State Estimation Performance Monitoring at ERCOT

Thinesh D. Mohanadhas, N. D. R. Sarma, Tim Mortensen

***Abstract*—State Estimator (SE) is an important tool that ERCOT relies on to monitor the real time state of power grid. SE allows the operator to monitor the power system and determine the level of reliability and security. Hence it is imperative to monitor the quality of "SE performance". This paper will present the details of the tools that ERCOT uses to assess SE performance.**

***Index Terms*— Electricity Reliability Council of Texas, Energy Management System, State Estimator, Real Time Contingency Analysis, Voltage Security Assessment Tool**

I. Nomenclature

EMS: Energy Management System
ERCOT: Electric Reliability Council of Texas
RTCA: Real Time Contingency Analysis
RTNET: Real Time Network Analysis
SE: State Estimator
SCADA: Supervisory Control and Data Acquisition
TDSP: Transmission and Distribution Service Provider
VSAT: Voltage Security Assessment Tool
ESAT: ERCOT State Estimator Assessment Tool

II. Introduction

Electric Reliability Council of Texas, Inc. (ERCOT) functions as the "independent organization" certified by the Public Utility Commission of Texas pursuant to Section 39.151 of the Texas Public Utility Regulatory Act. It is responsible for ensuring the reliability and adequacy of the regional electrical network and ensuring that electricity production and delivery are accurately accounted for among the generators and wholesale buyers and sellers in the ERCOT Region [1]. The scope of the ERCOT Region is approximately 200,000 square miles (75 percent of the land area in Texas), 77,000 megawatts of generation and 69,877 megawatts peak load (90 percent of the state's electric load). Nearly 16,000 MW of installed wind capacity with wind generation record of 14,023 MW. ERCOT Region has approximately 24 million retail customers [2]. ERCOT Region stands out among the other regions for the competitive performance of both its retail and wholesale markets.

To support its operations ERCOT has multiple systems which include Energy Management System (EMS) and Market Managements System (MMS). In EMS there are several application functions running both in real-time and in study mode. The real-time applications include State Estimator (also referred as real-time network analysis – RTNET), contingency analysis (CA) and dynamic stability analysis tools.

State Estimator (SE) plays a key role in ERCOT energy and market management system, as the reliability and market systems tools depend on the results provided by SE. The primary purpose of SE is to provide, in real-time, estimates of voltage magnitudes and angles of all energized buses in the ERCOT network model. A Supervisory Control and Data Acquisition (SCADA) system—which collects the real-time telemetry of various parameters, such as power generation, line and transformer power flows, and status of circuit breakers and switches to the control center—generates data for SE. With the SCADA data as an input, SE computes all bus loads and branch flows, whether they are operationally measured or not [3]. Specifically, in ERCOT EMS, State Estimator solution provides a starting point for the Real Time Contingency Analysis (RTCA), Voltage Security Assessment Tools (VSAT), Voltage Support Service (VSS) and other advanced network applications. It also provides data for various studies done such as outage evaluation, week-ahead, day-ahead and hour-ahead. Therefore, it is important to ensure the correctness and accuracy of the SE solution provided to other advanced network application functions. ERCOT uses GE Grid [4] EMS system for most of its EMS application functions. There are some functions internally developed within ERCOT and integrated with the EMS system.

In a large network, it is quite challenging to make the SE solution converge in a consistent fashion. The SE allows the operator to monitor the power system and determine the level of reliability and security. Hence it is imperative to monitor the quality of "SE performance".

The objective of this paper is to describe the functionality of the tools which helps ERCOT in assessing SE performance. The tools used by our Operations Engineers are introduced and the monitoring is illustrated with figures.

III. SE performance

ERCOT and the working groups comprising of market participants had developed the standards [5] for telemetry and state estimation requirements necessary to support ERCOT

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nodal market operation. These standards define the performance requirements necessary to provide SE results within a desired level of confidence. These standards also address the SE's ability to detect, correct, and/or otherwise accommodate communications systems failures, failed data points, and missing or inaccurate measurements. These standards were approved by Technical Advisory Committee (TAC).

