Real-time Monitoring and Mitigation and Offline Analysis of Forced Oscillations in RC West (CAISO)

Urmila Agrawal
CAISO (RC West)
UAgrawal@caiso.com

Justin Bohlen
CAISO (RC West)
JBohlen@caiso.com

Jim Hiebert
CAISO (RC West)
JHiebert@caiso.com

Kaden Penner
CAISO (RC West)
KPenner@caiso.com

Abstract

Forced oscillations have the potential to impact reliable and secure power systems operations. The Western Interconnection (WI) is observing an increase in forced oscillation events, both local and system-wide, with an increase of inverter-based renewable energy sources. This paper discusses SCADA and synchrophasor measurement-based operating procedures and tools implemented in the control center to monitor and mitigate forced oscillations. An example of a recent wide-area forced oscillation event is included that shows how the RC operators used these measurement-based tools and operating procedures to locate the source and mitigate the forced oscillations in the WI maintaining reliable and secure system operations. An offline analysis of the event is also included in this paper.

Keywords: Forced oscillations, RC West, Operating procedure, Control room applications, SCADA and PMU measurements

1. Introduction

Forced oscillations in a power system are responses of the system to periodic disturbances that continuously excite the system. These disturbances can include mis-operating or malfunctioning pieces of plant equipment, such as a hydro governor operating in a rough zone and incorrectly tuned process controllers [Xie and Trudnowski (2017)]. Depending on their frequencies, these forced oscillations can appear in a localized area or system-wide [Agrawal et al. (2017)]. The severity of these oscillations is quantified in terms of their amplitude as the forced oscillations resulting in higher power swings across the system-wide can lead to more severe consequences. Some of the potential impacts of forced oscillations include transmission line derates, equipment failure, thermal concerns and inadvertent control actions or equipment tripping [Agrawal and Alam (2022)]. With the increasing penetration of inverter-based resources (IBRs) such as wind, solar and battery storage units on the grid, forced oscillation related events have increased and are more often observed based on RC (Reliability Coordinator) West's operators' experiences. As seen in RC West, many of these events are related to control settings and once the source is identified, these issues can be resolved. However, the main challenge lies in the identification of the source of the forced oscillations. If the mitigation actions for these forced oscillations are not taken in a timely manner, this can result in severe consequences depending on the amplitude of the oscillations observed system-wide [Sarmadi and Venkatasubramanian (2016)].

As forced oscillations have the potential to affect reliable power system operations, several entities in North America have developed strategies to monitor and mitigate these oscillations [NERC's Synchronized Measurement Working Group (2017, 2021)]. Reference [NERC's Synchronized Measurement Working Group (2017)] aims at providing guidance and awareness to system operators and operations engineers for identifying and mitigating forced oscillations on the bulk power system (BPS). It discusses the fundamental behavior and characteristics of forced oscillations and includes recommended practices and strategies for monitoring and mitigation of these oscillations. Reference [NERC's Synchronized Measurement Working Group (2021)] provides a detailed framework of methods to perform analysis of natural and forced oscillations, and includes a discussion on determining

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and validating mitigation actions.

This paper discusses in detail RC West's effort to monitor and mitigate forced oscillations in its footprint by developing operating procedures and deploying measurement-based tools. An example of a recent forced oscillation event is included in this paper to show how RC operators were able to mitigate this event through the use of these procedures and measurement-based tools. This paper also includes some offline analysis of the event and discusses its impact on the system.

2. RC West operating procedure and tools for forced oscillations

As RC West has the responsibility and authority to act to address the reliability of the RC Area in Real-time operations, monitoring and mitigation of forced oscillations is a critical part of its operations. For this, RC West has developed a set of operating procedures and deployed measurement-based tools in the control center. Figure 1 shows the architecture of the Phasor measurement unit (PMU) applications in the RC West control center. These tools help RC operators with detecting forced oscillations and also identifying the source while the operating procedures provide guidance to the RC operators to take corrective mitigation actions during the occurrence of forced oscillation events. Actions taken by RC operators through the use of measurement-based tools and operating procedures is illustrated using an example of a recent forced oscillation event that was observed throughout the Western Interconnection (WI).

RC West also monitors SCADA (Supervisory Control and Data Acquisition) measurements of the generation output of most synchronous and non-synchronous units in real-time for situational awareness. This also has been helpful in locating the source of forced oscillations as will be shown later in this paper. RC West is currently working toward deploying a forced oscillation source localization tool in the control center.

