Recent BESS Oscillations: Root Cause Analysis and Wide-Area Impacts

NASPI Webinar, 7/10/2024

Matt Rhodes and Daniel Goodrich

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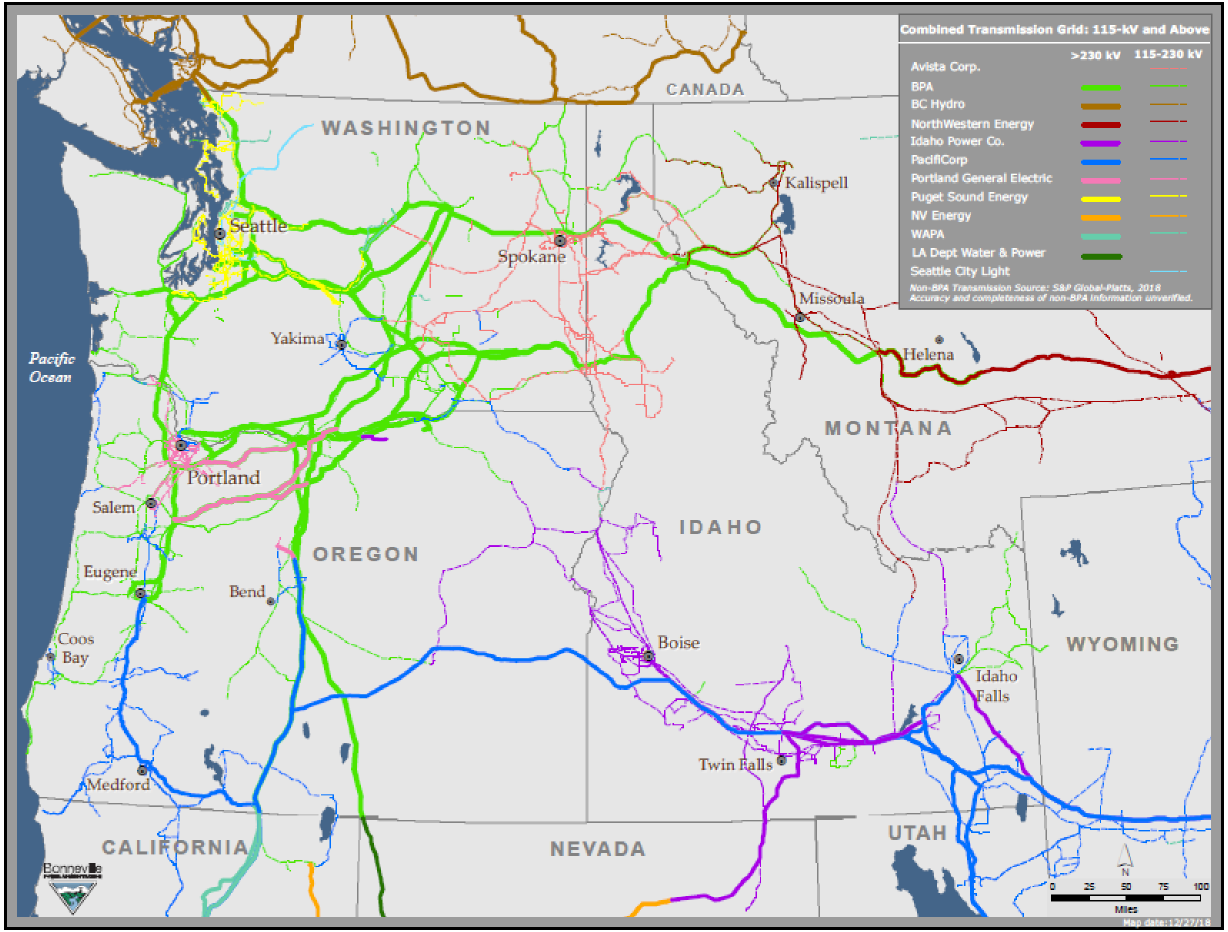
Agenda (SRP, then BPA)

- Challenges
- September 20, 2023 Event
- November 1, 2023 Event
- November 3, 2023 Event

SRP IBR Integration and Commissioning Challenges

- **BESS + PV Controller Logic Complexities** (Site Controller/PV Controller/BESS Controller)
- **Commissioning BESS and PV** (Partial Commercial Operation of Complete Commercial Operations)
- **IBR site meter compensation logic** (Operations, Power Accounting, and Control Security)
- **Robustnesss and vetting of controller logic** (Developer/Control Integrator vetting of controller logic and Hardware in the Loop testing)
- **Utility lack knowledge of controller logic**
- **IBR Event Root Cause Analysis** (Improving delivery of Root Causa Analysis from third party operated Power Purchase Agreement (PPA) IBR sites)

Combined Transmission Grid



Federal Columbia River Power System

General Info

- 20+ GW of hydro
- BPA has over 100 PMUs at 45 locations
- *Oscillation events give a priority 1 **audible** alarm

BPA’s Mode Meter Monitor

- Uses MAS (Modal Analysis Software), developed by Montana Tech

WECC

Modes of Inter-Area Power Oscillations in the Western Interconnection

Western Interconnection Modes Review Group

2021

https://www.wecc.org/Reliability/Modes%20of%20Inter-Area%20Power%20Oscillations%20in%20the%20WI.pdf

Summary of mode properties.

Mode	Freq. (Hz)	Shape	Interaction Path(s)	Controllability	Grade
NSA	0.20–0.30	Alberta vs. System	Alberta–BC (Path 1) Northwest–CA (Path 3)	Alberta	Well understood
NSB	0.35–0.45	Alberta vs. (BC + N. U.S.) vs. S. U.S.	COI (Path 66)	Widespread, incl. PDCI	Well understood
EWA	0.35–0.45	(Colorado + E. Wyo.) vs. System	Wyoming–ID (Path 19) Colorado–UT (Path 30) Colorado–NM (Path 31)	Colorado area	Marginally understood
BCA	0.50–0.72	BC vs. N. U.S. vs. S. U.S.	Unknown	Unknown	Not understood
BCB	0.60–0.72	W. edge vs. System vs. E. edge	Unknown	Unknown	Not understood

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 34, NO. 2, MARCH 2019 1579

Electromechanical Mode Estimation in the Presence of Periodic Forced Oscillations

Urmila Agrawal, *Member, IEEE*, Jim Follum, *Member, IEEE*, John W. Pierre, *Fellow, IEEE*, and Dongliang Duan, *Member, IEEE*

***Abstract*—Electromechanical modes are inherent to any interconnected power systems which provide a measure of the small-signal stability margin of the system. A number of algorithms have been developed for the estimation of these modes using synchrophasor measurements. However, most of these algorithms are not designed to operate in the presence of forced oscillations (FO). These FOs are results of periodic rogue input driving the system. When FOs are present, estimates of system modes can be biased depending on the frequency and the amplitude of the FOs.**

Key Point

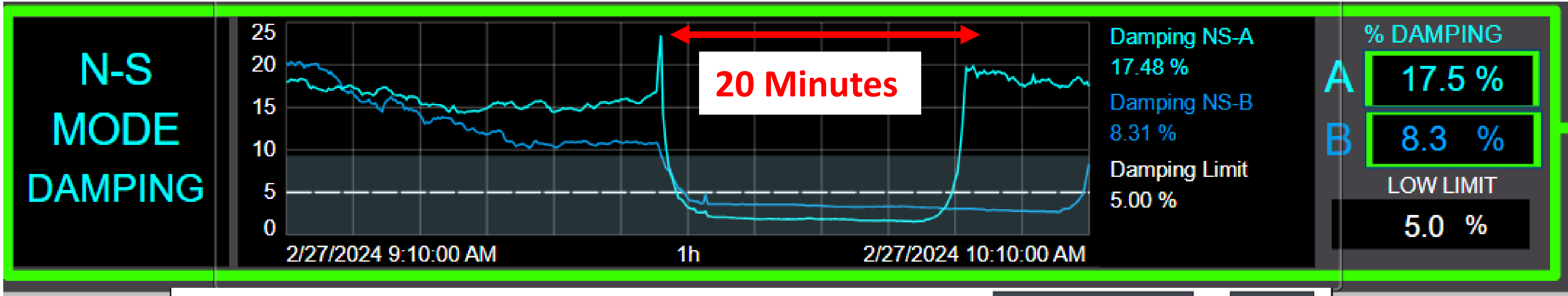
frequency and damping ratio. For a system to have a reasonable small–signal stability margin, damping ratio of all the system modes must be greater than some value, typically 3–5% [2]. A system event such as a critical line or generator trip can cause a decrease in the damping ratio of a system mode indicating that the system moved toward a less stable region, as was observed in the 1996 western grid outage [3]. Thus, continuous monitoring of these modes can provide critical information on

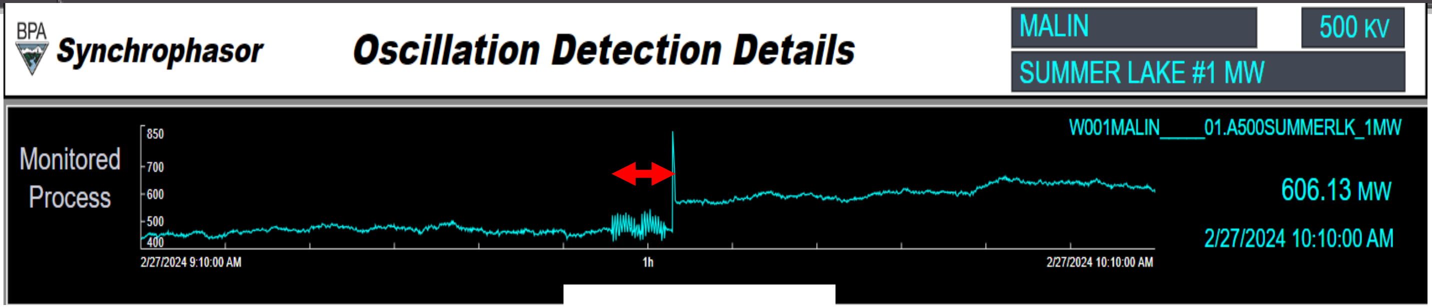
The Challenge: Forced Oscillations at or Near the Natural Mode

"When FOs [Forced Oscillations] are present, estimates of system modes can be biased depending on the frequency and the amplitude of the FOs."

