Synchrophasor Based Three-Phase State Estimator

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Abstract: ***State estimation is the core of the Energy Management System (EMS) and plays very significant role in continuous monitoring of the electric power systems. Dynamic State Estimator (DSE) facilitates the real time awareness of power system by providing real-time states of the system. Generally used estimation models are single phase, and based on some basic assumptions (i.e. balanced operating conditions) that mask natural behavior of power system. This paper focuses on the three phase-state estimation, and consider system imbalance while estimation of system states. Phasor measurement units (PMUs) provide synchronized measurements that make estimation problem linear in case of complete observability of system. Transmission system under unbalanced and widely varying operating conditions may also fail to hold its present balanced characteristics. IEEE 14 bus and New England 39 bus system have been used for test purpose.***

Keywords: Linear state estimation, three phase model, phasor measurement units.

1. Introduction

With the growing size and complexity, power system monitoring becomes more important for the proper operation and control of the system. The awareness of the real-time operating condition of the system reduces the probability of power system blackouts [1]-[2]. Monitoring the power system in real-time is therefore important. Measurement units are located at various remote areas in a power system. The collected measurements are sent to control centre, where estimation of the states of the system is carried out. By the set of minimal states in a power system in the steady state are usually meant, the bus voltage magnitudes and phase angles [3]-[4].

The state estimators (SEs) that are commonly used in power system control centres are single phase estimators, working on the assumption that the system is balanced, i.e., all phase values are same in magnitude and having 120^{o} angle difference with each other. This assumption leads to conversion of three-phase models to much simpler positive sequence network, because of absence of negative and zero sequence in balanced system. In a practical system, it is not certain to have fully symmetric or transposed transmission line structure, because of uneven geographical conditions during tower installation. Also, due to problem in getting new right-of-ways, some transmission lines even with different voltage levels, share a common corridor, which results in mutual coupling between two lines. Effects of mutual coupling of transmission lines, unbalanced loading conditions, and asymmetric faults may cause severe imbalance in a power system. Unbalanced loading is rare in transmission system, but can badly affect the estimator performance. Unbalanced operation of the system cannot be monitored with the help of conventional single phase state estimators. These imbalances can occur in both distribution and transmission systems, and can badly affect the performance of the state estimator.

A three phase state estimator, therefore, needs to be developed for monitoring the power system, under balanced and unbalanced conditions. The concept of three-phase state estimator was developed in 1995 [5]. Initially state estimators were designed to use measurements coming from supervisory control and data acquisition (SCADA) system. Development of synchrophasor based measurement devices has been proven to be useful in real-time state estimation because of their high accuracy and fast refresh rate.

In modern power systems, the deployment of Phasor measurement units (PMUs) for monitoring, protection, and control applications is being increased day by day. By exploring the high accuracy, high refresh rate, and time-synchronization capability of the PMU measurements, many researchers have successfully designed improved state estimators based on single phase models [6]-[9]. When installed at a bus, usually the PMUs are capable of providing measurements of the three phases, or the three sequence components, of the voltage at that bus and the currents through the incident lines (assuming sufficient number of current measurement channels) [6]. Usage of only PMU measurements makes the estimation process linear and non iterative and hence faster compared to the conventional state estimator. For balanced power system, the output of PMU has single frequency components, and thus positive sequence measurements are sufficient enough for state estimation, whereas, in unbalanced system, PMU outputs have two related frequencies [10]. In this case, imbalance is imperceptible by using only the positive sequence. Therefore, estimation of states must be done by considering the negative and zero sequence as well. By having complete idea of system imbalance while estimation, we can accurately identify the type of fault and location as well. Differentiation between bad data and any fault should be done at the occurrence of any anomaly. Sequence current component based identification of fault has been addressed in [11].

Considering above mentioned issues with single phase model, the present paper assumes that three phase (balanced or unbalanced) voltage and current measurements are obtained from the PMUs. Unbalance created due to various reasons, such as untransposed transmission line, unbalanced load, and unbalanced faults will be addressed in the paper using IEEE 14 bus and New England 39 bus systems as test networks.

