Calculation and Visualization of Power System Stability Margin Based on PMU Measurements

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Abstract— This paper introduces the concept of the Region Of Stability Existence (ROSE) and describes the framework for utilizing PMU data for computing of this region and operational margins. The approach presented in this paper is an automated process to continuously monitoring the transmission system in real-time environment by accurately calculating power system stability margins. Voltage constraints, thermal limits and steady-state stability are simultaneously monitored during the analysis. The region is shown on the planes of two phase angles and real powers. The paper also demonstrates the effect of remedial actions on the region. The approach is illustrated by using the ISO New England's real-time model, SCADA data and PMU measurements. The study results show that this approach is effective in improving the reliability of the ISO New England's transmission network and may be used for preventing major blackouts.

***Index Terms*— PMU measurements, steady-state stability, optimal remedial actions, region of stability existence, reliability analysis, operational margin.**

I. Introduction

WIDE-AREA monitoring and control is one of the key aspects of the Smart Grid, [1-6]. Some of the major applications of the phasor measurements units (PMUs) include wide-area monitoring and situational awareness, [7-9].

The past industry efforts have remained largely limited to installing the PMUs, collecting the data and establishing communication transfers of this data to the utility/ISO control centers, [10, 11]. There has been significant research and industry efforts in using the data for post mortem forensic evaluations and visualizing the data [12-15], but not in using the data effectively to predict voltage and/or transient instabilities.

As more PMUs are being installed, the problem of utilizing the data for analysis of power system behavior, and especially, for accurate computation of power system stability margin becomes more important. Steady-state (voltage) stability is one of the most severe problems facing the electric utilities. Aging transmission infrastructure, deregulation and the desire to operate system in the most economic way are the key factors that contribute to operating the transmission grid closer to a voltage stability limit.

To reliably operate the transmission system, a tool should be developed and utilized to compute the exact values of voltage stability margins under any system conditions in planning and especially in real-time environments [16].

This paper describes the framework for utilizing PMU measurements in order to continuously monitor the electric grid, identify system stability limit and alarm the operator about the impending crisis before a new State Estimator (SE) case arrives. The proposed framework allows for invoking optimal remedial actions to prevent a blackout.

This paper addresses the following issues related to the use of PMUs for steady-state stability assessment:

- Determining the region of stability existence and the system steady-state stability margins,
- Identification of the optimal remedial actions needed to increase the size of the region of stability existence.

The proposed technology is capable of computing system stability margin while utilizing measurements from multiple PMUs. In this paper, the technology is illustrated for two PMUs currently installed at ISO New England footprint.

The computations described in this paper were performed using the Region of Stability Existence (ROSE) application of the Physical an Operational Margins (POM) Suite of Applications [17 - 20]. POM [21] is an extremely fast loadflow, voltage stability, massive AC contingency analysis, and transfer analysis application, based on the Newton-Raphson method, that solves a 50000-bus case in approximately 0.1 s. The normal (no contingency) conditions model and each contingency are applied while simultaneously monitoring multiple constraints: voltage stability, thermal overload, voltage deviation, and voltage limit violations.

Fully integrated into the POM application, the ROSE defines the area where the system may securely operate. It incorporates the PMU, SCADA and SE data for on-line calculation and visualization of the current operating point and its proximity to the stability boundary.

Optimal Mitigation Measures (OPM) is a fast and powerful remedial actions program [22, 23] which is activated when ROSE finds a violation of at least one of the monitored constraints. Fully integrated into the ROSE application, OPM relieves thermal, voltage, and voltage stability violations identified by POM. OPM employs the following multiple

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measures to mitigate the constraint violations based on either automatically determined by the software or the user defined priorities: MW re-dispatch, Mvar re-dispatch, line switching in and out, forced phase-shifter adjustment, forced capacitor and reactor switching, forced transformer tap change, emergency load curtailment, and optimal capacitor placement.

