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Visualization and Animation of State Estimation Performance

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Abstract

Reliable real time system "visibility" depends on a reliable and accurate state estimator. Present experience with state estimators indicates that its reliability is below expectations (an average of 5% non-convergent cases). The causes of this poor performance have been identified in earlier work by the authors and alternative robust state estimators have been proposed. For any state estimator, it is important to develop techniques for monitoring the performance of the state estimator and identification of potential problems such as bad sensors, consistent errors, modeling errors, etc. The paper presents visualization and animation methods that assist this process. It is demonstrated that bad data many times can be detected via visualization methods. The methodologies are demonstrated with a hybrid three-phase state estimator which addresses the issue of systematic errors from modeling and imbalance errors. This estimator is enhanced by visualization and animation methods that provide valuable information to users and system operators "at a glance". The procedure and the visualization techniques are demonstrated on TVA's 500 kV transmission system.

1. Introduction

A reliable and accurate real time model of a power system is of paramount important for effective control and operation of the system. The real time visibility of the system is achieved with the use of the SCADA system and processing of the SCADA data via state estimators. The end result of this process is expected to be a reliable and accurate real time model of the system. The importance of this process has become abundantly clear during the August 14, 2003 blackout. Historically, the importance of this issue was recognized immediately after the 1965 blackout. Following the 1965 blackout, power system state estimators were implemented in the late 60s to achieve this objective. The initial implementation was based on single phase measurements and a power system model that is assumed to operate under single frequency, balanced conditions and symmetric system model. These assumptions are still prevalent today. The single frequency, balanced and symmetric system assumptions have simplified the implementation but have generated a disconnect between the model and the real time data, i.e. the model utilized generates biases. These biases have resulted in poor performance and several other practical problems [7]. The experience is that the State Estimation problem does not have 100% performance, i.e. there are cases and time periods that the SE algorithm will not converge. The state estimator can be drastically improved with GPS synchronized measurements. Specifically, recent technology of disturbance recorders introduced synchronized measurements. Synchronization is achieved via a GPS (Global Positioning System) which provides the synchronizing signal with accuracy of better than 1 $\mu\sec$. This time precision is translated into a precision of 0.02 degrees of the US power frequency (60 Hz). Therefore, the technology provides a means to measure the phase angles with a precision of 0.02 degrees. It basically provides a direct measurement of the system state. As such, it has been greeted by some as the replacement of state estimators. This assertion however is false. GPS synchronized measurements are imperfect measurements as any other measurement. While the GPS synchronized equipment may have higher precision than conventional metering, there are additional sources of error from the instrumentation channel, calibration errors and systematic errors introduced by the design of the equipment (for example a constant shift of frequency). In addition there are systematic errors from model inaccuracies and random errors from failed data acquisition systems, transmission errors, etc. Filtering of all of these problems requires use of state estimators.

In an earlier paper we propose an approach that uses data from various sources (SCADA as well as GPS-synchronized measurements) for the purpose of enhancing the state estimator. The methodology is based on a three phase detailed power system model. The detailed three phase model is very important and contributes to the performance of the hybrid state estimator. This method is utilized here in a variety of ways with emphasis on providing maximum information to system operators via visualization and animation methods. We focus on visualization methods that reveal bad data in the measurement set, visualization of system imbalances, power system operating status and voltage profile issues. Numerical experiments are presented that illustrate the benefits of the visualization methods using the hybrid state estimator. The numerical experiments are performed on the TVA 500 kV system.

2. Description of the Hybrid Three-Phase State Estimator

This section presents a short description of the hybrid three-phase state estimator. This state estimator uses a combination of standard SCADA data and synchronized data which are related to a full three phase system model to perform state estimation.