Important attributes which are to be monitored in SE are:

- Performance
- Accuracy
- Factors Affecting SE Solution

A. State Estimation Performance:

In ERCOT, SE solution has three different states:

- Valid Solution
- Solved with Excess Mismatch
- Invalid Solution

Valid Solution: SE solved without any problems.

Solved with Excess Mismatch: Even though the SE solution has converged, there is excessive bus mismatch in the system. Bus mismatch is defined as the MW/MVAR difference between flow going into the bus and the flow coming out of the bus. Excessive mismatch is caused by at least one bus exceeding the maximum MW/MVAR mismatch that is set in the SE parameters or unsatisfactory solution quality (i.e., exceeding the specified threshold set in the SE parameters). Operations Engineer must investigate the reason for a "Solved with Excess Mismatch" solution. This could be caused by suspect telemetry from an entire station or a problem with the Inter-Control Center Communications Protocol (ICCP) Link—a utility industry international standard communication protocol designed to facilitate data exchange between EMS/SCADA systems.

Invalid Solution: If the solution has not converged within the specified number of iterations it is flagged as invalid solution. An Invalid Solution could be caused by an incorrect transformer tap measurement or other significant telemetered data errors.

B. State Estimation Solution Accuracy:

Major SE Solution Quality Measuring Indices are as follows:

- Residuals
- Bus MW/MVAR mismatches

Residuals: Residual is defined as the difference between SCADA value and the SE estimated value.
Fig. 1 shows bus view of typical station. This display shows both SCADA value (in brown boxes) and SE value for different lines at this bus.

For example, MW Flow on line 6125_A is: SCADA value = 0.0 MW and SE Value = 106.5 MW. The MW Residual on line 6125_A = 106.5- 0 = 106.5 MW

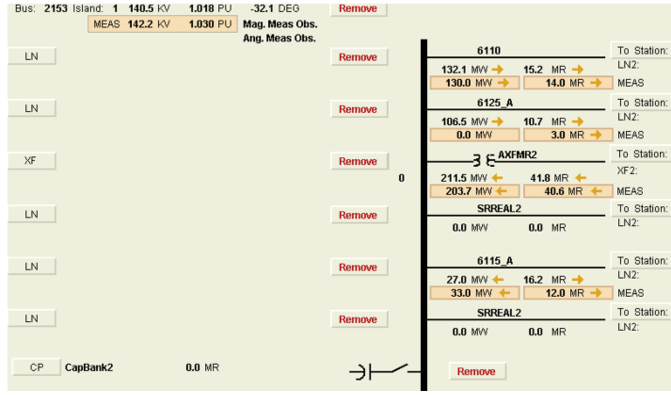

Fig. 1. Illustration of Residual

Bus MW/MVAR Mismatch: In SE, after all the bus voltages are estimated, all the flows in lines, transformers are calculated. We expect that the algebraic sum of the flows at any bus should be equal to zero. However, we specify a tolerance for MW and MVAR bus mismatch, so that if the bus mismatch is within this specified tolerance, the SE solution is acceptable. Otherwise, we say that SE was Solved with Excess Mismatch.

For example:
Incoming flow into the bus = 64.4 MW
Outgoing flow out of the bus = 44.9 MW
Mismatch = 64.4 - 44.9 = 19.5 MW

If we set 15MW as the tolerance for bus mismatch, then this solution is flagged as 'Solved with Excess Mismatch" since bus MW mismatch is 19.5 MW, which is more than the specified tolerance 15 MW.

