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## Implementation of Extended Kalman filter based dynamic state estimation on SMIB system incorporating UPFC dynamics

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### Abstract

Power system state estimation holds great relevance with increasing concern about system reliability and security now-a-days. There is an added dimensionality in the concept and underlying techniques used in power system state estimation; from static to dynamic and inclusion of important system components like FACTS. This paper is an attempt to review the state of the art of power system state estimation. A detailed discussion on widely used extension of Kalman filter i.e. Extended Kalman Filter is provided. This paper also discusses how incorporating FACTS controller, in particular UPFC affects the process of state estimation. In contrast to steady-state modeling of UPFC; dynamic model of UPFC is discussed. It is incorporated into an SMIB system and results for EKF based dynamic estimation are presented.

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### 1. Introduction

Power system keeps changing depending on the load requirements, technological advancements, etc. Even the commercial and managerial aspects affect the trends in power system. The importance of reliability assurance has increased manifold due to the changing scenario. There is a growing concern about the security and reliability of the power system networks. All these issues demand monitoring of the network. Monitoring of the generation and/or transmission networks provide the data which are required to carry out power system operations.

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To perform the operations effectively, accurate data is required. However in reality, it is very difficult to get because of large size, infrequent availability of measurements and also due to corrupted data. These limitations are overcome by a state estimator (SE).

State estimator is a computer program which processes the available measurements; including some of the redundant data, if any for the purpose of accuracy to obtain the best values of state variables. The general practice is to consider bus voltage magnitudes and angles as the state variables.

Extensive work has been done in the area of power system state estimation [1-7]. However, inclusion of FACTS into the process of power system state estimation is still atypical. Present work provides an insight into the state estimation of power system networks; with focus onto Dynamic State Estimation (DSE) which has gained much importance lately. This paper deals with modeling of UPFC into an SMIB system and application of Kalman filter based DSE technique to it.

This paper is organized into eight sections. Section II provides the overview of static and dynamic state estimation and section III describes Extended Kalman Filter (EKF) as a method for DSE. Section IV presents insight into the state estimation of power system included with FACTS devices. Section V describes dynamic modeling of SMIB system with UPFC. Section VI describes implementation of EKF into a test system, results of which are presented in section VII followed by concluding remarks in VIII.

## 2. State estimation : state of the art

Books first by Monticelli [2] in 1999 and then by Abur and Gomez Exposito [3] in 2004 provide extensive work on power system state estimation. Over the years WLS based state estimation has been worked upon in order to enhance numerical and computational capabilities. References [3-5] provide a detailed account on modifications in the technique for improved numerical formation. Various numerical methods have been explored to avoid the problem of ill-conditioning. A performance review of methods like orthogonal transformation, normal equations and hachels augmentation method is done by Holten et al. in [6]. This work reported the orthogonal transformation to be the most stable method amongst others. The extension of state estimation methods as constrained problem was later solved by Frey et al. [7] using the method of Weighted Least Average Value (WLAV).

Conventional State Estimation is static in nature. Static state estimation kind of takes snap-shots of the system and does not in true sense incorporate the system dynamics. Changes in power system are driven by loads. As the load varies, the generation is expected to change. Hence power flows through line and injections at buses change. This makes system dynamic. Also, the time constants for transient are faster than the rate at which conventional SCADA captures data/measurements.

Considering these things, if static state estimation is to be carried out, it has to be done at much smaller time intervals. This becomes cumbersome and computationally difficult. Requirement of large memory can also be an important issue. Conventional data acquisition provides steady but unsynchronized information and at low sampling density. Thus dispatching and controlling center cannot know the dynamic operating states of the system exactly. Thus an improvement in the available estimation procedures is of importance. This requirement is met by Dynamic State Estimators (DSE).

Using the information about state vector at time instant  $k$ , the Dynamic State Estimation technique can predict the state vector of power system at next time stamp  $k+1$ . Due to the prediction ability, it allows security analysis to be carried out in advance and hence the signal operator can have more time during emergencies.

Another important aspect of dynamic state estimation is that rather than conventional states like bus voltage and angle, states that truly depict the dynamics of a system like generator rotor angle, speed or generator internal voltages are estimated. Such parameters can be helpful to take predictive actions using generator controls in case of incipient emergencies. The said state variables are derived using the dynamical modeling of the system components.