The solution takes approximately 10 seconds for one contingency for a 50,000-bus case. The uniqueness of OPM is that it has the capability to automatically alleviate post-contingency violations during massive AC contingency analysis and increases the power system loadability and transfer capability.

II. The Concept of ROSE

A. Definition of ROSE

The Region Of Stability Existence (ROSE) defines the range of phasor measurements or other system parameters for which the system may securely operate in terms of the accepted N-k security criteria.

In addition to voltage stability, the following constraints may be simultaneously monitored, enforced and visualized on the boundary [24]:

- Voltage constraint (voltage range and/or pre-to post contingency voltage drop)
- Thermal overloads

Each point on the boundary corresponds to a "nose" point on the P-V curve, or a thermal or voltage constraint being violated. Inside the boundary is the region of existence of solutions to power flow equations, or the region of stability existence (ROSE) of the system. Operating within this region is secure; operating outside this region is infeasible or corresponds to unreliable operation a power system, [25, 26].

ROSE utilizes phasor measurements to predict steady-state instability and alarm the operator about the impending crisis. It uses PMU, SCADA and SE data for on-line calculation and visualization of the current operating point and its proximity to the stability boundary, see Fig. 1.

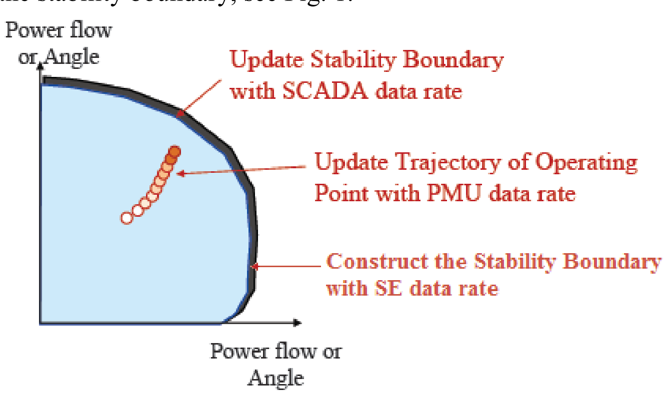

Fig. 1. ROSE Boundary and the Trajectory of the Operating Point

During ROSE analysis power system model and, thus, power flow equations that describe this model, are changed to incorporate phasor measurements.

Currently, each generator bus that regulates its own real power and voltage is described by real power balance equations and constant voltage magnitude at the generator bus until the point when the generator reaches reactive power limit. Each load bus is described by real and reactive power balance equations. These equations are used to compute approximate values of bus voltage magnitude and angle.

Use of PMUs allows us to incorporate the exact values of bus voltage magnitudes and angles. Power system model is changed to take into account PMU measurements. For buses where PMUs are installed, the exact values supplied by the devices are used. Thus, state measurements, not state estimation, are utilized in the ROSE.

For all other buses, power flow equations are solved and approximate values of bus voltage magnitudes and angles are determined. The use of phasor measurements improves the accuracy of the model at the buses where PMUs are installed as well as at all the buses connected to the buses with PMU installations. By changing the power system model the following two benefits are achieved:

1. Ability to produce a more accurate result; and
2. Capability to have these results faster (since fewer power flow equations will be solved).

The more PMUs are installed in the future as a part of the Smart Grid, the more accurate and faster the solution will be.

In the course of the analysis, ROSE automatically identifies the limit values based on real-time measurements. It also computes and displays the current operating point based on phasor measurements. The relationship between the current operating point and the boundary defines the "healthiness" of the power system network state and its proximity to steady-state collapse.

Fig. 2 shows the effect of the load increase on the size of the ROSE, where point 1 corresponds to the base case condition and point 2 - to the current operating condition. Point 2 moves from inside the ROSE (left plot) to the boundary (right plot) as the system becomes more stressed. Any further load increase beyond the limit value causes system instability.

