State Estimation Reloaded with Phasor Measurement for Transmission Systems

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Abstract — **The impact of reloading conventional state estimation with the addition of synchronized phasor measurements to implement a real time monitoring, supervision and control tool with better features including accuracy and convergence, is evaluated. The accuracy of various state estimation methods using a combination of available conventional and phasor measurements is compared. The most suitable state estimation method for the analyzed cases is determined. The results obtained for a practical case of the Colombian Transmission System are compared to support the obtained conclusions.**

Keywords—Phasor Measurement Unit – PMU, Real time Monitoring Supervision and Control, State Estimation, Synchronized Phasor Measurement Systems.

I. INTRODUCTION

State estimation is an essential tool for real-time monitoring, supervision and control of a power system. This tool designed in the 70s [1] was introduced to control centers from the 80s [2, 3] and since then it has served as the basis for real-time analysis of electric systems which are based on the solution of the model equations describing its behavior, resulting in a set of variables which define the operating condition of the electric system with a good approximation.

Despite the undeniable benefits this tool has brought to the power systems analysis, its development has been slow because an improvement in this process using a separate set of data than the normal rates used for SCADA has not been justified. As a consequence, state estimation has had to live with deficiencies such as:

- Non-simultaneity of the analogue data,
- Unobservability when a significant amount of measurements is lost,
- Occasional non-convergence of the solution process, etc.

With the implementation of a synchronized phasor measurement system, voltage and current measurements (magnitude and angle) are synchronously obtained in real-time, and therefore all measures derived from them can be calculated. Besides simultaneity, phasor measurement systems have been designed with sampling rates of 20 to 100 samples per second which transcends the needs of the real-time response of an operator of an electric system, allowing having a set of measurements for analysis applications of both steady and dynamic state. This provides an advantage, part of the state vector is being measured accurately in magnitude and angle for decision making in a given time by the system operator, and besides the measurements can be used for other purposes e.g. for system model validation [4].

This paper presents the basic concepts of conventional state estimation, followed by an explanation of the improvements of the addition of phasor measurements, studying different ways to take these measurements into account. The use of phasor measurements only (linear and nonlinear cases) and the use of both types of measurements (conventional and phasor in a mixed state estimation), is presented next. The results of the simulation for the Colombian National Transmission System (STN) for 500 kV and 230 kV voltage levels are discussed.

Based on the results obtained, a comparison between the different types of state estimations is performed evaluating the standard deviations of the estimated state vector. Finally, the results of a sensitivity analysis considering the number of implemented PMUs and a reduction of the conventional measurements, are analyzed.

II. STATE ESTIMATION

"State estimation" is the process of assigning a value to the set of unknown state variables of the system for a specific time, based on measurements of the system according to a given criterion. In general, the process involves imperfect measurements that are redundant, so that the state estimation can be based on a statistical approach that estimates the true value of the state variables to minimize or maximize a selected criterion.

Conventional state estimation is fed with measurements taken from the electric system that are collected at the same rate as those used by SCADA systems, usually in time windows ranging between 2 and 10 seconds depending on the sampling times of both equipment position and analog variables (commonly active and reactive power), the speed of available communication channels and the performance of computer systems that process these data.

It is vital for the system operator know the real-time operating conditions of the power system, since it can define

978-1-4799-6251-8/14/$31.00

whether the system is operating properly or not based on this information. This is done with the help of the system state estimator which has a number of stages to estimate the final values of the system state variables (magnitude and angle voltages). The model of the system can be validated using data from the state estimator i.e. to obtain a consistent model of the system in real-time.

The state estimation problem is formulated as:

$$\boldsymbol{z} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{\varepsilon} \tag{1}$$

Where $\boldsymbol{z}$ is the measurement vector of the power system with dimension $(m \times 1)$, $\boldsymbol{x}$ is the state variable vector with dimension $(n \times 1)$, $\boldsymbol{f}(\boldsymbol{x})$ is the function vector that relates the measurement vector with the state variables with dimension $(m \times 1)$ and $\boldsymbol{\varepsilon}$ is the measurement error with dimension $(m \times 1)$.