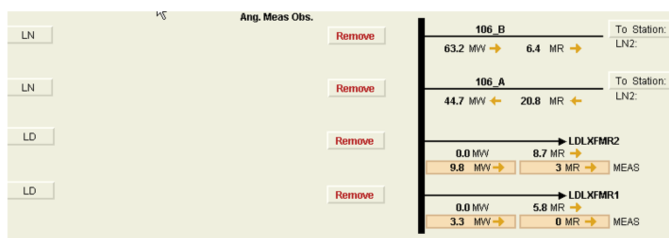

Fig. 2. Illustration of Bus mismatch

C. Factors Affecting SE Solution:

There are several factors which affect the SE Solution accuracy. Some important factors are as follows:

- **Modeling of devices.** Wrong parameters of the lines and transformers modeled in the system will result in estimated flows differing from actual flows.
- **Connectivity and mapping of telemetry.** Wrong connectivity in the model and wrong mapping of telemetry to the devices in the model will cause residuals in SE results.
- **Availability and quality of telemetry.** Unavailability of telemetry affects the Measurement Redundancy (the availability of multiple telemetered measurements for a single point) and Measurement Observability (the ability to determine the state of substation bus bars and connectivity equipment from available measurements) Status of communication links. Failure of communication links affects

the availability and quality of telemetry on a large scale and has an impact on SE results as mentioned above.

IV. SE STATICS TOOL

ERCOT EMS system has some tools to help monitor the performance of its State Estimation. This section describes the post-SE process to check the coherency between line/transformer status and Supervisory Control and Data Acquisition (SCADA) analog measurements. SE Statistics (SESTATS) is a tool developed in-house at ERCOT. It enables monitoring SE performance and metrics, and aids in identifying possible topology errors.

The primary function of the SESTATS application is to capture the relevant data from SCADA and SE applications, save the data, perform statistical analysis and output the statistics to the operators and operation engineers in the appropriate displays. The objective of SESTATS application is to allow ERCOT operations engineers to continuously monitor the SE heath and sense the quality of the current SE input in real-time and the past 72 hours. Therefore, SESTATS serves as an online auxiliary real-time analysis tool. The SESTATS application does not make any corrections to the system to improve the SE quality; instead the operations engineers will identify the errors and take actions to correct them.

The following metrics related to the quality of the SCADA values and the SE solutions are captured by SESTATS:

- Topology changes in the power system as seen by SE
- Availability of real-time telemetry to SE
- Quality of the real-time telemetry based on the estimates computed by SE
- Convergence quality of the SE solution and an SE execution summary SCADA data availability and quality
- Detected measurement residuals (categorized based on equipment types)
- Measurement redundancy and observability information
- Statistics data derived from the above information complied to analyze long term trends

A. *Branch Status Error:*

A branch in the SE model can be a transmission line, transformers or zero-impedance branch (ZBR) [6]. If the analog telemetry is available for a certain element, SESTATS will compare the analog value with the status of the element. If a discrepancy exists, meaning that analog value (MW/MVAR) is larger than 5 and the branch is open, the specific branch will be listed in SESTATS.

Fig.4a gives an example of an incorrect switch status, the transformer AXFMR1 was indicated open in the SE model because of the open switch, while the telemetry on the transformer showed 129MW. This discrepancy was captured by SESTATS and listed in “Dead Equipment with Significant Measurements”, as shown in Fig.4b It provided enough information for operations engineers to further investigate by checking the bus symbolic view (Fig. 4c) and correct the status of switch.

B. *Injection Status Error*

A similar mechanism is used to monitor the status of generators and loads. If a generator/load is open in the SE model, while the analog telemetry has a MW/MVAR larger than 5, the generator/load will be listed in SESTAT.

Fig.3 gives the example of an incorrect generator status. The generator WND was indicated open in SE model, while the telemetry shows it generating 61MW. The discrepancy is listed in SESTATS, and the incorrect status of CB 5232 was easily identified by checking the other power flow telemetry nearby and then confirmed by contacting corresponding QSE operators.

C. *CB Status Error*

SESTATS also detects a discrepancy between CB status and existing analog measurements assigned to the CB. It compares the status of CB and the analog MW/MVAR values on it.

As shown in Fig.4, the CB CB_802 is open while the analog values show significant power flow through it. This type of discrepancy on CB telemetry can help operations engineers detect and correct topology errors in the Bus-Breaker model.