The state of the system is defined as the phasors of the phase voltages at each phase of a bus, including the neutral node. A bus k may have three to five nodes, phases A, B and C, possibly a neutral (N) and possibly a ground node (G). The state of the system at this bus is the node voltage phasors. The system model is a three phase model with explicit representation of the neutral nodes and ground nodes if present. For a four node bus, we use the symbols A, B, and C for the phase nodes and N for the neutral node. The states are defined with:

$$\tilde{V}_{k,A} = V_{k,A,r} + jV_{k,A,i}$$
$$\tilde{V}_{k,B} = V_{k,B,r} + jV_{k,B,i}$$
$$\tilde{V}_{k,A} = V_{k,A,r} + jV_{k,A,i}$$
$$\tilde{V}_{k,A} = V_{k,A,r} + jV_{k,A,i}$$

In compact form, the state for a four node bus k will be:

$$\tilde{V}_k = \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{k,N} \end{bmatrix} = \begin{bmatrix} V_{k,A,r} + jV_{k,A,i} \\ V_{k,B,r} + jV_{k,B,i} \\ V_{k,C,r} + jV_{k,C,i} \\ V_{k,N,r} + jV_{k,N,i} \end{bmatrix}$$

The voltages of all buses of the system form the state of the system. We will refer to this as the state of the system, x.

The measurements can be GPS-synchronized measurements or usual SCADA data. A typical list of measurement data is given in Table 1. The measurements are assumed to have an error that is statistically described with the meter accuracy. Each measurement is related to the state of the system via a function.

Given a set of measurements, the state of the system is computed via the well known least square approach. Specifically, let z_i be a measurement and $h_i(x)$ be the function that relates the quantity of the measurement to the state of the system. The state is computed from the solution of the following optimization problem.

$$Min \quad J = \sum_i \left(\frac{z_i - h_i(x)}{\sigma_i} \right)^2$$

where σ_i is the meter accuracy.

Solution methods for above problem are well known. In subsequent paragraphs, the models of the measurements and the details of the hybrid state estimator are described.

Table 1. List of Measurements

GPS-Synchronized Measurements	
Description	**Type Code**
Voltage Phasor, $\tilde{V}$	1
Current Phasor, $\tilde{I}$	2
Current Injection Phasor, $\tilde{I}_{inj}$	3

Non-Synchronized Measurements	
Description	**Type Code**
Voltage Magnitude, V	4
Real Power Flow, P_f	5
Reactive Power Flow, Q_f	6
Real Power Injection, P_{inj}	7
Reactive Power Injection, Q_{inj}	8

3. Description of the Measurement Data Set

The available data in a power system can be classified into (a) GPS synchronized measurements (phasors measurements) and (b) non-synchronized measurements. A typical list of measurements has been given in Table 1. Since at each bus the model may have a neutral node as well as a ground node, the measured phase voltages are always considered as the phase to neutral voltages. As it has been mentioned, the measurements are related to the state of the system via the “model” equations. The state of the system has been defined in the previous section. Figure 1 illustrates some typical measurements. The model equations, i.e. the equations that relate the system state to the measurement are given below. The variables that appear in these equations are defined in Figure 1.

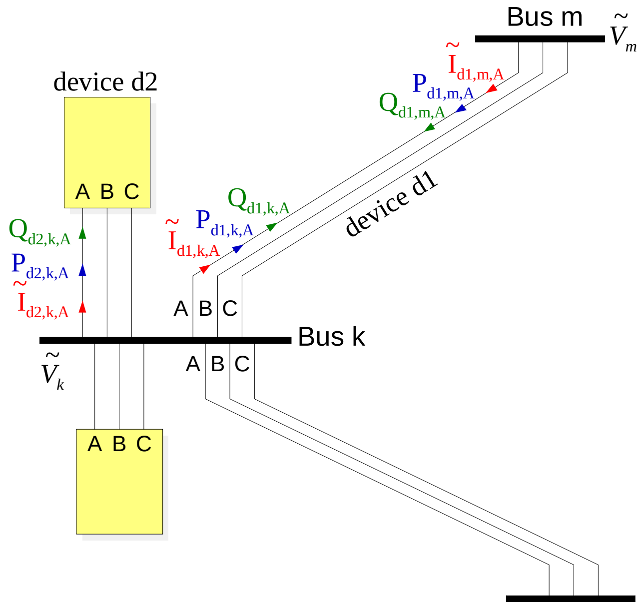

Figure 1. Measurement Definition – Three Phase Model

$$z_{V,k,A} = \tilde{V}_{k,A} = \tilde{V}_{k,A} - \tilde{V}_{k,N}$$
$$z_{V,k,B} = \tilde{V}_{k,B} = \tilde{V}_{k,B} - \tilde{V}_{k,N}$$
$$z_{V,k,C} = \tilde{V}_{k,C} = \tilde{V}_{k,C} - \tilde{V}_{k,N}$$

$$\tilde{I}_{d1,k,A} = C^T_{d1,k,A} \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \\ \tilde{V}_{k,C} \end{bmatrix}$$, similar equation for phases B and C.