The discussion so far indicates that there is an urgent need of estimating the dynamic states of a power system network. It becomes important that the chosen technique for such estimation must be robust, accurate, efficient, less time consuming and ensuring the result.

According to [8], dynamic state estimation techniques are broadly classified into Kalman filter-based, Robust dynamic techniques, Square root filter-based and Artificial Intelligence-based techniques. Authors have tried to categorize certain available techniques as mentioned above; however, it necessarily may not sum up all the available

techniques.

Majority of DSE techniques are in one or more way variants of Kalman filter technique. The reason why it is so widely-used is the relative ease of implementation over other available techniques. Kalman filter techniques also provide advantage that it is possible to predict the state at next instant; in addition to filtering out the noise from the available measurements.

Several variants of Kalman filter like Extended Kalman Filter (EKF), Unscented Kalman filter (UKF) are used [9-11]. EKF approach is widely used for the DSE. It is a non-linear version of Kalman filter. From the study of relative pros and cons, it is observed that UKF emerges as a better option to carry out state estimation [12]. Generally, the non-linearities in power system model are not so severe and hence linearization errors in EKF are also insignificant. As a result performance superiority of UKF is not so obvious. Over the years the use of EKF as a state estimator program has gained value. However in future, there can be a scope to employ extensive research put in the UKF for dynamic state estimation of power system.

The Kalman filter based technique assumes Gaussian distribution of noise. But frequently, the noise distribution deviates from the assumed model. The performance of Kalman filter based technique degrades in the presence of these outliers. For this purpose certain techniques called Robust techniques were developed. Authors of reference [13] have addressed the issue using a statistical approach based on M-estimation technique. However Robust techniques are computationally very complex and mathematical formulation is cumbersome.

Square root filter techniques were used to overcome numerical errors that may arise while computer implementations of Kalman filter techniques [14, 15]. It calculates square roots of covariance matrices rather than using them directly using special decomposition methods like Cholesky decomposition, etc.

Having briefed on other available techniques, following section describes EKF in detail. Readers are referred to [11-12] to have further insight on the available variants.

### 3. Extended Kalman filter as a dynamic estimator

It solves the problem of estimating the instantaneous state of a dynamic system which is corrupted by white noise. EKF utilizes the non-linear model of the system and process and measurement equations are developed as in (1)-(2).

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

$$z_k = h(x_k, \vartheta_k) \quad (2)$$

Here,  $f$  represents a non-linear function between the state at previous instant and present 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 summarized in Table 1.

Table 1. Extended Kalman filter equations

Prediction steps/Time update equations:	Correction steps/Measurement update equations:
$\hat{x}_k^- = f(\hat{x}_{k-1}, u_{k-1})$ $P_k^- = A_k P_{k-1} A_k^T + W_k Q_{k-1} W_k^T$	$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + V_k R_k V_k^T)^{-1}$ $\hat{x}_k = \hat{x}_k^- + K_k (z_k - h(\hat{x}_k^-))$ $P_k = (I - K_k H_k) P_k^-$

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  $\hat{x}_k^-$  for the next time step. The measurement update equations obtain an improved a posteriori estimate  $\hat{x}_k$  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 the a posteriori estimate  $\hat{x}_k$ .

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 (3) – (6).

$$A_{[i,j]} = \frac{\partial f_{[i]}}{\partial x_{[j]}}(\hat{x}_{k-1}, u_{k-1}) \quad (3)$$

$$W_{[i,j]} = \frac{\partial f_{[i]}}{\partial w_{[j]}}(\hat{x}_{k-1}, u_{k-1}) \quad (4)$$

$$H_{[i,j]} = \frac{\partial h_{[i]}}{\partial x_{[j]}}(\hat{x}_k) \quad (5)$$

$$V_{[i,j]} = \frac{\partial h_{[i]}}{\partial w_{[j]}}(\hat{x}_k) \quad (6)$$

#### 4. State estimation of power system incorporated with UPFC

FACTS is a progressive technology that has allowed utilities to make the most out of the existing grid and inadvertently control almost every governing parameter of transmission; be it series impedance, shunt impedance, phase angles of receiving and sending end voltages, etc. that affect the power flow and/or stability of the transmission and power system broadly.