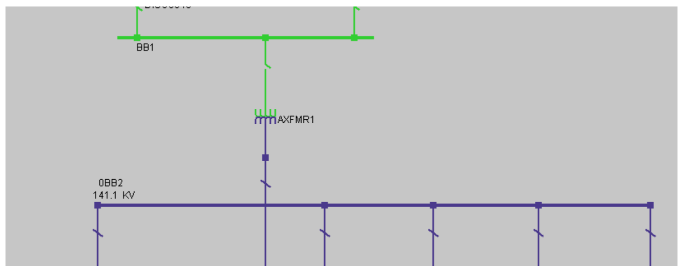

Fig. 2a Station one-line with incorrectly open transformer

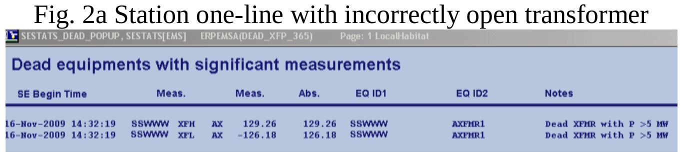

Fig.2b SESTATS display with suspicious dead transformers

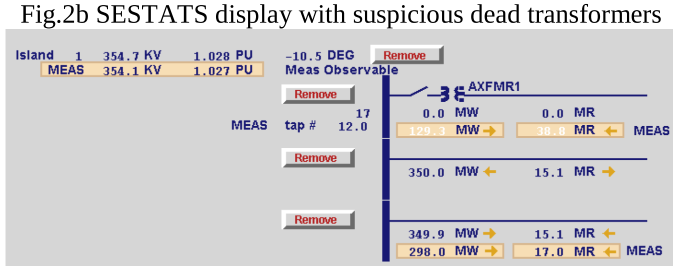

Fig. 2c Bus symbolic view with incorrectly open transformer

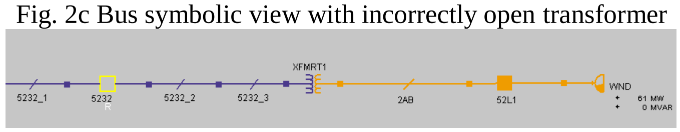

Fig.3a Station one-line with incorrectly open generator

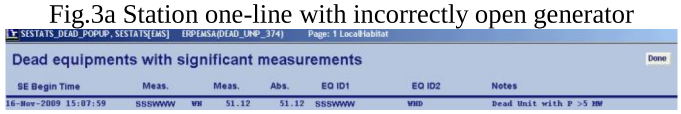

Fig.3b SESTATS display with suspicious dead generator

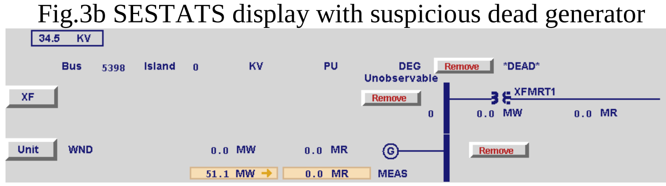

Fig. 3c Bus symbolic view with incorrectly open generator

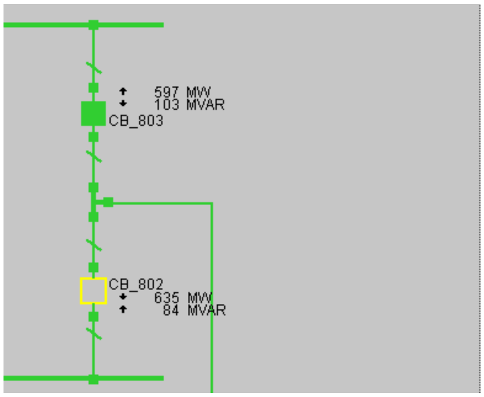

Fig.4a Station one-line with an incorrectly open CB

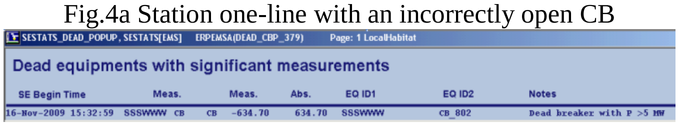

Fig.4b SESTATS display with suspicious open CB

The topology error is more difficult to identify if the incorrect status occurs for branches without good analog telemetry. However, in these instances, the bus mismatches become a good indicator for the possible locations of such errors. As shown in Fig.5, although there was no measurement on the erroneous line, the bus mismatch on the bus disconnected from the line showed up with a relatively large value. Also, the available measurements in the nearby area provided useful information to operations engineers to confirm that the wrong line status was the true cause of the large bus mismatch.

D. Detecting and identifying the bus splitting/merging issue via SE results

An error involving bus splitting or merging is more complicated than simple element status errors, because it usually involves the bus-breaker model. This type of topology error could be caused by an incorrect CB status or switches, or it could be caused by incorrectly modeled network components in the EMS database. The latter issue has to be solved with cooperation from the ERCOT Network Modeling Group and corresponding TDSP. Typical bus splitting or merging errors cause large bus mismatch and possible large measurement residuals on the lines on the bus involved.

Fig.6 and Fig.7 show an example of bus merging errors that can occur in SE. The error was caused by a temporary jumper circuit between two sets of 138kV buses. This temporary circuit was added to let transformer A1 feed both sets of 138kV buses while the A2 transformer was in-maintenance. However, when transformer A2 came back in-service and the jumper circuit was removed in the field; the physical change is not reflected in SE network model database immediately. As a result, the two sets of 138kV buses were still merged in the SE model while actually being split in the field. As shown in Fig. 7, it caused large measurement residuals on all lines connected to the bus, and large bus mismatches on the 138kV and 345kV buses.