$$V_{k,A} = \left|\tilde{V}_{k,A}\right| = \sqrt{V^2_{k,A,r} + V^2_{k,A,i}}$$

$$P_{d1,k,A} = \mathrm{Re}\left\{ \tilde{V}_{k,A} \left(C^T_{d1,k,A} \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \\ \tilde{V}_{k,C} \end{bmatrix} \right)^* \right\}$$

$$Q_{d1,k,A} = \mathrm{Im}\left\{ \tilde{V}_{k,A} \left(C^T_{d1,k,A} \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \\ \tilde{V}_{k,C} \end{bmatrix} \right)^* \right\}$$

It is also important to note that normally measurements of neutral or ground voltages are not available. On the other hand these voltages are very small under normal operating conditions. For this reason, we introduce one pseudo-measurement of voltage phasor for each neutral and ground node in the system. The value of this measurement is exactly zero. The "meter accuracy" for this measurement is assumed to be low. Typically a value of 10% is used.

4. Description of the Hybrid Three-Phase State Estimator

The hybrid three-phase state estimator uses standard SCADA data and synchronized data together with a full three phase system model to estimate the system state. The measurement data has been discussed in the previous section. The mathematical procedure is described next.

The measurements are assumed to have an error that is statistically described with the meter accuracy. Thus, each one of these measurements has the following mathematical model.

Phasor measurements:

$$\tilde{z}_v = \tilde{V}_{k,A} - \tilde{V}_{k,N} + \tilde{\eta}_v$$

$$\tilde{z}_v = \tilde{I}_{d1,k,A} + \eta_v = C^T_{d1,k,A} \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \\ \tilde{V}_{k,C} \end{bmatrix} + \tilde{\eta}_v$$

Pseudo-measurements for neutrals and grounds:

$$\tilde{z}_\nu = 0 + j0 = \tilde{V}_{k,N} + \tilde{\eta}_\nu$$

Non-synchronized measurements:

$$z_\nu = \left|\tilde{V}_{k,A} - \tilde{V}_{k,N}\right|^2 + 2\eta_\nu =$$
$$= \left(V_{k,A,r} - V_{k,N,r}\right)^2 + \left(V_{k,A,i} - V_{k,N,i}\right)^2 + 2\eta_\nu$$

$$z_\nu = P_{d1,k,A} + \eta_\nu = \mathrm{Re}\left\{\tilde{V}_{k,A}\left(C^T_{d1,k,A}\begin{bmatrix}\tilde{V}_{k,A}\\ \tilde{V}_{k,B}\\ \tilde{V}_{k,C}\\ \tilde{V}_{m,A}\\ \tilde{V}_{m,B}\\ \tilde{V}_{k,C}\end{bmatrix}\right)^*\right\} + \eta_\nu$$

$$z_\nu = Q_{d1,k,A} + \eta_\nu = \mathrm{Im}\left\{\tilde{V}_{k,A}\left(C^T_{d1,k,A}\begin{bmatrix}\tilde{V}_{k,A}\\ \tilde{V}_{k,B}\\ \tilde{V}_{k,C}\\ \tilde{V}_{m,A}\\ \tilde{V}_{m,B}\\ \tilde{V}_{k,C}\end{bmatrix}\right)^*\right\} + \eta_\nu$$

The state estimation problem is formulated as follows:

$$Min \quad J = \sum_{\nu \in phasor} \frac{\tilde{\eta}^*_\nu \tilde{\eta}_\nu}{\sigma^2_\nu} + \sum_{\nu \in non-syn} \frac{\eta_\nu \eta_\nu}{\sigma^2_\nu}$$

It is noted that if all measurements are synchronized the state estimation problem becomes linear and the solution is obtained directly. In the presence of the non-synchronized measurements and in terms of above formulation, the problem is quadratic, consistent with the quadratized power flow. Specifically, using the quadratic formulation, the measurements can be separated into phasor and non-synchronized measurements with the following form:

$$z_s = H_s x + \eta_s$$
$$z_n = H_n x + \left\{x^T Q_i x\right\} + \eta_n$$

In above equations, the subscript s indicates synchronized (phasor) measurements while the subscript n indicates non-synchronized measurements. The best state estimate is given by:

Case 1: Phasor measurements only.

$$\hat{x} = \left(H_s^T W H_s\right)^{-1} H_s^T W z_s$$

Case 2: Phasor and non-synchronized measurements.

$$\hat{x}^{\nu+1} = \hat{x}^\nu +$$
$$+ \left(H^T W H\right)^{-1} H^T W \begin{bmatrix} z_s - H_s \hat{x}^\nu \\ z_n - H_n \hat{x}^\nu - \left\{\hat{x}^{\nu^T} Q_i \hat{x}^\nu\right\}\end{bmatrix}$$

where:

$$W = \begin{bmatrix} W_s & 0 \\ 0 & W_n \end{bmatrix}, \qquad H = \begin{bmatrix} H_s \\ H_n + H_{qn} \end{bmatrix}$$

5. Visualization and Animation

The data available from SCADA, GPS-synchronized measurements and state estimation results are overwhelming to system operators in the usual tabular reports of numerical values on a single line diagram. Recent efforts resulted in displaying power flow data in 2-D or 3-D visualizations of the data [13], [14]. Visualization methods are powerful in enhancing the comprehension of system operating conditions for users and system operators. It is important to use the same technology for the results of state estimators for the purpose of enhancing the information transfer. An effective visualization method will help users and system operators to identify problems with one glance at the displays. The types of information that is important are (but not limited to this list):

1. Are all measurements good? Are there any bad data?
2. Can I trust the computed real time model of the system?
3. What is the true operating condition of the system?

The answer to these questions can be quickly assessed with a number of displays. At the research level, we have generated a matrix of useful information. The selection matrix is shown in Figure 2. Note that the user may select from a variety of quantities included the measurements, estimated values, residuals or normalized residuals. The quantities may be voltage magnitudes at any phase (or neutral), real or reactive power flow at any phase as well as electric current magnitude or phase at any phase of the system. The user may select a single quantity or multiple quantities and generate a visualization of this information in a 3-D or 2-D display.

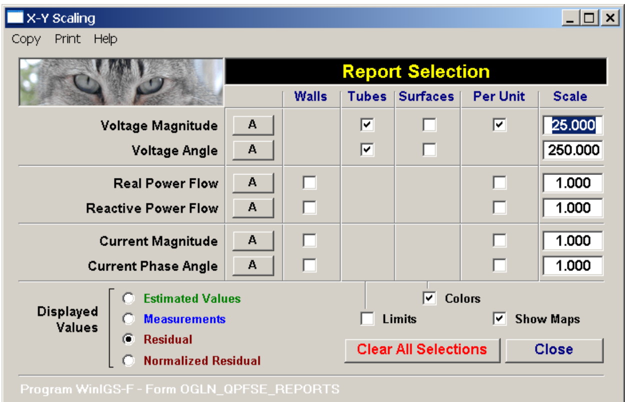

Figure 2. Illustration of the Selection Matrix for Visualizations

An example of the developed visualization modules with 3-D capability is illustrated in Figure 3. The visualization display shows the single line diagram of the system along with indicators of user selected quantities, such as estimated or measured values of bus voltages (in the case of Figure 3, magnitude (tubes) and phase (pies) residuals), circuit power and current flows, measurement errors (computed as the difference between estimated and measured values), and estimation residuals. All indicators are analog so that extreme values (large errors etc) can be easily spotted. For example, voltage magnitudes are indicated by vertical cylinders of height proportional to the voltage. Phase angles are indicated by pie charts. Circuit flows are indicated by walls along the circuit lines of height proportional to the flow, etc.

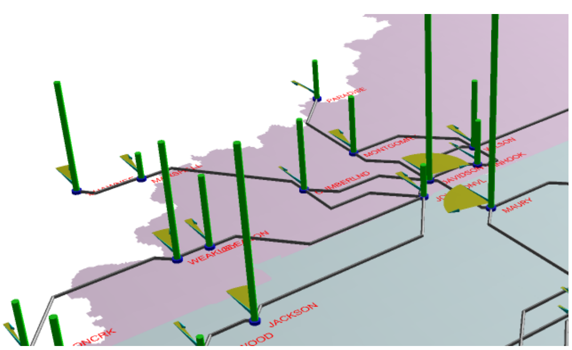

Figure 3. Example of Visualization – Voltage Magnitude (tubes) and Phase (pies) Errors