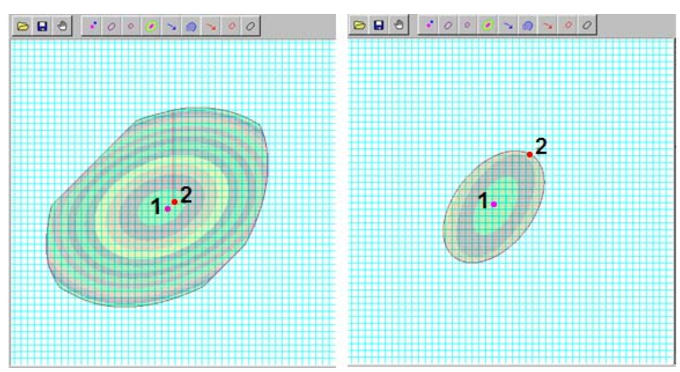

Fig. 2. The Effect of Load Increase on the ROSE: Plane of Two Phase Angles

ROSE may be constructed for different system stressing; for example load in the areas of interest or power transfers through major interfaces.

B. Capabilities of ROSE

ROSE provides continuous monitoring of the system conditions in terms of its proximity to voltage collapse, which allows us to alarm the operator before a new SE will arrive.

ROSE may be shown on the plane of various system parameters:

- Phase angles
- Power injections/Flows on the interfaces

The current operating point is shown inside the region to identify the closeness to the boundary (e.g., limit). The closeness of the operating point to the boundary is an indicator of the severity of the system conditions while the shape and the size of the boundary itself are secondary.

ROSE output includes:

- Visualization of the ROSE and its boundary on the plane of two phase angles or power injections or power flows;
- Displaying the current operating point;
- Tabular detailed results about limiting violation(s).

ROSE computes indices that can be easily understood and interpreted by the operators in order to increase situational awareness:

- MW index (MW margin on the interfaces or at load pockets);
- Other indices are under consideration.

It takes from 3 to 6 sec to construct a boundary for a SE model (the example is given for a 12000-bus SE model). There is no limit on the number of buses in the model, number of PMU installation, contingencies analyzed, etc.

C. Integration of ROSE into the On-line/Real-Time Environment

A new SE case is usually available every few minutes. Utilization of the proposed approach will enable continuous monitoring of the system conditions and alarming the operator of the changes in the power system conditions (e.g., whether the system is "moving" closer to the boundary) before the next SE case arrives. This will allow the operator to take timely remedial actions to prevent system instability.

Three sets of data are needed to reliably estimate the ROSE as shown in Fig. 3.

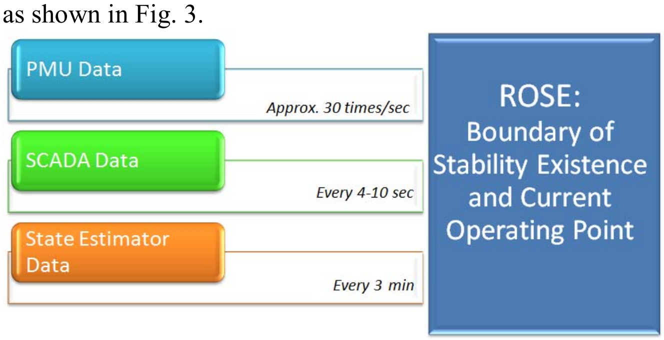

Fig. 3. ROSE Data Sets for ISO New England

These data sets are utilized as follows:

1. SE data is needed to compute an initial operating point and the boundary of stability existence
2. SCADA data is used to update the boundary of stability existence.
3. PMU data is utilized to compute the trajectory of the current operating point.

Use of PMU data will increase situational awareness of operators as follows:

1. Read a SE case each X-minute interval and compute and display a boundary of ROSE on the plane of two phase angles or other system parameters. The boundary is updated every several seconds (e.g., sampling intervals of SCADA).
2. Show the current operating point within the region at the PMU sampling rate.
3. Each second to several seconds ROSE determines system conditions – closeness of the current operating point to the boundary of stability. Operator should be alarmed if the operating point and the boundary are moving towards each other.