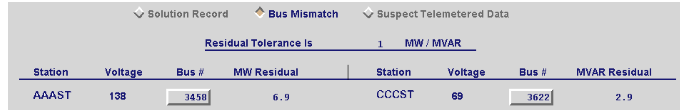

Fig. 5a Display of bus mismatch

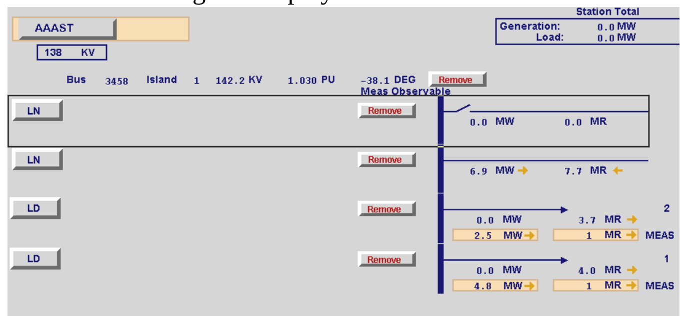

Fig. 5b Bus symbolic view with incorrectly open line

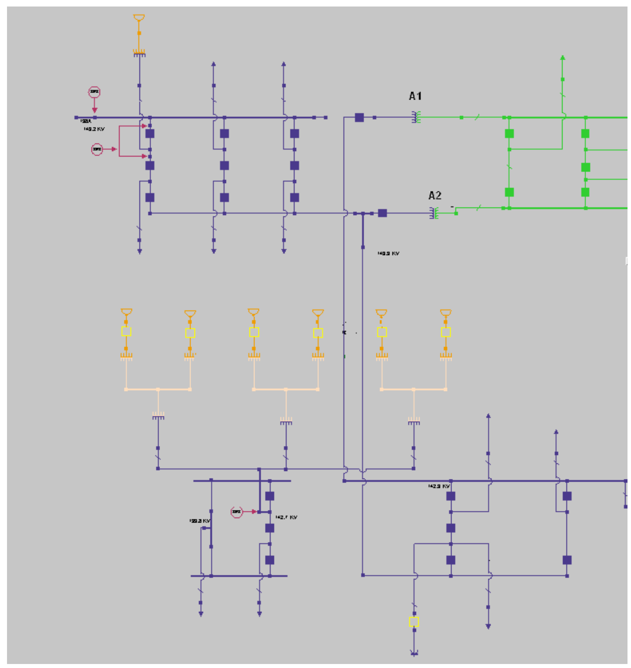

Fig. 6 Station one-line view with incorrectly merged bus

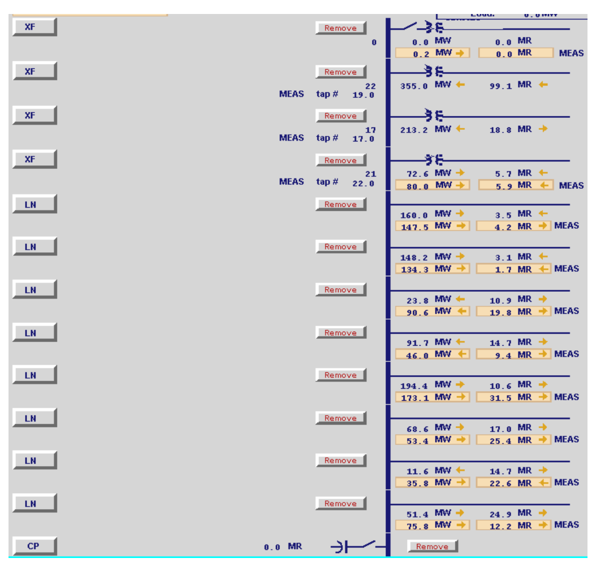

Fig. 7 Bus symbolic view with incorrectly merged bus

The robust measurement redundancy for this station allowed ERCOT engineers to notice that power flow through the jump line should be zero by adding the power flow telemetry values on the lines and transformers connected to each set of 138kV buses. This problem with study results are reported to ERCOT Network Modeling Group and corresponding TDSP modeling group. Once the modeling error is identified, a database load is done to correct the SE network model.

E. Detection and identification of parameter error using SE results

Parameter errors are another important issue affecting the quality of SE solutions. In ERCOT SE, the parameters of network devices, such as impedance values of line/transformers, nominal values of shunt capacitor/reactors, are stored in EMS database. Incorrect parameters in the database cause biased SE results in the immediate area. Fortunately, biased SE results, which show up in the form of large measurement residuals and bus mismatches, help the operations engineers find the parameter error.

The branch impedance error will be easier to detect if there is analog telemetry on the branch. Consider the line AAAA in Fig.8. The wrong impedance of the transmission line causes large measurement mismatch on itself and also other branches. The largest measurement mismatch is located on the line with the wrong impedance, which helps operation engineers to focus their attention on the erroneous line.

However, not all branches are measured with good quality telemetry in the ERCOT SE network. If the parameter error happens on branches without telemetry, the residuals will be spread out over all measurements in the immediate area and make detection and identification of the error difficult. In that scenario, multiple branches will be suspected as having parameter errors. It will take much longer for network modeling engineers both in ERCOT and the TDSP to determine the root cause of the error.

F. Detecting and identifying the shunt device parameter error via SE results

Incorrect nominal MVAR for shunt devices, such as capacitors and reactors, typically cause large MVAR bus mismatch and MVAR measurement residuals in the local area. In the ERCOT SE network model, there is no MVAR telemetry assigned to some shunt devices. For those shunt devices without telemetry, the incorrect parameters are detected and identified by checking the MVAR measurement residuals on the lines connected to the same bus, which requires good measurement redundancy on the stations.

G. Tracking Residuals

SESTAT tracks the residuals on equipment's in the EMS system as shown in Fig 9. Usually topology errors, like bad telemetry values, usually cause large measurement residuals around the locations of errors in SE results. The topology and parameter errors as discussed above would show-up as residuals and needs to be addressed as discussed earlier.