6. Numerical Experiments with the Hybrid State Estimator

The hybrid state estimator has been extensively tested with numerical experiments. The numerical experiments consist of a data generator that generates a set of measurement data from a solved three phase power flow condition. For the numerical experiments, a user selected random error is added to the data. This section describes the numerical experiments. The test system is the 500 kV TVA system shown in Figure 4. The model includes the entire TVA 500 kV system and the transformers and autotransformers to the lower kV levels (mainly 161 kV and some 230 kV). The remaining system (beyond the secondary of the included transformers) is represented by equivalents. The total number of nodes for this system is 1167 nodes.

Several scenarios have been studied that demonstrate the effectiveness of the visualization methods for providing useful information at a glance. Any problems are immediately identified. Here we present three simple scenarios. At the presentation of the paper these scenarios as well as any other can be demonstrated live.

Scenario 1: In this scenario it is assumed that the following measurements are available: (a) real and reactive power flow at the terminals of all circuits, all phases, and (b) voltage phasors of each phase at all buses.

Scenario 2: In this scenario it is assumed that the following measurements are available: (a) real and reactive power flow at the terminals of all circuits, phase A only, and (b) voltage phasors of phase A at all buses.

Scenario 3: In this scenario it is assumed that the measurement data are identical to those of scenario 1 except that a large error has been added to one datum (50 MW in one flow measurement).

The measurement data for the above scenarios were generated numerically using a load flow program and stored in data files. Random errors were added to the generated data to simulate typical measurement errors. The added errors were uniformly distributed with a specified range (for this data a standard deviation of 0.5% was used for flow measurements and 0.02 degrees for phase of synchronized measurements). Subsequently the estimator was executed with the numerically generated measurement data in order to evaluate its performance. In all tested scenarios the estimator converged within two to four iterations with excellent results.

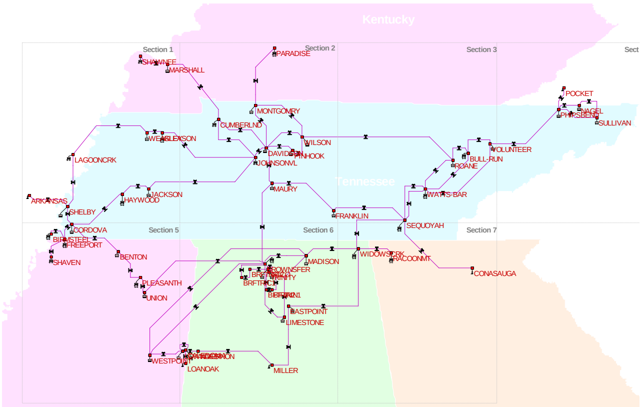

Figure 4. TVA's 500 kV System

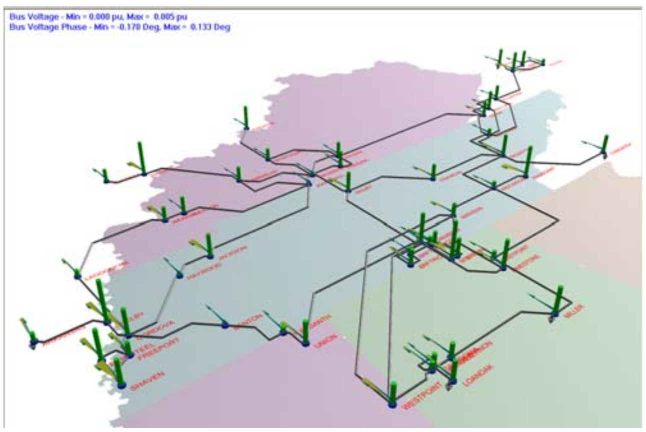

Figure 5. Residuals of Bus Voltage Magnitude and Phase – Scenario 1, Phase A – Magnitude Magnification: Magnitude: 10, Phase: 100