Illustration: Adrenaline rush lasts for several minutes after the event

Damping and Oscillation





3 Minutes

September 20, 2023 IBR1 BESS Oscillation Summary

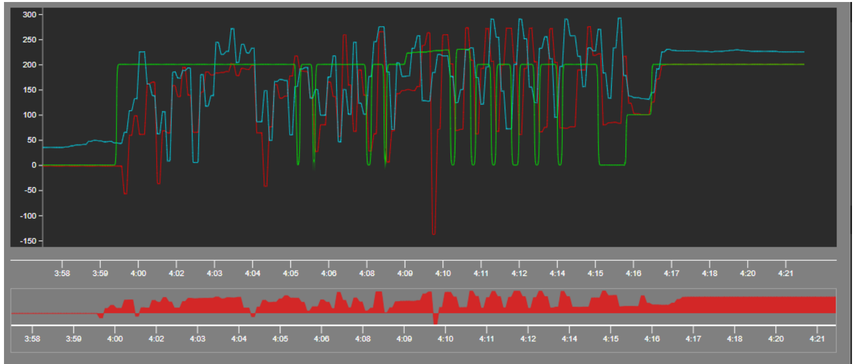
- **Event details:** Event identified after RC West called SRPs control room via Pi Vision displays. IBR Operator was able to take the unit to local to arrest the oscillation.
- **Cause:** Error in the Metering Loss Compensation Methodology
- **Solution:** Near term - Logic reverted to use uncompensated meter data. Long term – Fix compensated meter data and put back in place at this and other IBR operated sites for SRP – fix began 12/11/23 estimated completion 1/15/24.
- **WECC Impact:** Frequency of forced oscillations (0.25 Hz) was close to that of NS-A mode frequency causing the Modemeter to trigger alerts for NS-A mode critical damping ratio. Actual damping ratio remained unaffected (The damping ratio of a mode is essentially biased in the presence of forced oscillations having frequency close to that of the mode). RC West mode meters detected forced oscillation. RC West and BPA ODM (Oscillation Detection Module) tool detected forced oscillations with low damping ratio alerts triggered in the RC West Modemeter for NS-A mode. Oscillations in current and frequency across major WI 500kV lines.

September 20, 2023 IBR1 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Event Background

- Battery site was in an idle state when the site controller received a 200 MW discharge setpoint
- Site began to ramp but started oscillating prior to reaching the 200 MW discharge
- Oscillations lasted 17 minutes where maximum recorded output was 275 MW and minimum was -138 MW
- The site was placed in local mode with a 200 MW setpoint and followed that dispatch stopping the oscillations



Pen Name	Minimum	Maximum	Average	Axis	Plot	X Trace
BESS MW	-138	275	135.88	Default	0	
COMBINED MW	5	292	168.99	Default	0	
M580_1/HMI_PLANT_MW_SP_FB	0	230.15	159.43	Default	0	

Significant power output swings observed after site responded to discharge dispatch instructions

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September 20, 2023 IBR1 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Additional Event Details and Cause

- The metering EOR developed an algorithm to calculate losses for solar production when solar was passing through the transformer even when solar was charging the BESS
- This algorithm was approved by the operator and SRP and was tested by the operator with passing results
- The oscillation proved the compensated MW values were not plausible
- It was determined under certain conditions the algorithm would cause a divide by zero error that greatly increased the compensated MW values beyond the actual MW capacity of the site.

Under certain conditions, the algorithm used to calculate losses on the solar production caused a divide by zero error resulting in oscillation

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September 20, 2023 IBR1 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Countermeasures to prevent reoccurrence

Event Countermeasures

- On 9/24 the loss compensation logic was disabled in the meters for the solar charging BESS conditions
- New loss compensation logic has been written to eliminate the divide by zero scenario which has been approved by SRP and is currently being implemented by the metering EOR
- PLC compensation block will be revised to match the meter logic
    - Then, the PLC will control the power based on compensated power values

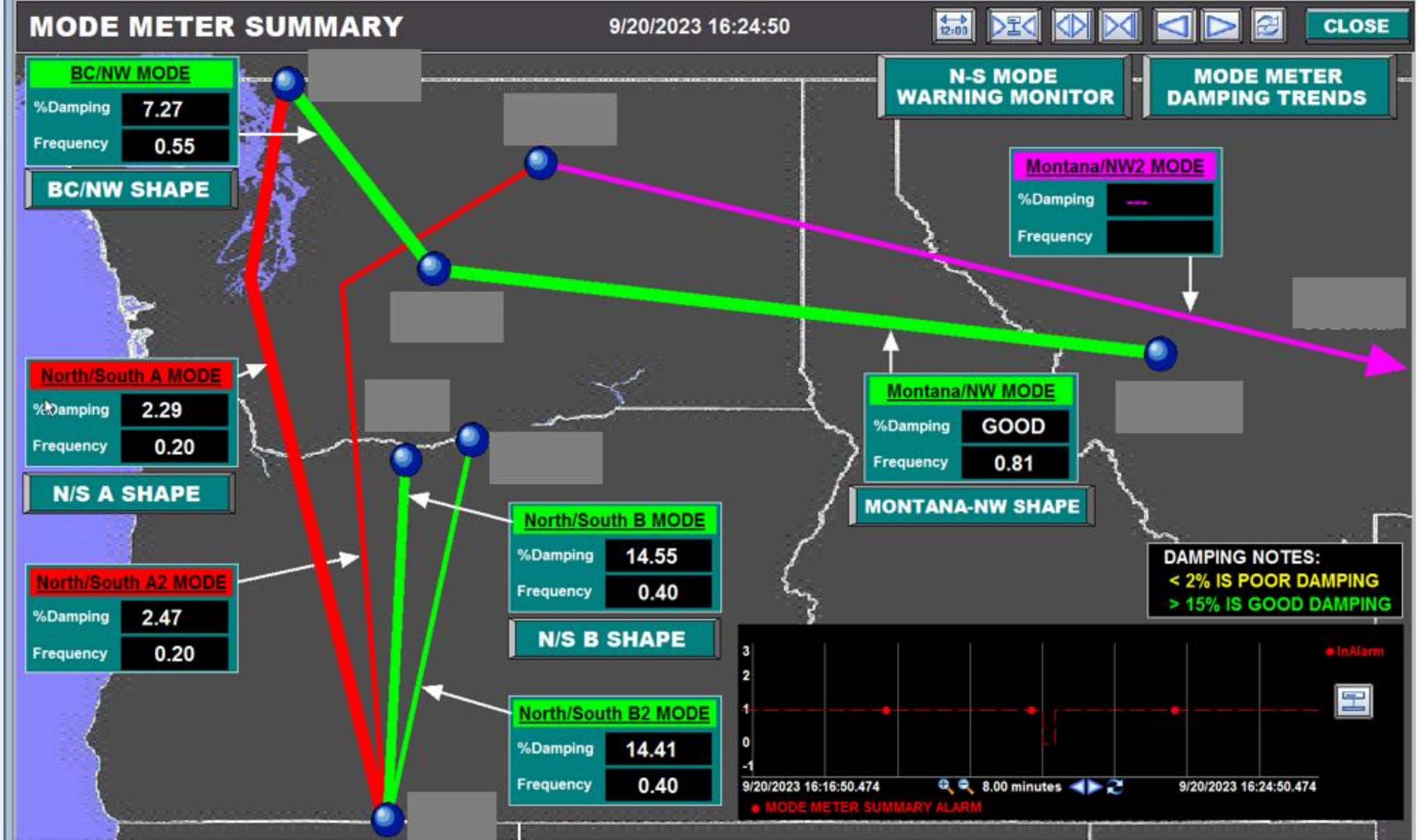
Additional Controls Enhancements

- During the troubleshooting, a deficiency in the frequency response logic was detected and corrected

