Real-Time Operational Use Cases for Time-Synchronized Measurements With Synchrowave Operations

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Glossary of Acronyms

Acronym	Definition
ACE	Area Control Error
AGC	Automatic Generation Control
BA	Balancing Authority
BAAL	BA ACE Limit
BAL	Resource and Demand Balancing (Standards)
BES	Bulk Electric System
BPS	Bulk Power System
CIGRE	International Council of Large Electric Systems
CRSTT	Control Room Solutions Task Team
DOE	Department of Energy
EMS	Energy Management System
EOP	Emergency Preparedness and Operations (Standards)
FERC	Federal Energy Regulatory Commission
FTL	Frequency Trigger Limit
GO	Generator Owner
IEEE	Institute of Electrical and Electronics Engineers
IRO	Interconnection Reliability Operations and Coordination (Standards)
IROL	Interconnection Reliability Operating Limit
kV	Kilovolt
MW	Megawatt

Acronym	Definition
MVAR	Megavolt Ampere Reactive
NASPI	North American SynchroPhasor Initiative
NERC	North American Electric Reliability Corporation
PMU	Phasor Measurement Unit
PV	Power-Voltage (PV) Curve
RC	Reliability Coordinator
RTA	Real-time Assessment
RTCA	Real-Time Contingency Analysis
SCADA	Supervisory Control and Data Acquisition
SEL	Schweitzer Engineering Laboratories, Inc.
SOL	System Operating Limit
TO	Transmission Owner
TOP	Transmission Operations (Standards)
TRS	Total Reliability Solutions LLC
TSAT	Transient Stability Assessment Tool
VAR	Voltage and Reactive (Standards)
VQ	Voltage-Reactive Power Curve
VSA	Voltage Stability Assessment
VSAT	Voltage Stability Assessment Tool

1 Purpose

This paper defines operational use cases that demonstrate the use of SEL's Synchrowave Operations software to improve situational awareness and support the performance of reliability-related tasks in the Real-time Operations Horizon.

This paper references specific North American Electric Reliability Corporation (NERC) Reliability Standard requirements for operating the North American Bulk Power System (BPS). While these requirements are not applicable to entities operating outside of North America, it is likely that similar regulatory requirements apply internationally.

2 Operational Use Case Approach

The operational use cases defined within this paper demonstrate SEL Synchrowave Operations use by System Operators and Operations Support Personnel to identify and address abnormal conditions and unacceptable system performance that could adversely impact Bulk Electric System (BES) reliability.

Collectively, these cases address the following key areas of electric system operations:

1. System Monitoring and Notifications
    - Frequency Monitoring and Resource and Demand Balancing
    - Bus Voltage Monitoring
    - Power System Oscillations
    - Real and Reactive Power Monitoring
    - SOL and IROL Exceedances
    - Excessive Phase Angle Differences
    - Major System Disturbances
    - Voltage Stability Events
    - Fault Detection and Location
2. Asset Investigation
    - Post-event analysis
    - Equipment health and assessment monitoring

The general reliability goals and NERC Reliability Standard requirements that are associated with each case are identified as well.

3 Frequency Monitoring and Resource and Demand Balancing

This use case demonstrates how the Synchrowave Operations application is used to:

1. Identify Balancing Contingency Events and off-nominal system frequency,
2. Determine the magnitude and severity of the event, and
3. Identify actions that can be taken to restore Demand and resource balance and return system frequency within acceptable bounds.

3.1 Introduction and Background Information

Although Synchrowave Operations is applied worldwide, it is useful to consider the North American situation, as the information is applicable, to varying degrees, around the world.

North America is comprised of two major and three minor ac power grids, which are often referred to as Interconnections:

- Eastern Interconnection
- Western Interconnection
- Texas Interconnection
- Quebec Interconnection
- Alaska Interconnection

All North American Interconnections operate at a synchronized frequency averaging 60 Hz. Each interconnection has one or more Balancing Authorities (BA) that are responsible for maintaining demand and resource balance within their respective BA areas and supporting Interconnection frequency in real-time.

The NERC Resource and Demand Balancing (BAL) Reliability Standards define requirements for BAs to control interconnection frequency within defined limits and act as necessary to return Area Control Error (ACE) within acceptable bounds following a Balancing Contingency Event.

The *Glossary of Terms Used in NERC Reliability Standards* defines Balancing Contingency Event as "Any single event described in Subsections (A), (B), or (C) below, or any series of such otherwise single events, with each separated from the next by one minute or less.

A. Sudden loss of generation:
    a. Due to
        i. unit tripping, or
        ii. loss of generator Facility resulting in isolation of the generator from the Bulk Electric System or from the responsible entity's System, or
        iii. sudden unplanned outage of transmission Facility;
    b. And, that causes an unexpected change to the responsible entity's ACE.
B. Sudden loss of an Import, due to forced outage of transmission equipment that causes an unexpected imbalance between generation and Demand on the Interconnection.
C. Sudden restoration of a Demand that was used as a resource that causes an unexpected change to the responsible entity's ACE."

While the Reliability Coordinator (RC) and Transmission Operator (TOP) functions are not directly responsible for Resource and Demand Balancing, they do monitor system frequency and are responsible for monitoring all Facilities within their respective areas to identify System Operating Limit (SOL) and Interconnection Reliability Operating Limit (IROL) exceedances. Therefore, these entities must also identify changes to the status of generating and transmission facilities and analyze the resulting system conditions to determine if a SOL or IROL exceedance has occurred.

3.2 Operational Roles and Responsibilities

When a Balancing Contingency Event causes a generation-load-Interchange imbalance and results in off-nominal system frequency, System Operators must:

1. Recognize the Balancing Contingency Event and its potential cause,
2. Determine the magnitude and severity of the event and resulting frequency excursion, and
3. Evaluate mitigating actions required to balance demand and resources and return frequency within acceptable bounds.