The criterion of weighted least squares (WLS) minimizes the sum of the weighted squared deviations of the estimated measurements:

$$\min \boldsymbol{J}(\boldsymbol{x}) = \sum_{k=1}^{m} \frac{(z_k - f_k(x))^2}{\sigma_k^2} \tag{2}$$

Equation (2) can be expressed using matrices as:

$$\min \boldsymbol{J}(\boldsymbol{x}) = [\boldsymbol{z} - \boldsymbol{f}(\boldsymbol{x})]^T R^{-1} [\boldsymbol{z} - \boldsymbol{f}(\boldsymbol{x})] \tag{3}$$

Where $R = cov(\boldsymbol{\varepsilon})$ is the covariance matrix of measurements errors.

It is assumed that the power system is operating at steady state under balanced conditions, transmission lines are fully transposed and the other series or shunt elements of the system are symmetric in all three phases, these assumptions allow the positive sequence equivalent circuit to model the complete system.

It is possible to use a model for transmission lines and transformers, in which the symmetry is maintained in order to use expressions of current (or active and reactive power) symmetrical with respect to the nodes to which the element is connected [5]. In Fig. 1 the model described is shown.

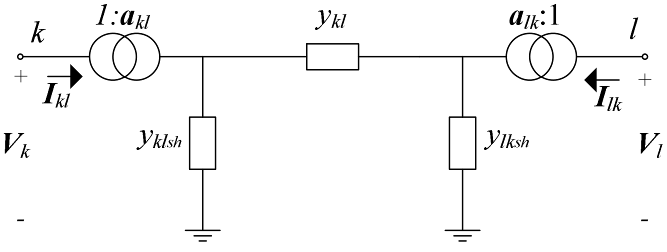

Fig. 1. Transmission Line and Transformer Generalized Model

III. STATE ESTIMATION USING PHASOR MEASUREMENTS

A. State Estimation Using Only Phasor Measurements

The linear relationship between the phasor measurements and the phasor vector of state variables is given by:

$$\bar{\boldsymbol{z}} = \bar{H}\bar{\boldsymbol{x}} + \bar{\boldsymbol{\varepsilon}} \tag{4}$$

Where $\bar{\boldsymbol{z}}$ is the phasor measurements vector, $\bar{\boldsymbol{x}}$ is the state vector expressed as phasor, $\bar{H}$ is a complex matrix and $\bar{\boldsymbol{\varepsilon}}$ is the complex error vector of phasor measurements.

Depending on how the phasor measurements and the state variables are decomposed, i.e. in rectangular or polar form, a linear or nonlinear formulation of state estimation problem can be obtained.

1) Nonlinear State Estimation (NLSE)

The state vector is considered to be expressed in polar coordinates; therefore, functions that relate the current phasor measurements to the state vector are obtained for the generalized π model shown in Fig. 1, with the admittance in rectangular coordinates and using the definitions $\boldsymbol{a}_{kl} = |\boldsymbol{a}_{kl}|e^{-j\varphi_{kl}}$ and $\boldsymbol{a}_{lk} = |\boldsymbol{a}_{lk}|e^{-j\varphi_{lk}}$ for the transformers ratios, are:

$$I_{kl_{re}} = |\boldsymbol{a}_{kl}|^2\left(g_{kl_{sh}} + g_{kl}\right)|\boldsymbol{V_k}|cos\theta_k - |\boldsymbol{a}_{kl}||\boldsymbol{a}_{lk}|[g_{kl}cos\,(\varphi_{lk} - \varphi_{kl}) - b_{kl}sin\,(\varphi_{lk} - \varphi_{kl})]|\boldsymbol{V}_l|cos\theta_l - |\boldsymbol{a}_{kl}|^2\left(b_{kl_{sh}} + b_{kl}\right)|\boldsymbol{V_k}|sin\theta_k + |\boldsymbol{a}_{kl}||\boldsymbol{a}_{lk}|[g_{kl}sin(\varphi_{lk} - \varphi_{kl}) + b_{kl}cos\,(\varphi_{lk} - \varphi_{kl})]|\boldsymbol{V}_l|sin\theta_l \tag{5}$$