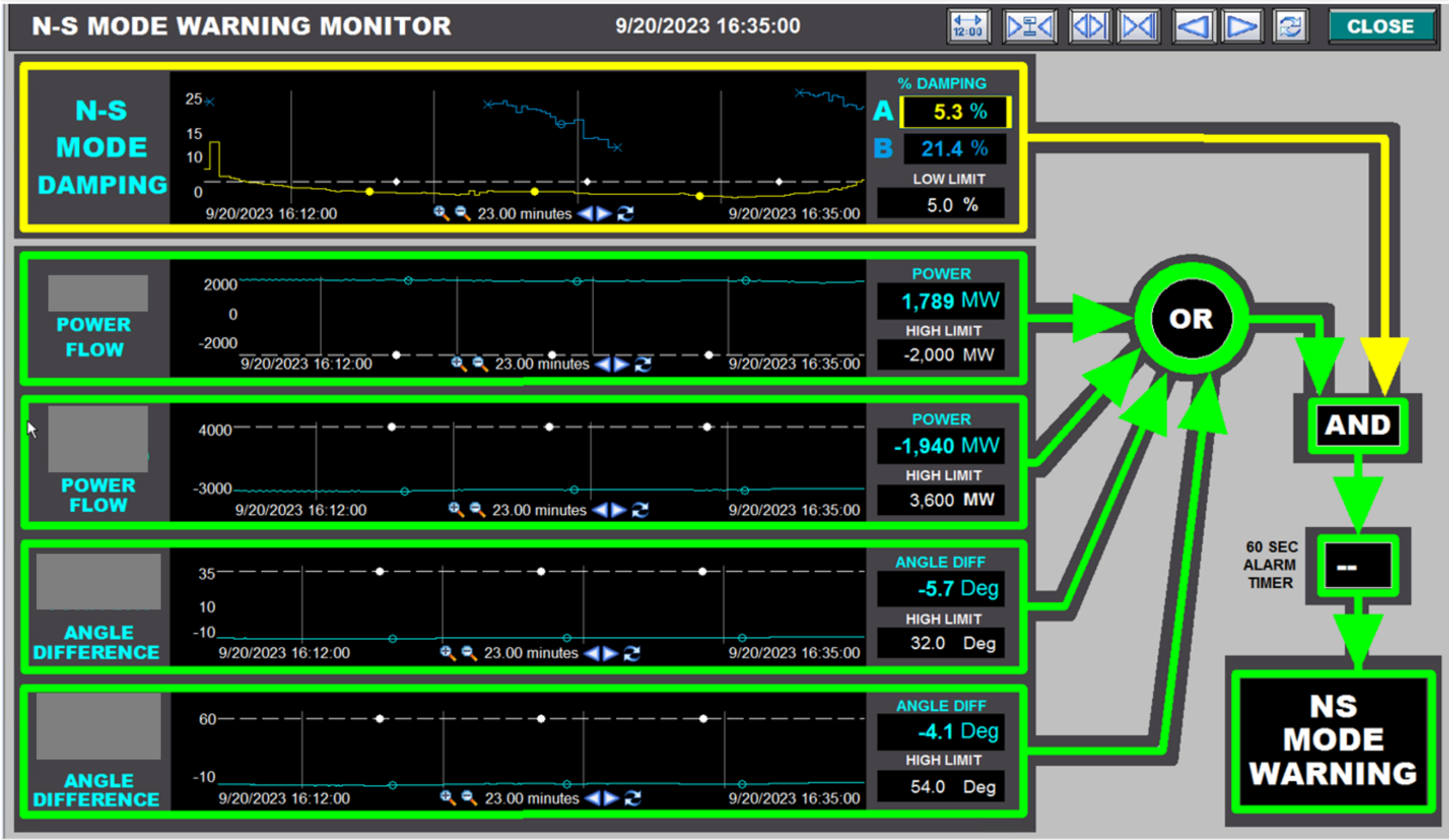
Video Board

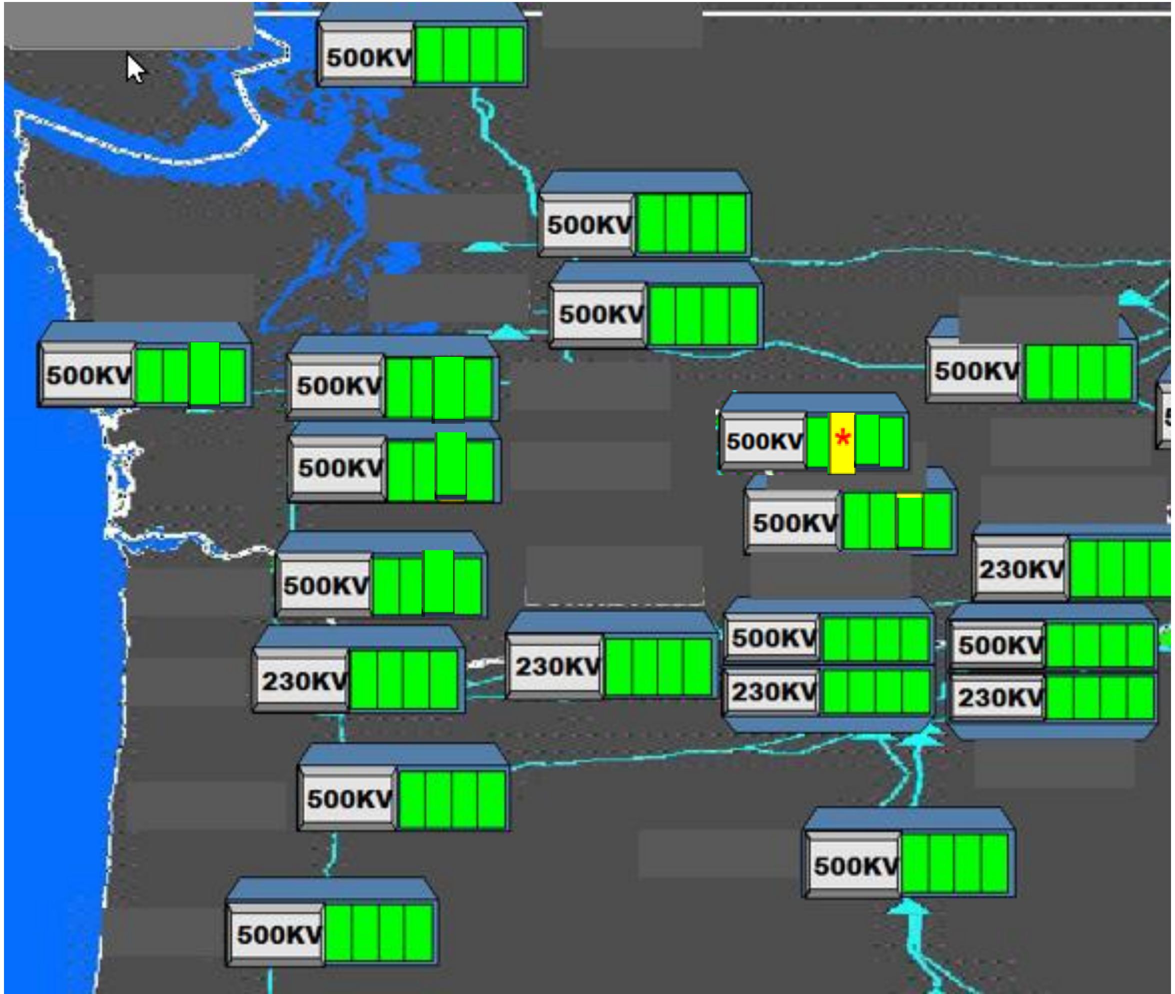
Oscillation Detection

Mode Meter

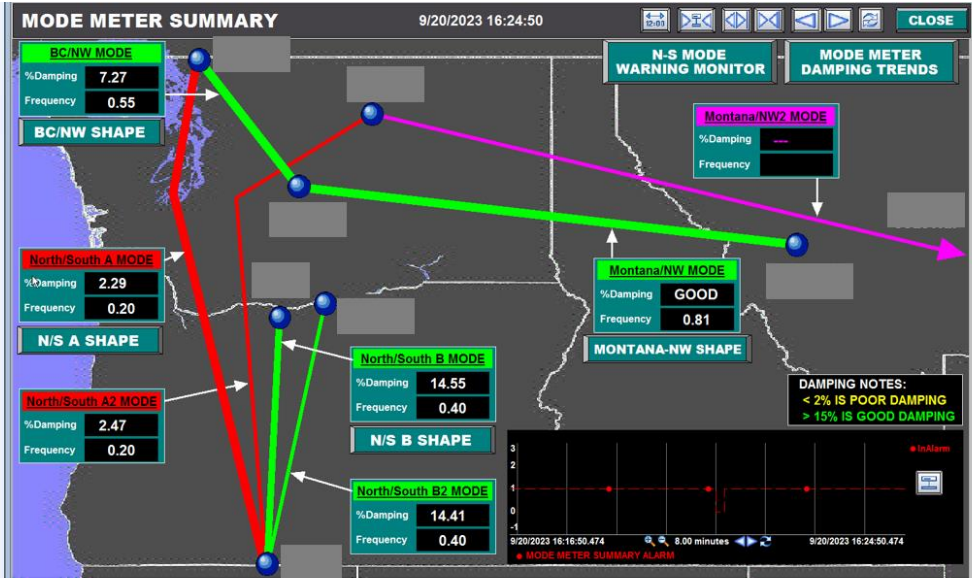


MODE METER SUMMARY
9/20/2023 16:24:50
CLOSE
N-S MODE WARNING MONITOR
MODE METER DAMPING TRENDS
BC/NW MODE
%Damping 7.27
Frequency 0.55
BC/NW SHAPE
Montana/NW2 MODE
%Damping ---
Frequency
North/South A MODE
%Damping 2.29
Frequency 0.20
N/S A SHAPE
Montana/NW MODE
%Damping GOOD
Frequency 0.81
MONTANA-NW SHAPE
North/South B MODE
%Damping 14.55
Frequency 0.40
N/S B SHAPE
North/South A2 MODE
%Damping 2.47
Frequency 0.20
North/South B2 MODE
%Damping 14.41
Frequency 0.40
DAMPING NOTES:
< 2% IS POOR DAMPING
> 15% IS GOOD DAMPING
InAlarm
9/20/2023 16:16:50.474
8.00 minutes
9/20/2023 16:24:50.474
MODE METER SUMMARY ALARM