3.3 Synchrowave Application

Synchrowave Operations displays time-synchronized, sub-second measurements alongside traditional Energy Management System (EMS) and SCADA data present to provide System Operators with a clearer view of how the electric grid responds to Balancing Contingency Events.

This enables System Operators to perform event analysis within seconds of an event occurring allowing them to quickly identify the expected location and cause of the event to help inform the operational decision-making process.

3.4 Use of Application for Frequency Monitoring and Resource and Demand Balancing

This section describes how the Synchrowave Operations application can be used to identify and respond to Balancing Contingency Events.

3.4.1 Normal Operations (Pre-Event)

SEL's Synchrowave Operations application has two distinct sets of dashboards, one for system monitoring and the other for event analysis.

System Monitoring Dashboards: Users typically rely on the System Monitoring dashboards to maintain situational awareness of actual and expected system conditions. Each dashboard consists of multiple panels that are customized to meet an individual user's needs. These panels are highly configurable and present measurements, calculations, and status points in several different ways (system overviews, station schematics, charts, trends, tables, etc.).

- Overview Dashboard: Most users will continuously monitor the primary Overview dashboard, which presents data and information critical to maintaining situational awareness and aids in identifying unacceptable system performance. This Overview dashboard includes panels for monitoring system frequency and Resource-Demand Balancing.

Overview Dashboard Example

- Customized System Monitoring Dashboards: Users can also view other customized dashboards that present data and information needed to perform further analysis of system conditions. For example, many grid operators and electric utilities will maintain Balancing and Generation dashboards that display load, generation, and interchange values.

3.4.2 Balancing Contingency Event (Event Trigger)

There are several ways a user can identify a Balancing Contingency Event and off-nominal frequency event using the Synchrowave Operations application.

Automatic Notification: No matter which dashboard a user is viewing, a Notification Summary is always visible in the upper right corner of the screen to alert users when a predefined threshold is being approached or exceeded. The type of notifications that appear in the summary may include, but are not limited to, Frequency, Angle, Voltage, Power, Oscillations, etc.

A resource loss within the area of responsibility and subsequent frequency drop will likely result in exceedances of predefined Real Power and system frequency thresholds, which will cause both the Frequency and Power tiles to highlight on the Notification Summary.

Event Analysis Dashboard: Selecting a notification tile will automatically navigate the user to an Event Analysis dashboard that presents data and information specific to the category the user has chosen.

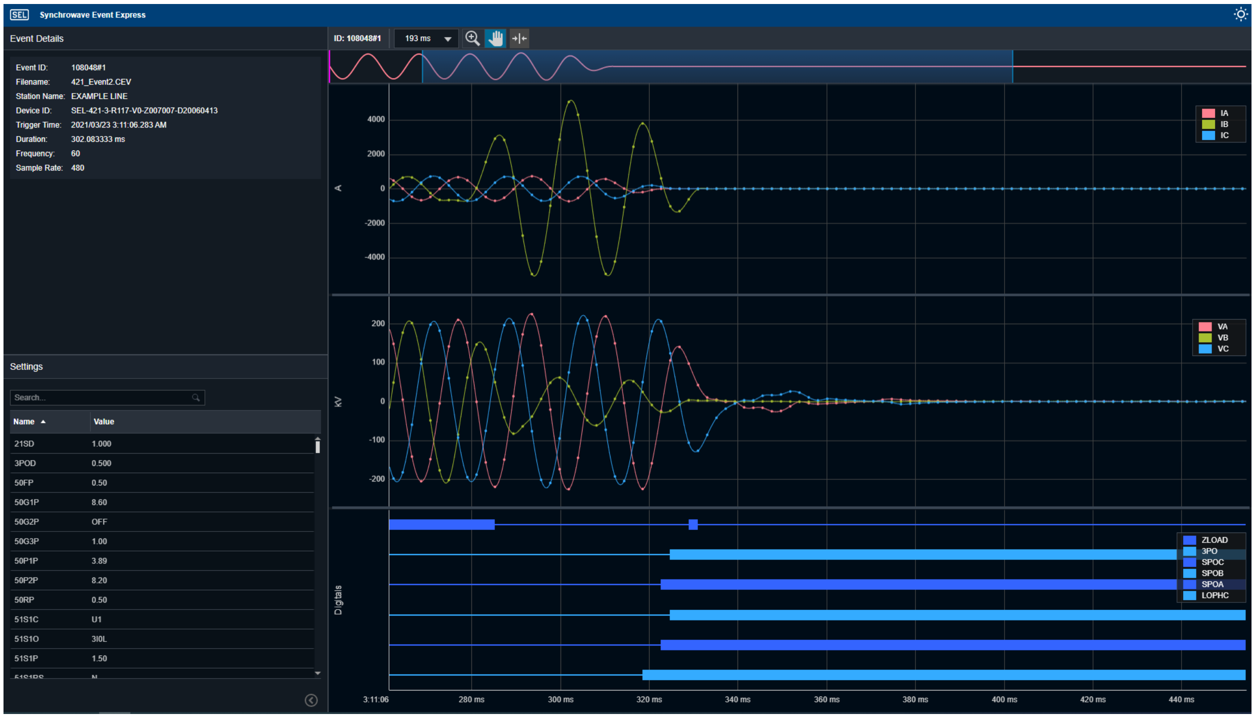
The application uses intelligent software that allows it to generate dashboards that are unique to each event. For example, when a generation loss results in an off-nominal frequency event, the user can select the Frequency or Power tile in the Notification Summary to view a dashboard that provides trends for each frequency measurement that exceeded a predefined threshold and presents information pertaining to event, such as the location of the resource loss and magnitude of the resulting frequency deviation.

Frequency Event Analysis Dashboard Example

<u>Event Records and Relay Information</u>: Furthermore, the Event Analysis dashboard includes a list of current and past events that provide critical information about the nature and scope of each event.

