Evaluating the Impact of Retiring Synchronous Fossil Fuel Generators on Inter-Area Oscillations in the U.S. Western Interconnection

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Abstract

To facilitate the decarbonization of the power grid, fossil-fuel-based synchronous generators are gradually being retired and replaced by inverter-interfaced renewable energy resources. As synchronous machines get displaced, the characteristics of inter-area oscillation modes in electrical interconnections are expected to change. This paper presents a model-based study of the impact of the retirement of synchronous fossil-fuel generators on the oscillatory characteristics of the US Western Interconnection (WI). Results show that if fossil-fuel-based synchronous machines are replaced by grid-forming inverters, then dominant inter-area modes seen in the WI today will change. New inter-area modes may appear due to the electromechanical energy exchange among the remaining hydropower generators clustered in geographical proximity in the northwestern part of the WI. This observation indicates that the evolution in modal properties needs to be closely tracked as the resource mix in electrical interconnections changes.

Keywords: inter-area oscillation, grid forming inverters, generation mix, renewable energy penetration

1. Introduction

Low-frequency inter-area oscillations, typically between 0.1 and 1 Hz, appear due to the electromechanical energy exchange among groups of generators located in distant parts of an electrical interconnection. Inter-area oscillation modes are characteristic properties of a power system and can be described by their frequency, damping ratio (DR), and shape [1]. Lightly damped system modes may pose stability concerns and hence need to be monitored. Moreover, as inverter-based renewable energy resources gradually replace fossil-fuel-based synchronous generators to facilitate grid decarbonization, the characteristics of existing dominant system modes are expected to change. It is essential to understand what changes may occur and flag potential stability concerns that may morph into reliability threats.

Previous research has shown that the properties of inter-area modes are influenced by several factors like system load, network topology, power flow patterns, and inverter-based resource (IBR) penetration. Several works in existing literature have sought to understand how increasing IBR penetration will impact system modes in different real interconnections, using both models [2–5] and measurements [6]. Measurement-based analyses allow examining how heterogeneous IBR fleets with diverse capacities and control methodologies interact with synchronous machines to impact oscillation characteristics, but separating the effect of coexisting factors is challenging. Moreover, as IBR penetration in today's grids is limited, conclusions drawn from field measurements may not be directly extrapolated to IBR-dominated future grids. On the other hand, model-based approaches facilitate the study of hypothetical scenarios and the impact of individual explanatory variables on modal properties, thereby complementing measurement-based work. Prior model-based research has concluded that mode frequencies tend to increase with increasing IBR penetration, while DR values change only if inverters displace significant proportions of synchronous machines in areas with high participation in a mode [3, 4, 7]. Depending on IBR location, DR may either increase [3] or decrease [2, 4]. The impact on mode shapes has not been studied in detail.

The existing literature has not adequately explored how high penetration of grid-forming (GFM) inverters

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will impact natural oscillation modes in large electric interconnections. GFM control is gaining acceptance in the industry as a promising technology for enabling high renewable energy penetration in power systems, and properly tuned GFM IBRs offer the additional advantage of quickly damping transient oscillations following system disturbances [8]. Hence, participation in low-frequency inter-area modes may not be observable at GFM inverter locations, and in high-penetration scenarios, these resources may significantly alter the frequency response of interconnections. Moreover, wide-area oscillations are primarily driven by the electromechanical energy exchange among synchronous machines. Thus, if conventional fossil fuel generators are replaced by GFM IBRs, dominant modes observed in baseline cases may shift or disappear, and new modes may emerge based on the characteristics of the generators remaining in the system.

To address the aforesaid gap, this work studies how replacing large fossil-fuel-based synchronous generators with droop-control-based GFM inverters [9] will change inter-area oscillations in the U.S. Western Interconnection (WI). The study leads to the conclusion that an oscillation mode may manifest due to the interaction among large hydropower generators (synchronous machines that do not use fossil fuels) clustered in British Columbia (BC) and the northwestern US with some presence along the California coast. The properties of this mode (including its shape) under different inverter penetration scenarios are further analyzed. As the hydro-generators are concentrated in a relatively small portion of the WI, the geographical spread of this mode may be limited as well. To the best of the authors' knowledge, this is the first work that examines the effect of varying levels of GFM inverter penetration on the oscillatory characteristics of a real large-scale electrical interconnection. The results presented are preliminary, dependent on modeling assumptions, and may not accurately capture how future IBR penetration unfolds in the WI. However, they indicate that under high-penetration scenarios, GFM inverters may significantly alter inter-area oscillations and hence, system operators must closely monitor these changes as the resource-mix continues to evolve.

The remaining paper is organized as follows. Section 2 provides a brief overview of the known WI inter-area modes and data-driven oscillation analysis techniques. With the help of model-based case studies, Section 3 details how the WI inter-area oscillatory behavior may change as fossil-fuel-based synchronous generators are retired and replaced by GFM IBRs. Section 4 outlines future research directions and concludes this paper.