2. Three Phase Representation of the System

The three-phase models of the transmission lines, transformers and loads are given below in brief.

2.1 Three Phase Line Model

Three phase impedance matrix for un-transposed transmission line is formulated using the self and mutual impedance between two phases and is given by,

$$\mathbf{Z}_{abc-l} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_{bb} & Z_{bc} \\ Z_{ac} & Z_{bc} & Z_{cc} \end{bmatrix} \tag{1}$$

where Z_{aa}, Z_{bb} and Z_{cc} are the self impedance of respective phases and Z_{ab}, Z_{bc}, and Z_{ca} are the mutual impedances between two phases.

2.2 Three Phase Transformer Model

The impedance matrix for three phase transformer is by given by,

$$\mathbf{Z}_{abc-Tr} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \tag{2}$$

where $Z_s = Z_0 + 2Z_1$ is the self impedance and $Z_m = (Z_0 - Z_1)/3$ is the mutual impedance of transformer windings. Z_0, Z_1 and Z_2 are the zero, positive and negative sequence impedance of transformer windings.

The three-phase transformer is assumed to be assembled of three single-phase transformers that are having balanced parameters.

2.3 Three Phase Load Model

The combination of single-phase and three-phase loads exists on the bus. Equation (3) shows the impedance matrix of a three phase load [12].

$$\mathbf{Z}_{abc-L} = \begin{bmatrix} \dfrac{|V_a|^2}{P_a - jQ_a} & 0 & 0 \\ 0 & \dfrac{|V_b|^2}{P_b - jQ_b} & 0 \\ 0 & 0 & \dfrac{|V_c|^2}{P_c - jQ_c} \end{bmatrix} \tag{3}$$

(3)

where P_a, P_b, and P_c are the active power and Q_a, Q_b, and Q_c reactive power, respectively, of each phase.

3. Linear State Estimator

The linear state estimator is based on linear relationship of measurement (voltage phasors and current phasors) and states and can be simply explained via π-model of transmission line as presented in [6]. Considering the two port π-model of a transmission line shown in Fig. 1.

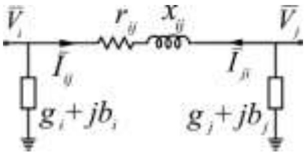

Figure 1: Two port π-model of transmission line

System state vector consists of bus voltages (in polar form), and is given by,

$$\mathbf{x} = [\bar{V}_i^{\,s} \quad \bar{V}_j^{\,s}]^T \tag{4}$$

The measurement vector $\mathbf{z}$ is assumed to be composed of voltage phasor measurements ($\bar{V}_i = V_i \angle \delta_i$, $\bar{V}_j = V_j \angle \delta_j$) and line flow measurements ($\bar{I}_{ij} = I_{ij} \angle \delta_{ij}$, $\bar{I}_{ji} = I_{ji} \angle \delta_{ji}$), is and expressed as,

$$\mathbf{z} = [\bar{V}_i \quad \bar{V}_j \quad \bar{I}_{ij} \quad \bar{I}_{ji}]^T \tag{5}$$

Series admittance and shunt susceptance of the transmission line are given by,

$$y_{ij} = (r_{ij} + jx_{ij})^{-1} \tag{6}$$

$$y_{i0} = g_i + jb_i \tag{7}$$

For this system, the linear relationship between the system states and measurements is given by,

$$\begin{bmatrix} \bar{V}_i \\ \bar{V}_j \\ \bar{I}_{ij} \\ \bar{I}_{ji} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ y_{ij} + y_{i0} & -y_{ij} \\ -y_{ij} & y_{ij} + y_{j0} \end{bmatrix} \begin{bmatrix} \bar{V}_i^{\,s} \\ \bar{V}_j^{\,s} \end{bmatrix} \tag{8}$$

Equation (8) can be easily solved using weighted least square (WLS) method. All the above variables are single phase complex quantities. In next section, the three phase formulation is presented.

