State Estimator Line-Based Phase Angle Alarming

Primer for Operations Engineers and System Operators
January 2017

Purpose

The NERC Synchronized Measurement Subcommittee (SMS) developed a technical reference document[1] on phase angle monitoring practices based on industry experience following the 2011 Pacific Southwest Outage. The reference document was developed to address Finding and Recommendation 27 from the FERC-NERC outage report[2], which stated:

- **Finding 27:** "Phase Angle Difference Following Loss of Transmission Line: "A TOP did not have tools in place to determine the phase angle difference between the two terminals of its 500 kV line after the line tripped. Yet, it informed the RC and another TOP that the line would be restored quickly, when, in fact, this could not have been accomplished."
- **Recommendation 27:** "TOPs should have: (1) the tools necessary to determine phase angle differences following the loss of lines; and (2) mitigation and operating plans for reclosing lines with large phase angle differences. TOPs should also train operators to effectively respond to phase angle differences. These plans should be developed based on the seasonal and next-day contingency analyses that address the angular differences across opened system elements."

The purpose of this primer document is to provide operations engineers and system operators a focused description on practices related to state estimator-based phase angle monitoring and alarming. The intent is to provide a concise description of the recommended practices outlined in the full SMS report related to this topic. The SMS report Recommendations 1, 2, and 4 address this issue and are provided here for reference.

- **Recommendation 1:** The contingency risk of interest is the outage of a transmission circuit and the phase angle difference across the out-of-service terminals of that line exceeding synchrocheck relay limits. Post-contingency angle differences should be monitored in real-time. The Planning Coordinator and/or Reliability Coordinator should identify key transmission circuits for which this monitoring is required. It is recommended that awareness of synchrocheck relay limit exceedances be provided to system operators for EHV transmission circuits, where applicable, with nominal voltage greater than or equal to 345 kV.

[1] North American Electric Reliability Corporation, "Phase Angle Monitoring: Industry Experience Following the 2011 Pacific Southwest Outage Recommendation 27", June 2016. [Online]. Available: HERE.
[2] Federal Energy Regulator Commission, "Arizona-Southern California Outages on September 8, 2011," Joint FERC/NERC Report, April 202. [Online]. Available: HERE.

- **Recommendation 2:** Phase angle differences for potential contingency conditions should be monitored in real-time and compared against synchrocheck relay settings, if applicable, for all EHV transmission circuits using Real-Time Contingency Analysis (RTCA) tools. Any N-1 or credible N-2 or N-1-1 exceedances of these limits should be provided to the system operator for advanced notice of potential line restoration issues.
- **Recommendation 4:** Line-based phase angle difference monitoring and comparison against known synchrocheck limits is not presently a universally adopted operating practice. It is recommended that the NERC Synchronized Measurement Subcommittee (SMS), in coordination with the NERC Operating Committee (OC), explore how this practice could be used or more widely adopted by the industry.

Practical Recommendations:

- Identify transmission circuits that have synchrocheck relays installed and have nominal voltage greater than or equal to 345 kV.
- Add these limits to the RTCA logic for monitoring the post-contingency line-based angle exceedances for any N-1 or credible N-2 or N-1-1 contingencies being studied.
- Increase situational awareness of system operators by providing these exceedances in a meaningful way. This will alert operators of any operating restrictions and high system stress points in the post-contingency operating condition.

Background

When the Hassayampa-North Gila 500 kV line tripped during the sequence of events leading up to the 2011 outage, system stress drove the phase angle difference between the two terminals of this line to larger than the synchrocheck relay setting. Therefore, the line could not be restored due to this large phase angle preventing closure of the line switching devices. The report highlighted the need for monitoring phase angle differences for the purposes of returning to service transmission elements in a coordinated, efficient manner. The FERC-NERC report highlighted improved situational awareness tools and mitigation and operating plans for Transmission Operators (TOPs) to improve reliability. Although operating plans may not explicitly rely on returning the outaged line to service, it is useful for operators and operations engineers to understand when line phase angle difference may exceed limits disallowing these lines to return to service both in the N-0 and N-1 operating conditions.

Unlike conventional contingency analysis which ensures that the outage of a system element will not have an adverse impact to other elements on the system (e.g., low bus voltage, thermal overload, instability, etc.), the practices outlined in this document focus specifically on the phase angle difference across the terminals of the outaged element in the system.

Focus: Monitoring and alarming on phase angle difference that exceeds the synchrocheck relay setting for the outaged transmission circuit.