2.1. Tools deployed in RC West's Control Center

RC West has deployed EPG's (Electric Power Group) RTDMS (Real Time Dynamics Monitoring System) tool for wide-area oscillation monitoring, visualization and analysis of oscillations in the system.[1] A detailed description on these tools including their algorithms can be found in the vendor's website and is beyond the scope of this paper. RTDMS uses PMU measurements to detect forced oscillations. RC West also monitors the generation output of the IBRs using SCADA measurements in real-time. Monitoring of IBR output can help locate the source of the forced oscillations if caused by IBRs and the oscillations have frequencies less than 0.5 Hz for SCADA measurements sampling rate of 1 sample/second based on Nyquist's rate criteria [Landau (1967)]. As will be illustrated using the example of a recent event, when an IBR unit is causing forced oscillations, only the source IBR output has fluctuations, while other IBR outputs remain unaffected. Thus, monitoring of IBR output can help locate the source of the forced oscillations caused by IBRs.

[1] RTDMS, ODM and OSL are registered products of Electric Power Group, LLC (EPG)

2.1.1. Oscillation Detection Module (ODM) The ODM in EPG's RTDMS tool monitors sustained oscillations in the four frequency bands at various locations across the RC West footprint in real-time and provides RC Operators with wide-area analysis, monitoring and visualization. This tool generates alarms to alert the RC Operator about the occurrence of any sustained oscillation event.

2.1.2. Oscillation Source Location (OSL) tool CAISO is currently working with EPG to get OSL deployed in the RTDMS. With increased forced oscillation events, having OSL tool will help RC West in identifying the potential source of forced oscillations. Unlike natural oscillations that does not involve a specific source, forced oscillations will be continuously present in the system unless the source of the oscillation is identified and removed from the system or the issue causing these oscillations at the source location resolves on its own.

2.2. Operating procedure

Once the RTDMS tool detects the presence of forced oscillations in the RC West footprint, the RC operators must take the following actions for oscillation mitigation.

- **Determine the extent of impact** - Identify the general area affected by the oscillations and the affected balancing authorities and transmission operators (BA/TOP(s)) and other RC(s)
- **Determine the severity of the impact** - Obtain the frequency and magnitude of forced oscillations as forced oscillations having large power swings could indicate a more severe problem and should be addressed more rapidly.

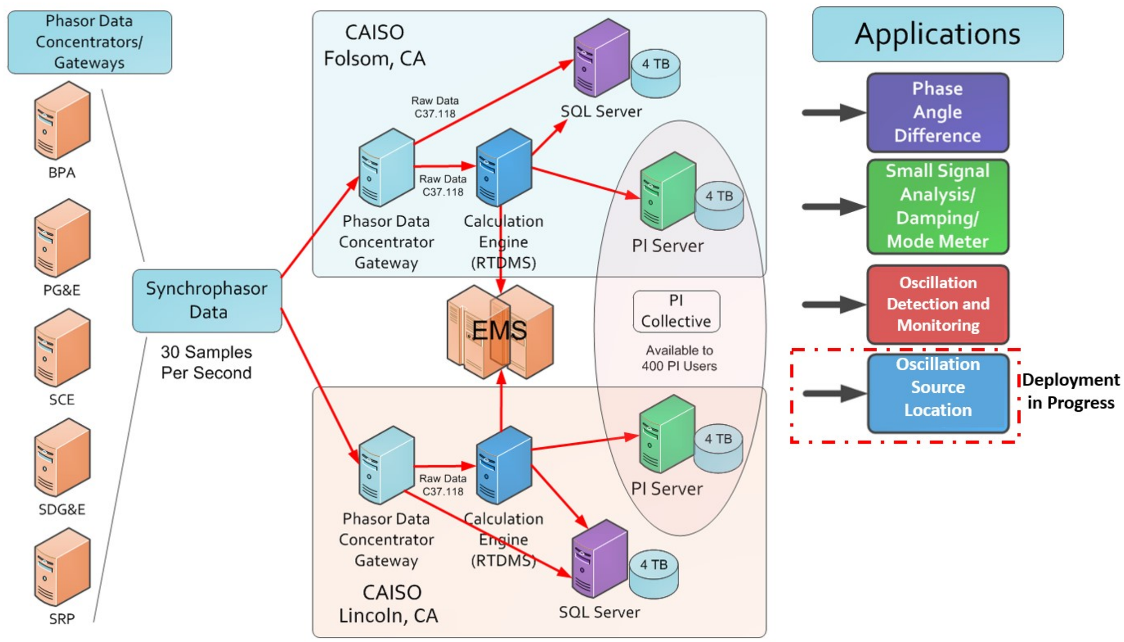

Figure 1. CAISO Synchrophasor Architecture/Applications

- **Identify the source**
  - Coordinate with the affected entities to identify the cause of forced oscillations
  - Monitor the MW and Mvar output of units in the affected areas for fluctuations