4. Three Phase Linear State Estimator

4.1 Main Algorithm

In three phase formulation, real and imaginary part of nodal phase voltages ($\mathbf{v}_{real}$ and $\mathbf{v}_{imag}$), have been taken as system states. Real and imaginary part of PMU voltage and current flow phasors ($\mathbf{v}^m_{real}$, $\mathbf{v}^m_{imag}$, $\mathbf{i}^m_{real}$, $\mathbf{i}^m_{imag}$) are used as measurements, to achieve linear measurement-state relationship, which is given by,

$$\begin{bmatrix} \mathbf{v}_{real}^{m} \\ \mathbf{v}_{imag}^{m} \\ \mathbf{i}_{real}^{m} \\ \mathbf{i}_{imag}^{m} \end{bmatrix} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \\ \mathbf{H}_1 & -\mathbf{H}_2 \\ \mathbf{H}_2 & \mathbf{H}_1 \end{bmatrix} \begin{bmatrix} \mathbf{v}_{real} \\ \mathbf{v}_{imag} \end{bmatrix} + \mathbf{e} \qquad (9)$$

where $\mathbf{H}_1 = real(\mathbf{yA} + \mathbf{y}_s)$ and $\mathbf{H}_2 = imag(\mathbf{yA} + \mathbf{y}_s)$.

Or, in simplified form,

$$\mathbf{z} = \mathbf{Bx} + \mathbf{e} \qquad (10)$$

Measurement data $\mathbf{z}$ have been generated using base case and then introducing Gaussian distributed error $\mathbf{e}$ for each phase. Matrix $\mathbf{I}$ is the three phase voltage incidence matrix and its size depends on the availability of voltage phasor measurements. Matrix $\mathbf{0}$ is the three phase null matrix having dimension same as $\mathbf{I}$. Series admittance $\mathbf{y}$ and shunt susceptance $\mathbf{y}_s$ matrix have been formulated on three phase basis. Current flow measurement locations decide the dimension of current-bus incidence matrix $\mathbf{A}$. Matrix $\mathbf{A}$ is a combination of unity matrix (3×3) at diagonal position corresponding to available current measurements, but with positive sign to leaving current and negative sign to incoming current with respect to sending end bus.

Weighted least square (WLS) method is employed for estimation process, where $\mathbf{W}$ is the weight matrix corresponding to PMU measurements,

$$\mathbf{x} = (\mathbf{B}^T\mathbf{W}^{-1}\mathbf{B})^{-1}\mathbf{B}^T\mathbf{W}^{-1}\mathbf{z} \qquad (11)$$

The above approach closely follows the methodology proposed in [13]. The present paper will extend and validate the method.

4.2 Bad Data Processing

Bad data detection is extremely important for any state estimator. State estimators must be able to detect, identify and remove bad data from the measurement set. PMU measurements may contain errors due to various reasons, such as: telecommunication system failures, bias errors, and noise.

In WLS state estimation, the bad data detection is typically done by examining the measurement residuals. This has to be done after the estimation process. Most commonly used bad data detection and identification methods are χ^2-test and normalized residual test. Once the bad data are identified, these measurements are eliminated from measurement set before the next iteration of state estimation. After each elimination, WLS state estimation procedure is repeated. In this work, instead of eliminating the bad data, it has been replaced by last estimated respective measurement to maintain redundancy level.

5. Simulation and Results

Depending on various operating conditions of test system, five cases have been simulated. The measurements are assumed to be coming from PMUs, and that make entire system observable. The measurement set consists of three phase voltage and three phase current measurements in rectangular form. In all cases, Gaussian distributed error with zero mean and 0.0001 and 0.0003 variance has been introduced to voltage and current measurements in per unit, respectively. Three phase state estimation have been carried out under different scenarios, i.e., fully transposed lines, some untransposed lines, unbalanced faults on bus, and some unbalanced loads. Bad data detection and processing is done under normal operating conditions.