When viewing an Event Analysis dashboard or an event record for an event where a protective relay has operated, the user receives indication that a relay has operated and is given the option to access relay information. This feature provides significant value as it allows the user to view relay oscillography alongside synchrophasor-based and traditional data to gain a better understanding of the type of event that occurred and sequence of events.

Correlation of Frequency Response and Relay Event Record



Relay Oscillography Analysis

Once the user completes an assessment of system conditions to determine the nature and severity of the event, the user can develop a mitigation plan to alleviate the condition and return to normal operations.

3.4.3 Restoring Resource and Demand Balance (Return to Normal Operations)

The user views each of the previously referenced dashboards to track recovery from the event and determine if additional actions are required to return to normal operation in an acceptable amount of time.

If the resource loss that caused the event occurred within the BA Area, then the user views the System Monitoring dashboards to identify resources that can be used to restore balance and monitor the BA ACE, BA ACE Limit (BAAL), and Contingency Reserve values to track recovery.

If the resource loss occurred outside of the BA Area, the user can monitor system frequency and other indicators of system health to track recovery and determine if a failure by another entity to respond could lead to an operating Emergency within the interconnection.

3.4.4 Related NERC Reliability Standard Requirements

The following NERC Reliability Standard requirements are related to this use case:

Normal Operations (Pre-Event)

- BAL-001-2 R2: BA System Operators can use this application to monitor the BA ACE and determine when the BAAL has been exceeded.
- IRO-008-2 R4: RC System Operators and Operations Support Personnel[1] can use this application to perform Real-time Assessments (RTA) at least once every 30 minutes.
- TOP-001-5 R13: TOP System Operators and Operations Support Personnel can use this application to perform RTAs at least once every 30 minutes.

Balancing Contingency Event (Event Trigger and Recovery)

- BAL-002-3 R1 and R3: BA System Operators can use this application to identify and track recovery from Reportable Balancing Contingency Events.
- IRO-002-7 R5: RC System Operators and Operations Support Personnel can use this application to monitor facilities within their RC area and neighboring RC areas to identify any SOL exceedances and to determine any IROL exceedances within its RC area.
- TOP-001-5 R2: BA System Operators and Operations Support Personnel can use this application to identify system conditions where they must act to maintain the reliability of the BA Area.
- TOP-001-5 R10: TOP System Operators and Operations Support Personnel can use this application to monitor facilities to determine SOL exceedances within their TOP Area.

[1] NERC defines Operations Support Personnel as “Individuals who perform current day or next day outage coordination or assessments, or who determine SOLs, IROLs, or operating nomograms, in direct support of Real-time operations of the Bulk Electric System.”

4 Excessive Power System Oscillations

This use case demonstrates how the Synchrowave Operations application is used to:

1. Recognize excessive power system oscillations,
2. Determine the magnitude and severity of the oscillations, and
3. Identify actions that can be taken to alleviate the excessive oscillatory behavior.

4.1 Introduction and Background Information

Oscillations are always present on the electric system because of the electromechanical nature of the grid. Power system oscillations can be categorized as Natural or Forced in nature.

The *NERC Reliability Guideline for Forced Oscillation Monitoring and Mitigation* dated September 2017, describes natural and forced oscillations as follows:

- **System (Natural)**: low-frequency rotor angle oscillations caused by instantaneous power imbalances. These are often differentiated further as follows:
  - Local: Oscillations where one power plant or generating unit oscillates with the rest of the system, generally caused by heavy loading and generator controls.
  - Intra-plant: Oscillations where generating units within a power plant oscillate with each other at the same location, generally caused by poor tuning, unit control interactions, and unit operating modes.
  - Inter-area: Oscillations characterized by several coherent units or parts of the system oscillating against other groups of machines, often predominant in power systems with relatively weaker interarea connections.
  - Torsional: High (subsynchronous) frequency oscillations caused by resonance conditions between highly compensated transmission lines and the mechanical modes of a steam-turbine generator (typically referred to as subsynchronous resonance).
- **Forced**: Sustained oscillations driven by external inputs to the power system that can occur at any frequency, such as unexpected equipment failures, control interactions, or abnormal operating conditions.

Forced power system oscillations can occur at any frequency and are becoming more prevalent because of the increase in sources and loads that are connected through power electronics, such as solar and wind.

4.2 Operational Roles and Responsibilities

Excessive power system oscillations are an indicator of abnormal conditions and may result in system instability, equipment damage, safety concerns, and power quality issues if left unaddressed.

When excessive oscillations are present on the power system, System Operators and Operations Support Personnel must:

1. Recognize the excessive oscillations based on the impact to system operating characteristics (e.g., frequency, voltage levels, real/reactive power flow),
2. Determine the magnitude and severity of the oscillations and their possible origin, and
3. Identify actions that can be taken to eliminate or reduce the severity of the oscillations.

4.3 Value of Synchrowave for This Use Case

This application allows System Operators and Operations Support Personnel to recognize and address excessive oscillatory behavior that could go undetected with traditional data sources.

Excessive power system oscillations can result in system instability, equipment damage, safety concerns and power quality issues if left unaddressed.

4.4 Use of Application for Oscillation Detection

This section describes how the Synchrowave Operations application is used to recognize and respond to excessive power system oscillations.

4.4.1 Normal Operations (Pre-Event)

The application attributes and features described in Section 3.4.1 apply to this case as well since excessive power system oscillations can often be recognized by users when viewing sub-second, time-synchronized trends.

Oscillation Detection and Modal Analysis Dashboard: This dashboard is specifically designed for monitoring local and inter-area oscillatory behavior and is the user's primary tool for recognizing excessive power system oscillations.

This dashboard includes various trends and dials to gauge oscillation frequency, oscillation damping levels, and oscillation amplitude.

SEL's Synchrowave Operations application displays outputs from other oscillation detection and mode meter applications that are in use.

