Small Signal Stability of the Western North American Power Grid with High Penetrations of Renewable Generation

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***Abstract*—The goal of this effort was to assess the effect of high penetration solar deployment on the small signal stability of the western North American power system (wNAPS). Small signal stability is concerned with the system response to small disturbances, where the system is operating in a linear region. The study area consisted of the region governed by the Western Electricity Coordinating Council (WECC). General Electric's Positive Sequence Load Flow software (PSLF®) was employed to simulate the power system. A resistive brake insertion was employed to stimulate the system. The data was then analyzed in MATLAB® using subspace methods (Eigensystem Realization Algorithm). Two different WECC base cases were analyzed: 2022 light spring and 2016 heavy summer. Each base case was also modified to increase the percentage of wind and solar. In order to keep power flows the same, the modified cases replaced conventional generation with renewable generation. The replacements were performed on a regional basis so that solar and wind were placed in suitable locations. The main finding was that increased renewable penetration increases the frequency of inter-area modes, with minimal impact on damping. The slight increase in mode frequency was consistent with the loss of inertia as conventional generation is replaced with wind and solar. Then, distributed control of renewable generation was assessed as a potential mitigation, along with an analysis of the impact of communications latency on the distributed control algorithms.**

***Index Terms*—small signal stability, renewable generation, distributed control of renewable generation.**

I. Introduction

Historically, large-scale power systems have been composed of directly coupled synchronous generators interconnected via transmission systems. The tendency of these systems to experience electromechanical oscillations is an inherent property which arises from the law of conservation of energy, Kirchoff's current law, and synchronism [1]. These fundamental laws of physics manifest themselves as oscillations within and between large generation complexes separated by weak transmission paths. As converter-based renewable sources become more prevalent, the characteristics of these oscillations may change. In order to ensure the stability of the system, it is imperative to understand the ways in which the modes of oscillation will be altered. This study aims to quantify the impact of high penetrations of wind and photovoltaic generation on inter-area modes in the western North American power system (wNAPS). It should be noted that this study does not address potential modes of oscillation arising from interaction between the controls of converter-based sources and the excitation systems of synchronous generators.

Inter-area modes are characterized by oscillations between groups of generators, or groups of plants, separated by long geographical and electrical distances. In a synchronous generator, the turbine either resides on the same shaft as the rotor or is mated to it through a gearbox. Hence, the turbine and the rotor are *directly coupled* and perturbations in electrical power propagate through to the mechanical dynamics of the machine. As a result, the rotor speeds of synchronous generators can oscillate slowly in response to a disturbance in electrical power. For generators separated by long electrical distances these oscillations tend to be out of phase. The frequency of these electromechanical oscillations, typically in the range of 0.1 to 1.0 Hz, is a function of the inertia and damping in each area as well as the impedance of the transmission system.

Previous studies that have investigated high renewable penetration in the western U.S. include the Western Wind and Solar Integration Study (WWSIS) [2]. This study analyzed the power system operated by the WestConnect group which includes utilities in Arizona, Colorado, Nevada, New Mexico, and Wyoming (California was not included because it had completed a renewable integration study). The primary objective of this effort was to identify and quantify any system performance or operational problems with respect to load following, regulation, and operation during low load periods. The frequency response of the three U.S. interconnections was explored in [3]. For the WECC analysis, this study utilized the 2012 light winter base case as a starting point. The base case was modified to reduce the load to 80 GW and to convert all wind turbine models to type 3 (doubly-fed asynchronous induction generator with voltage control and reactive power). The maximum wind generation in this study was 9 GW, and the system frequency nadir was recorded for 6 different scenarios.

The influences of distributed generation and renewable energy on transient stability are explored in [4]. This paper employs a test power network with two synchronous generators connected to a distribution network with distributed generation and a wind farm. The wind was modeled as a doubly-fed induction generator, and their simulation results showed a slight improvement in transient stability with the combination of distributed generation and wind.

An assessment of the WECC mode shapes as a function of topology changes appears in [5]. This study considered 277 "N-1" contingencies involving the loss of a 500 kV transmission line. A modified version of the 2009 heavy summer WECC operating case was employed. The California-Oregon Intertie (COI) flow was increased and several transmission lines were tripped to yield a low-damping case for the study. This analysis focused on the North-South B inter-area mode. The study found that for most scenarios, the mode shapes do not change significantly. The exception was changes in the BC hydro tie lines which resulted in a significant change in mode shape.