  For oscillations observed across a wide-area, identifying the source of forced oscillations can be difficult because of the associated challenges as described in [Agrawal et al. (2017)]. To deal with these challenges, the OSL tool is currently in the process of being deployed in the control center to help with locating the source of the forced oscillations.

- **Discuss potential mitigation options with affected entities**
  - Forced oscillations caused by generating unit(s) including inverter-based resources:
    * Increase or decrease the generator active output power away from an abnormal operating zone, such as a rough zone
    * Revert back to old control settings if the recent change in the control settings caused the oscillations
    * Curtail generation output to levels in which the forced oscillations do not appear, including shutting down the unit
  - Forced oscillations caused by a transmission element, such as HVDC and SVCs
    * Modify control set points or terminal conditions causing the oscillation
    * Increase system strength by returning to service any transmission elements out of service
    * Revert back to previous control settings, if any were inadvertently changed
  - Forced oscillations caused by load
    * Work with TOP to minimize or mitigate the cause to the extent possible
    * Change terminal conditions that may be causing oscillations

- **Evaluate the effectiveness of the mitigation actions being taken by the affected entities**
  - If the mitigation actions taken, or being taken, are not appropriate, timely or sufficient, issue Operating Instructions, including the specific mitigation actions and time frame; and/or request the neighboring RC to issue Operating Instructions to affected entity(s) in its area

3. An example of a recent system-wide forced oscillation event in the WI - Detection, Localization and Mitigation

A system-wide forced oscillation event recently occurred in the RC West footprint on the 27^{th} and 28^{th} January, 2022. The RTDMS snapshot showing areas in which this forced oscillation was observed is shown in Figure 2 with the approximate source location enclosed within the red circle. During the event, high amplitude power swings were observed in the North and South of the WI with more than 100 MW of power swings observed in the California-Oregon Intertie (COI) flow as shown in Figure 3. The RC operators identified the source of the oscillations to be two battery units in the Southern California region in a timely manner and subsequently took mitigation actions to clear the oscillations. The use of both SCADA and PMU measurements helped detect, locate and mitigate this oscillation event.

The output of the two battery units is shown in the Figure 4. A detailed analysis of the event and the actions taken by the RC operators are discussed next.

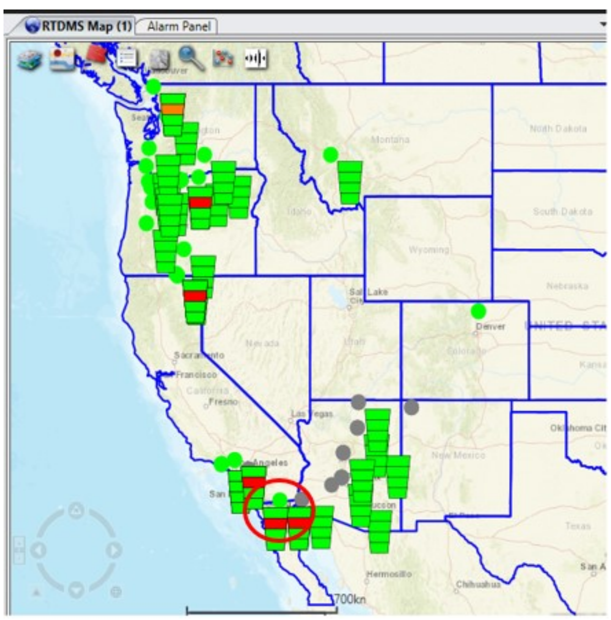

Figure 2. RTDMS snapshot showing the extent of the forced oscillation event in the WI.