III. Illustration of the ROSE Concept by Using ISO New England System[3]

A. Data Used for ROSE Analysis

The actual data sets were collected in July of 2009 for a 15-minute interval.

The following three data sets were used:

1. SE cases
   - Seven cases
2. Corresponding SCADA data
   - 30 sets at 30-second intervals
3. Corresponding data for two PMUs:
   - Includes relative angle between voltages of PMU locations and voltage magnitude
   - 30 measurements per second

1) SE Data

The ROSE works with SE cases that represent a full breaker model of the network. It consists of approximately 12000 buses and includes a lot of near to zero-impedance branches representing all circuit breakers and disconnects. Note that the same model in a bus-branch form after topology processing consists of about 2500 buses. The SE snapshots were made every three minutes. The cases that represent a full model correspond to SCADA snapshots.

2) SCADA Data

SCADA data was provided every 30 seconds, including a total of 31 snapshots for a 15 minute interval.

The total number of measurements (e.g., records) is 15998 for each snapshot. From the total number of records, 8242

[3]The ROSE analysis was performed under a CEATI project "Prediction of Power System Instability Based on PMU: Utilizing the ROSE (Region of Stability Existence) Approach".

records correspond to the actual measurements (for example, MW/MVAR line flow measurements), and 7756 records correspond to breaker status (TRUE/FALSE).

SCADA information includes the following records related to the actual measurements:

1. Line records: real flow, MW and reactive flow, MVAr;

2. Bus records: bus voltage, kV;
3. Generator records: real power output, MW and reactive power output, MVAr;
4. Load records: real load, MW and reactive load, MVAr;
5. Transformer records: real flow, MW; reactive flow, MVAr and tap position;
6. Switched shunts records: shunt reactive outputs, MVAr.

3) PMU Data

Currently, there are two PMUs installed within ISO New England footprint.

Phasor measurements were provided for voltage angles and magnitudes at both locations.

Data consists of 30 sets of phasor measurements per second for the same 15-minute interval as used to collect SE and SCADA data.

B. Study Results

Depending on the computer used, it takes from 3 to 6 sec to construct a boundary for the 12000-bus full SE model. In average, ROSE makes about 350 iterations of the Newton method to construct the boundary, which is ~ 0.01 sec per iteration.

The current operating point is shown inside the boundary. The closeness of the operating point to the boundary is an indicator of the severity of the system conditions. Voltage, thermal and steady-state stability were simultaneously monitored and enforced during the analysis.

Actual power system data used comprise a 15 minute interval. When these values were implemented into ROSE and displayed, the boundary and operating point practically didn't move, which indicates that there were no significant changes happening in the network within that 15-minute interval. To simulate stressed conditions, the system load was scaled up with the constant power factor. As the next step, remedial actions were identified to increase the size of the ROSE.

1) Displaying ROSE on the Plane of Two Phase Angles and Real Powers

First, the ROSE boundary was constructed on the plane of two PMU phase angles. Fig. 4 and Fig. 5 show ROSE for the base case and stressed conditions. Base case is indicated as "0". Stressed cases are indicated by numbers, which mean corresponding increase of MW load value over the base case.

Magenta portion of the curve corresponds to thermal constraint being violated on the boundary; green portion of the curve corresponds to voltage limit being violated.