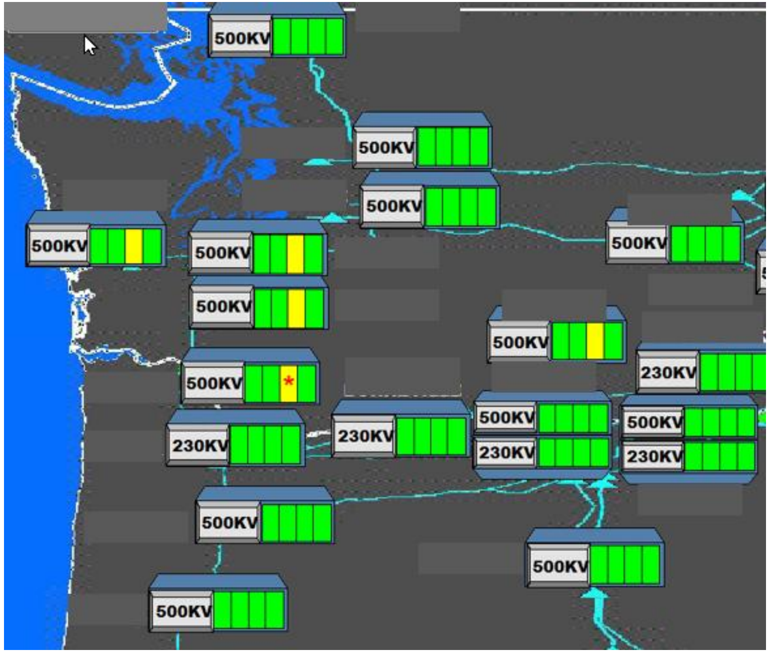

N-S MODE WARNING MONITOR
9/20/2023 16:35:00
CLOSE
N-S MODE DAMPING
% DAMPING
A 5.3 %
B 21.4 %
LOW LIMIT
5.0 %
POWER FLOW
POWER
1,789 MW
HIGH LIMIT
-2,000 MW
POWER FLOW
POWER
-1,940 MW
HIGH LIMIT
3,600 MW
ANGLE DIFFERENCE
ANGLE DIFF
-5.7 Deg
HIGH LIMIT
32.0 Deg
ANGLE DIFFERENCE
ANGLE DIFF
-4.1 Deg
HIGH LIMIT
54.0 Deg
9/20/2023 16:12:00
23.00 minutes
9/20/2023 16:35:00
OR
AND
60 SEC ALARM TIMER
--
NS MODE WARNING


500KV
500KV
500KV
500KV
500KV
500KV
500KV
500KV
500KV
500KV
230KV
500KV
230KV
500KV
230KV
500KV
230KV
500KV
500KV
500KV

Visual Alarm within seconds



Visual and audible Alarm in 2 minutes



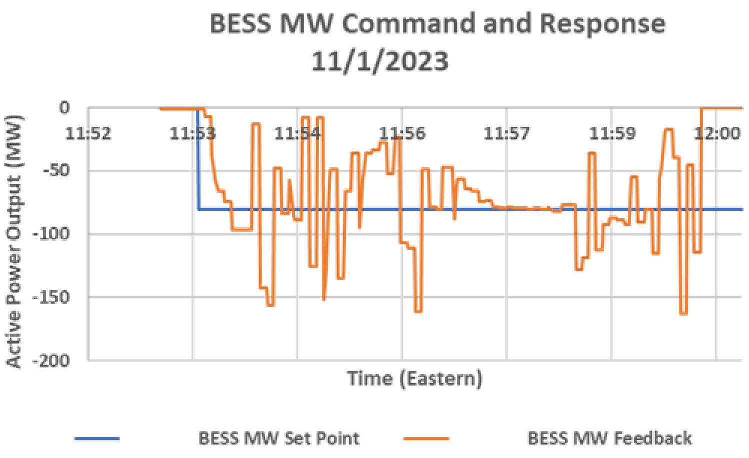
November 1, 2023 IBR1 BESS Oscillation Summary

- **Event Details:** SRP control room operators via the PI Vision displays, noticed the oscillation and called IBR Operator to address. Following 9/20 event, SRP implemented a POI breaker tripping procedure after 3 minutes of oscillations present. The event here looked to stabilize partway through the event. Once the oscillation re-engaged, SRP opened the POI breakers.
- **Cause:** Three GSUs delivered output with differing polarity (some discharging, and some charging) that resulted in erroneous GSU MVA limits. Severity of event aggravated by delayed inverter startup which was sourced from a control's integrator error the previous day to shut down all inverters for controller changes rather than placing inverters in idle. Some inverters were driven to startup upon receiving a non-zero dispatch command which led to unbalanced inverter startup.
- **Solution:** Fixed logic to ensure all inverters from all three GSUs are started up regardless of MW commands to site which also protects against potential inverter startup from a shut down state. GSU MW limit logic fixes put in place to prevent output signal polarity inversion.
- **WECC Impact:** Frequency of forced oscillations (0.25 Hz) was close to that of NS-A mode frequency causing the Modemeter to trigger alerts for NS-A mode critical damping ratio. Actual damping ratio remained unaffected. BPA operators thought the oscillations were caused by unstable NS-A mode and inserted series capacitors to improve mode damping ratio with essentially no effect. RC West and BPA ODM tool detected forced oscillations with low damping ratio alerts triggered in the Modemeter for NS-A mode.

November 1, 2023 IBR1 BESS Oscillation Root Cause Analysis
(Supplied by Plant Operator)

Event Background

- Battery site was dispatched from a 0 MW setpoint to 80 MW charge at ~11:53 EST on 11/1/2023
- Site ramped to -80 MW and began oscillating, with maximum output of ~-8 MW and minimum of -160 MW
- Adjacent PV site under commissioning and was injecting power at time of event



Significant power output swings observed after site responded to charge dispatch instructions

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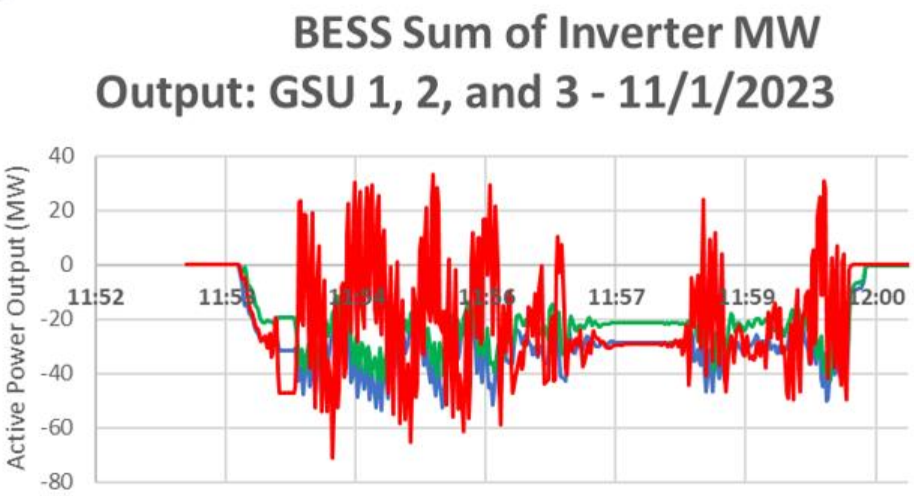
November 1, 2023 IBR1 BESS Oscillation Root Cause Analysis
(Supplied by Plant Operator)

Additional Event Details

- Site had control system update pushed on 10/31/23
  - Adjusted Ymin/Ymax values that reduced maximum and minimum values that can be commanded from site controller
  - Update was done by taking PLC offline and restarting controller
    - Not standard update practice for operatir units
- Oscillation was not consistent between the 3 site GSU transformers
  - GSUs 1/2 showed similar behavior, GSU 3 had more aggressive output swings



Inconsistent output swings observed across different portions of the facility. Differences in response between GSU Transformers indicate issue was not created by site level PID control, but with GSU-level translation of site commands