3.1. Actions taken by RC operators to mitigate the forced oscillations

On the afternoon of January 27, RC operators were alerted to potential system oscillations via the RTDMS tool. System-wide ACE, frequency, and voltages were within acceptable ranges but multiple phasor measurements indicated band 2 oscillations (having frequencies in the range of 0.1 to 1 Hz). An alarm of this type had not been activated since the inception of the monitoring tool, but internal procedures noted that band 2 threshold exceedances over a wide geographical area were likely an indication of inter-area oscillations. This condition was also indicated by an alarm on the North-South A (NS-A) mode in the mode-meter tool.

RC operators began contacting BA and TOPs within the RC West footprint to inquire whether abnormal system conditions were observed. Based on all the information available, RC operators were convinced this was a forced oscillation event owing to the lack of any major event that could have potentially reduced damping ratio instantly to 0%. As operators were investigating, the alarms cleared for a short period and then reappeared. Upon reappearing, one PMU reflected voltage deviations higher than the others. This was visually indicated by color-coded signals that reflected how close the magnitude was to the alarm threshold value. RC operators used this information to narrow their search and began contacting entities closest to this PMU to request assistance in locating the source of the disturbance. Some entities did not have access to PMU

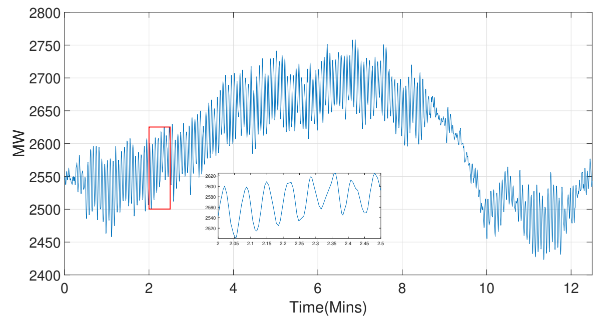

Figure 3. 100 MW power swings observed in the COI flow during the event.

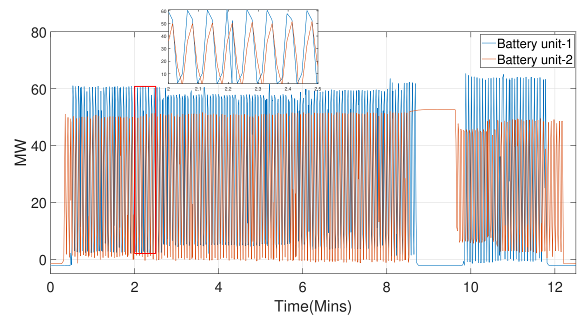

Figure 4. Power output measurements of the two battery units.

data and their normal RTU data indicated no concerns. Other entities had PMU data available but they were not actively monitoring it. These entities stated they would review the data and report back with their findings.

RC operators were then contacted by another RC in the interconnection that had received oscillation alarms at the same PMUs as well as an alarm on the NS-A mode in their own monitoring tool. This RC did not have any additional information as to the source of disturbance.

Eventually the alarms cleared without returning. Operators continued to review the individual outputs of generating units in the suspected geographic area. Shortly after the alarms cleared, RC operators discovered resources with rapidly deviating outputs during the disturbance time frame. Figure 5 shows the SCADA power output measurements of several large battery units that were online during the event within the CAISO footprint. As can be seen, power swings are only observed in the source battery units, while the other battery units are not participating in the oscillations. Similarly, wind unit outputs in CAISO footprint did not have any power swing as shown in Figure 6. The power swings are seen in the output of the synchronous units in Figure 7 as the NS-A mode was excited during the event. When a forced oscillation event excites a system mode, the observability of the forced oscillation follows the observability of that mode. The BA operators for the suspected resource were notified and were requested to monitor to prevent any additional disturbance.

A day later, RC operators once again observed alarms indicating band 2 oscillations over a wide geographical area. The output of the units from the previous day's disturbance again appeared to be the source of the disturbance. The RC West contacted BA operators within 1 minute of receiving the alarm and instructed them to take action immediately to disconnect the resource from the system or stabilize the output. Once the resource was disconnected the oscillations stopped and alarms cleared. The sequence of events for the two days is shown in Figure 8. Therefore, using the available tools and operating procedures, the source of the detected oscillations could be successfully identified and the oscillations were mitigated in a timely manner.