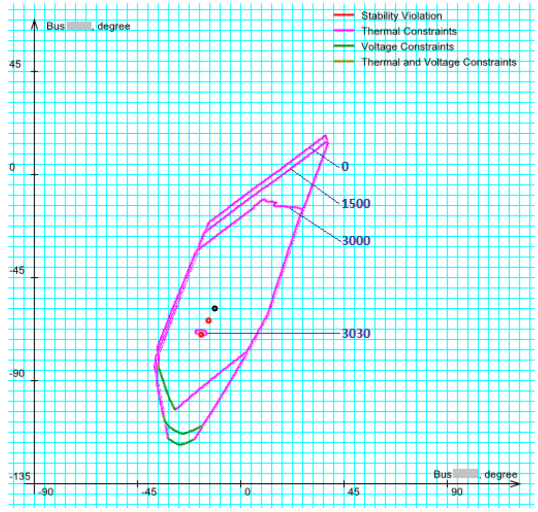

Fig. 4. ROSE Boundaries on the Plane of Phase Angles for the Base Case and Three Stressed Cases

At the limit value of stressing (e.g., at the maximum load level), the boundary degenerates. The operating point lies on the boundary, see Fig. 5.

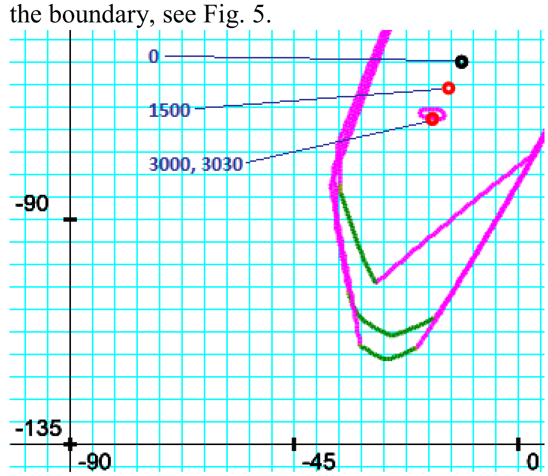

Fig. 5. Detail Fragment of the Fig.4

Fig. 6 shows the same two scenarios but on the plane of real powers.

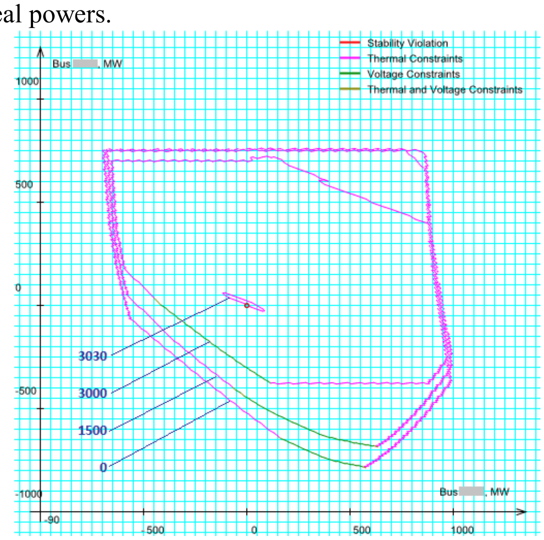

Fig. 6. ROSE Boundaries on the Plane of Real Powers

2) *Use of Remedial Actions*

As the next step, remedial actions were computed in order to increase the size of the ROSE. There might be various scenarios on how to implement the remedial actions. The one that is described in this paper is as follows:

- Identify the remedial actions to alleviate violations at the first "unhealthy" load step (that was 3040 MW in the system scaled with 10 MW step).
- Apply these remedial actions during ROSE calculation.

Minor load shedding (under 20 MW) at two buses was identified as the most effective remedial action. The effect of remedial actions on the ROSE boundary for the limit case of 3030 MW is shown in Fig. 7.

