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Practical Techniques of Improving State Estimator Solution

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***Abstract*—**State Estimator became an intrinsic part of Energy Management Systems (EMS). The SCADA measurements received from the field are processed by the State Estimator in order to accurately determine the actual operating state of the power systems and provide that information to other real-time network applications. All EMS vendors offer a State Estimator functionality in their baseline products. However, setting up and ensuring that State Estimator consistently produces a reliable solution often consumes a substantial engineering effort. This paper provides generic recommendations and describes a simple practical approach to efficient tuning of State Estimator, based on the working experience with major EMS software platforms and consulting projects in many electrical utilities of the USA.

***Keywords*—**Convergence, monitoring, performance, state estimator, troubleshooting, tuning, power systems.

I. INTRODUCTION

THE State Estimator (SE) is a real-time application used to determine accurately and consistently the operating state of a power system, which includes the voltage magnitude and angle for every bus in the network. Usually, SE provides information to all down-stream applications in real-time sequence, e.g. Contingency Analysis, Optimal Power Flow, Stability Analysis, as well as to the applications in the electricity market. In modern EMS, SE became an essential telemetry data processing component for running transmission operations. This paper discusses an approach for the effective and simple setup and tuning of SE based on the recent work performed in US electrical utilities, such as Duquesne Light and Power, Indianapolis Power and Light, Idaho Power, PacifiCorp, Arizona Public Service, and the Tennessee Valley Authority. These utilities have used different EMS vendor platforms, i.e. ABB, GE Alstom, OSII, and Siemens. However, in spite of the certain specifics of each EMS platform, there are basic similarities that can be extracted and generalized in establishing a practical approach to the set-up, tuning, and ensuring consistent and high performance of the SE application in real-time.

II. SE MATHEMATICAL FORMULATION

The SE problem is formulated as over-determined systems of non-linear equations solved as a Weighted Least Squares (WLS) optimization problem [1]-[3], and is based on the telemetered analog quantities in the real-time data base (MW, Mvar, KV) and the most current topology of the power system, previously determined by the Real-Time System Status Processor [4]-[6]. Accurate modeling of the transmission network and sufficient reliable telemetry are vital to SE.

Considering the nonlinear measurement model with m measurements and n state variables ($n< m$):

$$z_j = h_j(x) + e_j \tag{1}$$

where, z_j is the j-th measurement, x is the true state vector, h_j is a non-liner scalar function relating to the j-th measurement to states, e_j is the measurement error, which is assumed to have zero mean and error variance $\sigma_{j,}$ also known as measurement weights.

The traditional WLS SE is formulated mathematically as an optimization problem of minimizing the following quadratic objective function and with equality and inequality constraints.

$$J(x) = \sum_{j=1}^{m} \frac{r_j^2}{\sigma_j^2} \tag{2}$$

subject to $g_i(x)=0$ for $i=1,n_g$ and $c_i(x)\leq 0$ for $i=1,n_c$ where, r_j is the residual, which is $z_j-h_j(x)$, and $J(x)$ is the objective function, and g_i, c_i are functions representing power flow quantities.

III. SE ISSUES AND TUNING OBJECTIVES

Fig. 1 shows the major subsystems, telemetry processing, and data flows associated with SE execution and solution [6], [7]. The actual data flows in the diagram may vary for different EMS vendors and solution methods [8], [9].