In the first case, the system has been considered under balance conditions, i.e., all lines are fully transposed and loads are balanced under normal operating condition. Voltage measurements have been generated using actual load flow results, and current measurements have been simulated using three phase admittance matrix and actual nodal voltages. Gaussian error has been added to actual measurements with predefined weights. In this case, the estimated states are balanced and are same as obtained in positive sequence state estimation under normal operation.

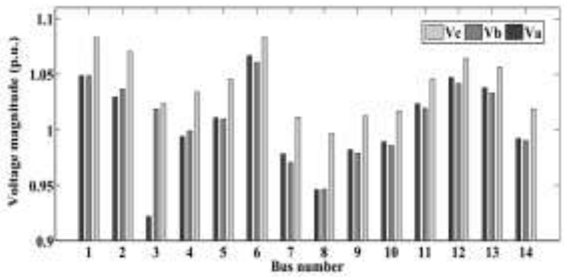

Figure 2: IEEE 14 bus system - Voltage magnitude in p.u. with some untransposed lines

In the second case, some of the transmission lines are assumed untransposed and having mutual coupling effect. In IEEE 14 bus system, untransposed transmission line data have been taken from [6] for seven lines that link buses 1, 2, 3, 4, and 5. In this case, the estimated states are unbalanced that represents the presence of negative and zero sequence components.

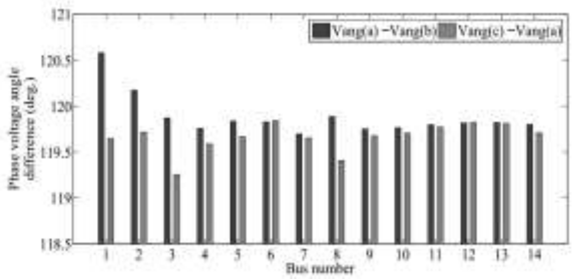

Figure 3: IEEE 14 bus system - Voltage angle difference (deg.) with some untransposed lines

Estimated states for IEEE 14 bus system is shown in Fig. 2 and Fig. 3. Effect of unbalance can be clearly seen in both figures. Fig. 3 shows the angle difference between two phases, and it should be 120^o in fully transposed lines.

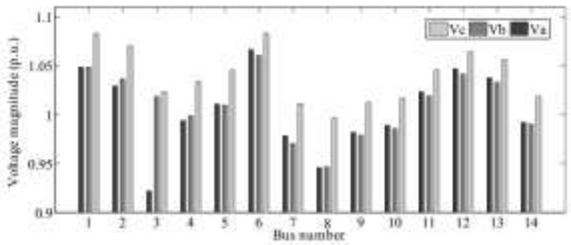

Figure 4: Voltage magnitude (p.u.) -IEEE 14 bus system with unbalanced loading

In third case also for IEEE 14 bus system unbalanced load data have been taken from [6]. As shown in Fig. 4 and Fig. 5 effect of unbalanced loading is much more in comparison to untransposed lines.

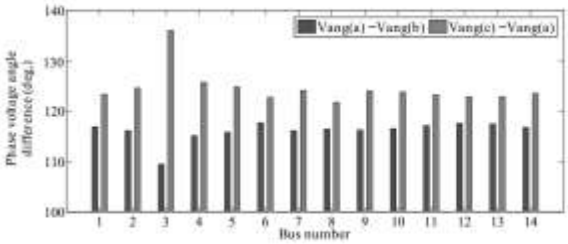

Figure 5: Voltage angle difference (deg.) -IEEE 14 bus system with unbalanced loading