Line-Based Phase Angle Differences

Phase angle difference refers to difference between bus voltage phasor angles[3]. Phase angle difference between the sending and receiving end of a short transmission line $(\delta_S - \delta_R)$ is primarily a factor of real power flow across the transmission line (P_R), and the electrical impedance (X) across the sending and receiving ends. Since voltages are generally held near their nominal operating level for pre- and post-contingency conditions, the sending (V_S) and receiving (V_R) end voltages do not significantly influence the angle difference. Increasing phase angle difference indicates system stress in the forms of increased power flow or increased electrical impedance between the two points.

Takeaway: Phase angle difference is indicative of system stress – increased power flow or electrical impedance. Removing lines from service increases electrical impedance.

When a system element is intentionally or unintentionally removed from service in the bulk power system (BPS), the electrical impedance between the two terminals of that element will increase. As the equation shows, an increase in impedance (X) results in increased phase angle differences. Significantly large phase angle differences across the grid, and across terminals of transmission circuits, can pose a risk to reliability. The goal is to effectively manage phase angle differences and mitigate to the extent possible significantly large phase angle differences.

State Estimator Based Phase Angle Monitoring

At each converged state estimator (SE) solution, the phase angle difference across each terminal in the modeled network can be obtained. This data can be compared against existing limits, similar to other alarms such as voltage or thermal overload alarms. Similarly, this information can be extracted from operations studies in the same manner. Commercial energy management system (EMS) software applications provide the capability of defining node or bus angle pairs and comparing calculated phase angle differences against defined settings such as synchrocheck relay settings.

The SE tools allow users to define a group of node pairs (NP) with pre-assigned limits[4]. These NP limits are where users can input the actual synchrocheck relay settings for each respective line[5]. Figure 1 shows a screenshot of the definition of the NP limits for the North Gila-Imperial Valley 500kV transmission circuit. Note that the vendor solution in this case uses Normal, Emergency, and PBI[6] as the three limit levels that will be monitored against. For this line the recloser limits are set to 50 degrees for the phase angle difference as per defined operating procedures, matching the Normal and Emergency Limits.

[3] Generally, the voltage measurement is used to report the phase angle within the PMU.

[4] Some EMS vendors use Normal and Emergency Limits to represent these angle limits, similar to branch overloads. The intent of monitoring angle differences exceeding synchrocheck limits is to make operators aware of potential post-contingency angle differences exceeding synchrocheck relay settings and the potential need for mitigating actions (e.g., redispatch) to bring the phase angle difference within the relay settings before attempting to close the line that has been lost.

[5] Synchrocheck relay settings change relatively infrequently; therefore, static limits are generally acceptable for these types of alarms.

[6] PBI is the Possible But Improbable limit – likely set large enough in this example that it does not come into play.

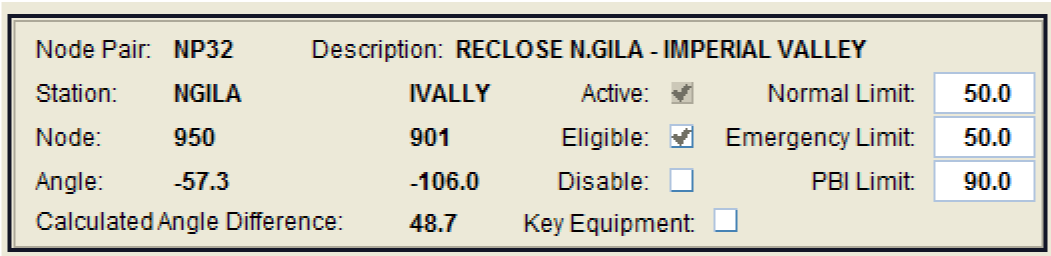

Figure 1: Phase Angle Difference Limits Based on Synchrocheck Relay Settings [Source: Peak Reliability]

Once limits are established in the SE tools, they can be monitored for each solved state estimate. Estimated bus voltage phase angle difference are compared against the selected angle separation threshold set by the user. Figure 2 shows a screenshot of the reported network "abnormal" bus voltage phase angle differences exceeding the user-defined threshold of 20 degrees in this example. This simply allows the user to quickly screen for high angle differences on their system in the current N-0 operating condition. In certain parts of the system with high transmission flows, this may be a useful tool for increased situational awareness.

