Effect of the Conductor Temperature on the State Estimation of Power Systems

A. de la Villa Jaén, J.C. del Pino López, P. Cruz Romero
Departamento de Ingeniería Eléctrica
E.S.I., Universidad de Sevilla
Camino de los Descubrimientos s/n, 41092 Sevilla (España)
e-mail: adelavilla@us.es, vaisat@us.es, plcruz@us.es

Jorge Tello Guijarro
Active networks and critical infrastructure
Unión Fenosa Distribución
Calle Antonio López 193 pl. 01. 28026 Madrid (España)
e-mail: jtellog@gasnatural.com

Abstract. The operation state of electric networks is customarily obtained in real time in the control center by means of the state estimator. This application uses databases with electrical parameters of lines and transformers to build the electrical model of the network. One of these parameters is the resistance of the line conductors, which is usually defined for a common reference temperature for all the lines. This way, the noticeable effect of the temperature on the conductor resistance is not considered in the electrical model of the lines.

In this work, the errors derived from this assumption are analyzed in two types of networks: a real HV distribution network from Unión Fenosa Distribución and a possible future European-level 800 kV supergrid.

Key words: state estimation, distribution network, supergrid, thermal model, bad data.

1. Introduction

The monitoring of electric networks is performed in the control centers by means of the state estimator (SE), which consists on an algorithm that obtains the operational state of the electrical network for a particular time instant from the available measurements. The estimated state, apart from being used to monitor the network, is the starting point of other applications running in the control center which rely on the quality of SE results [1, 2].

The redundancy of measurements existing in the information acquired from electrical networks allows to develop a procedure to detect and identify erroneous measurements that eventually are discarded from the SE [1,2].

SEs use the values of electrical parameters of the network in their electrical models of lines and transformers. The values of the line resistance are customarily considered constants and obtained for a particular reference temperature. However, when conductors are operating at temperatures different to the reference one, an additional error is introduced in the electrical model. SEs assume that the values of electrical parameters are exact, so the error due to the temperature variation results in measurement errors. As will be highlighted in this paper, these errors cause disturbances in the process of analysis of bad data filtering carried out by SEs.

In [3] a procedure to estimate the conductor temperature as a function of the ambient conditions and load level of lines is proposed. However, that work does not analyze the impact on the analysis of network operation state of erroneous information.

In the present work, the effect of the temperature variation on the identification of bad data inside the SE is analyzed. Apart from the temperature, the effects of network loading and type of measurements are also considered. To that end, in addition to the conventional measurements, other scenarios with measurements provided by phasor measurement units (PMU) will be considered.

2. State Estimation in Electrical Power Systems

The purpose of a SE is to obtain the operational state of an electric network starting from the whole information available in the control center. The estimated state is, statistically speaking, the optimum that can be obtained from both the incoming information and network models. Given the following measurement equation [1, 2]

$$z = h(x) + e \,, \qquad (1)$$

where *x* is the state vector to be estimated, *z* is the known measurement vector, *h* is the vector of functions (usually nonlinear) relating error free measurements to the state variables and e is the vector of measurement errors (customarily assumed to have a Normal distribution with zero mean and known covariance matrix R). The Weighted Least Squares (WLS) estimator provides the maximum likelihood estimation by minimizing the following scalar function:

$$J = r^T W\, r = \sum_{i=1}^{m} W_i r_i^2, \qquad (2)$$

where $r = z - h(\hat{x})$ is the measurement residual, $\hat{x}$ the estimated state vector, *m* the number of measurements and $W = R^{-1}$ the weighting matrix. When errors are independent, R is a diagonal matrix with values σ_i^2, where σ_i is the standard deviation of the error associated with measurement *i*.

The minimum of the scalar J can be obtained by iteratively solving the so-called Normal equations:

$$G_k \Delta x_k = H_k^T W[z - h(x_k)], \tag{3}$$

where $H_k = \partial h / \partial x$ is the Jacobian evaluated at $x = x_k$, $G_k = H_k^T W H_k$ is the gain matrix, $\Delta x_k = x_{k+1} - x_k$, and k being the iteration counter. Iterations finish when an appropriate tolerance is reached on x_k.