Table 1. Characteristics of WI inter-area modes [5]

Mode	Frequency (Hz)	Shape
NS-A	0.2-0.3	Alberta vs. system
NS-B	0.35-0.45	Alberta vs. (northern U.S. + B.C.) vs. southern U.S.
EW-A	0.35-0.45	(Colorado + eastern Wyoming) vs. system
BC-A	0.5-0.72	Not well-understood
BC-B	0.6-0.72	Not well-understood
MT	0.7-0.9	Montana vs. system

2. Background

Before further examining how wide-area oscillations will change with increasing IBR penetration, this section briefly recaps the known characteristics of WI natural oscillation modes. A short overview of modal property estimation techniques is also provided.

2.1. Inter-area Oscillation Modes in the Western Interconnection

Following the WI blackout in August 1996 caused by undamped oscillations [10], much effort has been invested in studying its inter-area modes, using both simulation-based studies and synchrophasor measurements. The current understanding of WI mode properties, including their excitability, observability, and controllability, is documented in detail in a recent report published by the Western Electricity Coordinating Council (WECC) [5]. The frequencies and shapes of modes discussed in [5] are summarized in Table 1.

The two north-south (NS) modes are the best-understood WI modes. The NS-A mode is well-damped, with DR values greater than 10% when the 500 kV intertie between Alberta and BC is in service. When Alberta disconnects from the rest of WI, the NS-A mode disappears. The NS-B mode is the most geographically widespread and lightly damped WI mode, with typical DR values ranging between 5 and 10%. When the Alberta-BC intertie is disconnected, the frequency and DR of the NS-B mode are reduced. Measurement-based correlation analysis shows that system load, IBR penetration and power flow on the California-Oregon Intertie (COI) also influence the properties of the NS modes [6]. Due to its wide visibility and low damping, the NS-B mode is carefully monitored by grid operators in the WI.

The east-west (EW)-A and NS-B modes have overlapping frequency ranges, but can be differentiated based on their shapes. Model-based studies find preliminary evidence for two modes (BC-A and BC-B) primarily driven by large generators in BC swinging against the northern US, but due to limited

PMU coverage, further research is needed to better understand their properties. The Montana (MT) mode is well-damped (DR $\sim 10\%$) and is primarily driven by a large coal generation facility in Colstrip, MT, whose retirement is expected to impact this mode's properties significantly.

2.2. Data-driven Oscillation Mode Analysis

Due to the underlying physics, synchronous power systems inherently are multimodal under-damped systems. Theoretically, a system with n interconnected synchronous machines has $n-1$ modes of oscillation, most of which tend to be localized to a few generators. Some modes, however, become widespread and involve a group of generators swinging against generators in other parts of the system. These modes are termed 'inter-area' and typically have frequencies between 0.1 and 1 Hz. During high system stress conditions (component outages, high power transfers across corridors, etc.), inter-area oscillations may become undamped, thereby increasing the risk of outages.

Oscillation modes are typically described by their frequency, DR, and shape. Damping is a measure of how fast a given mode dissipates in a transient. A mode is considered well-damped if its DR is above 10%. The shape of a mode describes its observability. Mode shape is a complex number whose amplitude indicates the relative participation of different machines in modal oscillations, and angle describes the relative grouping of participating generators. Generators with similar mode shape angles swing together against other generator groups whose angles are about 180 degrees apart.

Techniques used for estimating mode properties can be broadly grouped into three categories: a) ambient analysis [11, 12], b) ringdown analysis [13, 14], and c) eigenvalue analysis [15]. Ambient methods estimate modal properties (typically using phasor measurement unit (PMU) data) during steady-state conditions when the primary excitation to the system is provided by random load changes. Ringdown methods analyze natural oscillations following a large disturbance to estimate modal content, usually by employing curve-fitting techniques. Ringdown techniques can be employed for both field PMU measurements and simulation observations. Eigenvalue analysis methods seek to estimate modes by constructing a linearized model of the system from the mathematical description of its dynamics. These methods may be implemented using offline powerflow cases with associated dynamic data of system generators, but can get computationally expensive for large interconnections. Commercial tools like Small Signal Analysis Tool (SSAT) can be used for these studies [16]. For further discussion about power systems oscillations, their properties and analysis techniques, one can refer [1, 5].

Given the computational burden of eigen-analysis methods, this work has used ringdown analysis, specifically multi-signal Prony analysis, to estimate WI modal properties under different IBR-penetration scenarios [13]. Other ringdown analysis methods include matrix-pencil [14, 17], dynamic mode decomposition [5] etc. Prony methods express the post-disturbance "free-response" system output as a linear combination of damped sinusoids. It is assumed that the trajectory of the modeled state follows an autoregressive process. Results obtained are sensitive to several parameters that must be user-specified (model order, data window to be analyzed). Despite this, due to the relative ease of implementation, Prony methods are useful in estimating and comparing trends in mode properties when many model-based scenarios are to be examined. A brief review of the standard Prony method and its multi-signal extension for power system transient analysis is provided next.