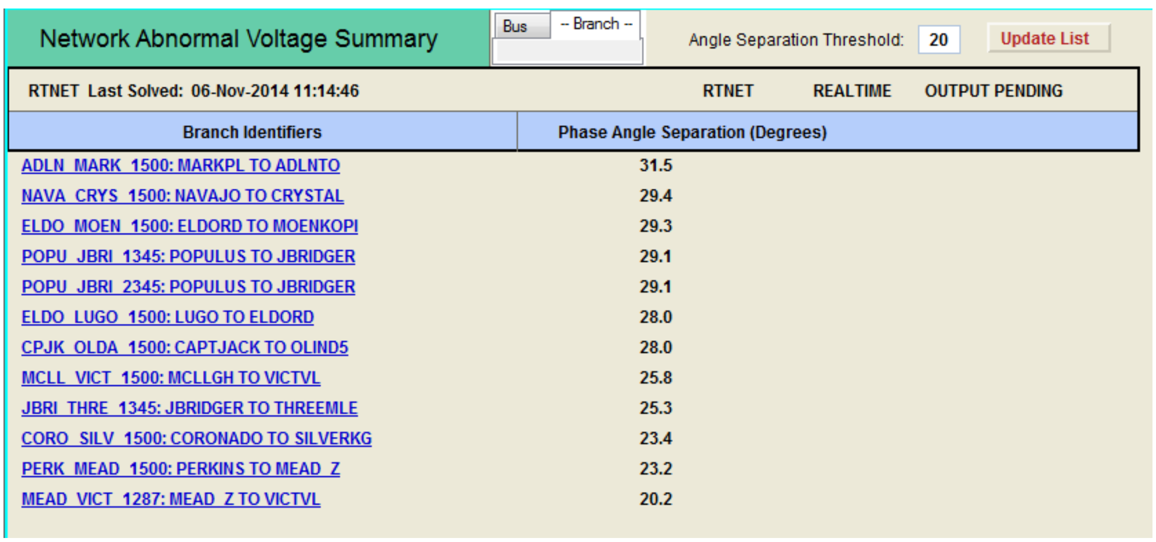

Figure 2: Reported Phase Angle Differences over Threshold in SE [Source: Peak Reliability]

In addition, some EMS vendors have a default display that shows transmission circuits with post-contingency phase angle differences approaching their specified angle difference limits. Figure 3 shows two circuits being monitored on the ATC system where outages result in post contingency angles greater than the defined synchrocheck limits as an example illustration. ATC elects to model the synchrocheck relay settings each end of the line – the Normal Limit corresponds to the lower synchrocheck phase angle setting and the Emergency Limit corresponds to higher synchrocheck phase angle setting for the line. ATC models these this way[7] since the actual relay settings may be significantly different for a line.

[7] This guideline does not recommend a specific modeling implementation – this should be discussed by each entity and implemented as best suitable for their system.

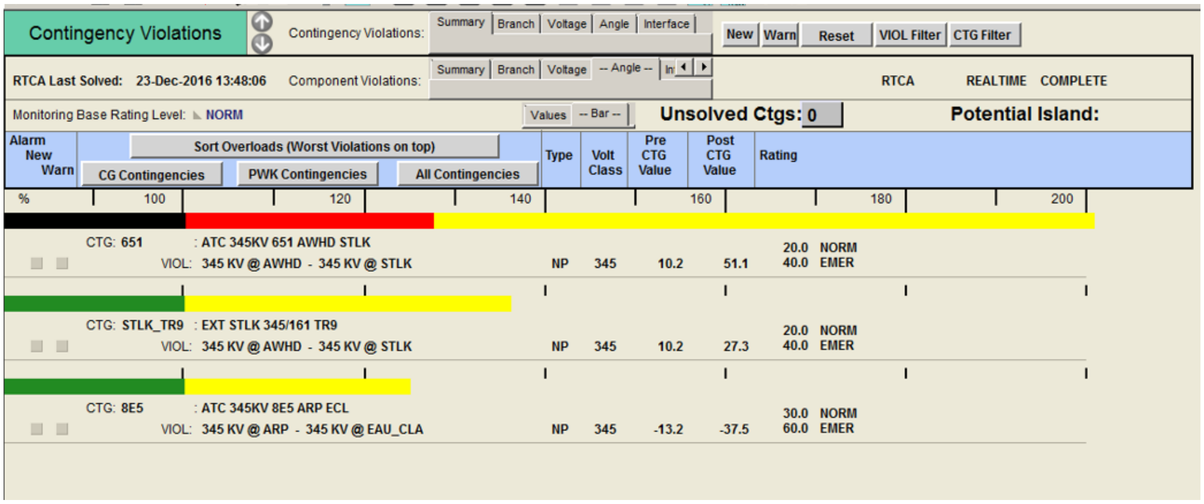

Figure 3: Example of Angle Difference Threshold Reporting in RTCA [Source: ATC]

At each iteration of the RTCA, the post-contingency exceedances can also be identified. Figure 4 shows an example of exceedances[8] of the phase angle limits for various contingencies, in this case for both Normal and Emergency Limits. This detects a potential exceedance of synchrocheck relay limits ahead of the actual contingency, so that system operators are aware that this exceedance would take place and a large angular separation would exist[9]. The mitigation plan can be derived from operations engineering guidance as well as operating procedures.

