Indonesian Journal of Electrical Engineering and Computer Science
Vol. 21, No. 2, February 2021, pp. 642~646
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v21.i2.pp642-646

Dynamic state estimation of multi-machine power system with UPFC using EKF algorithm

Meera R. Karamta, J. G. Jamnani
Department of Electrical Engineering, Pandit Deendayal Petroleum University, Gandhinagar, India

Article Info

Article history:

Received Jan 14, 2020
Revised Mar 17, 2020
Accepted Apr 13, 2020

Keywords:

Dynamic state estimation
Extended kalman filter
FACTS
State prediction
UPFC

ABSTRACT

Estimation of dynamic state variables in a multi-machine power system connected with UPFC is presented in this paper, using extended kalman filter (EKF) algorithm. A two-generator test case is used to estimate the generator rotor angle and rotor speed. The DC link voltage of the UPFC is the additional state variable to be estimated. Dynamic mathematical modeling of the multi-machine system with UPFC is explained in this work. DSE is done under transient condition of three-phase fault.

Corresponding Author:

Meera Karamta
Department of Electrical Engineering
Pandit Deendayal Petroleum University
Knowledge corridor, Raisan, Gandhinagar, India
Email: meera.kphd14@sot.pdpu.ac.in

1. INTRODUCTION

Power system operators depend on the results of state estimator for real time analysis. State estimation helps operators to take necessary decisions when an emergency occurs. Most power system operations such as load flow, contingency analysis, security assessment use the state estimation results. State estimator is a computer program which processes the available power system measurements to obtain the best values of state variables [1, 2]. Supervisory control and data acquisition (SCADA) collects information such as bus voltages, frequency, real and reactive power flow through line and/or at the buses and breaker status. The state estimator uses these data to compute the best value of the state variables. Well-known algorithms [3-6] such as weighted least squares (WLS), weighted least average value (WLAV) are commonly used in power system state estimation.

The power system is assumed to have no changes while the measurement is available from the field till it is processed by the estimation algorithm. This method of state estimation is thus called Static State estimation (SSE) [7]. Variations in the state variables is possible due to changes in the system like sudden load is connected or removed, or due to transients and faults. The SSE is not able to incorporate the dynamical system variations because of slow data capturing rates of SCADA. Presently, the measurements are also available from phasor measurement units (PMUs), which have much fast data sampling rate [8]. With the advancements in the type and the rate of availability of measurements, upgrading the estimation process is necessary. This is made possible due to new set of algorithms called as dynamic state estimator (DSE).

DSE considers the state variables of system which show the dynamic behavior of system. Thus generator rotor angle, speed or generator internal voltages are the power system dynamic state variable considered. Classification of DSE techniques is done into Kalman filter-based, robust techniques and artificial intelligence techniques as seen in [9]. Kalman filter techniques are better in mathematical and computer implementation when a white Gaussian noise model is assumed [10, 11]. It is a well-known algorithm having application in state estimation of various processes not only power system. [12] In this paper the non-linear version of kalman filter; extended kalman filter (EKF) is used and is discussed in the next section. flexible ac transmission system (FACTS) devices are a part of modern transmission network. They offer greater controllability and flexibility of operation [13-15]. SSE with UPFC can be seen in literature [16-20]. In this paper the DSE is done for a multi-machine power system connected with unified power flow controller (UPFC). Therefore, state estimation algorithms must also include the dynamics of these devices for a proper corrective action in case of disturbances [21-22]. In this paper dynamic modeling of a two-generator multimachine power system connected with UPFC is presented. EKF is used to estimate the system state variables. Section 2 discusses the system modeling. Section 3 discusses the EKF algorithm for DSE and results are presented in Section 3.

2. ESTIMATION ALGORTIHM: EXTENDED KALMAN FILTER

In the present work, extended kalman filter is used as an estimator. EKF utilizes the non-linear model of the system and process and measurement equations as shown by (1-2) [21].