Prony Method: Consider a linear time-invariant (LTI) dynamic system with an output of the form

$$y(t) = Cx(t) + Du(t), \tag{1}$$

where $x(t)$ is the state variable and $u(t)$ is the system input. As the Prony method is used to analyze measured ringdowns once the transient disturbance has been removed, the system input $u(t)$ is assumed to be zero. Hence, the continuous-time output signal $y(t)$ is modeled as:

$$\hat{y}(t) = \sum_{i=1}^{n} B_i e^{\lambda_i t}, \tag{2}$$

where $B_i \in \mathcal{C}$ is the output residue of the continuous time pole $\lambda_i \in \mathcal{C}$, $\lambda_i \neq \lambda_j$ for $i \neq j$. The values of residues, poles, and n that force $\hat{y}(t)$ to be a least-squares fit to $y(t)$ need to be estimated. Now, let the signal $y(t)$ be sampled at a constant sampling period (T) lesser than the Nyquist period. Then, (2) may be rewritten in the discrete form as:

$$\hat{y}(kT) = \sum_{y=1}^{n} B_i z_i^k, \qquad k = 0, \ldots, N-1 \tag{3}$$

Here, $z_i = e^{\lambda_i T}$ is the discrete-time pole. If the characteristic equation for $\hat{y}$ is,

$$d(z) = 1 - (a_1 z^{-1} + \ldots + a_n z^{-n}), \tag{4}$$

then $\hat{y}$ satisfies the autoregressive sequence:

$$\hat{y}(kT) = a_1\hat{y}((k-1)T) + \ldots + a_n\hat{y}((k-n)T) \tag{5}$$

A Prony solution for the above set of equations can be obtained through the following main steps.

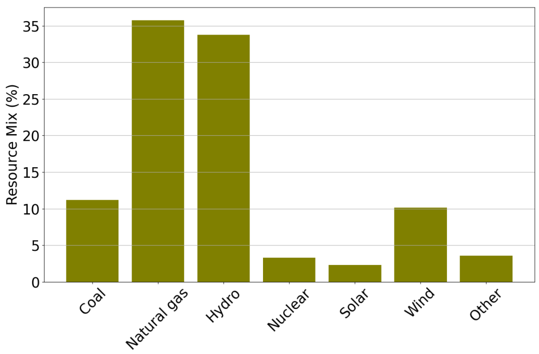

Figure 1. Generation resource mix in the WECC 2031 heavy winter planning case

1. By substituting y for $\hat{y}$ in (5), the linear equations can be solved to obtain a_i coefficient estimates. This step is called the linear prediction problem.
2. Using the a_i coefficients from step 1, the roots of the characteristic equation $d(z)$ may be determined.
3. Using the roots obtained in step 2 and substituting y for $\hat{y}$ in (2), the output residues can be solved for.

Further insight into applying Prony analysis to estimate power system modes is available in [18] and [19].

Multi-signal Prony Method: The accuracy of mode estimates may be improved by extending the standard Prony method to analyze multiple signals simultaneously. Consider a set of M signals $y_m(t), m = 1, \ldots, M$ that share a common set of eigenvalues. The m-th signal may be modeled as $\hat{y}_m(t) = \sum_{i=1}^{n} B_{mi} e^{\lambda_i t}$, or in the discrete-time form as:

$$\hat{y}_m(kT) = \sum_{y=1}^{n} B_{mi} z_i^k, \qquad k = 0, \ldots, N_m - 1 \quad (6)$$

As in the single-signal case, B_{mi} is the output residue for the continuous-time pole λ_i, and $z_i = e^{\lambda_i t}$. Similarly, each sampled signal $\hat{y}_m$ satisfies (4), and solving the linear prediction problem involves solving the equations

$$\hat{y}_m(kT) = a_1 \hat{y}_m((k-1)T) + \ldots + a_n \hat{y}_m((k-n)T) \quad (7)$$

for each $m = 1, \ldots, M$ simultaneously to obtain the a_i coefficients. The solution methods for the single-signal case can be directly extended. As more signals are added, more equations are added to the linear prediction problem, creating a highly over-determined system of equations. For a more detailed discussion of the multi-signal extension of the standard Prony method, one can refer [13].

3. Case Studies

Simulation-based studies in this work have been performed using the WECC 2031 heavy winter planning case (henceforth referred to as the *base case*) in PSS/E. This baseline model has ∼160 GW generation, with ∼12.5% contribution from inverter-based renewable resources (solar, wind, battery storage) and ∼33% from hydropower, as shown in Fig. 1.