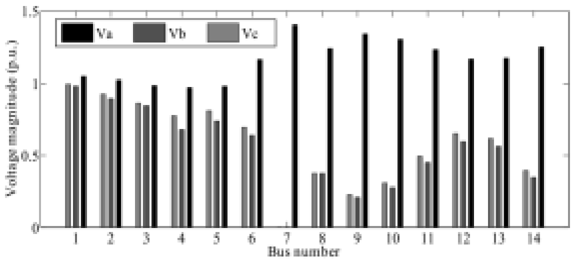

Figure 6: Voltage magnitude (p.u.) -IEEE 14 bus system with LLG fault at bus 7

In fourth case fault has been simulated on bus 7 and 18 for IEEE 14 and New England 39 bus system respectively. Different types of faults have been created and results have been shown for LLG and LG faults. Fig. 6 and Fig. 7 show the estimated phase voltage magnitudes and phase angle difference between two phases, at the time of LLG fault on phase b and c of bus 7.

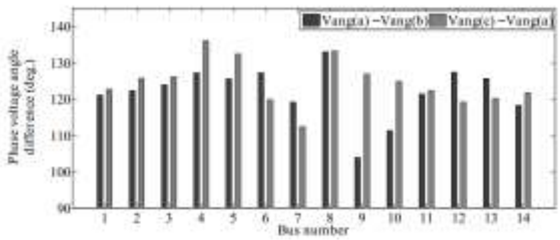

Figure 7: Voltage angle difference (deg.) -IEEE 14 bus system with LLG fault at bus 7

In fifth case some bad data have been introduced in generated measurement sets to see the effect considering system to be operated under balanced conditions. χ^2-test has been performed to locate the error. For IEEE 14 bus system 10 % error has been added to the specific iteration or time instant (as identified in test). Considering PMUs to be located at each bus, degree of freedom has been taken 59 with 95 % confidence level for χ^2-test. Corresponding threshold value (i.e. 77.9305) has been taken to identify the bad data. Results are shown in Table 1.

Table 1: Bad Data Detection and Identification: IEEE 14 Bus System

Bad Data	*Maximum Mismatch*	χ^2 *-value*	*Error Detection*	*Error Location*
0	0.049	22.6097	181	65
1	0.0808	87.3141*	25	15
1	0.077	84.3965*	80	21
2	0.0925 0.0918	106.1041* 99.2220*	95	9 14

*More than Threshold Value (i.e. = 77.9305)

Table 2: Bad Data Detection and Identification: New England 39 Bus Test System

Bad Data	*Maximum Mismatch*	χ^2 *-value*	*Error Detection*	*Error Location*
0	0.0177	140.3599	120	215
1	0.2114	214.3831*	30	7
1	0.2134	216.4268*	60	13
2	0.2125 0.2163	215.5498* 219.4354*	50	7 13

*More than Threshold Value (i.e. = 174.2242)

In New England 39 bus test system, the effect of untransposition have been considered on line 1, 2, 3, 4, 5, 6, 7, 8, and 9. These effects can be seen in Fig. 8.

Fig. 9 shows the estimated phase voltage magnitudes and phase angle difference between two phases, at the time of LG fault on phase a and LLG fault on phase b and c of bus 18.

For new England 39 bus test system 20 % error have been added to the specific iteration or time instant (as identified in test). Considering PMUs to be located at each bus, degree of freedom has been taken 138 with 98 % confidence level for test. Corresponding threshold value (i.e. 174.2242) has been taken to identify the bad data. Results are shown in Table 2. As soon as bad data is identified, we replace it with last measurement obtained from PMU, and re-estimate the state.