One of the most important FACTS devices being used in power systems is Unified Power Flow Controller (UPFC). A UPFC is an electrical device for providing fast-acting reactive power compensation on voltage electricity networks. It uses a pair of three-phase converter to produce current that is injected into a transmission line using a series transformer. The UPFC is a combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) coupled via a common DC voltage link [16].

The main advantage of the UPFC is to control the active and reactive power flow in the transmission line. The controllable parameters of the UPFC are reactance in the line, phase angle and voltage. The UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system [16]. Considering this device as apparently a universal FACTS controller, it is thus the subject matter for discussion in this particular paper.

In [17], UPFC is modelled into the system as a pair of voltage source; one in series and another in shunt. This paper deals with two cases, one being the absence of measurement errors while another being presence of bad-data into the measurement. Under both scenarios, WLS based estimator gives fair results. It is also reported that in the second case the number of iterations is less. However an indistinct approximation of an overdetermined system is taken. That is measurement data redundancy is very high.

Reference [18] shows that level of data redundancy also plays an important part in determining the accuracy of the results. It is reported that estimation results are less accurate in presence of the UPFC when data redundancy is less. It is also highlighted that reactive power injected at the bus of UPFC connection is decisive measurement for power system state estimation with FACTS controller.

Inclusion of PMU based high accuracy results into state estimation is demonstrated in [19]. The phasors of branch current injected by UPFC are utilized as measurements. Furthermore, one of the bus angle phasor measured by a PMU is considered as reference angle and other measurements are upgraded accordingly. Improvement in the results due to this is reported.

Galvani, Hagh and Sharifian in [20] used a Predictability Index (PI) for checking the effect of UPFC on prediction of system variables like bus voltages and line flows. Predictability of the variables is defined by the variance from the expected values. However this paper has not dealt with a priori prediction of state variables and models UPFC as a steady-state voltage source; making the estimation approach static.

Amongst papers that deal with the state estimation of a power system [17, 19, 21-27], popular methods can broadly be classified as:

- Weighted least Squares
- Recursive Least Squares
- Sequential Solution approach
- Predictor-Corrector interior point method

Weighted Least Square has been the most widely used method however in order to make it more robust and avoid mathematical ill-conditioning, Recursive Least Squares iterative method is proposed in [24]. The sequential solution approach as proposed in [25] uses matrix reduction having mathematical advantage but it does not include the constraints which appear in presence of the FACTS device connected.

It can be seen that the estimation approach followed uses a defined set of measurements taken considering a snapshot of power system. Hence is static in nature in most cases. The methods are in most cases unconstrained optimisation and hence not suitable while performing dynamic state estimation. If dynamic state estimation is to be done, following questions need to be addressed:

- What would be the dynamic state variables of system in presence of UPFC?
- Will the modeling of conventional components like generator, loads, etc. be affected by presence of UPFC?
- Will there be any change in the measurements?

The above discussed methods are static in nature and hence if applied for dynamic state estimation could take large time. These methods also do not consider the dynamic modelling of the UPFC. In-order to perform dynamic state estimation of the system with UPFC, dynamic modelling of UPFC is the primary requirement.

## 5. Dynamic modeling of UPFC into SMIB

It is 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. A few relevant papers which provide the dynamic modelling of UPFC are [28-32]. Under normal or steady-state conditions, there is no exchange of real power with the system if system losses are neglected. The voltage control of DC link capacitor results in this basic control function (Refer Fig. 1).

This means under steady-state, the DC link voltage remains constant. However this is not the case under 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.

Inclusion of FACTS device not only increases the practical relevance of state estimation but it can also provide parameters for controller setting for a FACTS device that is connected.

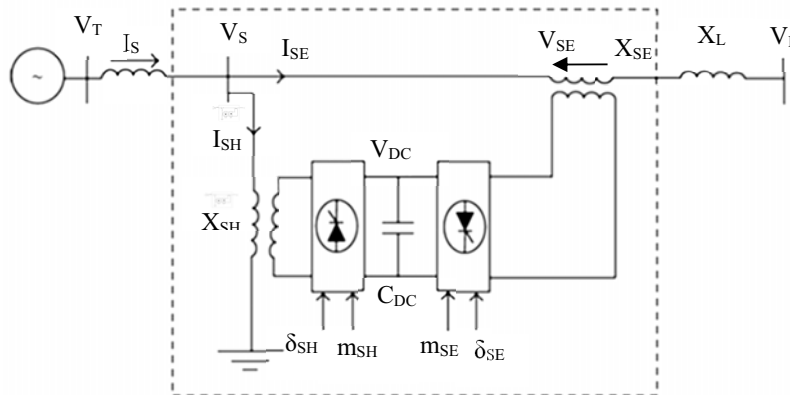


Fig. 1 SMIB incorporated with UPFC [30]