Disturbance Detector Dashboard: This dashboard is specifically designed for monitoring a wide range of oscillations and disturbances, including forced oscillations using statistic-based methods.

Example of Disturbance Detector Dashboard showing Forced Oscillation

4.4.2 Excessive Oscillatory Behavior (Event Trigger)

There are several ways a user can recognize excessive power system oscillations by using the Synchrowave Operations application:

System Monitoring Dashboards: As previously stated, users can often recognize excessive power system oscillations when viewing the synchrophasor-based measurements that are presented on the various System Monitoring dashboards.

Specifically, excessive oscillatory behavior can often be detected by monitoring current, voltage, and real/reactive power measurements at generating stations. In most instances, the user can determine whether the oscillations are of a local or inter-area nature based on number of locations where the oscillations are observed.

Automatic Notification: The Notification Summary will always appear in the upper right corner of the screen to alert the user when one of the automated oscillation monitoring applications detects an oscillation or disturbance.

Event Analysis Dashboard: Selecting the Oscillation tile in the Notification Summary will open an Event Analysis dashboard that presents data and information specific to the oscillatory behavior of the power system.

The application uses intelligent software to generate dashboards that are unique to each oscillation event. The user can view these dashboards to determine the nature and severity of the oscillation event.

Once the user completes an assessment of system conditions to determine the nature and severity of the event, the user can develop a mitigation plan to alleviate the condition and return to normal operations.

Example Oscillation Event Analysis Dashboard Showing Modal Analysis Results

4.4.3 Alleviating Excessive Oscillations (Return to Normal)

The user can view the previously referenced dashboards to track recovery from the event and determine if additional actions are required to return to normal operation in an acceptable amount of time.

The actions taken to alleviate excessive power system oscillations will vary depending on the cause and whether the origin of the oscillations is within the user's area of responsibility.

Excessive oscillatory behavior is typically addressed by identifying and addressing the external input that is forcing the oscillations (e.g., malfunctioning generator control or incorrect setting) or changing system operating characteristics to alleviate the condition (e.g., redispatching generation or reconfiguring transmission to reduce power flow).

Example Oscillation Event Analysis Dashboard Showing Disturbance Detector Results

4.4.4 Related NERC Reliability Standard Requirements

The following NERC Reliability Standard requirements are related to this use case:

Normal Operations (Pre-Event)

- IRO-008-2 R4: RC System Operators and Operations Support Personnel can use this application to perform RTAs at least once every 30 minutes.
  TOP-001-5 R13: TOP System Operators and Operations Support Personnel can use this application to perform RTAs at least once every 30 minutes.

Identifying and Addressing Excessive Oscillatory Behavior (Event Trigger and Recovery)

- TOP-001-5 R1: TOP System Operators and Operations Support Personnel can use this application to recognize excessive power system oscillations that must be acted upon to maintain system reliability.
- TOP-001-5 R2: BA System Operators and Operations Support Personnel can use this application to recognize excessive power system oscillations that must be acted upon to maintain system reliability.
- VAR-001-5 R2 and R3: TOP System Operators and Operations Support Personnel can use this application to recognize the need to operate devices to regulate transmission flow and reactive flow as necessary when mitigating an SOL or IROL exceedance.

NOTE: This case does not specifically address excessive power system oscillations that result in SOL or IROL exceedances. Refer to Section 5.4.4 for a list of NERC Reliability Standard requirements associated with such cases.

5 SOL and IROL Exceedances

This use case demonstrates how the Synchrowave Operations application is used to identify and address SOL and IROL exceedances.

5.1 Introduction and Background Information

Each Generator Owner (GO) and Transmission Owner (TO) must document its Facility Ratings methodology and establish Facility Ratings for the each of the facilities that it owns.

The *Glossary of Terms Used in NERC Reliability Standards* defines a facility as any set of electrical equipment that operates as a single BES Element (e.g., a line, generator, transformer) and a Facility Rating as the maximum or minimum voltage, current, frequency, or real/reactive power flow through a facility that does not violate the applicable equipment rating of any equipment at the facility.

Each RC must document its SOL methodology and each TOP must then establish SOLs for its portion of the RC area in a manner that is consistent with the methodology.

The *Glossary of Terms Used in NERC Reliability Standards* defines SOL and IROL as follows:

<u>System Operating Limit</u>: The value (such as MW, MVAR, amperes, frequency, or volts) that satisfies the most limiting of the prescribed operating criteria for a specified system configuration to ensure operation within acceptable reliability criteria. SOLs are based upon certain operating criteria. These include, but are not limited to:

- Facility Ratings (applicable pre- and post-contingency equipment ratings or Facility Ratings)
- Transient stability ratings (applicable pre- and post-Contingency stability limits)
- Voltage stability ratings (applicable pre- and post-Contingency voltage stability)
- System voltage limits (applicable pre- and post-Contingency voltage limits)

<u>Interconnection Reliability Operating Limit</u>: A SOL that, if violated, could lead to instability, uncontrolled separation, or cascading outages that adversely impact the reliability of the BES.

The NERC Interconnection Reliability Operations and Coordination (IRO) and Transmission Operations (TOP) Reliability Standards define requirements for identifying and addressing actual and potential SOL and IROL exceedances in the Same-day and Real-time Operations Horizons.

5.2 Operational Roles and Responsibilities

RC and TOP System Operators and Operations Support Personnel must perform RTAs at least once every 30 minutes to:

1. Identity actual (pre-Contingency) or potential (post-Contingency) SOL and IROL exceedances,
2. Determine the nature and severity of the event, and
3. Initiate mitigating actions to alleviate the condition.

In most instances, predetermined mitigating actions will be identified in an Operating Plan, which should also identify the entities that must act to address the condition and any timeframes associated with the performance of mitigation activities.