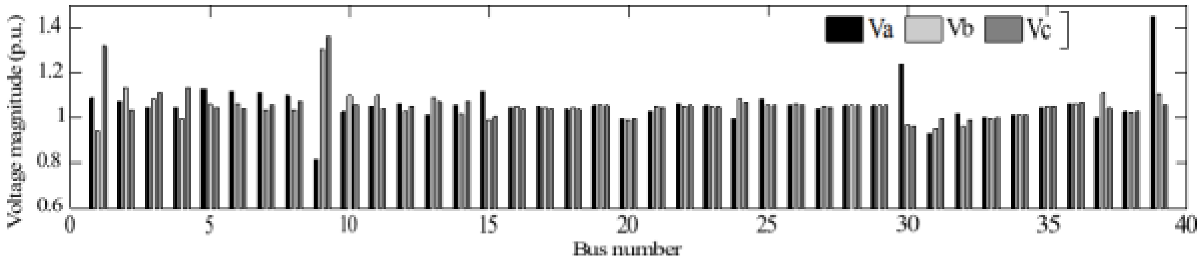

Figure 8: Voltage magnitude (p.u.) with fully transposed and some untransposed lines cases -New England 39 bus test system

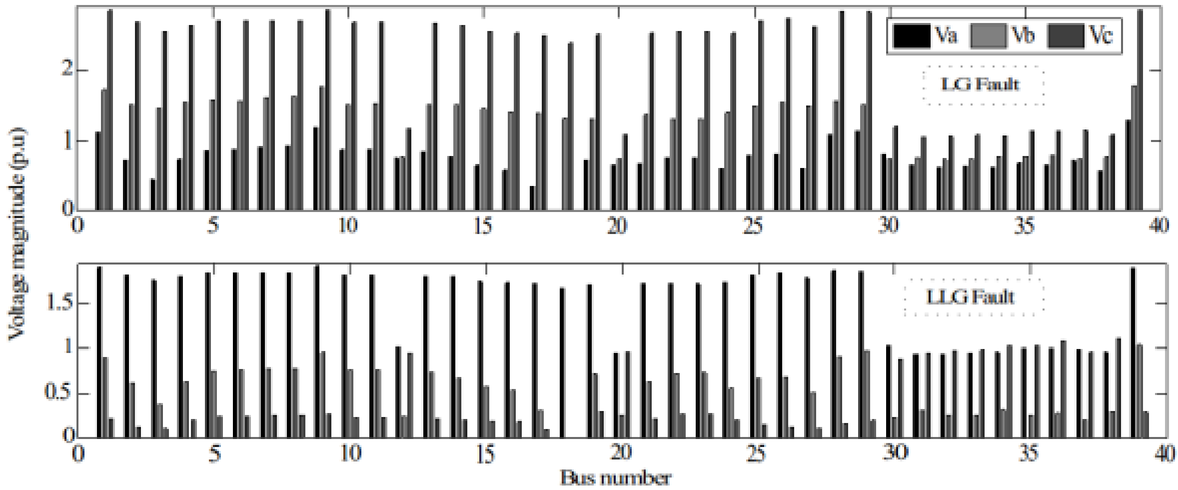

Figure 9: Voltage magnitude (p.u.) at fault LG and LLG -New England 39 bus test system

For new England 39 bus test system 20 % error have been added to the specific iteration or time instant (as identified in test). Considering PMUs to be located at each bus, degree of freedom has been taken 138 with 98 % confidence level for test. Corresponding threshold value (i.e. 174.2242) has been taken to identify the bad data. Results are shown in Table 2. As soon as bad data is identified, we replace it with last measurement obtained from PMU, and re-estimate the state.

6. Conclusion

Generally used state estimators consider the system completely balanced. This assumption masks the natural behavior of power system. This paper focuses on the three phase-state estimation, and consider system imbalance while estimation of system states. State estimation considering untransposed lines, unbalanced loads and various types of faults has been analyzed. For both the test systems, under normal operating condition all three-phase voltages at each buses are balanced with slight uncertainty due to introduced measurement errors. Untransposition of some transmission lines and some unbalanced loads, lead to system imbalance, that affects the single phase state estimator performance, so three phase state estimator using only PMU measurements is comparatively more accurate and faster than conventional three phase state estimator. Using three phase linear state estimator fault identification and location may become faster and system can be protected by taking possible control action immediately. Post-estimation bad data processing has been done successfully.

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