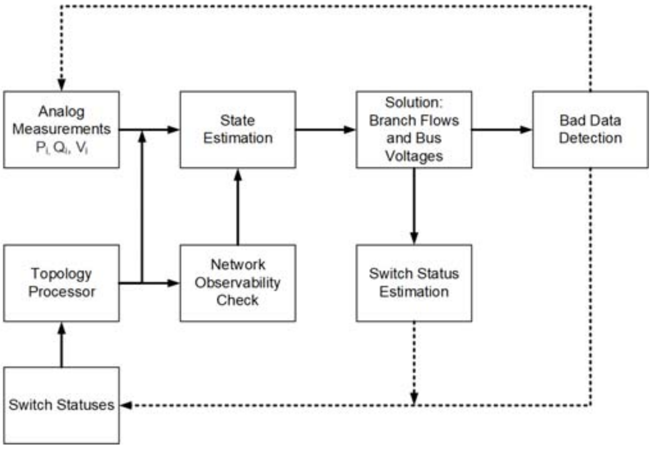

Fig. 1 Overview diagram for SE data flows

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Maintaining a successful SE requires continuous monitoring and management of the validity of individual measurements. Where an adequate telemetry redundancy level exists, the SE will eliminate the effect of bad data (erroneous analog measurements) and allow the temporary loss of measurements without significantly affecting the quality of the estimated values. SE is mainly used to filter redundant data, to eliminate incorrect measurements, and to produce reliable state estimates and, to a certain extent, it allows the determination of power flows in parts of the network that are not directly metered. The bad data detection and producing of a consistent set of reliable solution results (voltages and flows for the entire power system in the real-time analysis), is the main purpose and outcome of SE. Once an observable solution is obtained, some measurements will deviate significantly from their observed values. Such measurements, referred as anomalies, disturb the solution and are automatically removed from the original measurement set. Bad data analysis is the SE's major module, which is performed in order to detect and eliminate such measurements. In EMS, the measurement anomaly detection usually employs the normalized residual test.

Knowing the state of the power system makes it possible for SE to calculate the MW, Mvar, and MVA (or AMP if necessary) flows through all the transmission lines and transformers, and the MW and Mvar injections for all the loads, generation sources, and interchanges with other external systems. This calculation is based on the accurate knowledge of the series and shunt impedances of the power system network model. The estimated voltage and power values also provide useful operational information for the network areas where no telemetry is available. When valid telemetry does exist, the calculated quantities are used to identify measurement errors (if any) based on bad data detection analysis.

The SE must be highly available and provide a solution accurate enough to support the purposes for which it is intended. The following factors may have significant effect on the SE solution and in some cases, even cause the divergence [4], [9]:

1) Incorrect Network Topology: In state estimation, the network topology is usually treated as given and correct. In the event that the topology is incorrect, the SE may not converge, or yield grossly incorrect results. The topology error may be caused by inaccurate statuses of breakers and switching device or network modelling errors.
2) Inadequate observability: State estimation is extended to the unobservable parts of the network through the addition of pseudo measurements. The pseudo measurements are computed based on load prediction, using load distribution factors. The accuracy of these distribution factors may be questionable when not updated regularly to reflect current conditions.
3) Inadequate redundancy: Redundant measurements are crucial for the detection and identification of bad data. Higher redundancy ensures better reliability of the SE solution in the face of temporary loss of measurements.
4) Incorrect Load distribution factors for unobservable parts of the Network.

The following conditions can cause termination of the SE solution:

1) Maximum number of iterations exceeded.
2) Maximum number of gross measurement errors exceeded.
3) Missing voltage measurement.
4) Voltage magnitude not observable.
5) Voltage angle not observable.
6) Exceeding bus mismatch tolerances.
7) Not enough measurements.

IV. MONITORING SE TUNING PROGRESS

Monitoring SE solution performance is essential for monitoring the progress of tuning and achieving the desired quality targets during the migration to the new EMS platform. The SE solution quality can be checked through various metrics based on the values calculated by SE after every execution. Performance Index (PI) is usually evaluated as a weighted (not to be confused with the measurements weights above) average of line residuals, measurement mismatches, applications availability, bus mismatches, MW anomalies, and other SE solution parameters. For large Reliability Coordination entities, network applications solution quality is usually rolled into a single PI with the capability to view type of problem by control area, and that PI includes SE Solution Availability, Number of Measurements with MW/Mvar Mismatch, Sum of all Measurement MW/Mvar Mismatches, Sum of all MW/Mvar Bus Mismatches, Number of buses with MW/Mvar Bus Mismatch, Number of Unreasonable/ Abnormal Measurements, Solution Cost (calculation effort to obtain solution), Total Unit MW/Mvar Error, Total Tie Line MW/Mvar Error, real-time Data Availability. In case of an electrical utility, it probably makes sense to have simplified performance monitoring criteria, which encompass much fewer indicators and monitor these indicators individually for better transparency and direct relation to the actual values calculated by the SE implementation.