After convergence, the bad data processing function, based on the largest normalized residual test [1, 2], is run to detect, identify and eliminate bad analog measurements. This method is based on checking the normalized residual associated to each measurement, calculated by

$$r_i^N = \frac{|z_i - h_i(\hat{x})|}{\sqrt{\Omega_{ii}}} \tag{4}$$

where Ω is the residual covariance matrix. This matrix can be computed in an efficient way from

$$\Omega = R - H[H^T R^{-1} H]H^T. \tag{5}$$

If the largest normalized residual is higher than a threshold, then the respective measurement will be suspected as bad data and must be eliminated from the measurement set. Usually this threshold value is 3.

3. Test of a real HV distribution network

A. *Simulation based on a real case*

In this section several simulations on a real HV distribution network from the Spanish utility Unión Fenosa Distribución will be presented. The network is composed by 230 nodes and 320 branches, encompassing 400, 220, 132 and 66 kV. The network has been monitored, being the total number of measurements 2230.

The weights of the measurements used in these tests are employed by the planning SE of Unión Fenosa Distribución. These weights have been obtained individually for each measurement, considering the uncertainties of all the devices in the measurement chain.

As a base case, the operating state at the highest yearly demand of 2015 has been considered (January the 22th at noon), being the demanded power 6757 MW. The procedure has been as follows:

1. In the network model the resistances are calculated at 70 ºC.
2. The estimated state corresponding to the base case is obtained.
3. Starting from the estimated state, a set of exact measurements are obtained. The same distribution and type of measurements than the real case are considered.

In this simulation the errors incurred by the adoption of a constant resistance-based model at 20 ºC are considered. To that end, the resistance of the network model changes according to the considered temperature. The new values of resistances are obtained by means of

$$R_T = R_{20}[1 + \alpha(T - 20)], \tag{6}$$

where T is the new temperature, R_T the resistance at temperature T, R_{20} the resistance at 20 ºC, and α the coefficient of temperature. The set of exact measurements do not present errors when considering the temperature of 70 ºC.

Figure 1 shows the highest values of normalized residuals obtained in case of a simulation of the estimation process using a network model at 20 ºC with measurements obtained with the same model but at 70 ºC.

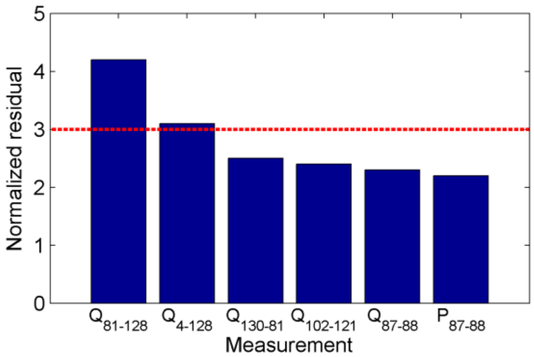

Figure 1. Highest normalized residuals in test 3-A.

B. *Load increase test*

In this test the impact of increasing the load level of the network by 50 %, and its resultant temperature is assessed. The scenario has been obtained as follows:

1. The network model is defined at 90 ºC.
2. The estimated state of the network with the real measurements scenario is obtained.
3. Starting from the estimated state, the power injections in all the nodes of the network are obtained.
4. A load flow using the slack bus voltage and increasing the injected power in the rest of the nodes by a 50 % is developed. This means a power demand of 10,136 MW.
5. With the state obtained by the load flow a set of exact measurements are generated. In the loaded scenario the same distribution and type of measurements than in the real scenario are considered.

The load scenario obtained does not introduce errors when using a network model at 90 ºC. Figure 2 shows the highest values of normalized residuals obtained when running a SE simulation using a network model at 20 ºC when the measurements correspond to the load scenario at 90 ºC.

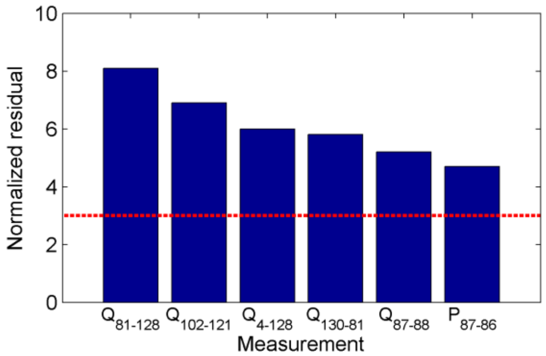

Figure 2. Highest normalized residuals in test 3-B.