This results in a dynamic modeling of UPFC which is actually a non-linear differential equation which describes variation of DC link voltage with the input control signals. Neglecting transients and the resistance of transformers, the basic set of DAE equations that govern the dynamics of UPFC under transient are represented as follows by Eqn. (7):

$$\frac{dv_{DC}}{dt} = \frac{3m_{SH}}{4C_{DC}} [\cos \delta_{SH} \quad \sin \delta_{SH}] \begin{bmatrix} i_{SHd} \\ i_{SHq} \end{bmatrix} + \frac{3m_{SE}}{4C_{DC}} [\cos \delta_{SE} \quad \sin \delta_{SE}] \begin{bmatrix} i_{SEd} \\ i_{SEq} \end{bmatrix} \quad (7)$$

where,  $v_{DC}$  is the DC link voltage,  $m_{SH}$ ,  $m_{SE}$  are amplitude modulation ratios of voltage source converters(VSCs) and  $\delta_{SH}$ ,  $\delta_{SE}$  are phase angles of control signal of VSCs.

The above equation along with modeling of other components of power system; like generator, transmission lines, etc. need to be utilized for formulating an estimator. Generator can be modeled as a second order DAE equation as provided in [33]. All the notations have conventional meaning as per [33], unless otherwise specified. The generator dynamics can be represented by means of two state variable which are generator rotor angle ( $\delta$ ) and generator speed ( $\omega$ ). Here classical model of the generator is used. Eqn. (8)-(9) represent the modeling of an SMIB system along with UPFC. Eqn. (7) is reproduced as Eqn. (10) for the sake of brevity.

$$\frac{d\delta}{dt} = \omega - \omega_0 \quad (8)$$

$$\frac{d\omega}{dt} = \frac{\omega_0}{2H} [Pm - Pe - D(\frac{\omega - \omega_0}{\omega_0})] \quad (9)$$

$$\frac{dv_{DC}}{dt} = \frac{3m_{SH}}{4C_{DC}} [\cos \delta_{SH} \quad \sin \delta_{SH}] \begin{bmatrix} I_{SHd} \\ I_{SHq} \end{bmatrix} + \frac{3m_{SE}}{4C_{DC}} [\cos \delta_{SE} \quad \sin \delta_{SE}] \begin{bmatrix} I_{SEd} \\ I_{SEq} \end{bmatrix} \quad (10)$$

As in Fig. 1,  $V_T$  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.

Relevant algebraic equations to model the system are developed as per [34] and represented as in Eqns. (11)-(13).

$$P_e = V_{Td}I_d + V_{Tq}I_q \quad (11)$$

where,  $V_{Td} = X_q I_q$ ;  $V_{Tq} = E_q' - X_d' I_d$ ;  $I_d = I_{SHd} + I_{SEd}$ ;

$$I_q = I_{SHq} + I_{SEq}; V_T = \sqrt{(V_{Td})^2 + (V_{Tq})^2}.$$

$I_{SHd}$ ,  $I_{SEd}$ ,  $I_{SHq}$ ,  $I_{SEq}$  are the d-q components of generator current injection. They can be obtained from the voltage injected by the UPFC in shunt and series;  $V_{SH}$  and  $V_{SE}$ . Current injections can be obtained from the following set of algebraic equations.

$$\begin{bmatrix} V_{SHd} \\ V_{SHq} \end{bmatrix} = \begin{bmatrix} 0 & -x_{SH} \\ x_{SH} & 0 \end{bmatrix} \begin{bmatrix} I_{SHd} \\ I_{SHq} \end{bmatrix} + \begin{bmatrix} m_{SH} \cos \delta_{SH} V_{DC}/2 \\ m_{SH} \sin \delta_{SH} V_{DC}/2 \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} V_{SEd} \\ V_{SEq} \end{bmatrix} = \begin{bmatrix} 0 & -x_{SE} \\ x_{SE} & 0 \end{bmatrix} \begin{bmatrix} I_{SEd} \\ I_{SEq} \end{bmatrix} + \begin{bmatrix} m_{SE} \cos \delta_{SE} V_{DC}/2 \\ m_{SE} \sin \delta_{SE} V_{DC}/2 \end{bmatrix} \quad (13)$$

## 6. DSE implementation on test system

In order to perform dynamic state estimation, a test SMIB system is used. The data is taken from [34]. 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 2.