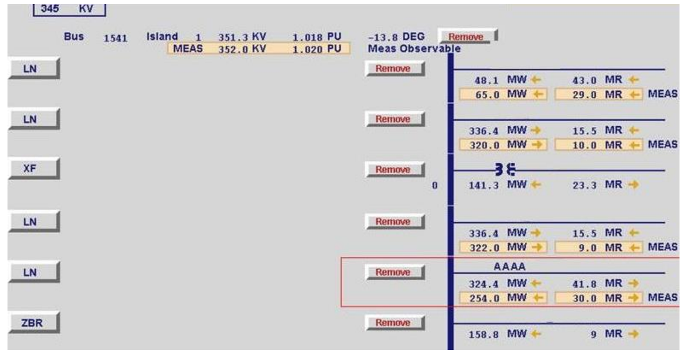

Fig. 8a Bus symbolic view with incorrect line impedance

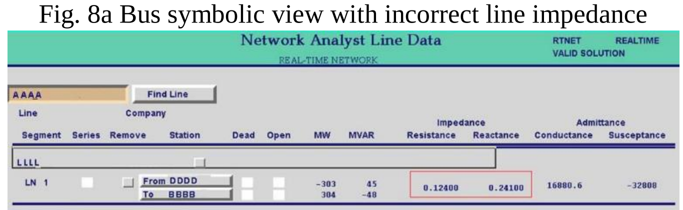

Fig. 8b Line parameter display in EMS

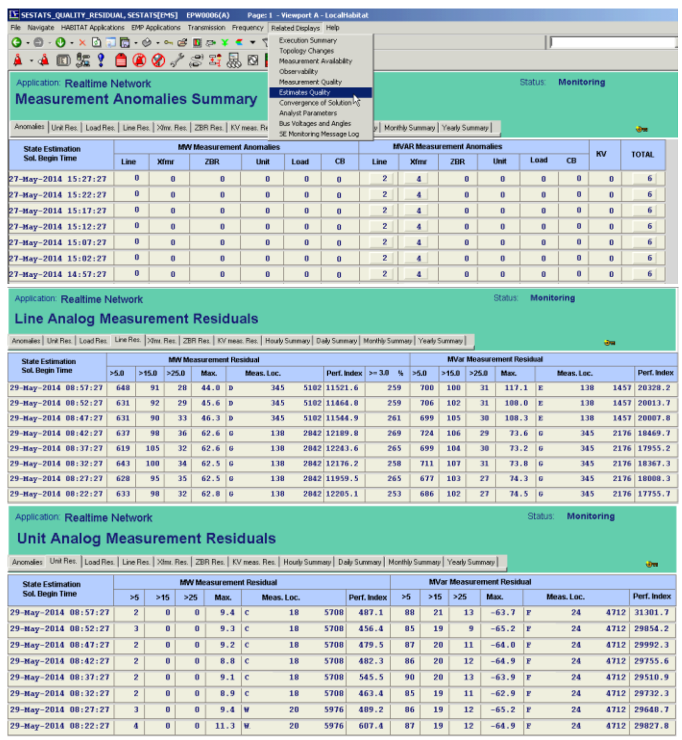

Fig. 9. Residuals Displays

H. Dashboard to display health of State Estimation

ERCOT has developed the **E**RCOT **S**tate Estimator **A**ssessment **T**ool (**ESAT**), which will display the health of SE in the form a dashboard as shown in Fig. 10. This helps ERCOT Operations Engineers to continuously monitor SE health, quality and performance in real-time. Therefore, ESAT serves as an auxiliary real-time analysis tool. All the data (telemetry and SE results) are archived and retrieved whenever required using a system called the Plant Information (PI) System. The PI [7] System is a set of Server-and-Client-based software programs designed to fully automate the collection, storage and presentation of plant information. The PI System provides both a user interface for process control visualization, and a troubleshooting and data exploration tool. ESAT extracts information from the PI System and displays it on the dashboard, as shown in Figure 10.

The top left side corner of Fig. 3 displays the state of SE solution as shown in Fig. 11a. The green bar denotes that the last SE run has a valid solution. The bar would be flashing red with corresponding text denoting 'Solved W.Mismatch' and 'Invalid' respectively when SE is 'Solved with Excess Mismatch' or 'Invalid' as shown in Fig. 11b and 11c. If SE is in one of these states, then it would draw the Operations Engineer's attention so that the problem can be debugged and fixed.