C. *Analysis of results*

The non-zero values of the normalized residuals obtained from Figures 1 and 2 are direct consequence of using an improper network model. These values are the best quantitative indicators of the impact that conductor resistances not depending on temperature have on the estimation process.

Comparing Figures 1 and 2, it is observed a significant increase of the value of the normalized residuals due to the increase of load and the temperature of conductors.

It is interesting to highlight that there are normalized residuals higher than the threshold of 3. Thus, there will be measurements that, in spite of being exact, are regarded as erroneous. For example, in the simulation 3-A the measurements of power flows through the line 81-128 at 132 kV are misclassified as erroneous, since the reactive power measurement presents a normalized residual of 4.2. However, and after being discarded and repeated the estimation, the measurement of active power at that line is now classified as erroneous (normalized residual of 3.4). Also in test 3-B more measurements regarded as erroneous are detected (Table 1), even though they are not really erroneous. In this table the value of the normalized residual of each measurement has been obtained at the moment of being the measurement identified as bad data. Thus, these measurements are discarded, reducing the global redundancy of the estimation.

Table 1. Bad data in simulation 3-B.

Measur.	NR	Measur.	NR	Measur.	NR
Q_{81-128}	8.1	Q_{81-130}	7.2	Q_{30-31}	3.3
$Q_{102-121}$	6.9	Q_{88-217}	4.2	Q_{31-30}	4
$Q_{121-102}$	8.7	P_{87-86}	3.9	Q_{31}	5.1
Q_{87-88}	5.1	P_{86-87}	4.4	Q_{33}	5
Q_{88-87}	6.4	P_{86}	6.5	Q_{1-75}	3.9
Q_{13-12}	4.9	Q_{75-74}	3.8	Q_{2-1}	3.8
Q_{12-13}	5	Q_{1-21}	3.6	Q_{1-2}	4.7
Q_{148-39}	4.6	Q_{21}	4.1	Q_{75-1}	4.4
Q_{39-148}	5.8	Q_{33-30}	3.6	Q_{13-21}	3.8
Q_{21-13}	4.4	Q_{30-33}	3.6	Q_{2}	3.9
Q_{130-81}	4.4	Q_{21-1}	3.6	P_{81-128}	3

On the other hand, even though the measurements regarded as erroneous have been discarded, an important number of non-erroneous measurements stay, but contaminated with non-zero normalized residuals due to the model error. Figures 3 and 4 show the values of normalized residuals after suppressing all the measurements misclassified as erroneous. It should be noted that this contamination in the normalized residuals will hinder the error analysis in real cases where the measurements have noise generated in the measurement chain. It is worthy to note that in the simulation 3-A there are 303 measurements (15 %) with normalized residuals higher than 0.5. This figure increases remarkably in the case 3-B, where there are 634 measurements (31 %)

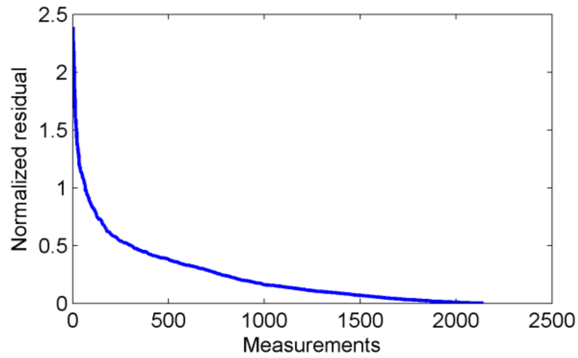

Figure 3. Normalized residuals in simulation 3-A.

3

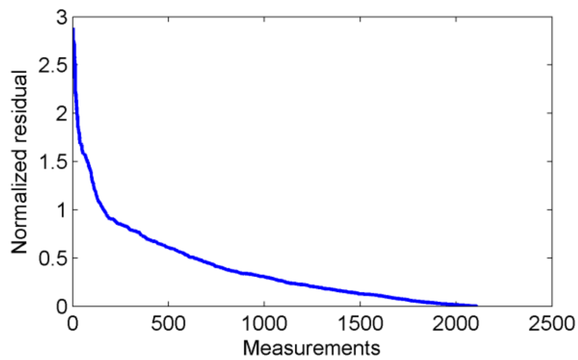

Figure 4. Normalized residuals in simulation 3-B.