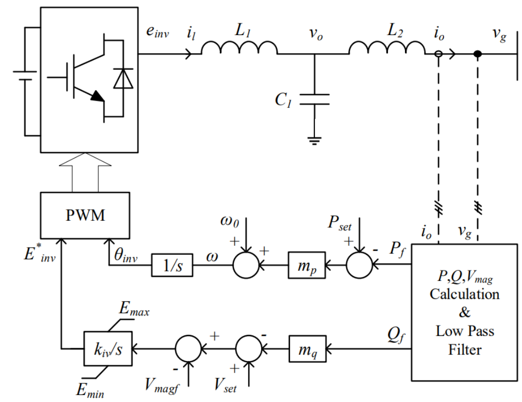

Figure 2. Single-loop droop-based control for GFM inverters [21]

As mentioned before, ringdown analysis methods estimate modal properties from the post-disturbance trajectories of power system variables. In this work, the disturbance was created by simulating the insertion of the 1200 MW Chief Joseph dynamic braking resistor for 0.5 seconds to reflect real-world system tests [5,20]. The Chief Joseph brake insertion is known to excite the NS-B mode, and analyzing ringdowns when brake insertions are simulated at other additional locations [4, 5] will be necessary to obtain a complete picture of other oscillation modes that may exist in the modified cases.

3.1. Grid Forming Inverter Model

To simulate different GFM inverter penetration scenarios, synchronous generators in the base case were incrementally replaced by GFM IBRs with single-loop droop-based control. The control diagram of the GFM IBRs is shown in Fig. 2. In the simulated scenarios, these IBRs had equal generation injections as the synchronous generators being replaced, as further elaborated in Section 3.2. Existing IBRs in the base case using grid-following (GFL) controls were also replaced by GFM inverters. While this may not be a realistic portrayal of how IBRs will be deployed in the WI, it provides a systemic approach for creating high GFM inverter penetration models for simulation studies. Similar methodologies have been adopted in existing literature to simulate inverter-dominated power systems as well [3,5].

The GFMDRP_A inverter model used in this work has been approved by the WECC Modeling

Parameter	Description	Value
X_L	Inverter coupling reactance	0.15 pu
m_q	$Q-V$ droop gain	0.05 pu
k_{pv}	Proportional gain of voltage controller	0 pu
k_{iv}	Integral gain of voltage controller	5.86 pu/s
m_p	$P-f$ droop gain	0.01 pu
k_{ppmax}	Proportional gain of the overload mitigation controller	0.01 pu
k_{ipmax}	Integral gain of the overload mitigation controller	0.1 pu/s
T_{Pf}	Time constant of low-pass filter for P measurement	0.01 s
T_{Qf}	Time constant of low-pass filter for Q measurement	0.01 s
T_{Vf}	Time constant of low-pass filter for V measurement	0.01 s
k_{pqmax}	Proportional gain of the Q_{max} and Q_{min} controller	3 pu
k_{iqmax}	Integral gain of the Q_{max} and Q_{min} controller	20 pu/s
I_{max}	Inverter maximum output current	1.2 pu

Table 2. Model parameters used for GFM inverters

and Validation Subcommittee (MVS) for use in initial studies aimed at evaluating the impact of IBR integration in transmission systems [9]. The GFM inverter is modeled as a controllable voltage source behind a coupling impedance. The droop controller controls its internal voltage magnitude and angular frequency. The model additionally comprises a fault current limiting function that limits the inverter current output during short-circuit conditions [21]. Model parameter values used (typical values for the GFMDRP_A model approved by WECC MVS) in this work are listed in Table 2.

Automation scripts have been developed to facilitate the replacement of specified synchronous generators by GFM inverters in large PSSE powerflow cases [22]. This will ensure that the methodology used in this work can be scaled to many IBR penetration scenarios with relative ease.

3.2. Scenario Creation

Three different scenarios with varying fuel mixes and resultant GFM penetration levels were created, as summarized in Table 3. To accelerate grid decarbonization, many US states have announced ambitious plans to retire fossil fuel fleets and replace them with renewable sources of power. In line with these objectives, while formulating hypothetical scenarios of increased renewables penetration throughout the WI, synchronous generators using clean fuel sources like hydropower and geothermal generators were retained. In the WI, large hydropower generators are concentrated in its northwestern portion, as shown in Fig. 3. Of the ~54 GW of hydropower generation in the base case, 39.5 GW is located in the BC, Northwest, and Montana regions. Hence, even when large portions of fossil fuel generators were replaced by GFM IBRs in the simulated scenarios, the GFM penetration in the northwestern WI never crossed 35%.

