} given by Eqs (14-15).

$$\begin{bmatrix} V_{SH_d} \\ V_{SH_q} \end{bmatrix} = \begin{bmatrix} 0 & -x_{SH} \\ x_{SH} & 0 \end{bmatrix} \begin{bmatrix} I_{SH_d} \\ I_{SH_q} \end{bmatrix} + \begin{bmatrix} m_{SH} \cos \delta_{SH} V_{DC}/2 \\ m_{SH} \sin \delta_{SH} V_{DC}/2 \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} V_{SE_d} \\ V_{SE_q} \end{bmatrix} = \begin{bmatrix} 0 & -x_{SE} \\ x_{SE} & 0 \end{bmatrix} \begin{bmatrix} I_{SE_d} \\ I_{SE_q} \end{bmatrix} + \begin{bmatrix} m_{SE} \cos \delta_{SE} V_{DC}/2 \\ m_{SE} \sin \delta_{SE} V_{DC}/2 \end{bmatrix} \quad (15)$$

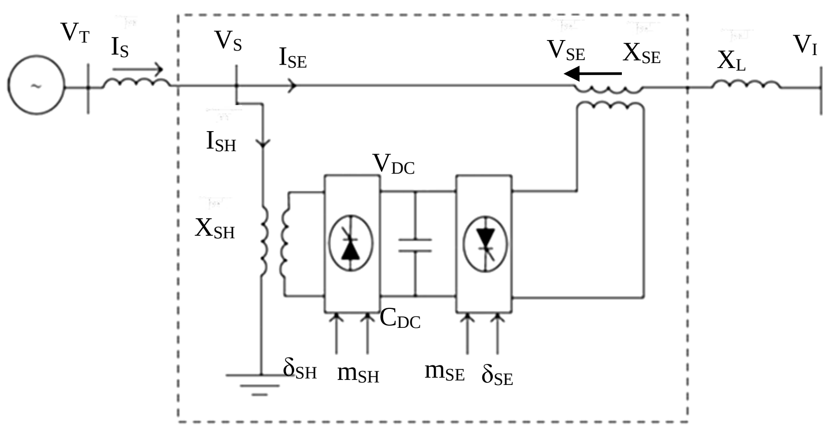

Fig.2 SMIB incorporated with UPFC

DSE IMPLEMENTATION

Extended Kalman filter: Estimator Methodology

In the present work, Extended Kalman filter is used as an estimator. Having briefed on other available techniques previously, details on the method are presented in this section. EKF utilises the non-linear model of the system and process and measurement equations. These equations are developed as in Eqs (16-17).

$$x_k = f(x_{k-1}, u_{k-1}, \omega_{k-1}) \quad (16)$$

$$z_k = h(x_k, \vartheta_k) \quad (17)$$

Here, *f* represents a non-linear function between the state variables at previous instant and current instant. *h* represents a non-linear measurement function. EKF initially predicts and then updates the state variable using available measurements.

The predictor and corrector steps are given by Eqs (18-19) respectively.

$$\hat{x}_k{}^- = f(\hat{x}_{k-1}, u_{k-1}) \quad , \quad P_k{}^- = A_k P_{k-1} A_k{}^T + W_k Q_{k-1} W_k{}^T \quad (18)$$

$$K_k = P_k{}^- H_k{}^T (H_k P_k{}^- H_k{}^T + V_k R_k V_k{}^T)^{-1}, \; \hat{x}_k = \hat{x}_k{}^- + K_k\big(z_k - h(\hat{x}_k{}^-)\big), \; P_k = (I - K_k H_k) P_k{}^- \quad (19)$$

The time update equations project the present state x_k forward in time and error covariance P_k estimates to obtain the a priori estimate x_{k-} for the next time step. The measurement update equations obtain an improved a posteriori estimate x_k by incorporating a new available measurement z_k into the a priori estimate. Before doing so, Kalman gain matrix K_k is calculated so as to minimize the error in a posteriori estimate x_k. Jacobians are used to relate state and measurements or even states at various instants. The matrices A and W are process Jacobians while H and V are measurement Jacobians and obtained as in (20) – (23).