Table I provides the minimal set of SE parameters with desired values, which will usually correspond to a reasonable quality of the SE solution. As the engineering team progresses with the tuning, the SE performance parameters need to be recorded on a weekly basis to monitor the SE tuning success.

TABLE I
SOME ESSENTIAL SE PERFORMANCE PARAMETERS

Description	Desired Value
Estimation Quality Index	Depends on vendor implementation
Maximum MW/Mvar bus mismatch	< 5 MW/Mvar
Maximum MW/Mvar residual	< 5 MW/Mvar
Number of abnormal measurements	< 10
Convergence (Availability)	>99%

As a result of the monitoring, the SE performance parameters will allow to ensure the consistent progress of SE tuning and to make quick adjustments in case some approaches do not yield expected results.

The effects of systematic SE tuning usually result in a consistent convergence, better solution quality, and faster execution. Monitoring some or all of the following parameters can provide simple indicators of the overall SE performance:

1) Estimation Quality (also known as, solution quality), which is usually an index automatically calculated by SE application and indicates the overall SE performance.
2) Maximum MW/Mvar mismatch based on the difference between estimated and telemetry values, i.e. weighted residual.
3) Maximum bus MW/Mvar mismatches.
4) Number of anomalous measurements.
5) Convergence rate of SE, average over a period of time and consecutive valid executions.
6) Number of diverged solutions over a period of time (e.g. per week/month).
7) Number of iterations for the cold start/initialization of SE.
8) Telemetry data availability.

V. SE TUNING APPROACH

A. General Considerations

Prior to embarking on SE tuning, it is usually recommended to perform an overall assessment of the SE solution quality and business practices related to SE support and maintenance:

1) Evaluate the network model practices, available guidelines, conventions, and business processes.
2) Review global parameter settings for SE.
3) Analyze overall SE solution quality based on the key performance indicators.
4) Analyze in detail, the SE solution for a representative selection of stations, e.g. about 10 stations.
5) Record all high measurement residuals, bus mismatches, unreasonable estimates for MW/Mvar flows and Busbar KV, and missing modeling components.

After a preliminary assessment is complete, a plan with clear objectives, schedule, and performance targets need to be established.

The general approach to SE tuning is to identify and resolve the large problems first, and then, work your way down to the smaller issues. The resolution of large ticket items very often results in significant reduction of the smaller ones, which sometimes may completely disappear (e.g. mismatches decrease to the tolerance levels) from the list of the errors identified by SE.

The tuning process is a complex and elaborate task. The tuning of SE is usually much more effective when it is possible to compare the SE results on the new EMS platform with the solution available in real-time from Reliability Coordinator or the solution on the previous EMS platform, assuming that the latter has been in operation for a considerable time and has reasonably good solution quality.

B. Configuring SE Parameters

Generally, it is recommended to start with the default SE parameters recommended by the EMS vendor and have thresholds slightly higher for ease of convergence if the model is not converging well. Then, based on the tuning progress, distinctiveness of the power system, known model quality for internal and external footprints, and the solution quality, the parameters can be gradually revised. Sometimes, it is also helpful to relax solution and regulation parameters in order to get some SE solutions and then improve the quality of that solution as it is always easier to troubleshoot a converged SE solution than a diverged one. The relaxation can include an increase of tolerance for the external network and directing the focus of tuning on the internal network footprint. The following parameter settings can be suggested as a starting point for tuning with relaxed objectives, especially when solution is not consistently converging:

1) Increase MW/Mvar tolerance for convergence in external areas.
2) Disable tap estimation.
3) Disable transformer regulation flags for LTC.
4) Disable voltage regulation on switched shunts.
5) Disable enforcement of Mvar limits on generating units and SVC.
6) Disable topology error detection for analysis of inconsistent topology (switch status estimation block on Fig. 1).
7) Increase the number of iterations
8) Start solution from a cold start initialization

C. Detecting and Eliminating Significant Issues

Troubleshooting and tuning SE is usually laborious process that requires thorough analysis of the SE solution for each station. The content of this section describes the general approaches to detecting the problems with SE solution and some ways to correct the problems. The proposed methods constitute only part of many different ways for tuning an SE solution and do not represent an exhaustive set of actions. An overview diagram of the proposed SE tuning methodology is presented on Fig. 2.

The following recommendations describe the common steps for troubleshooting and temporary fixing the large MW/Mvar residual (mismatch between estimated and telemetered values).

1) Display the station bus with high measurement mismatch.
2) Analyze SCADA’s MW flow direction and establish whether they are reasonable (i.e. not all flows go in the same direction, need in/out).
3) If available, check MW telemetry on both ends of the line to ascertain that the telemetry is correct (factor in some losses on the line).
4) Analyze SCADA’s MW flow values to balance the bus (total MW flowing into the bus is equal to MW flowing out of the bus). Sometimes one may need to trace the flow to the other side of the branch or even further to find the telemetry.
5) Investigate the largest mismatch between estimated MW flow and SCADA flow on the lines connected to the station. Follow to the next station and see whether the flow makes sense in terms of balancing the bus on the other station. Use telemetry flip or telemetry disable actions as necessary.
6) Attempt to remove the branch that has large measurement mismatch if the measurement cannot be trusted for one

reason or another.

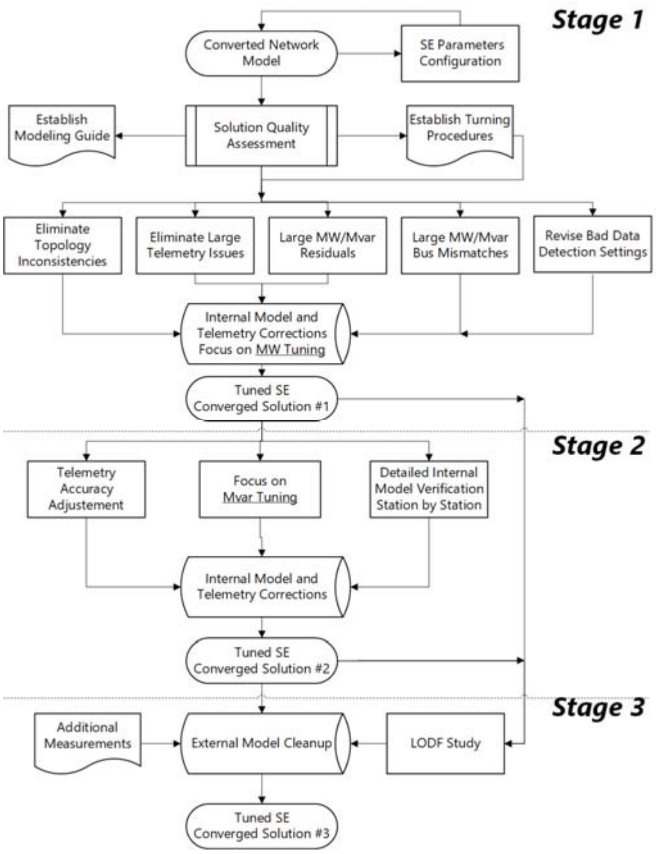


Fig. 2 Overview diagram of SE tuning stages

D.Bad Data Detection and Topology Inconsistencies

SE usually performs Bad Data detection to invalidate the erroneous analog telemetry data that fail topology tests and/or cannot balance well the nodes using Kirchhoff laws, telemetry reasonability limits, and redundant telemetry [7]-[9].