$$I_{kl_{im}} = |\boldsymbol{a}_{kl}|^2\left(b_{kl_{sh}} + b_{kl}\right)|\boldsymbol{V_k}|cos\theta_k - |\boldsymbol{a}_{kl}||\boldsymbol{a}_{lk}|[g_{kl}si\,n(\varphi_{lk} - \varphi_{kl}) + b_{kl}cos\,(\varphi_{lk} - \varphi_{kl})]|\boldsymbol{V}_l|cos\theta_l + |\boldsymbol{a}_{kl}|^2\left(g_{kl_{sh}} + g_{kl}\right)|\boldsymbol{V_k}|sin\theta_k - |\boldsymbol{a}_{kl}||\boldsymbol{a}_{lk}|[g_{kl}cos(\varphi_{lk} - \varphi_{kl}) - b_{kl}sin\,(\varphi_{lk} - \varphi_{kl})]|\boldsymbol{V}_l|sin\theta_l \tag{6}$$

Expressions (5) and (6) are simplified for the case of a transmission line as follows:

$$I_{kl_{re}} = \left(g_{kl_{sh}} + g_{kl}\right)|\boldsymbol{V_k}|cos\theta_k - g_{kl}|\boldsymbol{V}_l|cos\theta_l - \left(b_{kl_{sh}} + b_{kl}\right)|\boldsymbol{V_k}|sin\theta_k + b_{kl}|\boldsymbol{V}_l|sin\theta_l \tag{7}$$

$$I_{kl_{im}} = \left(b_{kl_{sh}} + b_{kl}\right)|\boldsymbol{V_k}|cos\theta_k - b_{kl}|\boldsymbol{V}_l|cos\theta_l + \left(g_{kl_{sh}} + g_{kl}\right)|\boldsymbol{V_k}|sin\theta_k - g_{kl}|\boldsymbol{V}_l|sin\theta_l \tag{8}$$

Expressions (7) and (8) provide relations between the real and imaginary parts of the currents for the power system with state variables, which are nonlinear, making it necessary to formulate an iterative process to obtain a solution for the state estimation.

2) Linear State Estimation (LSE)

Taking both phasor measurements and the state variables in rectangular coordinates, the state estimation using only phasor measurements is linear [6]:

$$\bar{\boldsymbol{z}} = A + jB = (H_{re} + jH_{im})(E + jF) + \bar{\boldsymbol{\varepsilon}} \tag{9}$$

Where, A is the vector containing the real parts of the phasor measurements, B is the vector containing the imaginary parts of the phasor measurements, H_{re} is the real part of the matrix $\bar{H}$, H_{im} is the imaginary part of the matrix $\bar{H}$, E is the vector that contains the real parts of the state variables and F is the vector containing the imaginary parts of the state variables.

Performing the operations indicated in (9):

$$A = H_{re}E - H_{im}F \tag{10}$$

$$B = H_{im}E - H_{re}F \tag{11}$$

Combining (10) and (11) in matrix form yields:

$$\begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} H_{re} & -H_{im} \\ H_{im} & H_{re} \end{bmatrix} \begin{bmatrix} E \\ F \end{bmatrix} + \varepsilon \tag{12}$$

From (12), it is shown that by means of this type of formulation, the solution of the state estimation problem is obtained in one step, given the data and the required model are available.

As an example, the linear relationship between the phasor measurements and the state variables for an elementary power system consisting of two nodes and an element represented by the generalized π model shown in Fig. 1 is presented assuming a Phasor Measurement Unit (PMU) at node k, it is measuring voltage $\boldsymbol{V}_k$ and current $\boldsymbol{I}_{kl}$ phasors. Expressing this current in rectangular coordinates, the following expression is obtained:

$$\boldsymbol{I}_{kl} = C_{kl} + jD_{kl} = |\boldsymbol{a}_{kl}|^2\left[\left(g_{kl_{sh}} + g_{kl}\right) + j\left(b_{kl_{sh}} + b_{kl}\right)\right](E_k + jF_k) - |\boldsymbol{a}_{kl}||\boldsymbol{a}_{lk}|[co\,s(\varphi_{lk} - \varphi_{kl}) + jsi\,n(\varphi_{lk} - \varphi_{kl})](g_{kl} + jb_{kl})(E_l + jF_l) \tag{13}$$