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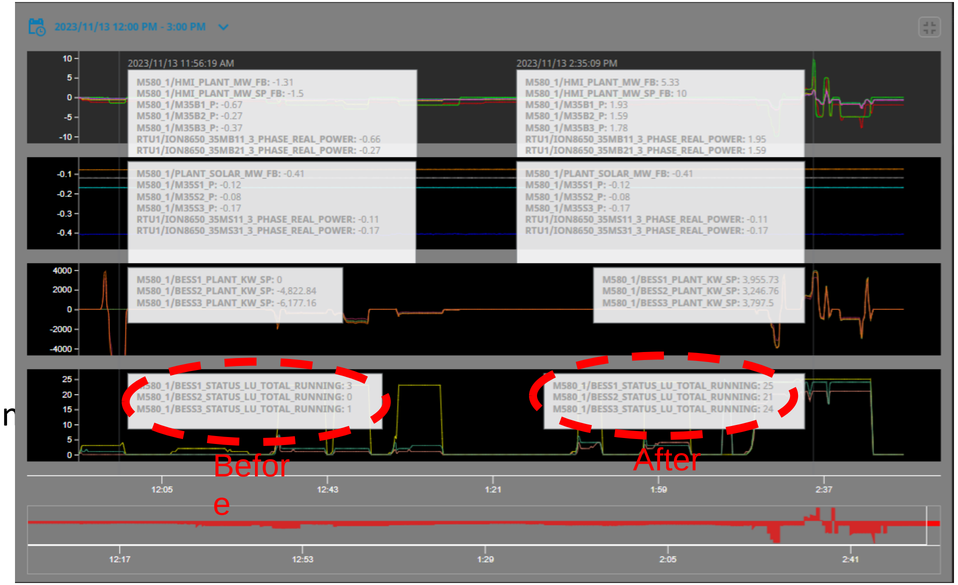
November 1, 2023 IBR1 BESS Oscillation Root Cause Analysis
(Supplied by Plant Operator)

Cause 1: Differences in start-up timing across GSUs

- The control update from 10/31/23 created condition that required all inverters on site to go through extended start sequence
  - Likely resulted in portions of the site waking at different times, creating an unbalanced condition that could shift load to specific portions of the facility
  - Testing confirmed asymmetric starts between transformers



Differences in response between GSU Transformers suspected of driving GSU near MVA limit

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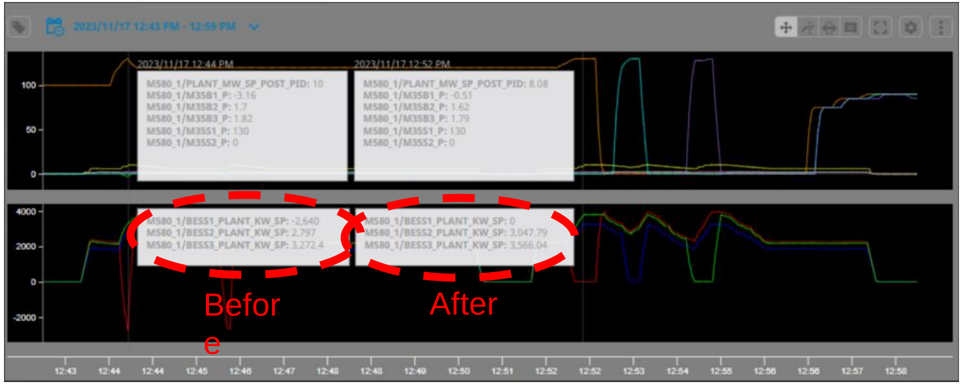
November 1, 2023 IBR1 BESS Oscillation Root Cause Analysis

(Supplied by Plant Operator)

Cause 2: GSU-level inverter setpoint polarity inversion

- Controller programming differences between GSUs revealed vulnerability in the code that translates site-level commands to inverter-level commands
  - When a GSU approached the specified MVA limit, it allowed for improper instructions to lineups to transition to discharge from charge (or vice-versa)
  - Testing confirmed disagreement of output that was consistent with behavior of GSU 3 during event



Differences in inverter-level setpoint command logic allowed inappropriate setpoints to be communicated to some inverters on site. The response of the remainder of the facility creates conditions for a sustained oscillation event.

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November 1, 2023 IBR1 BESS Oscillation Root Cause Analysis
(Supplied by Plant Operator)

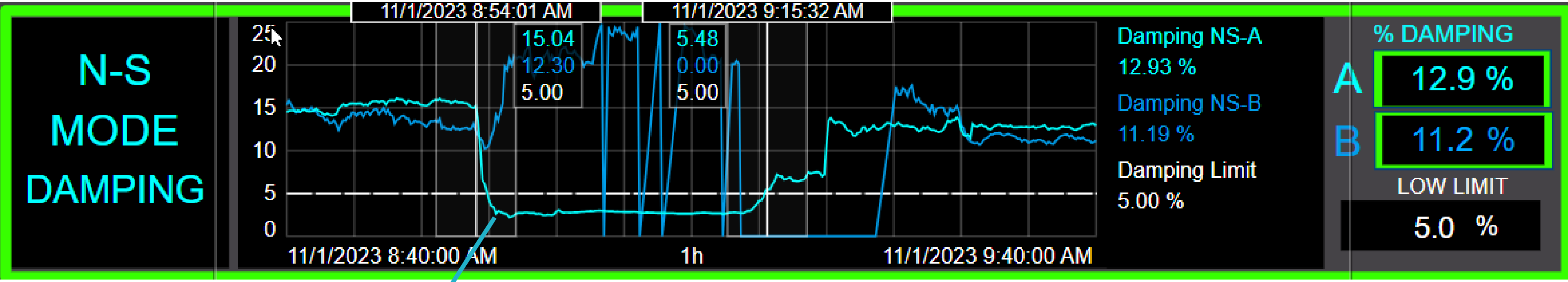
Countermeasures to prevent reoccurrence

Event Countermeasures

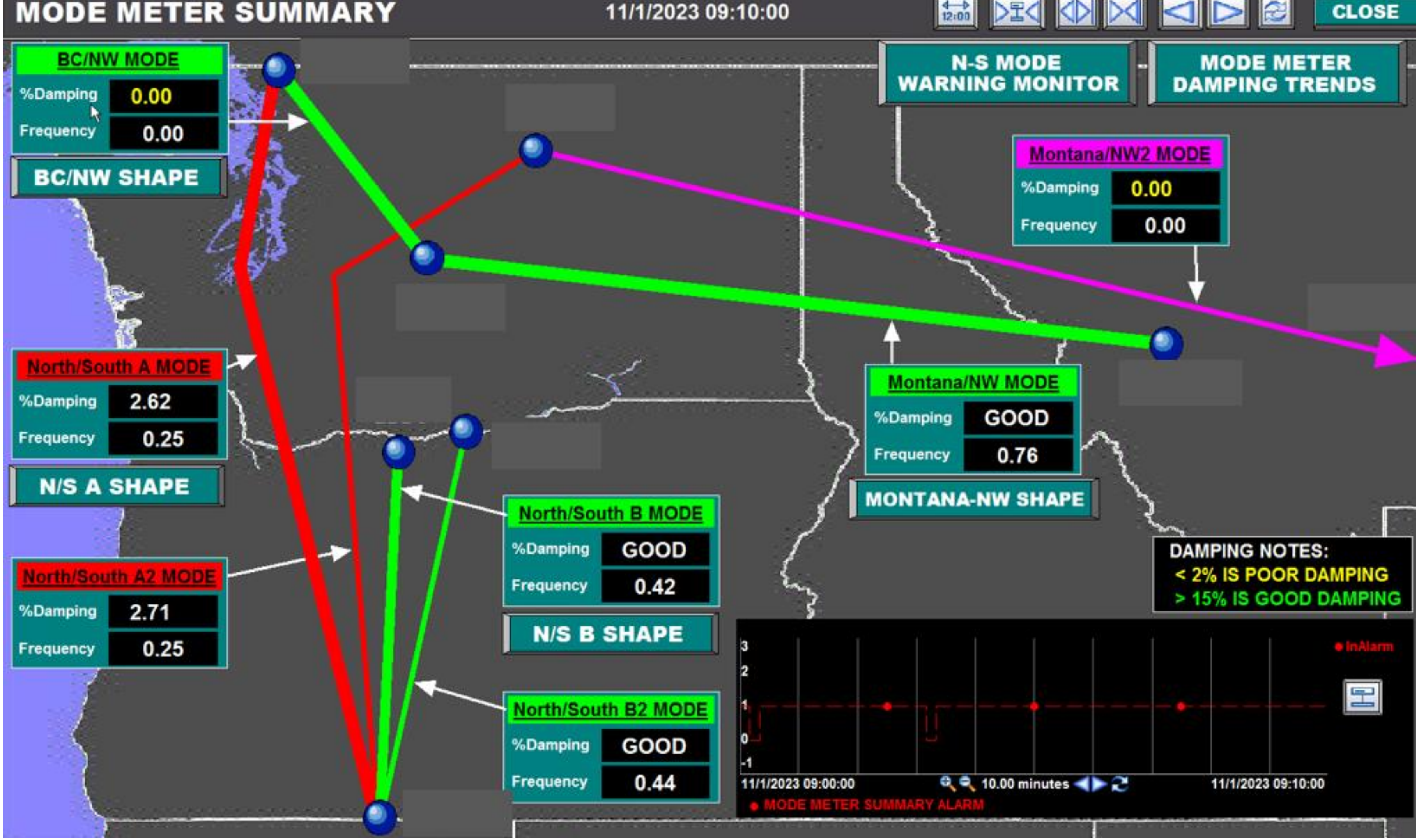
- Updated GSU MVA protection logic to prevent MVA remaining value from going negative
- Corrected code inconsistencies for idle stop and inverter reset across site PLCs
- Standardized values for Ymin, Ymax, and automatic/manual transition across site PLCs