3.2. Offline analysis of the event

Figure 9 shows the periodogram calculated using the source battery power output. As seen in this figure, the frequency of the forced input was 0.25 Hz and consisted of odd harmonic components at 0.75 Hz, 1.25 Hz and so on. Since the frequency of the forced input was close to that of the dominant NS-A mode (estimated to be 0.23 Hz during the event) in the WI, the damping ratio estimate of the NS-A mode was biased toward 0%, as shown in Figure 10, due to the limitation of the mode-meter algorithm that does not take into consideration the presence of forced oscillations in the algorithm [Agrawal et al. (2019) and Follum et al. (2017)]. The impact of the presence of the forced oscillation is longer than the actual duration of the event (shown by red dashed-lines in Figure 10) due to the overlapping data window length of 20 minutes that the mode-meter algorithm uses for estimating system modes. It should be noted here that the actual damping ratio of the NS-A mode remained unaffected due to the presence of the forced oscillation itself. Figure 11 and Figure 12 show the periodogram calculated using COI flow measurements and power measurements at one of the 500 kV substations situated in the Northern area of the WI. While the harmonic components are present marginally in the COI flow, these harmonic components can be easily observed in the 500 kV substation measurements.

3.3. Impact of the event

During this event, the frequency of the forced input was very close to that of the dominant NS-A mode and the source was located in the area that participates in the NS-A mode thereby meeting two of the three requirements for the resonance condition [Sarmadi and Venkatasubramanian (2016)]. This resulted in oscillations that propagated across a wide-area in the WI due to the excitation of the NS-A mode. If the damping ratio of the NS-A mode were to be critical or close to 0%, then the third requirement of the resonance condition would have been met thereby potentially resulting in significantly higher amplitude power swings that could have resulted in a system-wide outage. However, during the event, the damping ratio of the NS-A mode was high ($> 15\%$) and therefore resulted in a near-resonant event. Despite this, close to 100 MW of power swings were observed in the COI flow with the amplification of approximately 1 as compared to the magnitude of the forced input observed in the sum of the output of the two battery units (105 MW). During stressed system conditions, power swings of this magnitude could impact system security and reliable operations. However, since the source of the forced input was quickly identified due to the proactive actions from RC operators, the system operations were not affected significantly except the shutting down of the battery units causing these oscillations.

Further investigation revealed that the interruption of the network connectivity in the battery facility resulted in some issue in the software control which caused these

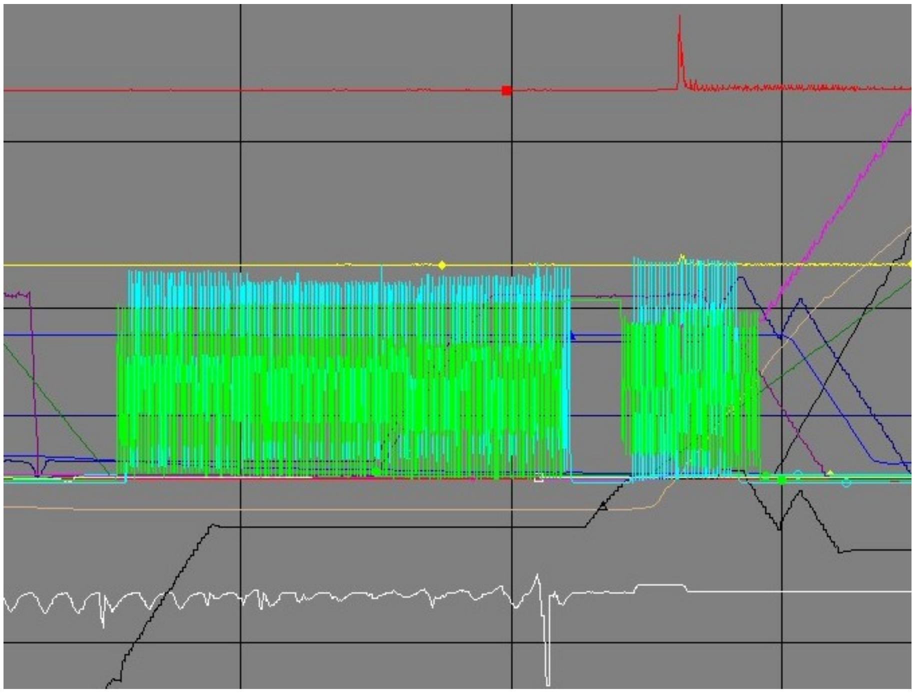

Figure 5. Power output (SCADA measurements) of several large battery units in CAISO footprint that were online during the event. The oscillating unit outouts in the plots are of the source battery units. (X-axis and Y-axis represent time in minutes and power output in MW respectively)