Scenario	Description	GFM Penetration
1	Existing GFL inverters and coal generators in base case replaced by GFM	$\sim 23\%$
2	50% of natural gas generation in each balancing area also replaced by GFM	$\sim 46\%$
3	All natural gas and nuclear generators also replaced by GFM	$\sim 62\%$

Table 3. Creating scenarios with varying levels of GFM IBR penetration in the WI

In Scenario 1, GFL inverters ($\sim$ 20 GW) and coal generators ($\sim$ 18 GW) were replaced by GFM inverters, leading to a system-wide GFM penetration of ~23%. In Scenario 2, half of the natural gas generation (~28.3 GW) from each balancing area was replaced, thereby increasing GFM penetration to ~46%. To decide which generators to replace, all natural gas plants in each balancing area were first arranged in increasing order of their active power outputs. Then the largest generators, making up about half of a given area's natural gas power output, were replaced. In Scenario 3, the remaining natural gas generators and all nuclear generators in the base case ($\sim$ 5.3 GW) were replaced. This increased the GFM penetration to $\sim$ 62%. The relative geographic distribution of inverter-based and rotating machines in the created scenarios influence the insights about evolving inter-area oscillations obtained from this work.

3.3. Inter-area Modes in Different Scenarios

As previously discussed, modal properties were estimated by simulating the Chief Joseph brake insertion and then employing Prony analysis to express the system output as a linear combination of damped sinusoids.

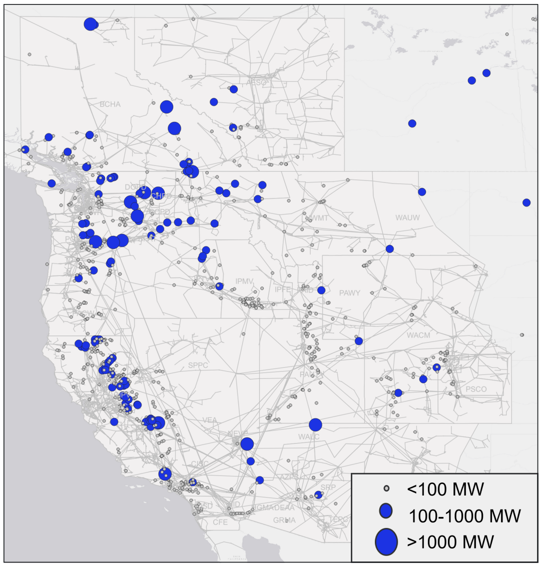

Figure 3. Location of hydropower generators in the WI [23]. A significant proportion of hydropower resources are concentrated in the northwestern USA and the BC Hydro region in Canada.

Scenario	Frequency (Hz)	Damping Ratio (%)
Base	0.38	11
1	0.69	15.4
2	0.71	14
3	0.72	14.5

Table 4. Estimates of properties of the dominant inter-area mode observed due to Chief Joseph dynamic brake insertion

Prony analysis results are sensitive to the choice of parameters. In this work, the data window to be analyzed was determined through visual inspection; the first two post-disturbance cycles were eliminated, and it was ensured that the data window did not contain any 'flat response' after the oscillations had dissipated. The model order was tuned to achieve a good match between the simulated measurements and the reduced-order Prony model while avoiding overfitting.

Modal properties estimated from the base case were first validated against the report published by the WECC [5]. Frequency, DR, and mode shape estimates for the NS modes (NS-A: 0.27 Hz, 14%; NS-B: 0.38 Hz, 11%) approximately matched the findings in the report.

Mode around 0.7 Hz: After GFM penetration was increased following the procedure described in Section 3.2, modal content in the 0.2-0.4 Hz range was no longer visible from post-disturbance data. This is in contrast to the findings from [5], where it was noted that the frequency and DR of the NS modes in the WI change with a system-wide increase in IBR penetration, but the Chief Joseph brake insertion still excites them. This difference may be because- a) the powerflow cases being analyzed are different, and b) this work uses GFM inverters while [5] used GFL IBRs.

Modal content was visible around 0.7 Hz, providing preliminary evidence of the presence of a mode. This frequency is very close to the existing BC modes, although the shape estimates do not match, as elaborated later in this section. Modal content in this frequency range was present in all the GFM penetration scenarios simulated in this work, and the estimated mode frequency and DRs are shown in Table 4. The mode appears to be well damped, with DR estimates higher than 10% in all cases, thereby not posing immediate system stability concerns.

It is observed that the frequency and DR estimates are consistent in the three simulated scenarios, although a slight increasing trend is observed in mode frequency with an increase in inverter penetration. A possible reason behind this observed consistency could be the fact that the GFM penetration in the northwestern US, where generator participation in the 0.7 Hz mode is observed, does not vary much in the simulated scenarios. Previous research corroborates that modal frequencies typically tend to increase as inverter-based generation increases in a system [2,4,6]. DR estimates do not show a consistent trend, in line with prior observations that inverter locations significantly influence whether mode damping increases or decreases with IBR penetration [3, 4, 6, 7]. Further investigation of mode shapes show that as synchronous generators incrementally get replaced by GFM inverters, the geographical spread of this mode decreases and the shape changes. The present work has not investigated what impact, if any, the disconnection of the Alberta-BC 500 kV intertie will have on the 0.7 Hz mode, and this is a direction the authors plan to pursue in future research.