When SE tuning is performed, special attention is required in reviewing all entries detected by the Bad Data Detector function. The invalid data are discarded from use in the SE solution.

The alarm/event is issued when analog telemetry is invalidated based on the network model topology verification tests of the power system network model using the in-service status, the bus bar connection of the model equipment, and the equipment's analog measurements. The analog telemetry invalidation entries are presented on the SE Anomaly Equipment Summary display.

The data invalidation may be due to one or more of the following:

1) Erroneous analog value coming from the field, e.g. bad wiring to telemetry malfunction.
2) Stale analog value.
3) Invalid breaker status associated with the analog measurement.
4) Insufficiently modeled topology, e.g. breaker modeled, but not the associated switch, which happens to have a diffident status than the breaker.
5) Accuracy (sigma) erroneously defined for the analog value (e.g. very high sigma compared to other redundant values on the bus, or very low sigma that cannot be satisfied).
6) Invalid analog measurements due to excessive noise, meter calibration or scale factor conversion coefficients.
7) Erroneous measurement definition in the model.
8) Erroneous mapping of the SCADA telemetry to Network Model.
9) Measurements coming in with good data quality but with unreasonable values.

Bad Data Detection is an absolutely necessary component for production grade quality SE. However, in some instances, Bad Data Detection may discard some good data while searching for the best SE solution and the solution quality gets worse with the reduced number of good data available. At the beginning of the tuning when the telemetry may contain a lot of bad measurements, sometimes, it may be more useful to start the tuning with disabled Bad Data Detection, and to first better understand the telemetry issues in the network by manually discarding bad measurements rather than it to be automatically carried out by the application.

A basic design assumption in the SE is that the topology, i.e. network connectivity, is correct and the bad data detection performs the analysis to identify and remove from the solution bad analog values as described above, i.e. discrepancies detected by the SE between equipment connectivity and analog measurements are assumed to be errors in the analog values. However, network topology errors (bad breaker statuses) can cause major convergence challenges for obtaining the converged SE's solution. The topology errors can be a result of modelling errors, lack of status telemetry for breakers and switches, defective telemetry readings, and invalid configuration definitions.

E. Verification of Regulation Schedules

Incorrect setting of regulated bus and regulation voltage targets may result in an invalid solution of the power flow base case produced after completion of the SE. Incorrect schedules may also result in SE convergence problems for the regulation in unobservable areas of the power network.

If there are not readily available regulation schedules, then it is recommended to start with a simple one-fixed voltage target for each generator regardless of the time. The voltage targets are usually in the range from 0.95 p.u. to 1.05 p.u. This will help perform SE tuning in an organized and predictable fashion when the voltage targets on a regulated bus are easily predictable and managed. Then, after a reasonable SE solution quality is achieved, the voltage schedules for generating units can be refined to reflect the time variable if necessary. It should also be noted that, sometimes regulation buses for generators are configured as local buses connected to the node between the generating unit and the generating unit circuit breaker. It is always recommended to set the regulation bus to the correct busbar (e.g. after step-up transformer or generator connection node) in order to reflect the realistic power plant settings. Plant operators usually know the correct regulation settings for generating units, and especially large ones. Network support and modeling engineers should contact either the plant operator or planning department in order to obtain correct information on the regulation settings.

F. Telemetry Accuracy Adjustment

It is important to ensure that analog telemetry is available with some redundancy [9], [10], and it also has to be sufficiently accurate, especially, on all internal generating units, tie-lines, and large loads. Having correct injections in the power system model is already a good basis for obtaining an SE convergence. It is also important to get accurate telemetry for the high voltage transmission 345 KV and above.