Performing the indicated operations, grouping terms and assuming that the elements connected between nodes k and l is a transmission line, the following equations are obtained from (13):

$$C_{kl} = (g_{kl_{sh}} + g_{kl})E_k - g_{kl}E_l - (b_{kl_{sh}} + b_{kl})F_k + b_{kl}F_l \tag{14}$$

$$D_{kl} = (b_{kl_{sh}} + b_{kl})E_k - b_{kl}E_l + (g_{kl_{sh}} + g_{kl})F_k - g_{kl}F_l \tag{15}$$

Expressing in matrix form the relationship between the measurement vector and the state vector, the following expression is obtained:

$$\begin{bmatrix} E_k \\ C_{kl} \\ F_k \\ D_{kl} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ g_{kl_{sh}} + g_{kl} & -g_{kl} & -(b_{kl_{sh}} + b_{kl}) & b_{kl} \\ 0 & 0 & 1 & 0 \\ b_{kl_{sh}} + b_{kl} & -b_{kl} & g_{kl_{sh}} + g_{kl} & -g_{kl} \end{bmatrix} \begin{bmatrix} E_k \\ E_l \\ F_k \\ F_l \end{bmatrix} + \begin{bmatrix} \varepsilon_{E_k} \\ \varepsilon_{C_{kl}} \\ \varepsilon_{F_k} \\ \varepsilon_{D_{kl}} \end{bmatrix} \tag{16}$$

a) Determination of the Slack Node

When no phasor measurements in the system are available, state estimation is calculated by taking voltage phase angle of a node as reference; typically, this reference is the same as used in load flow analysis. Usually, the phase angle of the reference node (slack) is taken as zero for convenience but it may take any value. In the case where there was a single angle phasor measurement, this measurement value could be taken as angular reference.

With the introduction of multiple phasor measurements, the selection of the slack node ceases to be arbitrary and there are two possibilities:

- Select a node with PMU as slack node: in this case the reference angle can be taken as the value measured by the PMU at the time of synchronization; the values of the other angle measurements are referenced to this phase reference. This option works properly while the reference PMU and the communication system are operating normally. If for some reason the reference angle measurement is lost, the state estimation process is affected.
- Another alternative is to perform the state estimation without having to select a reference node. The angular difference between the different angle phasor measurements is what really needs to be considered in this case.

B. Mixed State Estimation

At present power systems have implemented a wide range of conventional measurements, and phasor measurements are getting more and more acceptance. For this reason, it is appropriate to consider a state estimation based on both conventional and phasor measurements particularly during a period of implementation of the latter as a step towards the evolution of SCADA systems based primarily on phasor measurements.

1) Linear Mixed State Estimation (LMSE)

Conventional state estimation (CSE) of the power system is performed. The estimated state vector and their covariances are taken as input data, i.e. measurements that can be called "pseudo-phasor" with their respective errors to perform a liner state estimation increasing the set of phasor measurements from PMUs. To formulate the estimation as a linear problem, it is necessary to consider the measurements vector and state vector in rectangular coordinates. In equation (17) the suggested approach is shown [7].

$$\begin{bmatrix} \begin{bmatrix} \hat{E} \\ \hat{F} \end{bmatrix}_{conv} \\ \begin{bmatrix} A \\ B \end{bmatrix}_{pmu} \end{bmatrix} = \begin{bmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \\ H_{re} & -H_{im} \\ H_{im} & H_{re} \end{bmatrix} \begin{bmatrix} E \\ F \end{bmatrix} + \begin{bmatrix} \boldsymbol{\varepsilon}_{\hat{E}_{conv}} \\ \boldsymbol{\varepsilon}_{\hat{F}_{conv}} \\ \boldsymbol{\varepsilon}_{A_{pmu}} \\ \boldsymbol{\varepsilon}_{B_{pmu}} \end{bmatrix} \tag{17}$$

Where "**1**" is an identity matrix, "**0**" is a matrix of zeros.

The main advantage of this approach is that it preserves the structure of the existing state estimator and it must simply perform an additional step of linear estimation.