Additional Controls Enhancements

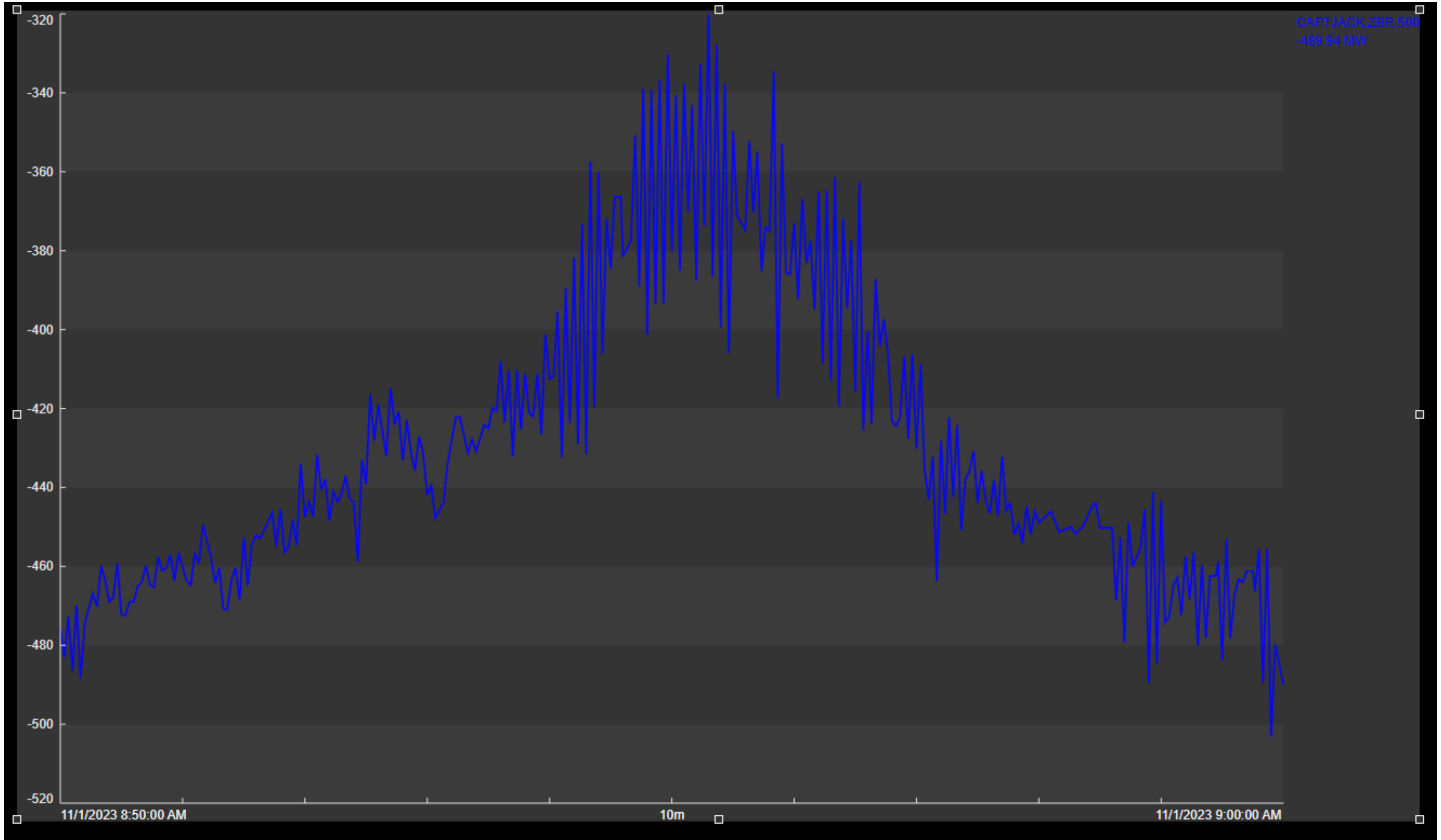
- Tuned site MW PI controls to have a less aggressive ramp rate, and make more consistent with similar projects in operation
- Removed derivative function from site PID MW control loop
- Removed delays in processing feedback to MVAR output and line voltage at POI
- Set AVR to default “ON” after controller restart
- Corrected default MW / MVAR ramp rate to 240 MW / MVAR per minute
- Added condition to prevent MVAR PI wind-up when MVAR setpoint is zero


N-S
MODE
DAMPING
11/1/2023 8:54:01 AM
11/1/2023 9:15:32 AM
25
20
15
10
5
0
15.04
12.30
5.00
5.48
0.00
5.00
11/1/2023 8:40:00 AM
1h
11/1/2023 9:40:00 AM
Damping NS-A
12.93 %
Damping NS-B
11.19 %
Damping Limit
5.00 %
% DAMPING
A
12.9 %
B
11.2 %
LOW LIMIT
5.0 %

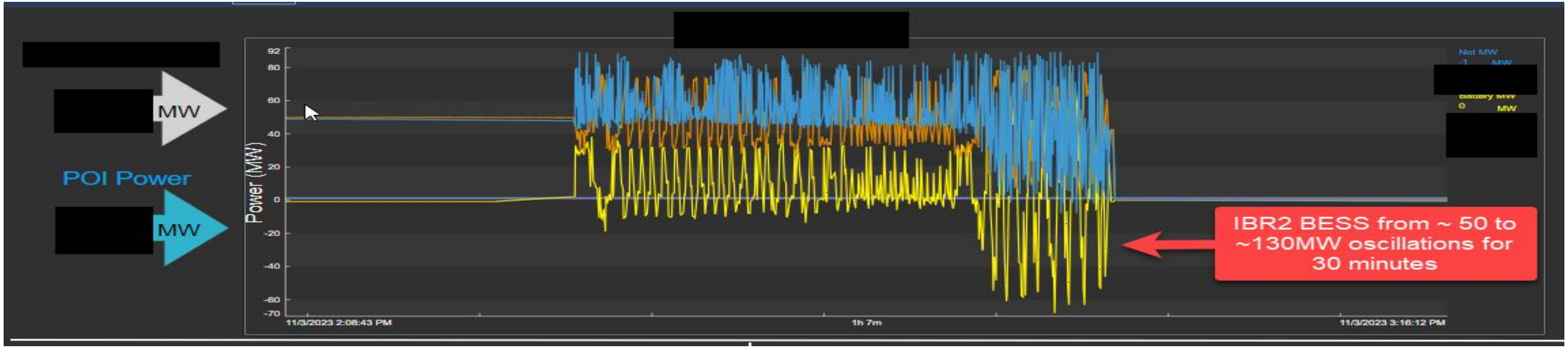
Low Damping


MODE METER SUMMARY
11/1/2023 09:10:00
12:00
CLOSE
N-S MODE WARNING MONITOR
MODE METER DAMPING TRENDS
BC/NW MODE
%Damping 0.00
Frequency 0.00
BC/NW SHAPE
Montana/NW2 MODE
%Damping 0.00
Frequency 0.00
North/South A MODE
%Damping 2.62
Frequency 0.25
N/S A SHAPE
Montana/NW MODE
%Damping GOOD
Frequency 0.76
MONTANA-NW SHAPE
North/South B MODE
%Damping GOOD
Frequency 0.42
N/S B SHAPE
North/South A2 MODE
%Damping 2.71
Frequency 0.25
DAMPING NOTES:
< 2% IS POOR DAMPING
> 15% IS GOOD DAMPING
North/South B2 MODE
%Damping GOOD
Frequency 0.44
3
2
1
0
-1
InAlarm
11/1/2023 09:00:00
10.00 minutes
11/1/2023 09:10:00
MODE METER SUMMARY ALARM

Fluctuations on 500 kV line



November 3, 2023 IBR2 BESS Oscillation Summary



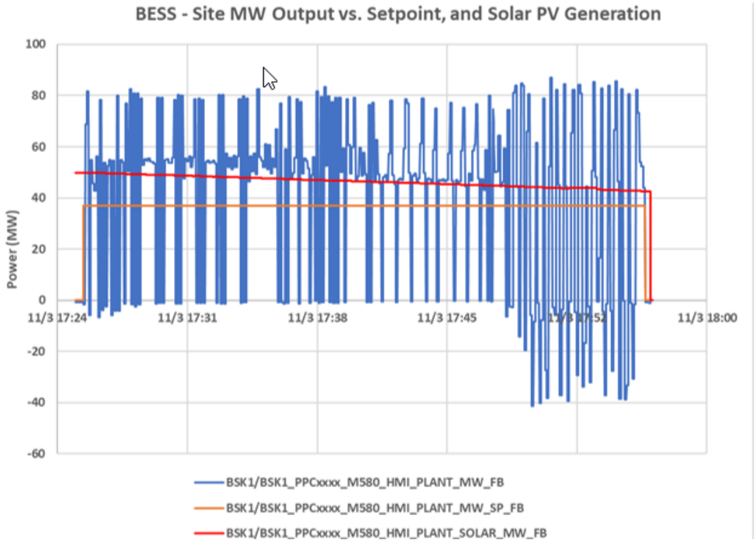
- **Event details:** SRP control room operators noticed the oscillation via PI Vision displays and called IBR Operator to address. SRP opened the POI breakers after a delay in response from the IBR Operator.
- **Cause:** Dual meter switching logic (BESS meter for charging and BESS+PV meter for discharging) aggravated by erroneous PV output signal test hard coded to 0MW instead of actual PV output.
- **Solution:** Removed dual meter logic at all operator sites at SRP until more robust logic can be implemented. Improve operator process improvements for communicating and approving controller logic changes and testing to operator controls integrator and SRP. Improve operator control center oscillation detection logic and near term 24/7 SRP site monitoring personnel.
- **WECC Impact:** Frequency of forced oscillations (0.25 Hz) was close to that of NS-A mode frequency causing the Modemeter to trigger alerts for NS-A mode critical damping ratio. Actual damping ratio remained unaffected. RC West and BPA ODM detected forced oscillations with low damping ratio alerts triggered in the RC West Modemeter for NS-A mode.