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

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

f denotes the non-linear relation of the state variables at current time stamp with the previous time instant. The non-linear measurement function, h, relates the measurements with state variables. EKF predicts the state variable and the covariance matrix using information of the previous time instant as shown by (3-4). When the measurement is available, then state variable and covariance matrix are updated using (5-7).

$$\widehat{x}_k^{\,-} = f(\hat{x}_{k-1}, u_{k-1}) \quad (3)$$

$$P_k^{\,-} = A_k P_{k-1} A_k^{\,T} + W_k Q_{k-1} W_k^{\,T} \quad (4)$$

$$K_k = P_k^{\,-} H_k^{\,T} (H_k P_k^{\,-} H_k^{\,T} + V_k R_k V_k^{\,T})^{-1} \quad (5)$$

$$\hat{x}_k = \hat{x}_k^{\,-} + K_k\big(z_k - h(\hat{x}_k^{\,-})\big) \quad (6)$$

$$P_k = (I - K_k H_k) P_k^{\,-} \quad (7)$$

In the above equations, matrices A and W are the process Jacobians calculated by (8-9). The measurement Jacobians; H and V are calculated by (10-11).

$$A_{[i,j]} = \frac{\partial f_{[i]}}{\partial x_{[j]}} (\hat{x}_{k-1}, u_{k-1}) \quad (8)$$

$$W_{[i,j]} = \frac{\partial f_{[i]}}{\partial w_{[j]}} (\hat{x}_{k-1}, u_{k-1}) \quad (9)$$

$$H_{[i,j]} = \frac{\partial h_{[i]}}{\partial x_{[j]}} (\hat{x}_k) \quad (10)$$

$$V_{[i,j]} = \frac{\partial h_{[i]}}{\partial w_{[j]}} (\hat{x}_k) \quad (11)$$

3. DYNAMIC MODEL OF MULTI-MACHINE SYSTEM WITH UPFC

As show in Figure 1, a two-generator test system [23-24] connected with UPFC is used in this work. The system parameters and initial conditions are as shown in Table 1.

Table 1. Data for test system

P_1 = 0.5 p.u	Q_1 = 0.3 p.u	X_{L1}=0.33 p.u=X_{L2}	X_{SR} =0.1 p.u =X_{SH}
G_3-jB_3= 0.3 – j0.2 p.u	G_4-jB_4= 1.0– j0.4 p.u	δ_1 = 0.341 rad	δ_2 = 0.086 rad
V_3 = 1.018 ∠0.037rad	V_4 = 1.0 ∠0.0rad	X_{t1} = 0.1 p.u = X_{t2}	
X_d=1.2 p.u , $X_{d'}$=0.11 p.u, X_q=0.8 p.u	M_1=M_2=10MJ/MVA, D=1.2	f= 60 Hz	

Classical model of synchronous generators [25] is assumed in this work, hence only generator state variables are considered; the rotor angle, δ and the rotor speed, ω. The classical generator model can be represented as:

$$\dot{\delta_i} = \omega_i - \omega_0 \tag{12}$$

$$\dot{\omega_i} = \frac{1}{2H_i}\left[Pmi - Pei - D_i\left(\frac{\omega_i - \omega_0}{\omega_0}\right)\right] \tag{13}$$

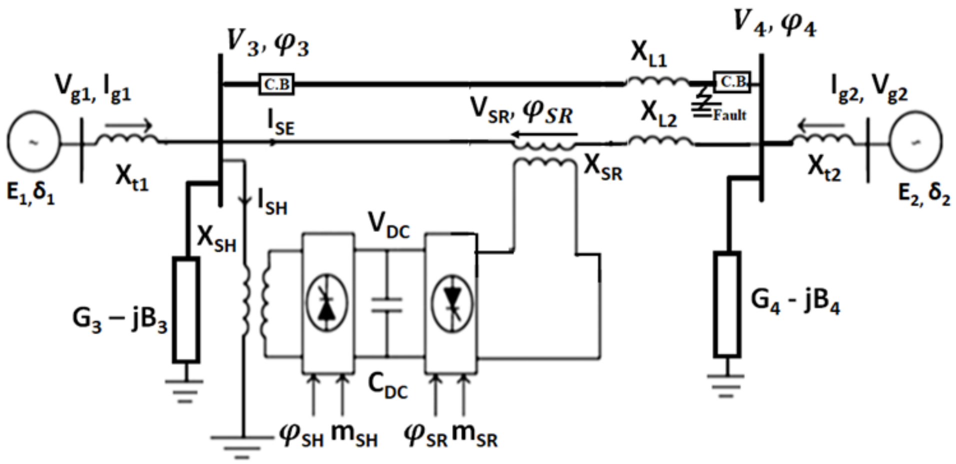


Figure 1. Two-generator test system with UPFC

The additional state variable due to UPFC is the DC link voltage. The variation of DC link voltage during transient conditions can be modeled as [19]:

$$\dot{V}_{DC} = \frac{1}{V_{DC}C_{DC}}\begin{bmatrix} V_{SHd} & V_{SHq} \end{bmatrix}\begin{bmatrix} i_{SH_d} \\ i_{SH_q} \end{bmatrix} - \frac{1}{V_{DC}C_{DC}}\begin{bmatrix} V_{SRd} & V_{SRq} \end{bmatrix}\begin{bmatrix} i_{SR_d} \\ i_{SR_q} \end{bmatrix} \tag{14}$$

here, $V_{SHd} = \frac{m_{SH}}{2\sqrt{2}} \sin\varphi_{SH}$, $V_{SHq} = \frac{m_{SH}}{2\sqrt{2}} \cos\varphi_{SH}$, $V_{SRd} = \frac{m_{SR}}{2\sqrt{2}} \sin\varphi_{SR}$, $V_{SRq} = \frac{m_{SR}}{2\sqrt{2}} \cos\varphi_{SR}$.
i_{SH_d}, i_{SH_q} are the d-q component of the shunt current injected by UPFC and i_{SR_d}, i_{SR_q} are the d-q components of the series current injected by UPFC.

4. RESULTS AND DISCUSSION

This section presents the result of EKF implementation on the dynamic system model described in the previous section. DSE is done under transient condition. A three-phase fault is simulated on the transmission line connecting bus-3and bus-4 at t=3 sec. Total 4 generator state variables are estimated. The state vector [x = $=\delta_{21}, \omega_1, \omega_2, V_{DC}]$.]. Generator #1 is the reference angle. The real power injected by generators and the speed are considered as the measurement variables. The estimation results can be seen in Figure 2, Figure 3, and Figure 4. A three-phase fault causes the transmission line to fail and hence electrical power supplied to the system reduces. The mechanical input power to the generators remain constant and thus the rotor angle and speed increases. As seen by Figure 4, the DC link voltage of UPFC increases when a three phase fault occurs. The control signals to UPFC are also assumed to be constant as modeling of the control part is out of the scope of this work. Therefore, DC link voltage also seen to be increasing as there is less utilization.

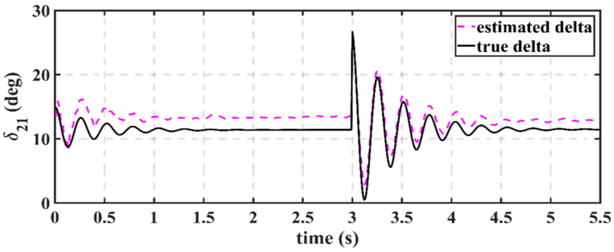
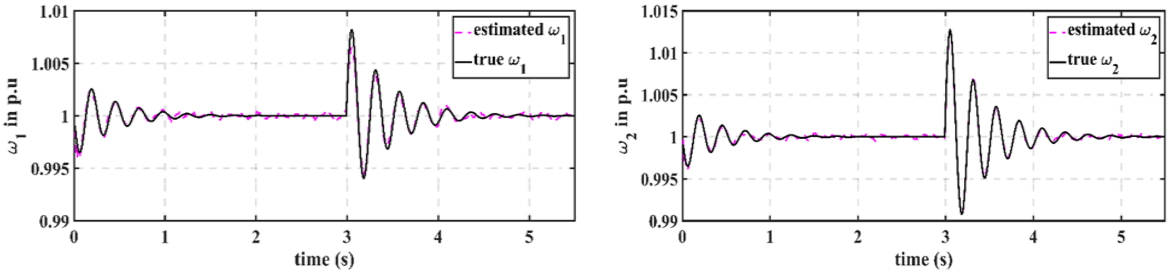