The following general recommendations can be applied for individual sigma values (in (2) the error variances σ_j) for internal network:

1) Internal Voltage magnitude KV – very low.
2) Internal Generation, synchronous condensers, and SVC MW/ Mvar – very low.
3) Internal Branches (lines/transformers) MW/Mvar – low.
4) External measurements – slightly higher than the corresponding internal ones above and depending on the known telemetry issues with external measurements usually received via ICCP links.
5) Tie-lines MW/Mvar - low.
6) Internal Pseudo MW/ Mvar – high.
7) External Pseudo MW/Mvar – very high.

It is important to ensure that pseudo measurements have significantly higher sigma value than telemetered values.

The above values should be treated as general guidelines only, and if there is field information available on poor accuracy of some telemetry it should certainly be used, e.g. inaccurate telemetry sigma value can be set higher than normal.

The sigma value for the external network depends on the accuracy of the received ICCP data. In general, it is recommended to set higher accuracy on the well modeled substations in the vicinity of intertie and for high voltage network.

G. Detailed Internal Model Verification

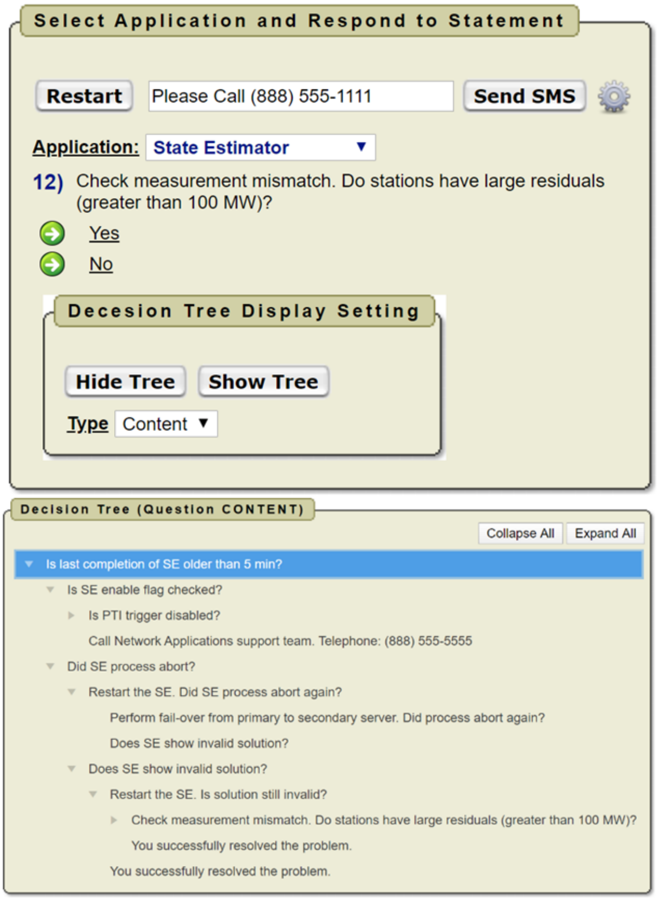
After correcting topology inconsistencies, large mismatches, and big issues detected by SE and bad data analysis, the solution quality usually significantly improves. However, it is still recommended to perform a comprehensive validation of model topology and essential parameters (impedances, load values, capability curves, etc.). The validation should be carried out using the published one-line diagrams with all substations' details (devices, connections, metering points).

H. External Model Expansion

In order to determine the reasonable representation of the external model in SE (and Contingency Analysis), a Line Outage Distribution Factors (LODF) study needs to be performed for equivalencing. LODF is a sensitivity measure of how a change in a line's status affects the flows on other lines in the system. On an energized line, the LODF calculation determines the percentage of the present line flow that will show up on other transmission lines after the outage of the line. The study can be performed using node-oriented model from PSS/E software. The full network model is available from PJM.