4. Simulation of an European supergrid

The increase of the electric energy through the European transmission network, together with the possibility of integrating renewable energy from areas with a high potential, (e.g. North Sea. Northern part of Africa), are the driving forces behind the project of building an European supergrid [4]. One of the possibilities is the construction of a HVAC supergrid of 800 kV. The exploitation of this kind of network is characterized by high levels of load in order to recover the initial investment. Henceforth, it is expected that the conductor temperature may be high for long periods of time. Hereafter, the effect of the conductor temperature on the SE of a supergrid is considered.

A. *European supergrid with conventional measurements*

Figure 5 shows a hypothetical HVAC supergrid at 800 kV in Europe, adapted from [4]. Table 2 shows the lengths of the considered lines. The values of the electrical parameters of the lines are: (1) resistance:

0.00879 Ω/km at 20 ºC; (2) reactance: 0.2629 Ω/km; (3) susceptance: 4.216e-6 S/km. Notice that for supergrids the series resistance is much smaller than the reactance in comparison with networks with lower voltage.

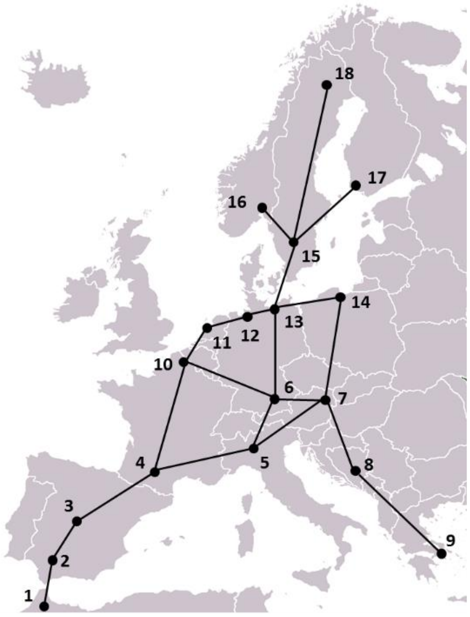

Figure 5. European Supergrid.

Table 2. Lengths of the lines in the supergrid.

Line	Length (km)	Line	Length (km)
1-2	1000	10-11	300
2-3	350	11-12	300
3-4	600	12-13	250
4-5	650	6-13	650
5-6	550	13-14	600
6-7	400	7-14	750
7-8	150	13-15	450
8-9	850	15-16	350
5-7	650	15-17	650
4-10	800	15-18	1000
10-6	600		

The procedure for the simulation is as follows:

1. The value of the resistances of the network model are calculated at 90 ºC.
2. A power flow with the values of Table 3 (global demand of 10.4 GW) is performed.
3. With the output of the load flow a scenario of exact measurements is generated. All the node voltages, all the power flows at both ends of the lines and all the node power injections have been considered.

The set of exact measurements obtained does not exhibit any error when considering a supergrid network at 90 ºC. The standard deviations of the measurements have been 4.32 kV for the voltage measurements, 3.5 MW for the real power measurements and 3.5 Mvar for the reactive power measurements.
When the state estimation is performed assuming a conductor temperature of 20 ºC the identified erroneous measurements are those shown in Table 4. Despite of the fact that series resistance has a much lower value than reactance at 800 kV, the table shows that some of the measurements have normalized errors higher than 3, wrongly identifying the presence of erroneous measurements.
Notice that power injections at node 5 are wrongly detected as erroneous measurements, being this node where there is more power injection. This valuable information is lost in the process of SE.

Table 3. Load flow in the supergrid.

Node	City	P_i (GW)	Q_i (Gvar)
1	Rabat	1.4	
2	Córdoba	-0.2	-1.6
3	Madrid	-2	-1
4	Toulouse	-0.6	-2.4
5	Milan	5.2	
6	Munich	-0.8	-2.8
7	Viena	-1.6	-2.1
8	Sarajevo	-0.4	-1.1
9	Atenas	1.6	
10	Lille	-0.5	-2.2
11	Amsterdam	-1.2	-0.6
12	Bremen	-0.8	-1.2
13	Rostock	-1	-2
14	Gdansk	-0.8	-2
15	Jönköping	-0.5	-2.8
16	Oslo	1.2	
17	Åbo	0.7	
18	Harsprånget	0.5	

Table 4. Bad data in simulation 4-A.