5.3 Value of Synchrowave for This Use Case

SEL's Synchrowave Operations application provides System Operators and Operations Support Personnel with the data and information necessary to identify actual and potential SOL and IROL exceedances and determine viable mitigating actions based on the severity of the event.

This application is particularly useful when analyzing protective relay operations to determine the sequence of events that led to a SOL or IROL exceedance since it allows user to view relay records alongside synchrophasor-based measurements, which presents a clearer view of when certain events occurred and how the electric grid responded to changing system conditions.

5.4 Use of Application for SOL and IROL Monitoring

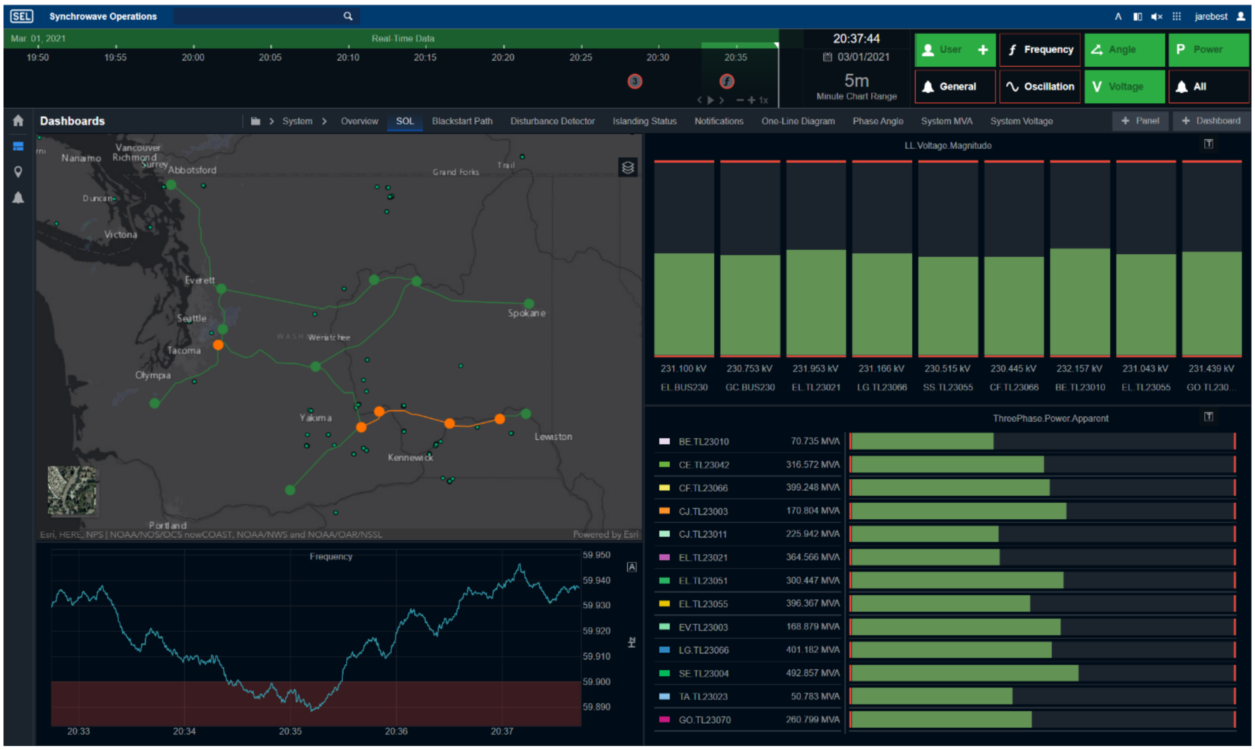
This section describes how the Synchrowave Operations application is used to identify and address SOL and IROL exceedances.

5.4.1 Normal Operations (Pre-Event)

The application attributes and features described in Section 3.4.1 apply to this case as they can be used to perform RTAs of actual and expected system conditions to identify SOL and IROL exceedances.

In addition, grid operators and electric utilities will typically maintain set of customized System Monitoring dashboards for monitoring established SOLs and IROLs.

SEL's Synchrowave Operations application can display outputs from State Estimator, Real-Time Contingency Analysis (RTCA), and Voltage/Transient Stability Assessment (VSAT/TSAT) tools so users can view network applications data alongside synchrophasor-based measurements and traditional EMS and SCADA data to assess all data and information pertaining to SOLs and IROLs in one centralized location.



Example Synchrowave Operations Dashboard Showing Limits

5.4.2 SOL and IROL Exceedances (Event Trigger)

There are several ways a user can recognize SOL and IROL exceedances using the Synchrowave Operations application:

System Monitoring Dashboards: Users identify when an SOL or IROL is approached or exceeded via the various System Monitoring dashboards. In some instances, the associated limit will appear next to the measurement being monitored (e.g., amps, volts, MW, MVAR) so the user can observe the exceedance. In addition, the measurement will typically change color indicating that it is approaching or exceeding an established threshold.

Automatic Notification: The Notification Summary will always appear in the upper right corner of the screen to alert user when a predefined threshold is being approached or exceeded.

The tile that lights up upon when a SOL or IROL is exceeded will depend on the type of limit exceeded. When a thermally-based limit is approached or exceeded, the Power tile will highlight. When a voltage-based limit is approached or exceeded, the Voltage tile will highlight. Other tiles may highlight depending on the nature and cause of the exceedance.

Event Analysis Dashboards and Event Records: Selecting a tile that is highlighted in the Notification Summary will navigate the user to an Event Analysis dashboard that presents data and information specific to the SOL or IROL that has been exceeded.

The application uses intelligent software to generate dashboards that are unique to each event and group notifications together to declutter the user's view so an Event that results in multiple limit exceedances may have a common screen and Event Record to capture information about the nature and scope of the event. The user views these dashboards and records to determine the nature and severity of the limit exceedances.