2) Nonlinear Mixed State Estimation (NLMSE)

In equation (18) shows the suggested approach [7, 8, 9, 10, 11].

$$\begin{bmatrix} \boldsymbol{z}_{conv} \\ \boldsymbol{z}_{pmu} \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}_{conv}(\boldsymbol{x}) \\ \boldsymbol{f}_{pmu}(\boldsymbol{x}) \end{bmatrix} + \begin{bmatrix} \boldsymbol{\varepsilon}_{conv} \\ \boldsymbol{\varepsilon}_{pmu} \end{bmatrix} \tag{18}$$

Where, $\boldsymbol{z}_{conv}$ is the vector containing conventional measurements, $\boldsymbol{z}_{pmu}$ is the vector containing phasor measurements, $\boldsymbol{f}_{conv}(\boldsymbol{x})$ is the vector of nonlinear functions relating conventional measurements with the state variables, $\boldsymbol{f}_{pmu}(\boldsymbol{x})$ is the vector of nonlinear functions relating phasor measurements with the state variables, $\boldsymbol{\varepsilon}_{conv}$ is the error vector of conventional measurements and $\boldsymbol{\varepsilon}_{pmu}$ is the error vector of phasor measurements.

In the two cases mentioned, it must involve an iterative method at some point in the process of solution due to the presence of conventional measurements and their nonlinear relationship with the state vector.

IV. SIMULATION AND RESULTS

Simulations to obtain results for test systems that are commonly used in similar studies to this were performed. In [12] the results are available for the IEEE 14 and 57 nodes test systems. Given that results for real cases are considered more useful, the results of the simulation for the Colombian National Transmission System (STN) for 500 kV and 230 kV voltage levels are presented. The system used is the expected by 2014 which has 101 nodes [13].

For the simulation process, load flows were conducted to obtained the base case defining the “real values” that conventional and phasor measurement devices attempt to measure. In order to simulate the measurement errors of each device, a source of random errors with a Gaussian distribution (white noise) was applied by a script developed in MATLAB®. The magnitude of error built into each measurement depends on its type (conventional or phasor). After the simulation of errors, it was proceeded to run the state estimation methods described in section III.

Since the errors of the measurements in the process of state estimation used are random variables, 500 executions of state estimation which feed the process allowing calculating the statistical behavior of errors were made.

A. *Characteristics of the MeasurementsUsed*

1) *Conventional Measurements*

For conventional measurements, typical values of standard deviations which are shown in Table I. were used [14].

TABLE I. CONVENTIONAL MEASUREMENTS STANDARD DEVIATION

Measurement	***σ [p.u.]***
$P_{kl} - Q_{kl}$	0.008
$P_{kk} - Q_{kk}$	0.010
$\lvert V_k \rvert$	0.004

2) *Phasor Measurements*

To model errors of phasor measurements the definition of the total vector error (TVE), defined in the IEEE Standard for phasor measurements [15], was considered. This error must not exceed 1%.

For a calibrated PMU, a TVE value of 0.03% [16] can be typically obtained. The value of this error is taken as a maximum and a normal distribution of the error to which about 99% of the possible values are in the $[-3\sigma, 3\sigma]$ interval [17]. Standard deviations of the PMUs are around 0.01% (0.0001 p.u.) for the magnitude and the minimum error for phase angle is given by the synchronization error with the GPS signal which is 0.0216° (≈ 0.000037 rad).

To determine the standard deviation of the magnitude and angle errors introduced by the PTs or CTs, the same process as done for the PMUs was adopted. For example, for a PT or CT class 0.2, the maximum errors are 0.2% and 0.166° in magnitude and angle respectively [18]. Assuming a normal distribution of errors, standard deviation in magnitude is taken as 0.00067 p.u. and 0.00097 rad for phase angle.

The standard deviations of the transformer and the PMU are denoted σ_{k1} and σ_{k2} respectively, according to the law of error propagation and also considering that the device errors are independent, the error standard deviation of the output signal y can be expressed as [19]:

$$\sigma_y = \sqrt{\sigma_{k1}^2 + \sigma_{k2}^2} \tag{19}$$

Applying (19), the final standard deviation in magnitude is 0.00067 p.u. and the standard deviation in phase angle is 0.00097 rad.