$$A_{[i,j]} = \frac{\partial f_{[i]}}{\partial x_{[j]}} (\hat{x}_{k-1}, u_{k-1}) \quad (20)$$

$$W_{[i,j]} = \frac{\partial f_{[i]}}{\partial w_{[j]}} (\hat{x}_{k-1}, u_{k-1}) \quad (21)$$

$$H_{[i,j]} = \frac{\partial h_{[i]}}{\partial x_{[j]}} (\hat{x}_k) \quad (22)$$

$$V_{[i,j]} = \frac{\partial h_{[i]}}{\partial w_{[j]}} (\hat{x}_k) \quad (23)$$

Test System Description

In order to perform dynamic state estimation, a test SMIB system is used. The data is taken from Jose *et al* [18]. The estimator runs on the EKF algorithm as explained in previous sections. A computer program is developed in

MATLAB for the same. The data used for the SMIB system and the UPFC which is used to initialize the algorithm are as shown in Table -1.

Estimation Results

As per the dynamic modeling discussed in the previous section, three state variables have been considered for generator; generator rotor angle (δ), generator speed (ω) and q-axis synchronous voltage (E_q'). The variation in DC link voltage for the converters in UPFC is the added state variable. The measurements considered for the process of state estimation are electrical power injected by the generator and the terminal voltage. The state and measurement vectors are : $x = [\delta , \omega , E_q' , v_{DC}]$; $y = [P_e , V_t]$To validate the results to actual scenario, Gaussian noise is added to the measured values by using 'random' function in MATLAB. Variance of 0.01 p.u. is added to the measured electric power and variance of 0.01 p.u to the terminal voltage. The noisy measurements are plotted as seen in Figure 3.

Figure 4-7 show the estimation results for generator dynamics. It can be seen that the algorithm efficiently tracks the system dynamics as well as UPFC state variable even in presence of noisy measurements. In the absence of fault, the state variables remain constant and the true variables are obtained same as predicted by the algorithm.

Table -1 Data for Test System

Parameters for SMIB	UPFC Initialization
V_T = 1.0 pu	X_{SE} = 0.1 pu
V_I = 1.0 pu	X_{SH} = 0.1 pu
$X_{d'}$= 0.3 pu	V_{DC} = 10 pu
X_q = 0.6 pu	C_{DC} = 2.0 pu
D = 1.2	m_{SE}= 0
M = 8 MJ/MVA	m_{SH}= 0.1935pu
X_t= 0.1 pu	δ_{SE} = 131.5°
X_L = 0.3 pu	δ_{SH} = 52.76°
Pe = 1.2 pu	

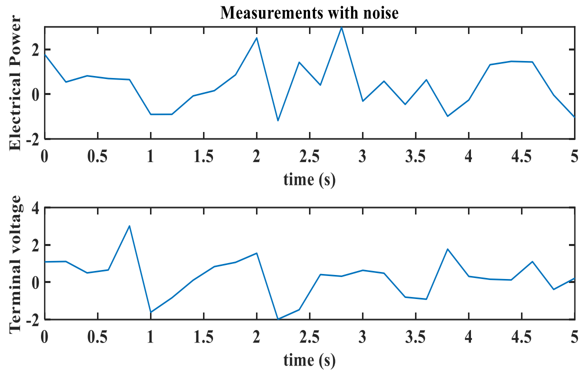

Fig. 3 Noisy Measurements: vector y

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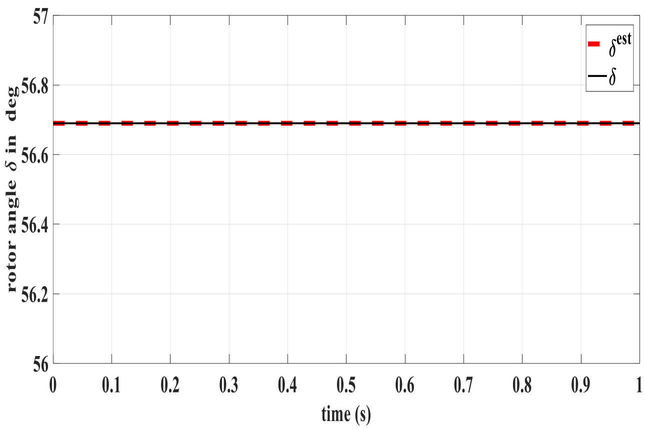