Relay Information: The user will receive indication when a protective relay has operated and given the option to access relay information. This feature provides significant value as it allows the user to view relay oscillography alongside synchrophasor-based and traditional data to gain a better understanding of the type of event that occurred and sequence of events. This is of significant importance when developing a mitigation plan to address an SOL or IROL exceedance because a fault condition may eliminate the use of certain Facilities.

Once the user completes an assessment of system conditions to determine the nature and severity of the event, the user can develop a mitigation plan to alleviate the condition and return to normal operations.

5.4.3 Mitigating SOL and IROL Exceedances (Return to Normal)

The user can view the previously referenced dashboards to validate the effectiveness of a mitigation plan and determine when the SOL or IROL is no longer exceeded.

The actions taken to mitigate an exceedance will vary depending on the cause, the equipment owner(s), contractual obligations, etc. However, the mitigating steps typically require an operator to redispatch generation, reconfigure BES facilities, or adjust load.

As described in Section 5.2, predetermined mitigating actions are often identified in Operating Plans along with the entities that are responsible to act and the timeframes associated with the performance of mitigation activities. Grid operators and electric utilities will often take those mitigation actions into account when designing System Monitoring dashboards so the user can easily assess the status of associated facilities to determine if action is viable given the actual system conditions.

5.4.4 Related NERC Reliability Standard Requirements

The following NERC Reliability Standard requirements are related to this use case:

Normal Operations (Pre-Event)

- IRO-008-2 R4: RC System Operators and Operations Support Personnel can use this application to perform RTAs at least once every 30 minutes.
- TOP-001-5 R13: TOP System Operators and Operations Support Personnel can use this application to perform RTAs at least once every 30 minutes.

Identifying and Mitigating SOL and IROL Exceedances (Event Trigger and Recovery)

- IRO-002-7 R5: RC System Operators and Operations Support Personnel can use this application to identify SOL exceedances and to determine any IROL exceedances within the RC area.
- IRO-008-2 R5: RC System Operators and Operations Support Personnel can use this application to identify actual or expected conditions that result in, or could result in, SOL or IROL exceedances within the RC's wide area.
- TOP-001-5 R1: TOP System Operators and Operations Support Personnel can use this application to recognize adverse operating conditions and that must be acted upon to maintain system reliability.
- TOP-001-5 R14: TOP System Operators and Operations Support Personnel can use this application to identify SOL exceedances and recognize the need to initiate Operating Plans to mitigate such exceedances.
- VAR-001-5 R2 and R3: TOP System Operators and Operations Support Personnel can use this application to recognize the need to operate devices to regulate transmission flow and reactive flow as necessary when mitigating an SOL or IROL exceedance.

6 Excessive Phase Angle Differences

This use case demonstrates how the Synchrowave Operations application is used to:

1. Monitor the voltage phase angle difference between two electrical busses, and
2. Determine when a line is exceeding the maximum allowable closing angle.

6.1 Introduction and Background Information

Grid operators and electric utilities monitor the voltage phase angle difference between electrical busses to:

- Determine when a transmission facility is exceeding its maximum allowable closing angle such that, if that facility were to relay, it could not be returned to service until actions are taken to reduce the standing angle within acceptable limits.
- Identify excessive phase angles across the wider electrical system that could result in angular instability.

There are no NERC Standards that specifically require NERC functional entities to monitor phase angles. However, the FERC/NERC report titled *Arizona-Southern California Outages on September 8, 2011: Causes and Recommendations,*[2] which was released in April 2012, does include a finding and recommendation specific to phase angle monitoring:

<u>Finding 27</u>: Phase Angle Difference Following Loss of Transmission Line: A Transmission Operator (TOP) did not have tools in place to determine the phase angle difference between the two terminals of a 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.

<u>Recommendation 27</u>: 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

[2] http://www.ferc.gov/legal/staff-reports/04-27-2012-ferc-nerc-report.pdf

Also note that *NERC Standard IRO-002-7 – Reliability Coordination – Monitoring and Analysis* requires RCs to provide their System Operators with the capabilities necessary to monitor and analyze data needed to perform their reliability functions.

The rationale provided by NERC for including certain requirements states the following, "Changes made to the proposed definitions were made in order to respond to…recommendations on phase angles from the SW Outage Report (recommendation 27). The intent of such changes is to ensure that Real-time Assessments contain sufficient details to result in an appropriate level of situational awareness. Some examples include 1) analyzing phase angles which may result in the implementation of an Operating Plan to adjust generation or curtail transactions so that a Transmission facility may be returned to service, or 2) evaluating the impact of a modified Contingency resulting from the status change of a Special Protection Scheme from enabling/in-service to disabling/out-of-service."

6.2 Operational Roles and Responsibilities

When excessive voltage phase angles are observed on the electric system, System Operators and Operations Support Personnel must:

1. Determine when a transmission facility is exceeding (pre-Contingent) or expected to exceed (post-Contingent) its maximum allowable closing angle, or when angles are large enough to warrant concern about angular instability,
2. Identify possible causes and contributors to the large voltage phase angle, and
3. Develop a mitigation plan that includes actions that can be taken to reduce voltage phase angles within acceptable bounds and associated timeframes to act.

6.3 Value of Synchrowave for This Use Case

Following a transmission line relay operation, grid operators and electric utilities have traditionally waited until a line is energized to scope across the open terminal and determine if the line is within the maximum allowable closing angle.

SEL's Synchrowave Operations application allow utilities to measure the voltage angle difference between the electrical busses, and determine if the line will be within limits, prior to energizing for test. This increases the amount of time an entity must perform corrective actions to reduce phase angle to within acceptable limits if needed.

6.4 Use of Synchrowave Operations Application for Phase Angle Monitoring

This section describes how the Synchrowave Operations application can be used to monitor the voltage phase angle difference between two electrical busses and determine when a line is exceeding the maximum allowable closing angle.