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Event Background

- Battery site was dispatched from a 0 MW setpoint to 37 MW discharge at ~17:25 EST on 11/3/2023
- Site output immediately began oscillating, with maximum output of ~85 MW and minimum of -40 MW
- Adjacent PV site under commissioning and was injecting ~50 MW at the time of event start



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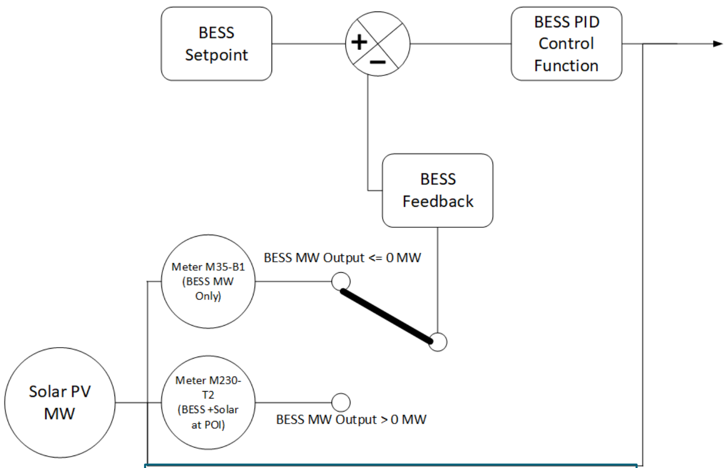
November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis
(Provided by Plant Operator)

Sequence of Mis-operation: As-found PID Controls Scheme

- Battery MW output value that is fed back to PID loop is dependent on if the site is charging or discharging
  - Discharging logic must include solar contribution to prevent interconnection limit violations
- Solar PV output was not yet added to metering scheme
  - Resulting in the controller misinterpreting the measured value as if the BESS site was exporting too much power when that meter source was selected



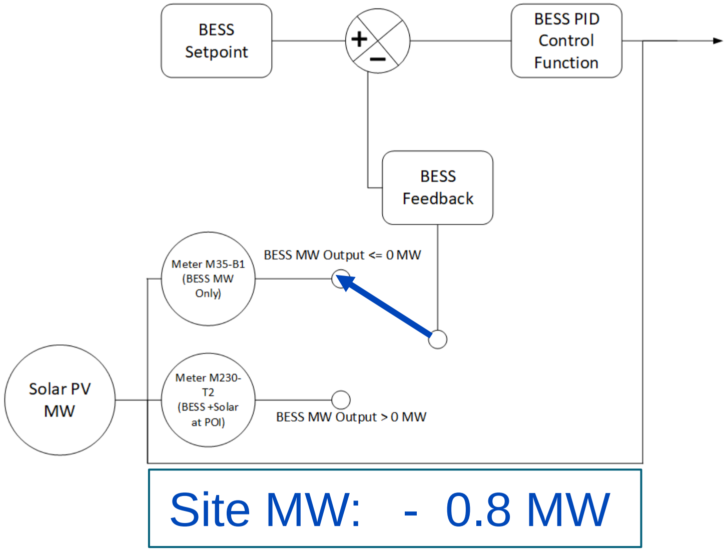
Simplified as-found site MW output feedback control logic

The dispatch period on 11/3 was the first instance of a BESS site command for a discharge value that was less than PV actual output

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis
(Provided by Plant Operator)

Sequence of Mis-operation

- Battery idle w/ ~-0.8M of auxiliary load
- Setpoint of 37 MW received
- BESS inverters wake and export power
- BESS output now positive, switch to alternate meter scheme
- PID sees battery MW too high, instruct rapid reduction of output
- Site MW goes negative, swaps meter scheme
- PID sees battery MW too low, instruct rapid increase in output
- Cycle repeats until shutdown



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November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

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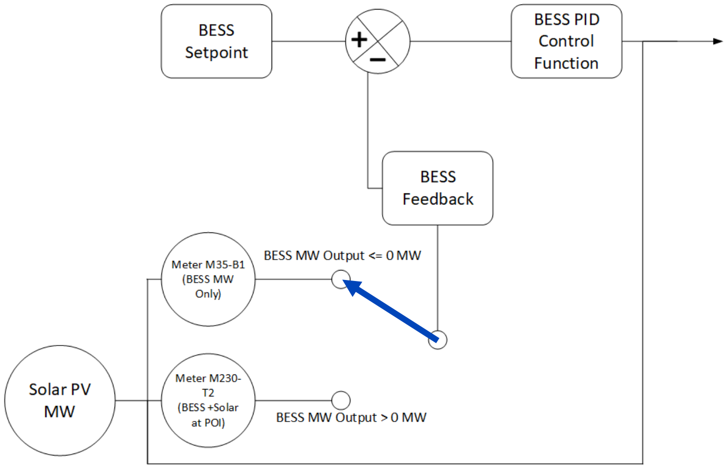
- Cycle repeats until shutdown



Site MW: - 0.8 MW

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

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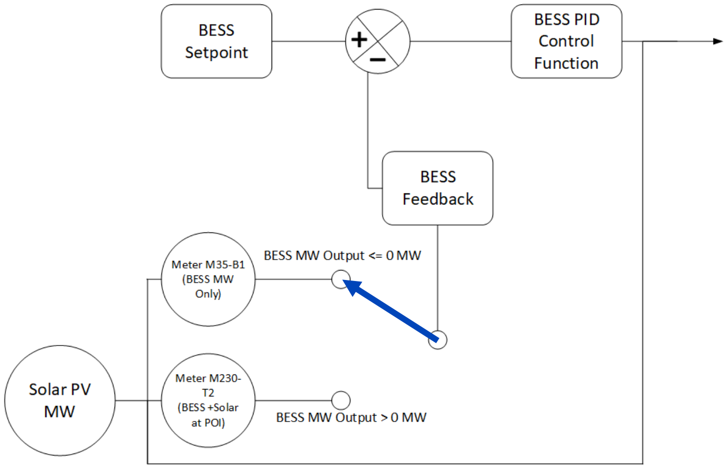
- Site MW goes negative, swaps meter scheme
- PID sees battery MW too low, instruct rapid increase in output
- Cycle repeats until shutdown



Site MW: - 0.1 MW

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Sequence of Mis-operation

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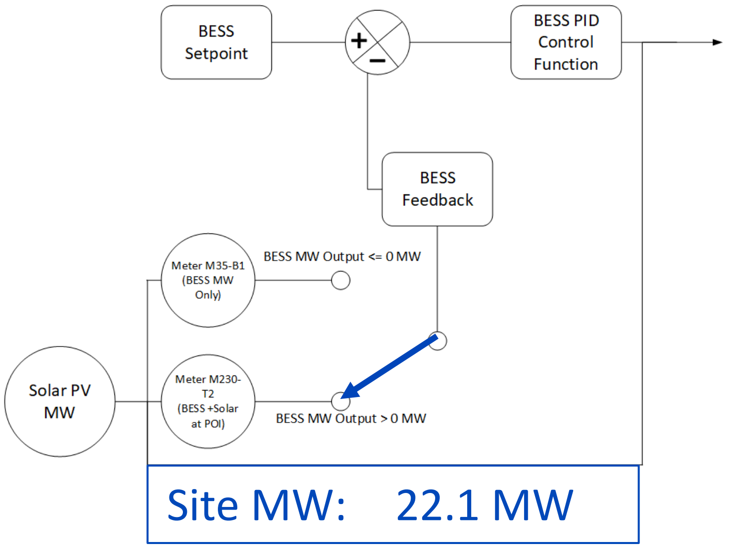
- Site MW goes negative, swaps meter scheme
- PID sees battery MW too low, instruct rapid increase in output
- Cycle repeats until shutdown



Battery site discharging against unachievable command

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis
(Provided by Plant Operator)