Resource mix in relevant areas: To support observations from the simulations, first examining the fuel mix in areas with significant hydropower generation is useful. Fig. 4 shows the base-case resource mix in the three areas where hydropower makes up a large portion of the generation portfolio and that show participation in the 0.7 Hz mode, namely California, BC Hydro and Northwest.

In California, natural gas is the largest power source in the planning case considered, although significant generation from hydropower and renewable resources is also present. A very small amount of generation comes from coal plants. Hence, behavior differences observed for the region between the base case and Scenario 1 are primarily due to GFL inverters being replaced by GFMs. The replacement of significant natural gas generation in

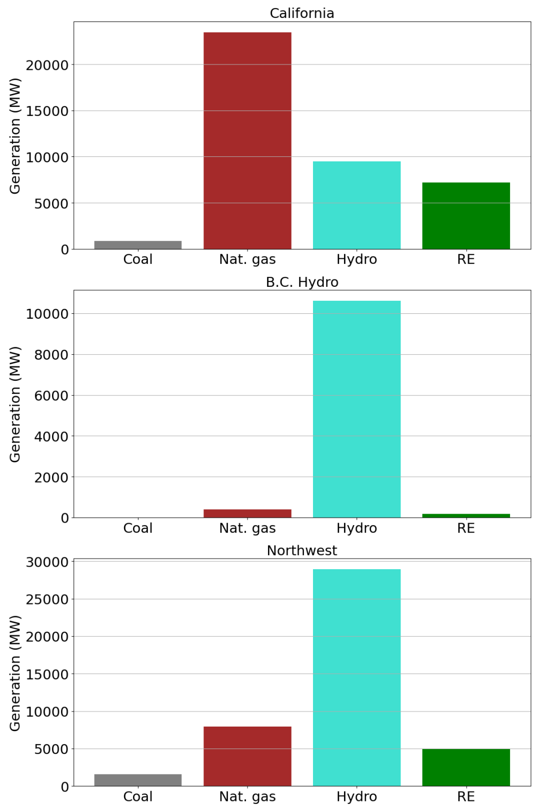

Figure 4. Contribution of different fuels to generation outputs of three areas (Base case)

the subsequent scenarios impact inter-area oscillations observed in California. The major generation source for the BC Hydro region is hydropower. Therefore, the amount of synchronous generation in the region shows little variation across the simulated scenarios. Generators in BC Hydro exhibit high participation in the 0.7 Hz mode.

The Northwest region comprises the states of Washington, Oregon, Idaho and Montana, where several large hydropower plants are present. Some amount of coal, natural gas and inverter-based renewable generation also exist, but participation in the observed 0.7 Hz mode is primarily driven by the energy exchange among hydro-generators.

Mode shape estimates in different scenarios: In Scenario 1, participation in the 0.7 Hz mode is observed from generators in the Northwest, BC and California, as seen from the compass plot in Fig. 5. Compass plots help visualize mode shapes in polar coordinates. Each arrow represents the mode shape of one location; the arrow length is proportional to mode shape amplitude and direction indicates mode shape angle. The amplitude and angle are expressed in relation to the reference signal whose shape is $1\angle 0^o$. The reference signal here is the derived frequency (first derivative of

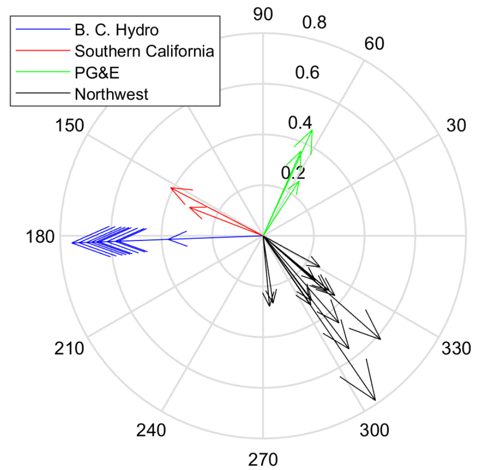

Figure 5. Mode shape estimates: Scenario 1 (Frequency: 0.69 Hz, DR: 15.4%)