Table 2. Data for test system

Parameters for SMIB	UPFC initialization data
$V_T = 1.0$ 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	$m_{SH} = 0.1935$ pu
$X_i = 0.1$ pu	$\delta_{SE} = 131.5^\circ$
$X_L = 0.3$ pu	$\delta_{SH} = 52.76^\circ$
$P_e = 1.2$ pu	

As per the dynamic modeling discussed in the previous section, three state variables have been considered. Generator rotor angle ( $\delta$ ), generator speed ( $\omega$ ) and the variation in DC link voltage VDC for the converters in UPFC. The measurements considered for the process of state estimation are electrical power injected by the generator and the generator speed. In order to validate the results to actual scenario, Gaussian noise is added to the measured values by using 'random' function in MATLAB. The variance of 0.0001 p.u. is added to the measured electric power and variance of 0.001 rad/s to the measured rotor velocity.

## 7. Results and discussion

The performance of estimator is checked in two scenarios. In case 1, a sudden reduction in the load is simulated. It is seen as a sudden change in the value of load angle from  $\delta_0 = 0.9894$  rad to  $\delta = 0.7800$  rad at time  $t = 1$  sec. In case a scenario of fault is simulated which correspond to the increment in value of load angle to  $\delta = 1.200$  rad at time  $t = 1$  sec. Fig. (2)- (4) show the estimation results using EKF algorithm. It can be seen that the results obtained by dynamical mathematical modeling of UPFC is able to estimate the dynamics of UPFC DC link. In the event of increase of load, the DC link voltage is seen to be reducing. This behaviour can be attributed to the increase in reactive power and active power demand of the system.

### 7.1. Estimation results Case I: sudden change in load

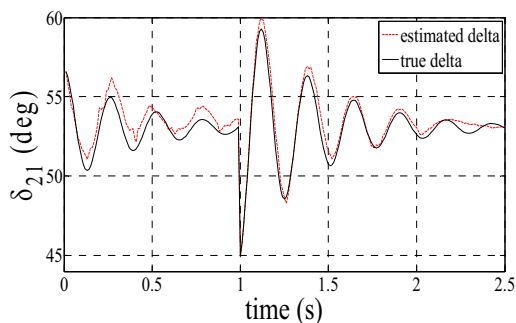


Fig. 2. Estimated rotor angle of generator

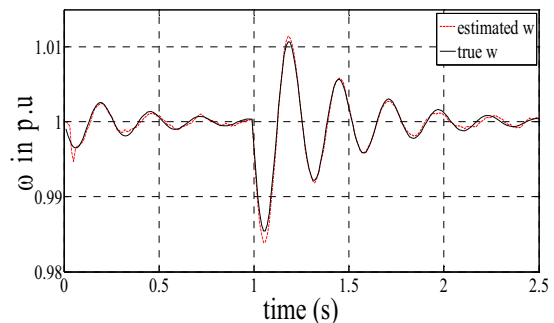


Fig. 3. Estimated speed of generator

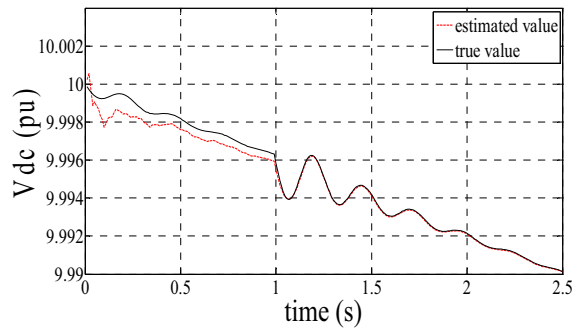


Fig. 4. DC link voltage variation

### 7.2. Estimation results Case II: scenario of fault: Loss of line

Fig. (5)- (7) show the estimation results in case of a fault. The DC link voltage is seen to be increasing. This behaviour can be attributed to the reduction in ability of system to supply power due to loss of line. Since classical model is considered; the mechanical input to the system is assumed to be constant. Hence there is a sudden swing in the rotor angle as can be seen. Correspondingly the need of the system is less and hence lesser burden on DC link can be seen.