Figure 2. Rotor angle estimation



(a) (b)

Figure 3. Speed of generator, a) speed of generator 1 b) speed of generator 2

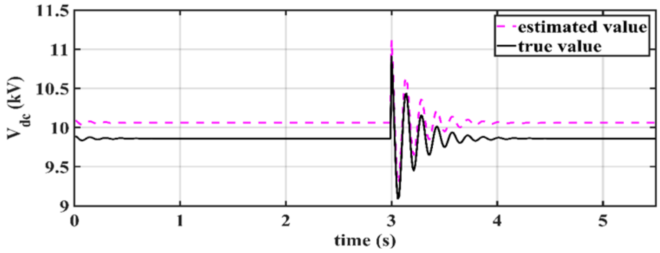


Figure 4. DC link Voltage of UPFC

5. CONCLUSION

In this paper, the dynamic mathematical model of UPFC device connected to multi-machine power system is shown. A two-generator test system is used to implement EKF algorithm as a dynamic state estimator. DSE is done under transient condition of three-phase fault on the system. The variation in the DC link voltage of UPFC is seen as an additional state variable.

REFERENCES

[1] Wood A. J, Wollenberg B. F, Sheblé GB., "Power generation, operation, and control," John Wiley & Sons, 2013.
[2] Gomez-Exposito A., Abur A., "Power system state estimation: theory and implementation," CRC press, 2004.
[3] Monticelli A., "State estimation in electric power systems: a generalized approach," *Springer Science & Business Media*, 2012.
[4] A. Abur and M. K. Celik, "A fast algorithm for the weighted least absolute value state estimation (for power systems)," in *IEEE Transactions on Power Systems*, vol. 6, no. 1, pp. 1-8, 1991. doi: 10.1109/59.131040.
[5] Clements K. A., Davis P. W., Frey K. D., "An interior point algorithm for weighted least absolute value power system state estimation," In *IEEE PES Winter Meeting*, 1991.
[6] L. Holten, A. Gjelsvik, S. Aam, F. F. Wu and W. E. Liu, "Comparison of different methods for state estimation," in *IEEE Transactions on Power Systems*, vol. 3, no. 4, pp. 1798-1806, 1988. doi: 10.1109/59.192998.
[7] F. C. Schweppe and E. J. Handschin, "Static state estimation in electric power systems," in *Proceedings of the IEEE*, vol. 62, no. 7, pp. 972-982, July 1974. doi: 10.1109/PROC.1974.9549.
[8] Lee G, Kim DI, Kim SH, Shin YJ., "Multiscale PMU Data Compression via Density-Based WAMS Clustering Analysis," *Energies*, vol. 12, no. 4, pp. 617, 2019.

[9] N. R. Shivakumar and A. Jain, "A Review of Power System Dynamic State Estimation Techniques," *2008 Joint International Conference on Power System Technology and IEEE Power India Conference*, New Delhi, pp. 1-6, 2008.doi: 10.1109/ICPST.2008.4745312.

[10] Bishop G., Welch G., "An introduction to the Kalman filter," *Proc of SIGGRAPH*, pp. 41, 2001.

[11] D. D. Trivedi, S. C. Vora and M. R. Karamta, "Analysis of extended Kalman filter based dynamic state estimator's performance under anomalous measurement conditions for power system," *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, Bhopal, 2016, pp. 557-563. doi: 10.1109/ICEPES.2016.7915990.

[12] Tammam Khadour, Michel Al Saba, Louay Saleh, "Improving bearings-only target state estimation tracking problem by using adaptive and nonlinear Kalman algorithms," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 15, no. 1, pp. 190-198, 2019.

[13] Ethmane I. A, Mahmoud A.K., Maaroufi M., Yahfdhou A., "Transient stability enhancement of statcom integration in power grid," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 16, no. 2, pp. 553-561, 2019.

[14] Samina. E. Mubeen, Baseem Khan, Nema R. K., "Application of Unified Power Flow Controller to Improve Steady State Voltage Limit," *IAES International Journal of Robotics and Automation (IJRA)*, vol. 6, no. 4, pp. 277-285, 2017.