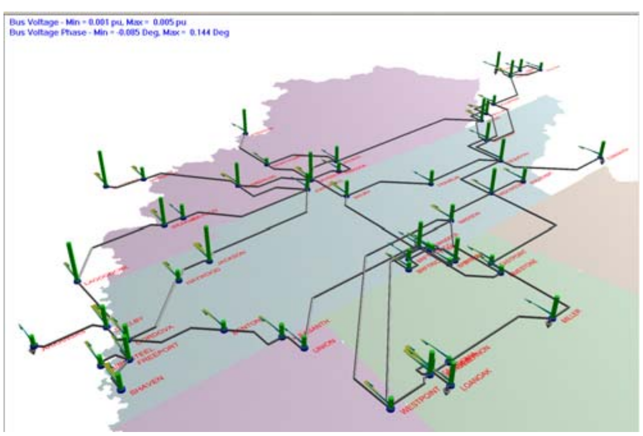

Figure 6. Residuals of Bus Voltage Magnitude and Phase – Scenario 1, Phase B – Magnitude Magnification: Magnitude: 10, Phase: 100

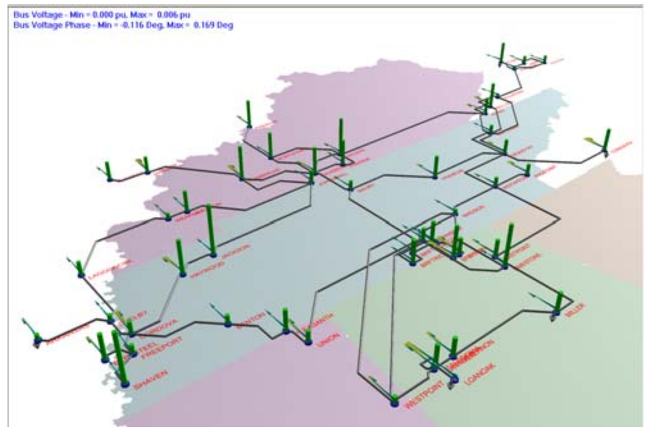

Figure 7. Residuals of Bus Voltage Magnitude and Phase – Scenario 1, Phase C – Magnitude Magnification: Magnitude: 10, Phase: 100

The results of scenario 1 are illustrated in Figures 5, 6 and 7. Note that the errors are uniformly distributed and of very low magnitude for all phases A, B and C. The range of the errors is reported at the upper left corner of the display.

The results of scenario 2 are illustrated in Figures 8, 9 and 10. Note that the errors for phase A are uniformly distributed and of relatively low magnitude. The errors for phases B and C (Figures 9 and 10) are substantially greater. The source of these errors is the asymmetry of the system.

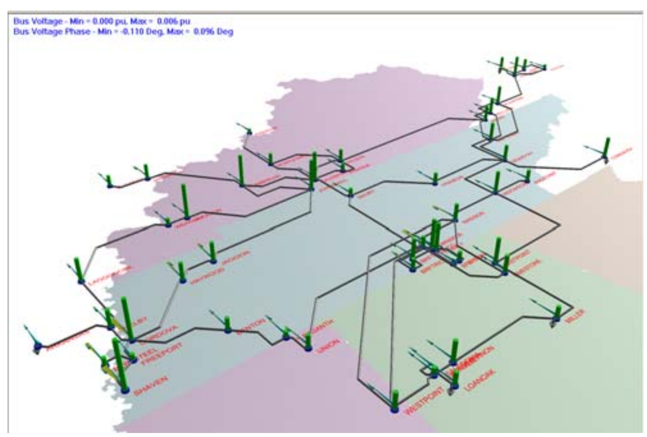

Figure 8. Residuals of Bus Voltage Magnitude and Phase – Scenario 2, Phase A – Magnitude Magnification: Magnitude: 10, Phase: 100

Figure 11 illustrates the estimation results for the same measurement data set, but with a fictitious error (100 MW) introduced at one circuit MW flow measurements. The visualization display shows both magnitude and phase errors. Note that at one location of the network,

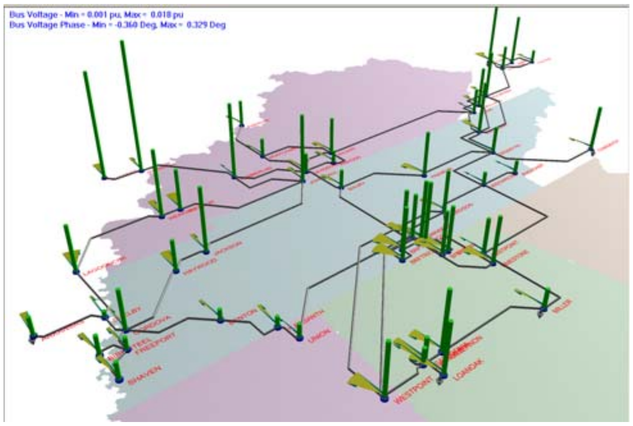

Figure 9. Residuals of Bus Voltage Magnitude and Phase – Scenario 2, Phase B – Magnitude Magnification: Magnitude: 10, Phase: 100