Sequence of Mis-operation

- Battery idle w/ ~-0.8M of auxiliary load
- Setpoint of 37 MW received
- BESS inverters wake and export power
- BESS output now positive, switch to alternate meter scheme
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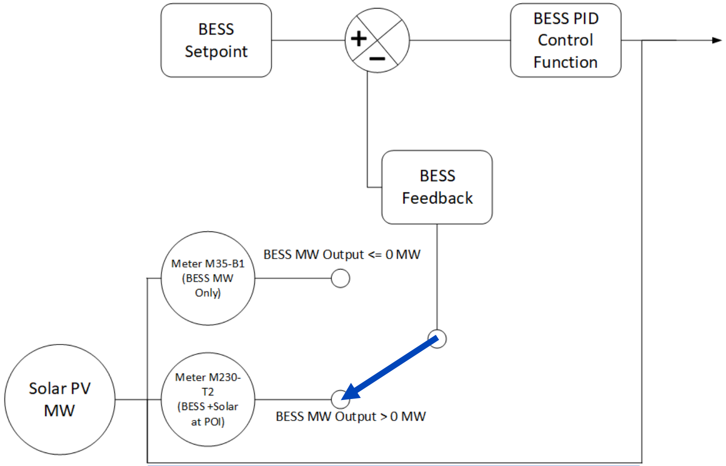
- Cycle repeats until shutdown



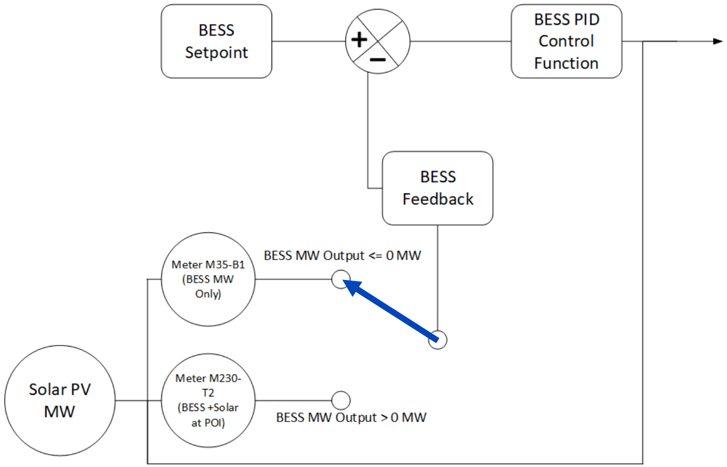
Site MW: 80.4 MW

Battery instantly over-discharges, output control adjusts

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis
(Provided by Plant Operator)

Sequence of Mis-operation

- Battery idle w/ ~-0.8M of auxiliary load
- Setpoint of 37 MW received
- BESS inverters wake and export power
- BESS output now positive, switch to alternate meter scheme
- PID sees battery MW too high, instruct rapid reduction of output
- Site MW goes negative, swaps meter scheme
- PID sees battery MW too low, instruct rapid increase in output
- Cycle repeats until shutdown



Site MW: - 2.5 MW

Battery output driven down to a charge condition, transitions back to alternate meter

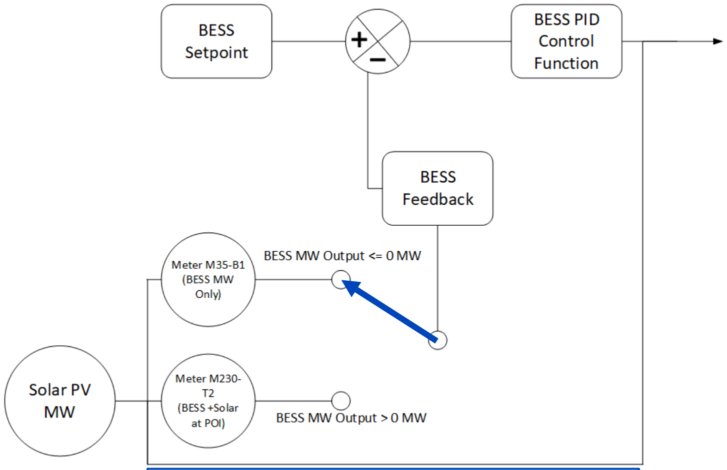
Delivering water and power™

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Sequence of Mis-operation

- Battery idle w/ ~-0.8M of auxiliary load
- Setpoint of 37 MW received
- BESS inverters wake and export power
- BESS output now positive, switch to alternate meter scheme
- PID sees battery MW too high, instruct rapid reduction of output
- Site MW goes negative, swaps meter scheme
- PID sees battery MW too low, instruct rapid increase in output
- Cycle repeats until shutdown



Site MW: - 3.3 MW

Battery output begins increasing output and will overshoot

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Sequence of Mis-operation

- Battery idle w/ ~-0.8M of auxiliary load
- Setpoint of 37 MW received
- BESS inverters wake and export power
- BESS output now positive, switch to alternate meter scheme
- PID sees battery MW too high, instruct rapid reduction of output
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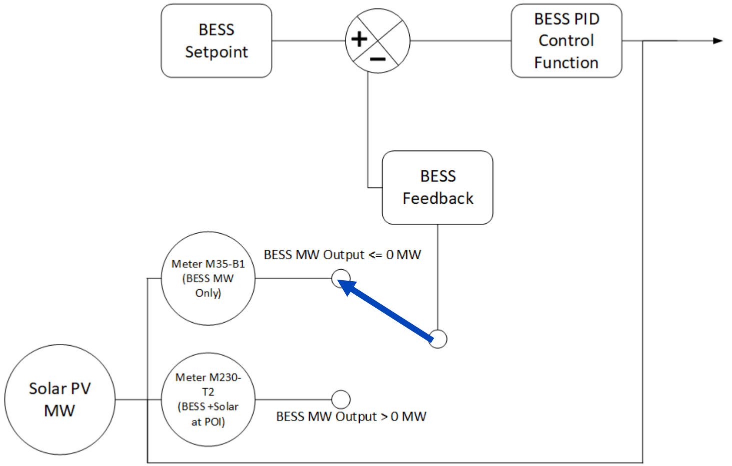
- Cycle repeats until shutdown



Site MW: - 3.3 MW

Oscillating MW response will continue until either site is stopped, or MW setpoint to battery is above solar output/below or equal to 0 MW

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Review of Potential Causes and Findings

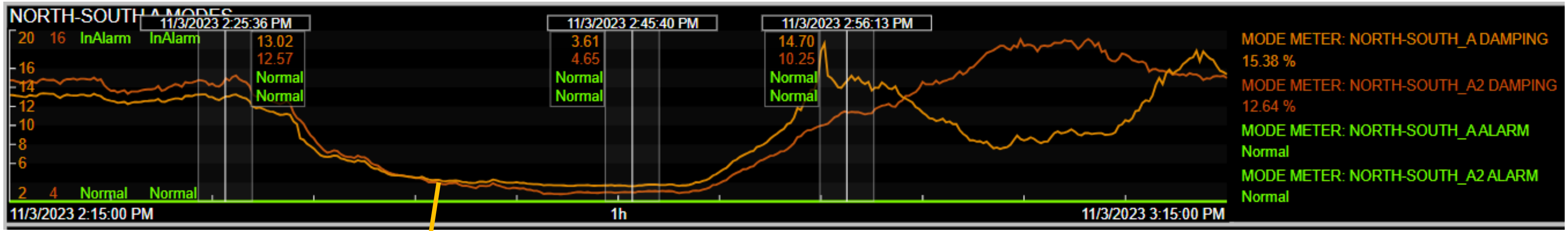
- Site network performance
    - No contribution to event. Given timing of solar site commissioning, concerns presented around new installed device creating excessive data traffic or conflicts to increase data latency – Verifications confirmed no contribution
- Site metering
    - No contribution to event. Compared historized data to assure no mis-operation of meters on site
- Site EMS control logic
    - No contribution from control functions that assign inverter-level commands. The oscillation was confirmed to occur on both site output and site MW PID control output
    - **Root cause 1:** Forced parameter set to zero from time of BESS site commissioning on solar PV MW Meter
        - For oscillation to occur, site needed a BESS Setpoint >0, and less than solar actual output. 11/3 was first time this condition occurred
    - **Root cause 2**: Commissioning control change management process inadequate to identify forced value

November 3, 2023 IBR2 BESS Oscillation Root Cause Analysis

(Provided by Plant Operator)

Countermeasures to prevent reoccurrence

- Short-term: Force PID feedback to only one source (BESS GSU low-side metering)
- Long-term: Add Solar PV into BESS site MW feedback function
  - Validate countermeasure applied at all co-located Solar / BESS facilities under construction
  - Update integrator functional design specifications
- Enhanced historization on multiple site control functions
  - Increase sample rate on all tags associated with site main controls (Pre/Post PID MW/MVAR output, network latency, etc.)
- Assign dedicated site operators 24/7 for monitoring and control of all SRP facilities
  - Additional level of observation versus existing exception based and alarm centric monitoring
- Reduce gains on site PID with dynamic tuning
  - Would not have prevented this event, but would have increased oscillation period and is generally more stable for other destabilizing events
- Oscillation detection in PLC
  - Identify MW PID output swapping polarity with significant output in short period



Damping Drops, but does not get below 2%, thus no alarms

The Challenges:

1) Each oscillation has a unique cause due to integrating new control technology.

"Happy families are all alike; every unhappy family is unhappy in its own way." Anna Karenina

2) Forced oscillations bias the mode monitor.