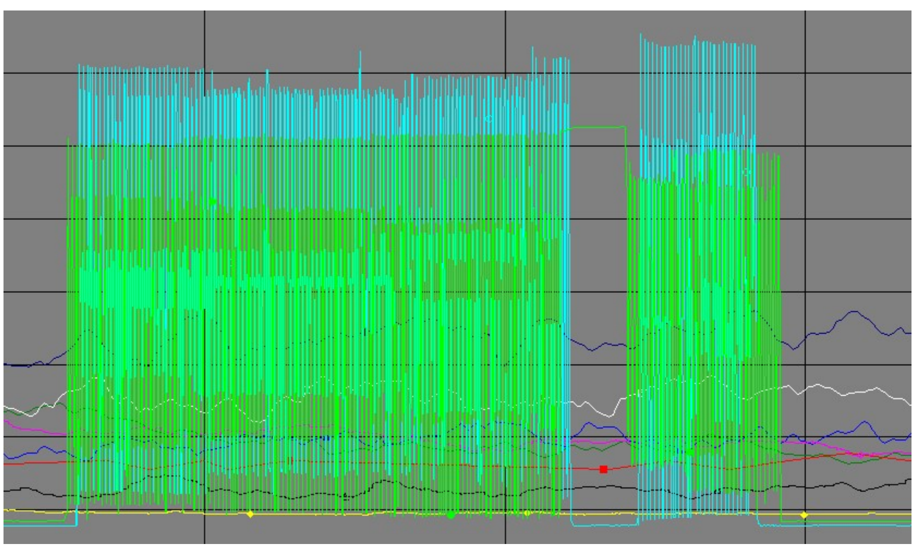

Figure 6. Power output (SCADA measurements) of some wind units in CAISO footprint that were online during the event. The only oscillating unit outputs in the plots are of the source battery units. (X-axis and Y-axis represent time in minutes and power output in MW respectively)

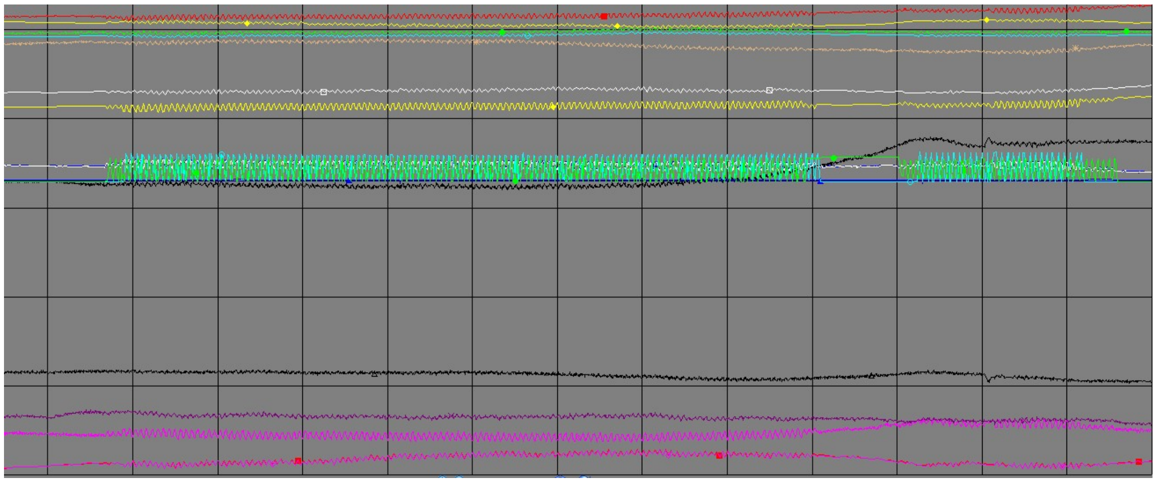

Figure 7. Power output (SCADA measurements) of some synchronous generation units in WI that were online during the event. (X-axis and Y-axis represent time in minutes and power output in MW respectively)

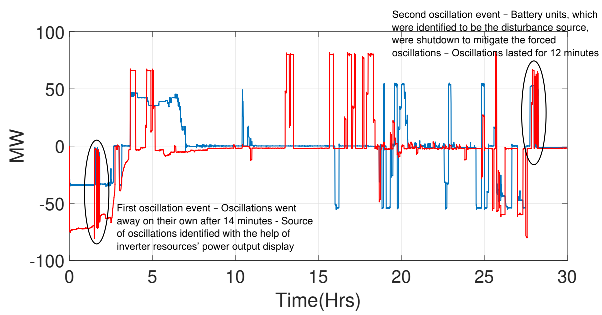

Figure 8. Power output of the two battery units causing wide-area forced oscillations on 27th and 28th January 2022.