6.4.1 Normal Operations (Pre-Event)

System Monitoring Dashboard: Phase angle difference measurements from across a system can be displayed together on system diagram so users can view any areas of system stress. In addition, panels can be placed on system dashboards to view phase angles in trends, tables, and dials.

Example Phase Angle Monitoring Dashboard

6.4.2 Recognizing Excessive Phase Angles (Event Trigger)

There are several ways a user can identify excessive voltage phase angle differences using the Synchrowave Operations application:

System Monitoring Dashboards: Users determine when a voltage phase angle is approaching or exceeding a predefined threshold via System Monitoring dashboards.

In instances where the voltage phase angle being monitored is associated with a line that has a maximum allowable closing limit, that limit is likely to appear in proximity to phase angle measurement so the user can observe the exceedance. In addition, the measurement will typically change color indicating that it is approaching or exceeding the established threshold. The same attributes can also be observed on associated trends, tables, and dials.

Automatic Notification: The Notification Summary will always appear in the upper right corner of the screen to alert user when a predefined threshold is being approached or exceeded. The Angle tile will highlight when a voltage phase angle between select busses is approaching or exceeding a predefined threshold.

Event Analysis Dashboards and Event Records: Selecting the Angle tile that is highlighted in the Notification Summary will navigate the user to an Event Analysis dashboard that presents data and information specific to voltage phase angle that is approaching or exceeding its limit.

The application uses intelligent software to generate dashboards that are unique to each event and generate an event record to capture information about the nature and scope of the event. The user can view these dashboards and records to determine the magnitude of the voltage phase angle difference.

Relay Information: The user will receive indication when a protective relay has operated and given the option to access relay information. This feature provides significant value when evaluating the voltage phase angle difference on a line that has relayed as it allows the user to determine if there are any testing restrictions before taking action to reduce the angle within acceptable closing limits.

Once the user completes an assessment of system conditions to determine the nature and severity of the event, the user can develop a mitigation plan to reduce the phase angle difference as needed based on actual and expected system conditions.

6.4.3 Reducing Phase Angle Differences (Return to Normal)

In most instances, voltage phase angles can be reduced by redispatching generation reduce power transfers or reconfiguring transmission (e.g., bypassing series compensation). However, in extreme cases, it may be necessary to interrupt load.

6.4.4 Related NERC Reliability Standard Requirements

The following NERC Reliability Standard requirements are related to this use case:

Normal Operations (Pre-Event)

- IRO-008-2 R4: RC System Operators and Operations Support Personnel can use this application to perform RTAs at least once every 30 minutes.
- TOP-001-5 R13: TOP System Operators can use this application to perform RTAs at least once every 30 minutes.

Identifying and Addressing Excessive Phase Angles (Event Trigger and Recovery)

- TOP-001-5 R1: TOP System Operators and Operations Support Personnel can use this application to identify excessive voltage phase angles that must be acted upon to maintain system reliability.
- TOP-001-5 R2: BA System Operators and Operations Support Personnel can use this application to identify excessive voltage phase angles that may require generation dispatch to maintain system reliability.

7 Major System Disturbances

This use case demonstrates how the Synchrowave Operations application can be used to:

1. Recognize major system disturbances resulting from extraordinary contingencies or other high impact-low frequency events,
2. Determine the nature and severity of the event, and
3. Prioritize corrective action to return the system to safe and reliable operation.

7.1 Introduction and Background Information

The NERC Reliability Standards define the reliability requirements for planning and operating the North American BPS. These standards include criteria to prepare for and respond to credible Contingencies. NERC defines a Contingency as “The unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, switch or other electrical element.”

However, complying with these standards does not guarantee the ability to maintain BPS reliability as the occurrence of extraordinary contingencies can result in an operating Emergencies and/or major system disturbances.

NERC defines a Disturbance as:

1. An unplanned event that produces an abnormal system condition.
2. Any perturbation to the electric system.
3. The unexpected change in ACE that is caused by the sudden failure of generation or interruption of load.

NERC defines an Emergency as, “Any abnormal system condition that requires automatic or immediate manual action to prevent or limit the failure of transmission facilities or generation supply that could adversely affect the reliability of the Bulk Electric System.”

While the term “extraordinary contingency” is not defined by NERC, for purposes of this paper, it is considered to be the occurrence of a non-credible contingency and/or loss of generation beyond the most severe single contingency.

In accordance with *NERC Standard EOP-011-1 – Emergency Operations*, BAs and TOPs must have Operating Plans in place to mitigate operating Emergencies, and RCs must review such plans for compatibility and inter-dependencies to identify and address any reliability risks that exist.

In addition, RCs and TOPs must develop their own separate restoration plans to implement when a Disturbance occurs in which one or more areas of the BES shuts down and Blackstart Resources must be utilized for restoration or when system separation occurs.

7.2 Operational Roles and Responsibilities

Generally, when an extraordinary contingency or other type of event results in an operating Emergency or major system disturbance, system operations staff must:

1. Perform an initial assessment of system conditions to determine the nature and severity of the event,
2. Take immediate action to stabilize and maintain reliable operation of Facilities that remain energized if necessary, and
3. Conduct further analysis and implement restoration plans or other Operating Plans to alleviate the Emergency condition and return to normal operations.

7.3 Value of Synchrowave for This Use Case

SEL's Synchrowave Operations application allows System Operators and Operations Support Personnel to easily transition between system overviews, station displays, and custom dashboards to gain wide-area situational awareness and evaluate local area impacts to determine the nature and severity of major system Disturbances.

This application allows users to quickly identify abnormal conditions or unacceptable system performance that requires immediate manual action to prevent or limit the failure of transmission facilities or generation supply that could adversely affect the reliability of the BES, including system islanding conditions and partial or total system shutdowns that require implementation of a restoration plan.

7.4 Use of Synchrowave Operations Application During Major System Disturbances

The following table identifies how the Synchrowave Operations application can be used to recognize, analyze, and respond to major system Disturbances and references the related NERC Reliability Standard requirements.