Measur.	NR	Measur.	NR
P_5	4.3	Q_1	4
Q_{9-8}	3.8	Q_{1-2}	3
Q_5	3.8	Q_{5-4}	3.1
Q_9	5.2		

Figure 6 shows the values of normalized residuals that remain after suppressing erroneous measurements. There are 74 out of 132 measurements with normalized residuals higher than 0.5 (56 % of the available measurements).

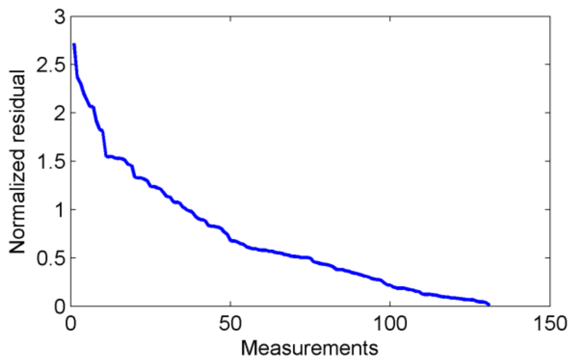

Figure 6. Normalized residuals for simulation 4-A.

B. *European Supergrid with measurements of PMU*

The measurements of synchrophasors provided by the PMUs are nowadays being incorporated in the process of SE to monitor in a more precise way the network operation state [5]. These measurements are characterized for having higher accuracy than conventional ones, so their weights are more significant in the process of SE.

In this work a polar formulation (magnitude and phase) is used for the voltage synchrophasors, and a rectangular formulation for the current ones.

The process followed to perform the test has been similar to the one described in the previous section, changing only the type of measurement considered. A measurement of synchrophasor of current has been included at each line end and injection, and a measurement of voltage synchrophasor at each node. The standard deviations for these measurements have been 1.9 kV in the magnitude and 0.05º in the phase for the voltage measurements, and 0.7 A for the rectangular components of current synchrophasors [6].

Table 5 shows the measurements wrongly identified as erroneous when testing the scenario created with a network model at 20 ºC. It can be shown that the normalized residuals have increased significantly with regard to the conventional measurements.

Table 5. Bad data in simulation 4-B.

Measur.	NR	Measur.	NR	Measur.	NR
$Im(I_{10})$	6.3	V_1	4.4	$Im(I_{15-17})$	3.9
$Im(I_9)$	5.7	$Im(I_5)$	3.8	V_{17}	4.1
$Im(I_{9-8})$	7.1	$Im(I_{1-2})$	3.8	$Im(I_{5-7})$	3.6
V_9	4.6	$Im(I_1)$	5	$Im(I_{5-4})$	3.6
$Im(I_{18-15})$	4.5	V_5	3.9	$Im(I_{5-6})$	3.7
$Im(I_{18})$	5.6	$Im(I_{15-18})$	3.4	V_{16}	3.6

Note: Im denotes for imaginary part.

Figure 7 shows the normalized residuals of the measurements not identified as erroneous. It is observed that the contamination level is high, being 50 measurements (38 %) with a normalized residual higher than 0.5.

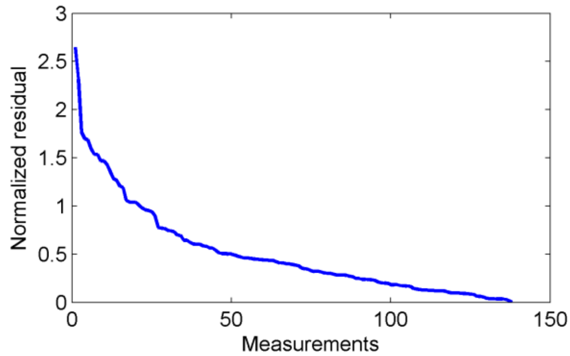

Figure 7. Normalized residuals for simulation 4-B.

If we compare these results with the test of the previous section, it is observed that the number of contaminated measurements that have normalized residuals higher than 0.5 has been reduced. The reason is that in this test all the state variables of the system (magnitude and phase of voltage in the nodes) are measured directly and the network parameters are not needed. Only the current synchrophasors use the power system parameters. Despite that, several voltage measurements are identified as erroneous.

5. Reference temperature to calculate the resistance of conductors

The tests performed previously assumed a temperature of 20 ºC for the calculation of conductor resistivity.