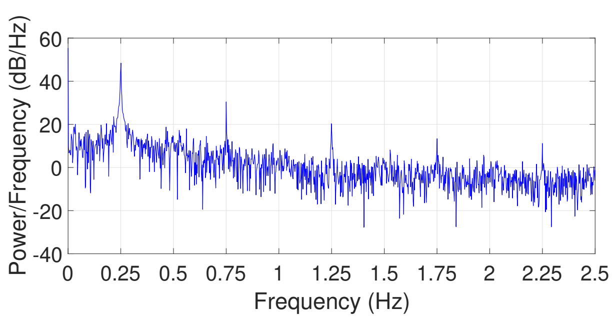

Figure 9. Periodogram calculated using power output PMU measurements of the two battery units showing the presence of odd harmonic components in the forced input.

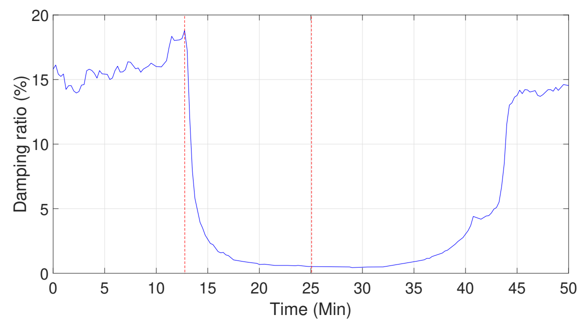

Figure 10. Damping ratio estimate of the NS-A mode biased in the presence of forced oscillations toward 0%.

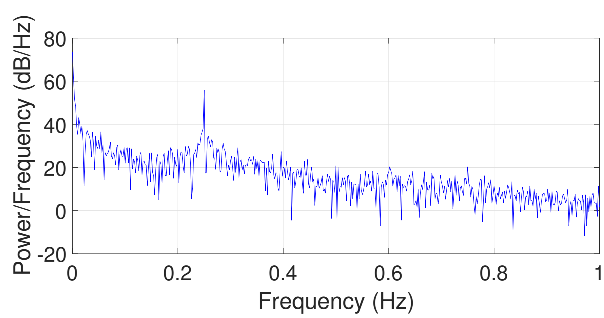

Figure 11. Periodogram calculated using COI flow PMU measurements.

oscillations. The issue has since been resolved and no event has been reported again caused by these battery units.

This event highlights the significance of having wide-area monitoring and situational awareness tools with detailed operating procedures to deal with the challenges brought by the higher penetration of IBRs in maintaining secure and reliable system operations. These tools will be more critical in maintaining secure and reliable system operations as we are likely to see a further increase in such forced oscillation events.

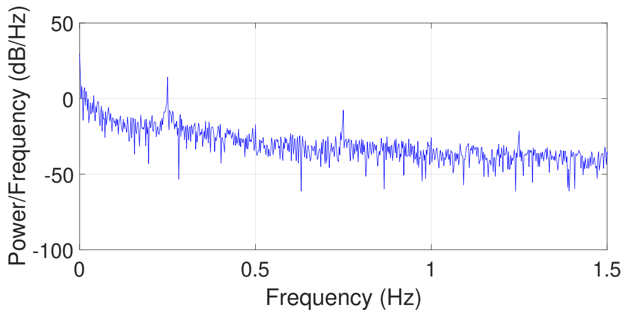

Figure 12. Periodogram calculated using the power flow PMU measurements in 500 kV substation situated in the North of WI.

4. Conclusion

This paper discusses the tools and operating procedures deployed by RC West in monitoring and mitigation of forced oscillations. With an increase of IBRs, RC West is observing an increase in forced oscillation events, one such event is discussed in detail in this paper. This forced oscillation event was caused by two battery units in the Southern California area and was observed across a wide-area in the WI. The use of SCADA and PMU measurements and operating procedures implemented in the RC West's control center helped mitigate this event in a timely manner.

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