B. *Comparison of State Estimation Accuracy*

For comparison between different types of state estimation, the standard deviations of the estimated state vector are evaluated. As 500 state estimations are taken for a specific state of the power system, the standard deviation can be obtained from the value obtained from the load flow or base case.

$$\sigma_k = \sqrt{\frac{1}{N_e - 1} \sum_{i=1}^{N_e} \left(x_{k_i} - x_{B_k}\right)^2} \tag{20}$$

Where, σ_k is the standard deviation of the state variable k, N_e is the number of state estimations performed, x_k is the state variable k and x_{B_k} is the base value (load flow) of the state variable k .

In Fig. 2 and 3 standard deviations in magnitude and angle of the state variables (nodal voltages) are shown for the selected system. When a slack node is considered, it was considered as node 1.

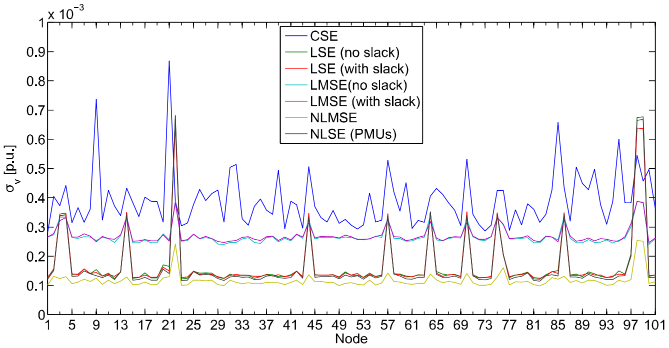

Fig. 2. Magnitude Standard Deviation Comparison

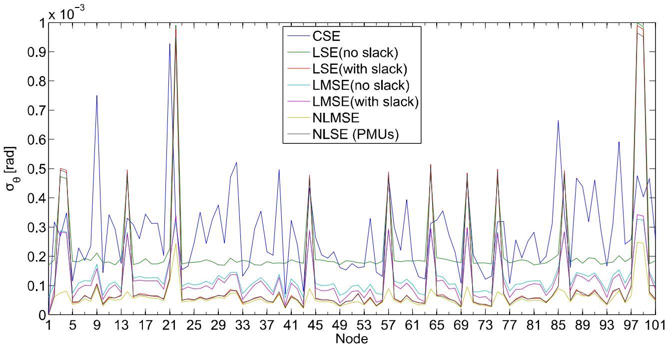

Fig. 3. Angle Standard Deviation Comparison

In the case of the standard deviation of voltage angle for the linear state estimation methods, LSE and LMSE which may or may not consider a reference node, it is evident that when no reference node is considered, angle standard deviations are larger than when considering a reference node. This is because when considering a reference node, the angle value of this node is the absolute reference for the estimation process, while when the angle is included in the estimation process, there is no absolute reference, increasing the standard deviations of the estimated voltage angles.

The above figures show that the state estimation method with larger values of standard deviation in both magnitude and phase angle is the conventional state estimation (CSE), while nonlinear mixed state estimation (NLMSE) shows the lowest values of standard deviation. Furthermore, it becomes apparent that standard deviations in magnitude and angle are reduced for cases that have a larger number of conventional and phasor measurements.

For the case of a nonlinear state estimation only with PMUs (NLSE), the standard deviations in magnitude and angle have an average value of 1.67×10^{-4} p.u. and 1.22×10^{-4} rad respectively. For the NLMSE method, the results are 1.17×10^{-4} p.u. and 0.59×10^{-4} rad respectively. The results of these two methods are the most accurate and are not far apart, i.e. with few high quality phasor measurements, excellent results for state estimation can be obtained.

Knowing that the actual power systems have a large number of conventional measures which can be used in spite of introducing phasor measurements, the obtained results based on the accuracy of state estimation methods, indicate that the nonlinear mixed state estimation method is the best selection when conventional and phasor measurements are combined.

C. Practical Considerations of the NLMSE

1) Sensivity Analysis considering the number of PMUs

A sensitivity analysis was performed running state estimation for the Colombian test system, starting from a state estimation with only conventional measurements and increasing gradually the number of PMUs until all the nodes of the system are equipped with them.

To perform this analysis, two strategies for the PMUs placement were considered:

- Placement Order 1. First the PMUs that belong to the optimal set to make the power system numerically observable only with phasor measurements are gradually implemented [20], starting with those phasor measurements associated to the nodes with the largest number of interconnections with other nodes in the system i.e. the PMUs associated with larger number of measurements, gradually increasing the number of PMUs to cover all nodes of the system.
- Placement Order 2. Only takes into account the number of measurements of each PMU, starting with the node with larger number of interconnections and gradually increasing the number of PMUs in descending order of the number of interconnections until all nodes of the system are included.