Fig.4 Rotor angle estimation : x(1)

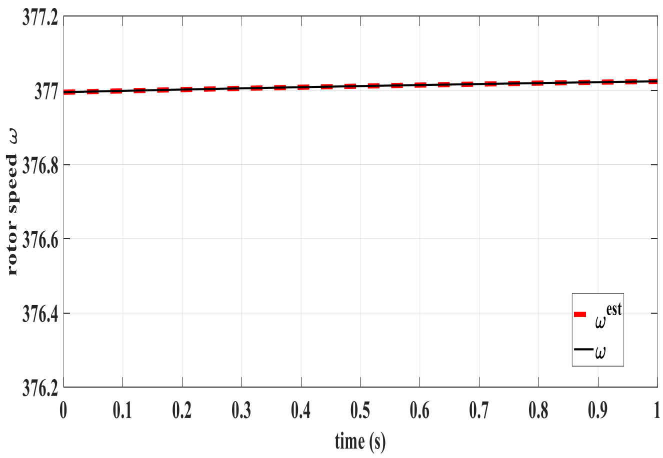

Fig. 5 Rotor speed estimation : x(2)

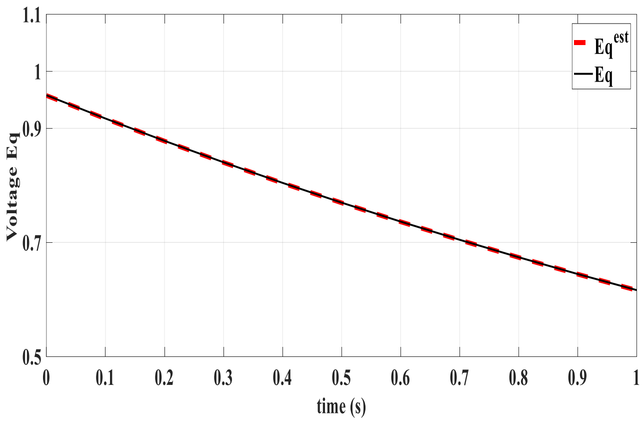

Fig. 6 Voltage estimation : x(3)

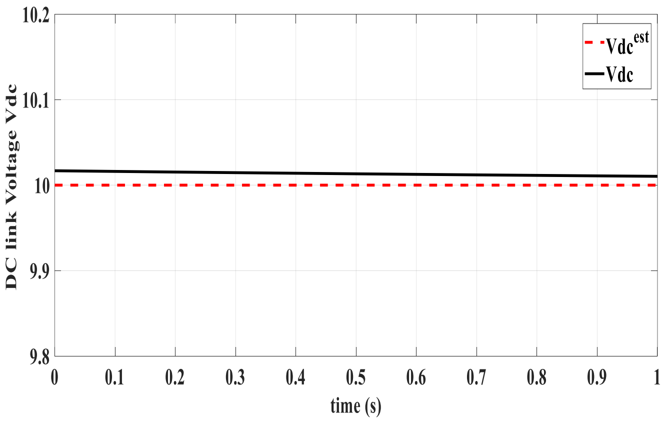

Fig.7 UPFC DC link estimation : x(4)

CONCLUSION

Dynamic State Estimation is very important for modern power system. Actual system dynamics if incorporated properly into the estimation process provides a greater degree of controllability and stability to power system. Power system dynamic state estimation including FACTS controller is a potential research area as future grids are expected to be equipped with FACTS controllers for better operation. This paper discusses the dynamic modeling of UPFC device. Conventional steady-state models assume equivalent voltage source circuit. Thus estimation of additional voltage magnitude and angles is the only challenge. However dynamical model suggests using DC link voltage as the state variable for UPFC. The dynamic model of UPFC is integrated to the SMIB system. Extended Kalman Filter algorithm is applied to perform dynamic state estimation. It is to be noted that system dynamics are interrelated to UPFC dynamics and it cannot be ignored. The outcomes of UPFC dynamic estimation can play a crucial role in designing the controllers.

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