An alternative to reduce the effect of temperature increase due to the load is increasing the conductor reference temperature. In this section the simulation performed in section 3-B is repeated for the case of the distribution network from Unión Fenosa with a higher load level. In this case the reference temperature is 40 ºC.

Table 6 shows the measurements wrongly identified as erroneous. The value of the normalized residuals is lower than in Table 1, where a reference temperature of 20 ºC was considered. Thus, the number of measurements wrongly identified as erroneous is lower.

Figure 8 shows the normalized residuals obtained after suppressing all the erroneous measurements. The result obtained is that, even though the reference temperature has been raised, there remains an important contamination in a significant number of measurements: a total of 595 measurements (29 %) have normalized residuals higher than 0.5.

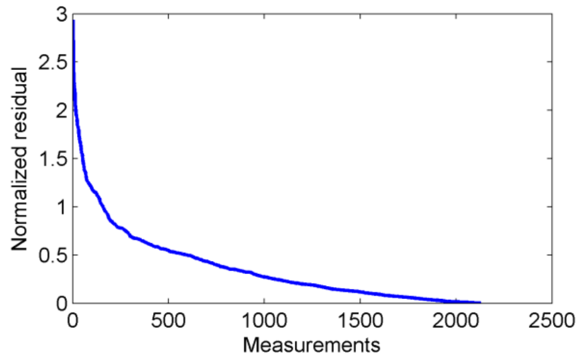

Figure 8. Normalized residuals for simulation 5.

Table 6. Bad data in simulation 5.

Measur.	NR	Measur.	NR	Measur.	NR
Q_{81-128}	6	Q_{13-12}	3.7	Q_{130-81}	3.3
$Q_{102-121}$	5.1	Q_{12-13}	3.8	Q_{81-130}	5.4
$Q_{121-102}$	6.5	Q_{148-39}	3.5	P_{87-86}	3.1
Q_{87-88}	3.7	Q_{39-148}	4.4	P_{86-87}	3.5
Q_{88-87}	4.7	Q_{21-13}	3.3	P_{86}	5.2

6. Conclusions

In this work the impact of the temperature variation of line conductors on the process of SE of electrical networks is analyzed. Two types of network have been tested: a real distribution network and a synthetic supergrid of 800 kV.

The simulations show that the variations of temperature leads to a misbehavior in the analysis of the bad data performed by the SE. On one hand some measurements are identified as erroneous despite on the fact that are exact. On the other hand the rest of measurements remain contaminated in a significant way due to the wrong network model.

It has been checked that this behavior is reinforced with the network load level, the operating temperature or the quality of measurements (e.g. PMUs).

As an alternative the resistance reference temperature was increased, reducing the number of measurements wrongly identified as bad dat, but persisting a significant contamination of the rest of measurements.

The results of this work suggest that it is advisable to include in the electrical model of the lines the effect of temperature. This way, the contamination in a great number of available measurements would be reduced.

These aspects will be further tackled by the authors.

Acknowledgements

This work has been supported by the collaboration agreement between Unión Fenosa Distribución and the Department of Electrical Engineering of the University of Sevilla, and by the Spanish Ministry of Science & Innovation (ENE2013-48428-C2-1-R) and the Spanish Ministry of Economy and Competitiveness (ENE2014-54115-R).

References

[1] A. Monticelli, *State Estimation in Electric Power Systems: A Generalized Approach*. Norwell, MA: Kluwer, 1999.

[2] A. Abur, A. Gomez-Exposito, Power System State Estimation: Theory and Implementation. Marcel Dekker, 2004.

[3] M. Bockarjova, G. Andersson, “Transmission Line Conductor Temperature Impact on State Estimation Accuracy”, IEEE Power Tech, 2007 Lausanne.

[4] G. Asplund, B. Jacobson, B. Gerggren, and K. Lindén, “Continental Overlay HVDC-Grid”, Cigré Session 2010, B4-109, Paris.

[5] Gomez-Exposito, Ali Abur, P. Rousseaux, A. de la Villa Jaen, C. Gomez-Quiles, “On the Use of PMUs in Power System State Estimation”, 17th Power Systems Computation Conference PSCC, Stockholm 2011.

[6] S. Chakrabarti, E. Kyriakides, “PMU Measurement Uncertainty Considerations in WLS State Estimation”, IEEE Transactions on Power Systems, Vol. 24, No. 2, May 2009.