The results obtained for these two placement strategies are shown in Fig. 4 and 5.

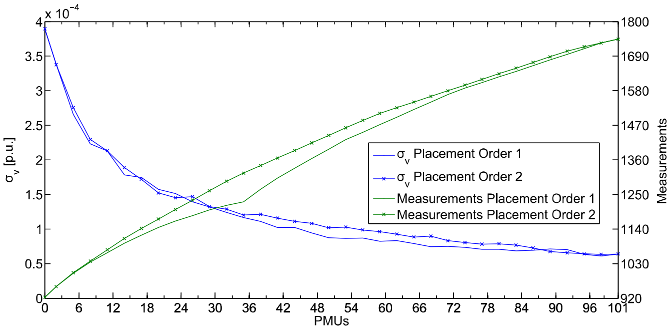

Fig. 4. Average Magnitude Standard Deviation

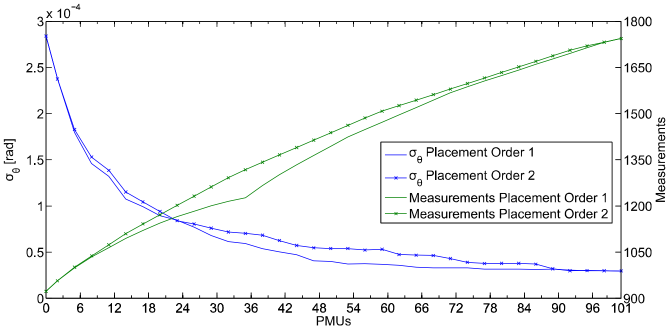

Fig. 5. Average Angle Standard Deviation

To obtain the graphs above the average of the standard deviations of magnitude and angle for all nodes of the power system are plotted. Since in both placement strategies, first the PMUs with larger number of measurements are considered, it is observed that the reduction in standard deviation in magnitude and angle is significant for the first PMUs installed. The placement order 1 shows a better behavior in reducing the standard deviations but the difference with respect to the placement order 2 is not significant.

There are reductions of 70% for the average magnitude standard deviation and 79% for average angle standard deviations for the placement order 1 until the optimal set of

PMUs is completed. After reaching this number of PMUs (35 PMUs), the reduction in the average standard deviations is less.

2) *Reduction of Conventional Measurements*

Considering the advantages of phasor measurements in accuracy, simultaneity and sample rate, it is reasonable to assume that they will be used for SCADA and applications in the future replacing conventional measurements. To take into account this trend, an analysis of the reduction of conventional measurements at nodes where PMUs belonging to the optimal set are implemented, was carried out. Two scenarios were considered:

a) Scenario 1

Whenever a PMU is implemented in a node, the existing conventional measurements on that node are removed. The starting point is the case without PMUs. The process starts with the node with the largest number of conventional measurements and continues until the node with the least number of measurements is taken into account. This situation represents a migration of a conventional measurement system to a phasor measurements system in an existing substation.