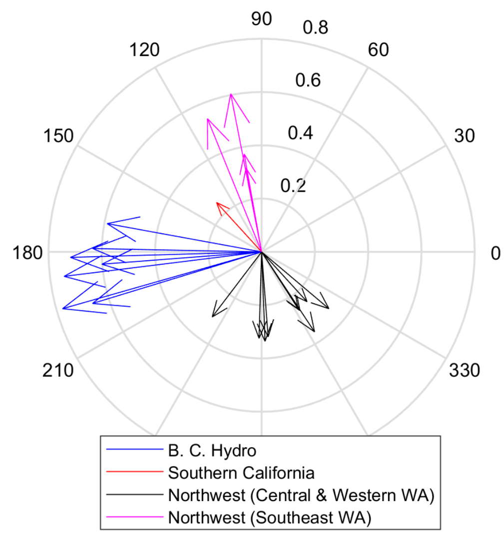

Figure 6. Mode shape estimates: Scenario 2 (Frequency: 0.71 Hz, DR: 14%)

voltage angle) from positive sequence voltage angle difference at Wanapum and Kemano buses. To avoid visual clutter, only locations that had amplitudes greater than 0.2 have been included in the plots shown here. The highest amplitudes are observed in generators in BC Hydro and Northwest regions, and the participation in California is from natural gas generators, small hydropower, and geothermal machines. No GFM IBR location had mode shape amplitude estimates higher than 0.2. Because geographically close generators appear to swing together, the mode shape estimates look reasonable.

In Scenario 2, with the replacement of large natural gas generators, participation from California generators in the 0.7 Hz mode decreases significantly, as evident

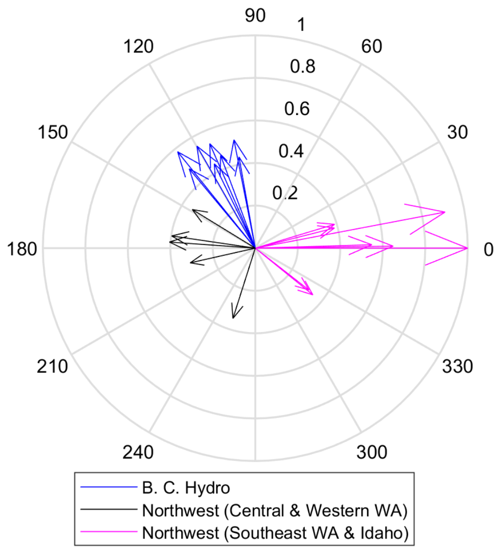

Figure 7. Mode shape estimates: Scenario 3 (Frequency: 0.72 Hz, DR: 14.5%)

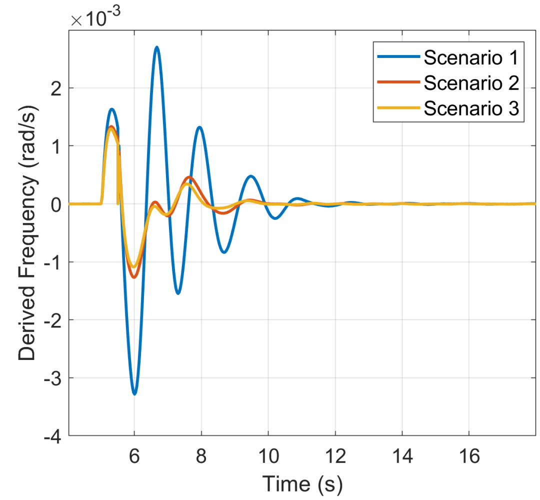

Figure 8. Derived frequency at a California natural gas generator for the three simulated scenarios (replaced by a GFM IBR in Scenarios 2 and 3)

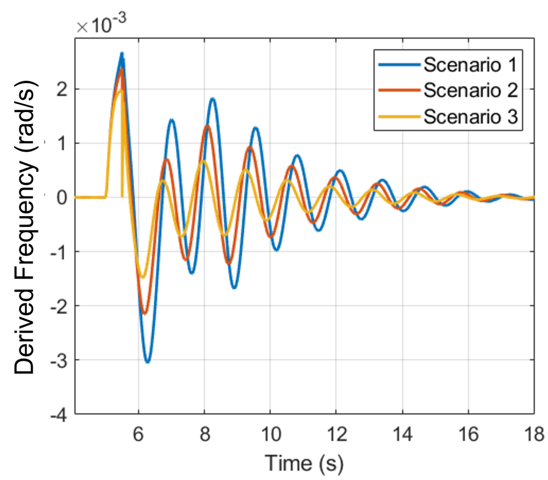

Figure 9. Derived frequency at a California hydropower generator for the three simulated scenarios

from Fig. 6. This may be explained by the fact that in the base case, California comprised about 23.4 GW of the total 55 GW natural gas generation. Hence, between Scenarios 1 and 2, California sees significant reduction in the number of synchronous machines. It can also be observed that the mode shape angle difference among generators within the Northwest region increases from Scenario 1 to Scenario 2. This shows that the geographic spread of the mode has shrunk, and hydropower generators in central and western Washington are exchanging energy with those in southeastern Washington.