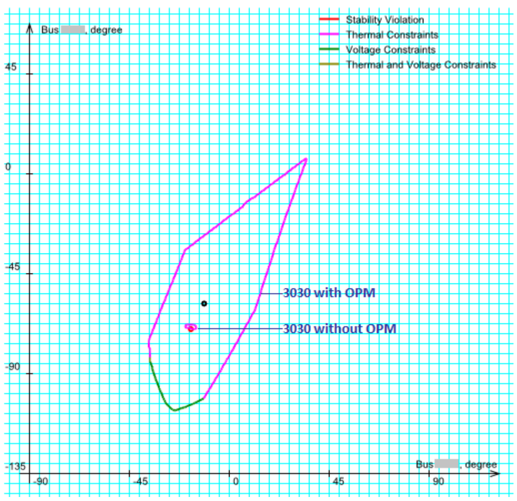

Fig. 7. ROSE Boundaries on the Plane of PMU Phase Angles after the Use of Remedial Actions

Then, the same set of remedial actions was utilized to increase the stressing level. Identified remedial actions increased the maximum load level from 3030 MW to 4920 MW.

Fig. 8 shows the boundaries and the operating points for the base case conditions and stressed cases after the remedial actions have been employed.

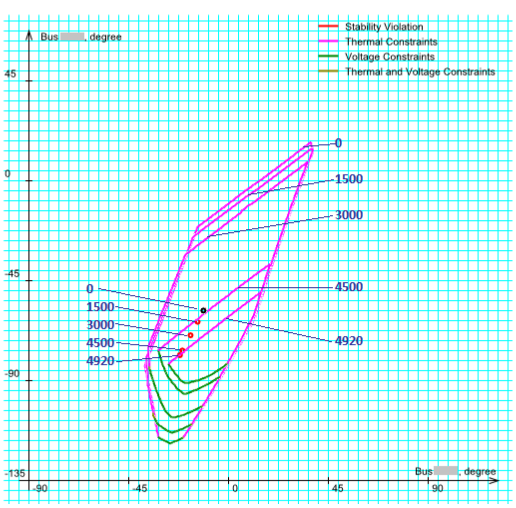

Fig. 8. ROSE Boundaries after the Use of Remedial Actions

IV. Planned Future Work

The Department of Energy has selected ISO New England to receive Smart Grid Investment Grant award as a part of American Recovery and Reinvestment Act of 2009, [27]. In the course of the project, synchrophasors will be installed at approximately 30 additional locations. Large quantities of additional data will be available with addition of new synchrophasors. ROSE will be utilized as one of the synchrophasor applications.

ROSE framework will be extended to account for multiple PMU installations. The tool will identify the most critical phase angles and display the boundary on the plane of those angels. ROSE will be able also to identify the most representative coordinates, where the operating point moves faster than the boundary shrinks in order to take advantages of more frequent PMU signal for visualization of a margin.

V. Conclusion

This paper describes a framework for utilizing PMU measurements for steady-state stability analysis and computation of system stability limits.

One of the major advantages of Region Of Stability Existence (ROSE) is that it provides continuous monitoring of the system conditions in terms of its proximity to voltage collapse, which alarms operator before a new SE arrives.

Three ISO New England data sets were used for ROSE computations: SE data, SCADA data and PMU measurements. Voltage and thermal constraints together with steady-state stability were simultaneously monitored and enforced during computations. These are the limits that bound the region. If the current operating point and the boundary move close to each other, an alarm is issued. Then, remedial actions can be utilized to increase the size of the region.

As the next step, ISO New England is planning to utilize ROSE as a part of its Smart Grid Investment Grant for multiple PMU installations.

VI. Acknowledgement

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VIII. Biographies

Michael Vaiman (M’91) received his MSEE degree from Kaunas Polytechnic University, Lithuania, Ph.D. degree from Moscow University of Transportation Engineering, Russia, and D.Sc. degree from St. Petersburg Polytechnic University, Russia. He has over 40 years of power industry experience. Dr. Vaiman is a President and Principal Engineer at V&R Energy Systems Research, Inc. (V&R Energy). His main areas of interest are power system stability and control, power flow and optimal power flow analysis, computer modeling of power system networks, selection of remedial actions for stability preservation, dynamic stability analysis, and predicting cascades. He leads the development of the POM Suite, consulting, and research and development activities at V&R Energy. He has authored over 100 publications devoted to the issues of power system stability and control.

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