Action	Synchrowave Operations	Related NERC Standard Requirements
Normal Conditions	Provide visuals of time-series synchrophasor data along with a wide range of other data for wide-area monitoring and RTA performance.	IRO-008-2 R4, TOP-001-5 R13
Recognize Contingency Event and Resulting Operating Emergency	Provide automated notifications along with visualization of a wide range of data to help users recognize a Contingency Event and the resulting operating Emergency. Visuals include wide-area and station-specific views so users can quickly assess unacceptable system performance (e.g., thermal and voltage-based SOL exceedances and capacity shortage) and prioritize corrective response.	TOP-001-5 R1 and R2, EOP-011-1 R2, IRO-002-7 R5, TOP-001-5 R14
Determine Viable Mitigation	Quickly guide users to the relevant information necessary to determine mitigating actions.	EOP-011-1 R1 and R2
Return to Normal Operation	Provide the wide-area situational awareness necessary to determine when all operating parameter exceedances have been mitigated and any energy deficiencies have been addressed.	EOP-011-1 R6

8 Voltage Stability Events

This use case demonstrates how the Synchrowave Operations application is applied to identify potential voltage stability issues and determine mitigating actions that can be taken to alleviate the condition.

8.1 Introduction and Background Information

As described in Section 5, each RC must document its SOL methodology for use in developing SOLs within its RC area and each TOP must establish SOLs for its portion of the RC area in a manner that is consistent with its RC's methodology.

SOLs are values that satisfy the most limiting of the prescribed operating criteria for a specific confirmation. These criteria include any *voltage stability* or *transient stability* limits that may exist. An IROL is a SOL that, if violated, could lead to *instability*, uncontrolled separation, or cascading outages that adversely impact the reliability of the BES.

Voltage stability is one of the fundamental concepts in power system stability analysis and is essential for maintaining normal operation of today's power systems.

There are multiple definitions of voltage stability, including:

- "Voltage stability is the capability of the system to supply the load with reactive power for a given real power demand", V. Venikov.
- "Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition," IEEE/CIGRE Joint Task Force on Stability Terms and Definitions (P. Kundur, et al.), "Definitions and Classification of Power System Stability," IEEE Trans. on Power Systems, vol. 19, no. 2, August 2004, pp. 1387-1401.

System dynamics influencing voltage stability are usually slow, therefore, steady-state analysis offers an effective way to perform Voltage Stability Assessment (VSA). Power-Voltage (PV) and Voltage-Reactive Power (VQ) curves are the most frequently used steady-state techniques for performing VSA.

Online VSA is usually performed at the State Estimator sampling rate, which usually ranges from three to ten minutes and can be up 1000 times slower than the typical synchrophasor data sampling rate. The advantage of synchrophasor data is that it allows for continuous monitoring of the power system and computation of operating margins at much higher resolution rates than what has been available with VSA using SCADA and State Estimator data.[3]

8.2 Operational Roles and Responsibilities

RC and TOP System Operators and Operations Support Personnel must perform RTAs at least once every 30 minutes, which includes identifying potential voltage stability issues and initiating mitigating actions to alleviate the condition.

The way that voltage stability issues are identified will depend on the operational tools that are available to the System Operators and Operations Support Personnel and how voltage stability limits have been established within the entity's area of responsibility.

8.3 Value of Synchrowave for This Use Case

SEL's Synchrowave Operations software enables the development of applications that connect to VSA solutions so that System Operators and Operations Support Personnel can monitor voltage stability limits and/or margins alongside other critical operating data and information to more effectively monitor the power system state and identify conditions where a potential voltage collapse could occur.

9 Imminent Equipment Failure

This use case demonstrates how the Synchrowave Operations application can be used to monitor equipment health and identify indicators that failure is imminent.

9.1 Introduction and Background Information

Today's electric system faces many persistent and new challenges, including aging infrastructure and difficulties siting and constructing new transmission assets.

The last forty years have seen limited investment in the North American transmission grid. Figures provided by the United States Department of Energy (DOE) show that 70 percent of transmission lines and power transformers are 25 years or older and 60 percent of circuit breakers are 30 years or older. Catastrophic failures of transmission assets threaten system reliability and changing system dynamics may increase the likelihood of such events.[4]

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[3] North American SynchroPhasor Initiative (NASPI) Control Room Solution Task Team (CRSTT), *Using Synchrophasor Data for Voltage Stability Assessment Focus Area Document*, October 2015.
[4] U.S. DOE's Grid Modernization Multi-Year Program Plan, November 2015.

With widespread deployment of Phasor Measurement Units (PMU) and wider availability of synchrophasor data, many grid operators and transmission owners have discovered that they can use these data to gain unprecedented visibility into the status and health of equipment. Although most of the entities that have installed synchrophasor systems did so to enhance wide-area situational awareness and real-time monitoring capabilities, operations engineers working at several grid operators and electric utilities are using PMU data to uncover and diagnose a variety of equipment health issues and misoperations.[5]

9.2 Operational Roles and Responsibilities

This case does not specifically address the performance of reliability-related tasks. However, System Operators and Operations Support Personnel are responsible for monitoring facilities within their respective areas of responsibility and are expected to act upon discovering abnormal conditions that could have an adverse impact to safety, reliability, or economics. Therefore, providing system operations staff with the ability to identify and proactively address potential equipment failures before they occur provides significant value.

9.3 Use of Synchrowave Operations Application for Equipment Health Monitoring

Display and automated monitoring of a wide variety of information from many sources aids in assessing equipment health. The software provides high-speed access to all historical data. Engineers use the built-in calculation engine to analyze the historical data. Data can also be easily exported for external analysis tools.

[5] NASPI technical report, *Diagnosing Equipment Health and Mis-operations with PMU Data*, May 2015.