In Scenario 3, with the retirement of further synchronous generators, the geographic spread of the mode reduces again. The highest amplitudes are observed in southeastern Washington, where a large number of high-capacity hydropower plants are concentrated. The large generators in southeast Washington and Idaho appear to swing against those in the central and western Washington as well as the BC Hydro region (Fig. 7). The mode shape is similar to Scenario 2, except high participation from California generators is not observed.

To illustrate the changing oscillations in California, Figs 8 and 9 show the oscillatory responses of example generators in the time domain. It can be seen that the oscillations observed at the natural gas bus change when the synchronous machine in Scenario 1 is replaced by a GFM inverter in the remaining scenarios. This may be explained by the fact that the $P - f$ loop of the inverter acts as a high-gain power system stabilizer (PSS) in the range of the electromechanical modes, thereby damping out oscillations. For the hydropower generator, oscillation amplitudes appear to decrease as GFM penetration increases, in line with the observations described in this section. Modal content outside the 0.7 Hz mode may also be present, and further analysis with dynamic brake insertion at other locations like Palo Verde may be needed to better understand the oscillations in California generators.

It must be reiterated here that the conclusions from the case studies are dependent on modeling assumptions. For instance, evidence of poorly tuned inverter controls adversely impacting the damping of oscillatory modes has been documented [24]. However, this work has not examined how improper tuning of GFM control parameters may affect WI modes; the focus is on inter-area oscillations driven by synchronous machines in a GFM inverter-dominated WI. Future work will seek to understand modal property changes with different GFM control strategies, parameter values, etc.

3.4. Discussion

Different hypotheses exist regarding the behavior of inter-area modes in future inverter-dominated grids. For example, [25] posits that even in grids with 100% inverter penetration, inter-area oscillations will not disappear, and will manifest with different characteristics at higher frequencies. On the other hand, [26] says that since the behavior of inverter-dominated grids will no longer be linear around an operating point, the properties of observed oscillations will be highly dependent on contingencies and their locations. The modal properties estimated in this study are preliminary, and dependent on the assumptions about which generators are retired and replaced by GFM IBRs. Moreover, simulations with different power flow models and brake insertions at multiple locations will be necessary for obtaining a complete picture of changing oscillatory modes in the WI.

In any case, as the GFM IBR-penetration scenarios studied in this work are hypothetical, the observation that inter-area oscillation modes will be driven by hydropower generators is a more interesting insight than the exact mode property estimates obtained. The study indicates that hydropower generator locations that do not show high participation in existing WI modes may end up with increased participation in inter-area oscillations following the reduction of synchronous machines in the system. As regional fuel-mix and IBR control methodologies will dictate future modal properties to a large extent, continuous monitoring will be critical for flagging changes before dramatic transitions in modes occur. Some other actionable insights are listed next.

First, field experience has shown that improperly tuned control parameters of GFM inverters can adversely impact modal properties, especially if the inverters are located in areas with high participation in a mode [24]. Hence, attention must be paid to control parameters of any GFM inverter deployed in northwestern WI. At present, a consensus exists that electromagnetic transient (EMT) studies are necessary for identifying IBR performance issues in areas with high inverter concentration due to low grid strength concerns [27]. Observations from this study indicate that EMT studies may also be necessary in areas with high participation in inter-area modes to ensure that improperly tuned inverter parameters do not exacerbate oscillations caused by transient disturbances.

Second, if modes appear due to the energy exchange among hydropower generators, new interaction paths along which modal energy is transferred may also emerge. Hence, PMU coverage may be necessary for these areas to develop a granular understanding of the WI modal properties.

4. Conclusion

In this work, the impact of retiring fossil-fuel-based synchronous generation on the inter-area oscillation modes of the WI has been studied. It is concluded that as inter-area oscillations are primarily driven by the exchange of energy among rotating machines, the synchronous machines remaining in the system and their geographic distribution will dictate the properties of the modes observed. In the WI, as hydropower generation is concentrated in the northwestern portion of the interconnection, retirement of fossil fuel fleets may lead to the emergence of a mode driven by energy exchange among the hydropower generators. Simulations indicate that the mode will be well-damped, thereby not posing immediate threats to system stability. The geographic spread of this mode appears to be limited, and its frequency shows an increasing trend with inverter penetration.

The results described in this paper are preliminary, and studies with different power-flow cases, network topologies and contingency locations will help better understand the evolving oscillation modes. Future research will explore these avenues and also study the impact of targeted plant retirements on individual WI system modes (for example, how will the retirement of Colstrip generation units change the properties of the Montana mode?). As future IBR-dominated grids are expected to use a heterogeneous mix of GFL and GFM technologies with different control schemes such as droop-control and virtual inertia, the impact of IBR fleets with diverse control methodologies on inter-area modes will also be investigated.

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