> **Goal:** Synchrocheck relay settings can be configured as limits in RTCA. These settings can be monitored for pre- and post-contingency conditions to inform operators of excessive angle differences, areas of high system stress, and potential operating limitations.

[8] These exceedances are based on the phase angle difference limits set for the defined node pairs. These may be treated differently operationally in terms of mitigation and secure operation of the BPS. However, the recommendation is for operators to be aware of these post-contingency angle difference exceedances prior to the contingency occurring.

[9] These large angular separations greater than the synchrocheck relay settings are (1) indicative of high system stress conditions, and (2) hinder the ability to reclose the transmission circuit. While this may not be the first priority operational action, it is still useful to understand when these conditions could occur.

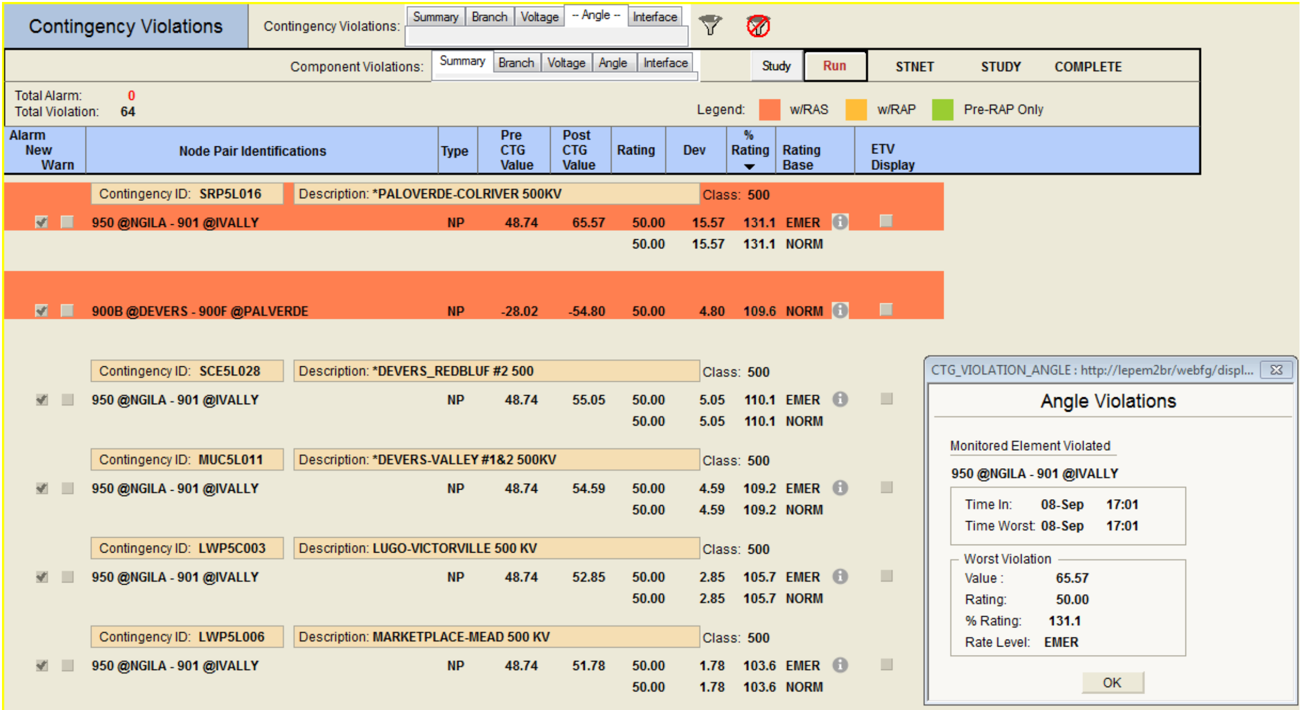

Figure 4: Post-Contingency Angle Monitoring through RTCA
[Source: Peak Reliability]

Mitigation and Operating Procedures for Line Restoration

As highlighted in the 2011 Southwest Outage Finding and Recommendation 27, monitoring excessive phase angle differences across transmission circuits to identify lines that cannot be restored following outage is viable and relatively straightforward. Thresholds for these angle differences are based on synchrocheck relay settings. Practical control actions that can be utilized for phase angle exceedances may include:

- Reconfiguration of in-series capacitors/reactors for compensation of transmission circuits
- Generation redispatch
  - Reducing generation on the sending end of the angle difference path
  - Increasing generation on the receiving end of the path
- Use of phase-shifting transformers to reduce power flow (if available)
- Reconfiguration of system topology to reduce power flow (if possible)
- Curtailment of interruptible load, if necessary
- Firm load shedding, if necessary
- Point-to-point transmission service curtailment