Most of the other details displayed in the dashboard are self-explanatory and will not be discussed in this paper due to lack of space.

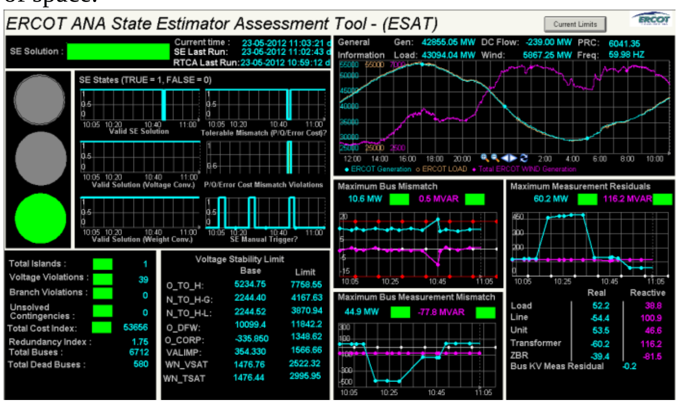

Fig. 10. ESAT Dashboard

Fig 11a: SE Solution Status

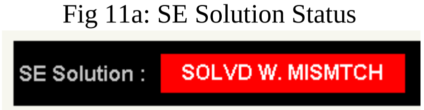

Fig. 11b. SE Solution Status – Solved with Mismatch

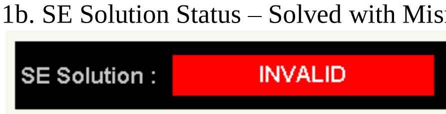

Fig. 11c. SE Solution Status – Invalid

V. Conclusion

In the ERCOT EMS, the correctness and accuracy of the solution provided by the SE is very important for the advanced network applications. SESTATS Tool described in this paper has significantly helped Operations Engineers monitor SE performance, and provides them with a tool that enables them to take a proactive approach to address SE issues.

VI. Reference

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VII. Biographies

Thinesh D. Mohanadhas received an associate degree in Electrical and Electronics Engineering from State Board of Technical Education, Tamil Nadu, India in 1997. He received a Bachelor of Engineering degree in Electrical and Electronics Engineering from Manonmanium Sundaranar University, India in 2000, and Master of Engineering degree in Power System Engineering from Annamalai University, India in 2004. He obtained his Master of Engineering. degree in Electrical and Computer Engineering from University of Maryland, College Park, USA in 2008. He is currently working as Senior Operations Engineer in Advanced Network Applications group at ERCOT. He is a member of IEEE.

N. D. R. Sarma (M'86, SM'01) obtained his B.Tech (Electrical) and M.Tech (Power Systems) degrees from National Institute of Technology (formerly, Regional Engineering College), Warangal, India in 1983 and 1986 respectively and Ph.D. degree from Indian Institute of Technology, Delhi, India in 1995. He is currently working as Research Scientist at Texas A&M University (TAMU) at College Station, Texas, USA. Prior to joining TAMU in March 2016, he worked for more than 8 years in the area of Grid Operations Support at ERCOT. Prior to working at ERCOT, he was at CMC Limited, Texas A&M University and at the International Institute of Information Technology, Hyderabad. He is currently chairing an IEEE Task Force on Real-Time Contingency Analysis. His areas of interest include Synchrophasor Technology, Load Dispatch and Distribution Automation Systems for power utilities. He is a senior member of IEEE and a member of IEEE Power and Energy Society (PES). He is also IEEE PES Distinguished Lecturer.

Tim Mortensen has 25 years of electrical engineering experience in the electric utility industry. He is a licensed Professional Electrical Engineer with a background in Real-Time Operations Engineering Support, Operator Training Simulator Support, Energy Management System software development and Transmission Planning. He is currently supervisor for Grid Applications Support group in ERCOT.