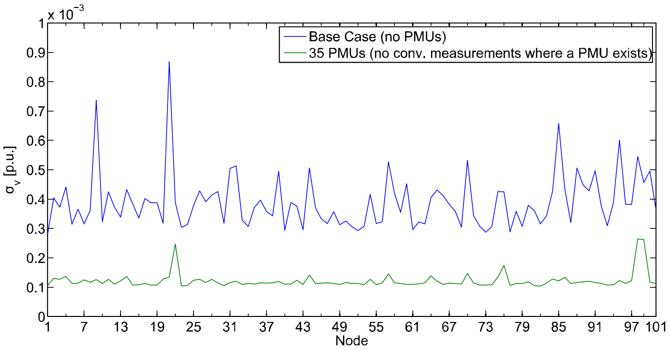

Fig. 6. Magnitude Standard Deviation – Scenario 1

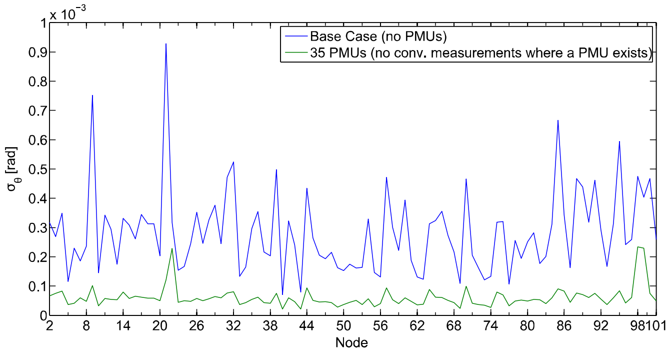

Fig. 7. Angle Standard Deviation – Scenario 1

The results for this scenario are shown in Fig. 6 and 7. A reduction is evident in the standard deviations in magnitude and angle of the estimated variables for the test system. Even if it is decided to eliminate the conventional measures when having phasor measurements in a substation of the system, a reduction is obtained in the standard deviations of estimated variables, because the number of conventional measures removed is almost equivalent to the number of phasor measurements included. Furthermore, the quality of phasor measurements is better improving the quality of the accuracy results of state estimation.

b) Scenario 2

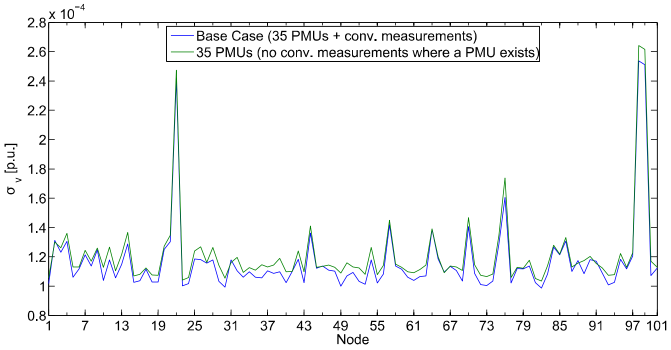

Fig. 8. Magnitude Standard Deviation – Scenario 2

It is considered that all PMUs belonging to the optimal set in the power system have been implemented and then conventional measurements are gradually removed in these same nodes, starting with the node in which a larger number of measurements exist.

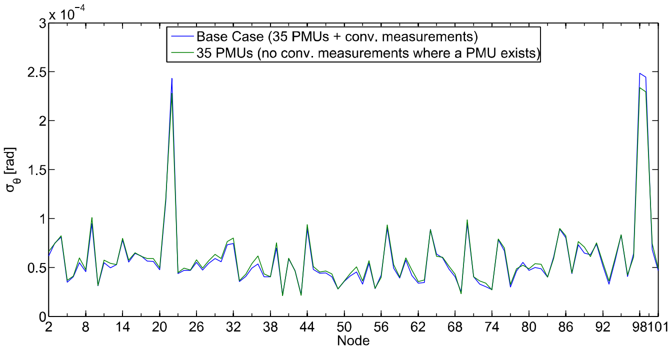

Fig. 9. Angle Standard Deviation – Scenario 2

In this scenario it is not possible to consider that there is a significant increase or decrease of the standard deviations of the estimated variables, therefore, the comparison between the base case (the one with the "optimal" number of PMUs and conventional measurements) and the final case (the one with the "optimal" number of PMUs and retirement of conventional measurements on those nodes), shows no a winning strategy regarding the obtained state estimation results. This is due to the change from one case to another is very small for the test system as seen in the Fig. 8 and 9.

V. CONCLUSIONS

The main objective of this work was to illustrate the expected behavior of state estimation by including phasor measurements that are being implemented primarily in transmission systems. The results obtained show some of the expected benefits of this trend.

Taking into account considerations such as accuracy, robustness and loss of measurements, the nonlinear mixed state estimation is considered as the best option for a power system where conventional and phasor measurements coexist.

Using the nonlinear mixed state estimation, more benefits in the reduction in the standard deviations of the estimated variables are obtained when PMUs have been implemented in approximately one third of the nodes of the power system.

Although the long-term trend is to have a large number of PMUs, the results indicate that it is not advisable to dispense with existing conventional measurements since these measurements increase the accuracy of the state estimation process.

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