[15] R. Arora, V. Kumar Tayal and H. P. Singh, "Series FACTS controllers for power oscillations damping of power system," *2017 Recent Developments in Control, Automation & Power Engineering (RDCAPE)*, Noida, pp. 245-250, 2017. doi: 10.1109/RDCAPE.2017.8358275.

[16] Bei Xu and Ali Abur, "State estimation of systems with embedded FACTS devices," *2003 IEEE Bologna Power Tech Conference Proceedings,*, Bologna, Italy, vol. 1, pp. 5, 2003. doi: 10.1109/PTC.2003.1304122.

[17] T. Okon and K. Wilkosz, "WLS state estimation in polar and rectangular coordinate systems for power system with UPFC: Significance of types of measurements," *2010 Modern Electric Power Systems*, Wroclaw, pp. 1-6, 2010.

[18] Sun Guo-qiang and Wei Zhi-nong, "Power system state estimation with unified power flow controller," *2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, Nanjing, pp. 775-778, 2008. doi: 10.1109/DRPT.2008.4523510.

[19] M.T. Hagh and M.A. Jirdehia, "A Robust Method for State Estimation of Power System with UPFC," *Turk J Elec Eng & Comp Sci.*, vol. 18, no. 4, pp. 571-582, 2010.

[20] Qifeng D, Boming Z, Chung TS., "State estimation for power systems embedded with FACTS devices and MTDC systems by a sequential solution approach," *Electr Power Syst Res*., vol. 55, no. 3, pp. 147-156, 2000.

[21] M. R. Karamta and J. G. Jamnani, "A review of power system state estimation: Techniques, state-of-the-art and inclusion of FACTS controllers," *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, Bhopal, 2016, pp. 533-538. doi: 10.1109/ICEPES.2016.7915986.

[22] Karamta MR, Jamnani JG., "Implementation of extended Kalman filter based dynamic state estimation on SMIB system incorporating UPFC dynamics," *Energy Procedia*, vol. 100, pp. 315-324, 2016.

[23] H. F. Wang, "Applications of modelling UPFC into multi-machine power systems," in *IEE Proceedings-Generation, Transmission and Distribution*, vol. 146, no. 3, pp. 306-312, 1999. doi: 10.1049/ip-gtd:19990170.

[24] J. P. Therattil and P. C. Panda, "Modeling and control of a multi-machine power system with FACTS controller," *2011 International Conference on Power and Energy Systems*, Chennai, 2011, pp. 1-6. doi: 10.1109/ICPES.2011.6156654.

[25] Kundur P., Balu N. J., Lauby M. G., "Power system stability and control," New York: McGraw-hill, 1994.

BIOGRAPHIES OF AUTHORS

Meera Karamta is working as a research scholar/lecturer with Electrical Engineering, School of Technology at Pandit Deendayal Petroleum University (PDPU), Gandhinagar (Gujarat), India, since December 2015. She received her M.Tech degree in Electrical Engineering (specialization: Power System) from the Nirma University, Ahmedabad, in the year 2013. She is currently pursuing Ph.D. in the area of Electrical Power system state estimation. She has presented several papers in prestigious conferences abroad and India. Her areas of interest include power system operation and control, power system stability, modelling and mathematical analysis of power systems, computer application to power systems, FACTS, etc.

Jitendra Jamnani is currently serving as the Head of the Department of Electrical Engineering, School of Technology, Pandit Deendayal Petroleum University (PDPU). He is working with PDPU since October 2013. His educational qualifications include M.Tech. Electrical with specialization in Power Systems from Indian Institute of Technology (IIT) Roorkee and Ph.D. in Electrical Engineering from M.S. University, Vadodara. He has over 22 years of teaching experience at both UG and PG levels and one and half year's Industrial experience. He has published more than 32 papers in National/International conferences/Journals and completed four consultancy projects for Industry. He has authored four popular books on "DC Machines & Transformers", "AC Machines", "Elements of Electrical Design" and "Switchgear." He has also presented research papers at IEEE/IET International conferences held in India and Abroad. He is a life member of ISTE and member of IEEE.