After the required external footprint is clearly established, the ICCP measurements need to be obtained for the external model through Reliability Coordinator (RC) or Market Operator, and the breaker-oriented model needs to be subsequently developed in EMS using one-line diagrams for the external substations. Only after that, the external model correction and SE tuning of the external model will become truly efficient exercises. In the absence of a fully executed LODF study, it is recommended to review the external footprint manually and model in detail: 1) the high voltage (e.g. 230 kV and above) network that significantly affects the electrical utility internal network; 2) two levels of substations from the utility's tie-lines into the external footprint.

VI. CAPITALIZE ON TUNING EXPERIENCE



Please Call (888) 555-1111

Application: State Estimator

12) Check measurement mismatch. Do stations have large residuals (greater than 100 MW)?

Yes

No

Type Content

- Is last completion of SE older than 5 min?
  - Is SE enable flag checked?
    - Is PTI trigger disabled?
    - Call Network Applications support team. Telephone: (888) 555-5555
  - Did SE process abort?
    - Restart the SE. Did SE process abort again?
      - Perform fail-over from primary to secondary server. Did process abort again?
      - Does SE show invalid solution?
    - Does SE show invalid solution?
      - Restart the SE. Is solution still invalid?
        - Check measurement mismatch. Do stations have large residuals (greater than 100 MW)?
        - You successfully resolved the problem.
      - You successfully resolved the problem.

Fig. 3 SE troubleshooting with web-enabled assistant

The SE issues identified and corrected in one place of the network often happen in other parts of the network. Therefore, it is very important to accumulate the SE tuning knowledge and capitalize on tuning experience that can be applied to

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similar situations in the future.

The following summarizes the recommended approach on leveraging your SE tuning experience and growing your knowledge base in-house:

1) Document all tuning and troubleshooting experience for Network Applications. Many reoccurring issues can be applied to similar cases.
2) During tuning, establish the typical patterns and formalize them to capture knowledge of applications tuning experts.
3) Use simple logic for incremental SE solution improvement.

Online troubleshooting guidance may significantly reduce the need in calling upon EMS experts, expedite the process of localizing the problem, and find an effective solution for most typical situations.

The SE troubleshooting and tuning can be documented in different formats: simple “if-then” notes, logic diagrams special software applications aids. An example of an application aid developed to assist troubleshooting/tuning SE is presented in Fig. 3. The Troubleshooting Assistant, which is web-enabled and can also run on a smart phone, was developed by the author using Application Express from Oracle and can be easily adapted to troubleshooting other EMS applications as the questionnaire is driven by a table in Oracle database.

VII. CONCLUSION

Real-time operations heavily depend on SE for reliable transmission management. Setting up, tuning, monitoring performance and maintaining high-solution quality of SE is an important task for electrical utilities, RCs, and Market Operators. The described methodology is simple as it is based on practical experience of setting up and systematic tuning of SE in US utilities using modern software/hardware platforms from major EMS vendors. The following is a summary of the general actions that are common for setting SE reliable for real-time operations:

1) Establish a strategy and plan for comprehensive tuning of SE. Record all SE tuning activities, including parameter changes, real-time analog telemetry adjustments (e.g. disabling or changing polarity/flow direction of MW/Mvar measurements), overrides of breaker/switch telemetered or not telemetered status.
2) Verify the network model data (impedances, voltage class settings for transformers, capability curves, etc.).
3) Analyze the values discarded by Bad Data Detection; in some instances, it may discard some good data while searching for best SE solution. Consider starting the tuning by disabling Bad Data Detection to understand the telemetry issues in the network.
4) Monitor real-time telemetry MW/MVar balances on all stations to help the troubleshooting activity, which must be close to zero.
5) Adjust MW and Mvar accuracies/weights to refine the SE solution after major issues and large residuals have been dealt with.
6) Configure Measurement Consistency Analyzer (e.g. tolerances, alarms) in order to make the report useful for detecting and troubleshooting topology issues when they occur in real-time.

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