Fig. (8) is a representation of one of the set of noisy measurements that have been used to estimate the actual state variables of the system. Fig. (8a) is the measured electrical power injected by generator and Fig. (8b) is the measured values of generator speed.

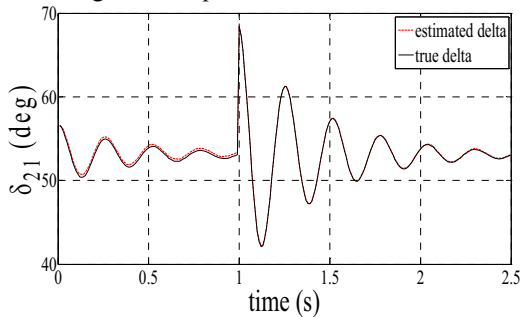


Fig. 5. Estimated rotor angle of generator

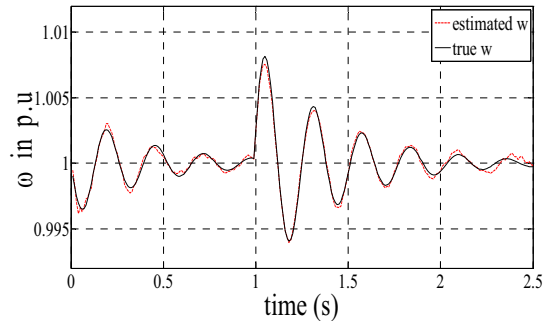


Fig. 6. Estimated speed of generator

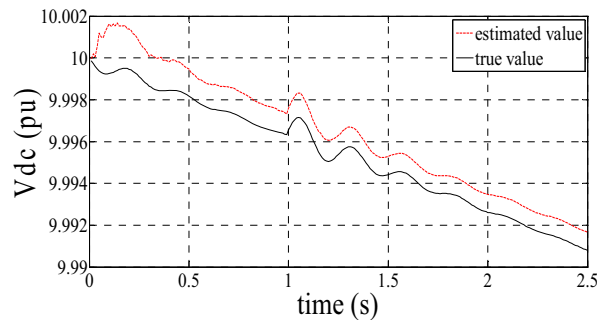


Fig. 7. DC link voltage variation



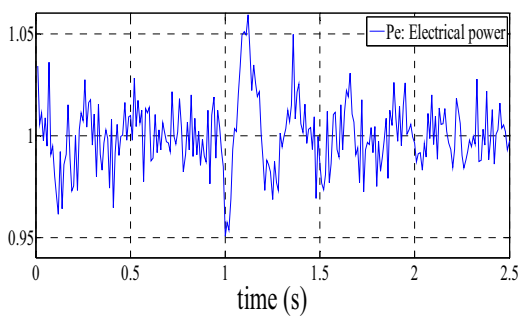


Fig. 8(a). Measured Electrical Power with noise

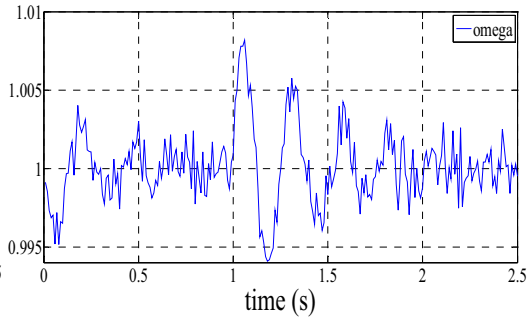


Fig. 8(b). Measured Generator speed with noise

## 8. Conclusion

This paper provides a brief review of the state estimation of power system. It is established the necessity of dynamic state estimation. Much work has been done into DSE techniques for power system. However extension of this to power system including FACTS controller is rare much to the knowledge of authors. This paper discusses the dynamic modeling of UPFC device. In contrast to assuming it as a voltage source and estimation of additional voltage magnitude and angles, dynamical model suggests using DC link voltage as the state variable. It is integrated to the SMIB system model. EKF algorithm is applied to perform state estimation in order to also estimate UPFC dynamics. 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. Modeling of controller and its subsequent effect into controlling UPFC dynamics is not in the scope of this paper.

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