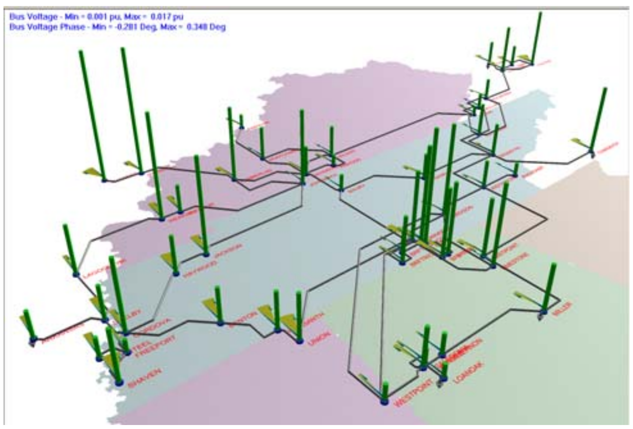

Figure 10. Residuals of Bus Voltage Magnitude and Phase – Scenario 2, Phase C – Magnitude Magnification: Magnitude: 10, Phase: 100

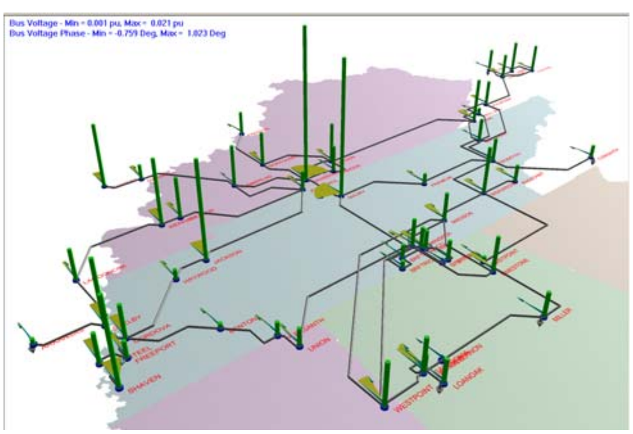

Figure 11. Residuals of Bus Voltage Magnitude and Phase – Scenario 3, Phase B – Magnitude Magnification: Magnitude: 10, Phase: 100

both magnitude and phase errors are much higher than anywhere else. These increased errors clearly identify the two end of the circuit with the “bad data”. It is important to note that 100 MW for a 500 kV circuit is not really a large error. Yet the three phase state estimator with the visualization of Figure 11 clearly identifies the location of the bad datum.

6. Summary and Conclusions

State estimators have a plethora of information that may be overwhelming. The information include in a state estimator solution may include bad data, overall performance of the system, accuracy of the real time model, etc. Visualization methods provide an excellent tool to communicate this information in a very effective way. The paper has discussed the state of the art of state estimators, the existing biases and presented a hybrid state estimator that is based on a full three phase model of the system. Visualization methods provide a variety of state estimator performance quantities in 3-D or 2-D displays. The effectiveness of the visualization methods has been demonstrated with three simple scenarios. These scenarios illustrate the effectiveness of the visualization methods to communicate the performance of the system, the expected errors as well as any bad data. With respect to bad data identification with visualization methods it is important to note that the state estimator used in the research is a hybrid estimator that uses highly redundant measurements. In this case, bad data are immediately identified with visualization methods. In case of low redundancy it is possible that bad data become leverage points which limit the effectiveness of the visualization methods.

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8. Biographies

A. P. Sakis Meliopoulos (M '76, SM '83, F '93) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, *Power Systems Grounding and Transients*, Marcel Dekker, June 1988, *Ligthning and Overvoltage Protection*, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993, and the monograph, *Numerical Solution Methods of Algebraic Equations*, EPRI monograph series. Dr. Meliopoulos is a member of the Hellenic Society of Professional Engineering and the Sigma Xi.

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