A reduced-order transient-simulation model of the WECC, termed the "minniWECC", was utilized in [6] to estimate the observability of inter-area oscillations. The WECC model was reduced to 34 generators, 171 lines and transformers, 19 load buses, and 2 DC lines. This study evaluated the performance of real-power injection, reactive power injection, and series compensation devices for system-wide damping control applications. The effort focused on the North-South B mode and the British Columbia mode since they have the greatest impact on COI oscillations.

Baseline damping and mode shape estimates derived from Pacific DC Inertie (PDCI) probing are summarized in [7]. This research identified the following four major inter-area modes of interest:

1) The North-South A mode nominally near 0.25 Hz
2) The North-South B mode nominally near 0.4 Hz
3) The British Columbia mode near 0.6 Hz
4) The Montana mode nominally near 0.8 Hz

Other modes exist in the system, but these four are observed most often. This is especially true in the northern half of the system. The North-South A and B modes are the most widely observed and widespread. This, combined with their lower frequency makes them the most troublesome. Historically, the status of the transmission link between Alberta and British Columbia (primarily the 500 kV Cranbrook to Langdon line) has a strong influence on the North-South A and B modes. When Alberta is not connected, these two modes combine to form a single mode at approximately 0.32 Hz (near the middle of the two modes).

For larger system models, which are required to accurately model large interconnected power systems, techniques have been developed that evaluate a selected subset of system eigenvalues. Two common approaches include the AESOPS (Analysis of Essentially Spontaneous Oscillations in Power Systems) algorithm and the modified Arnoldi method (MAM) [8]. The AESOPS algorithm is described in more detail in [9]. The MAM algorithm is presented in [10].

Another approach for performing small signal analysis of large scale power systems is nonlinear simulation, followed by analysis of input-output data. Typical stimuli for the system include resistive brake insertions and modulation of power injection at different nodes in the system. One advantage of this approach is that results can be compared to synchrophasor measurement unit data of real-world disturbances for model validation. Once the data has been obtained from the simulation, common analysis techniques include Eigensystem Realization Algorithm (ERA), Prony analysis, and the Matrix pencil algorithm. The ERA algorithm is described in [11] and power system applications are presented in [12], [13], [14]. A comparison between Matrix Pencil and Prony methods for power system modal analysis appears in [15].

The same models employed in this study were analyzed using Prony analysis and the Implicitly Restarting Arnoldi Method (IRAM - incorporated in SSAT from Powertech Labs) in [16]. This paper builds on these results by using ERA, which enables the design of distributed control algorithms using the linearized system model. The control approach applied in this paper, optimal fixed structure control, is described in more detail in [17]. Modal analysis results for the north-south modes are found in Section II. Modal analysis results with an optimal fixed-structure controller designed using the linearized system and tested on the PSLF nonlinear model are found in Section III. The impact of communications latency on the control algorithm is assessed in Section IV.

II. ERA Modal Analysis

To perform the ERA analysis, the system was stimulated by inserting a resistive brake simultaneously in the north and the south of the system. The northern brake is the Chief Joseph dynamic brake. Bus frequencies were monitored at 26 locations distributed through the WECC. The ERA algorithm was then applied to the observed bus frequencies given the known input signal (measured resistive brake power). The results for the NS Mode A and B are presented in the following figures. Figures 1 and 2 show the mode frequency and damping as a function of renewable penetration for the 2016 heavy summer base case. Similarly, Figures 3 and 4 present the mode frequency and damping as a function of renewable penetration for the 2022 light spring base case. The trajectory of the eigenvalues in the complex plane as a function of renewable penetration for the 2016 heavy summer case is presented in Figures 5-6. The trajectory of the eigenvalues for the 2022 light spring case appears in Figures 7-8. For both the 2016 heavy summer and 2022 light spring base cases, the movement of the NS-A and NS-B modes was very consistent. The increase in renewable penetration and subsequent replacement of system inertia resulted in a slight increase in mode frequency with minimal impact on damping.

III. ERA Modal Analysis with Distributed Control

This section presents results with distributed control aimed at mitigating the north-south modes in the system for the 2016 heavy summer WECC base case with a 10 GW of solar generation. To achieve this level of penetration, 23 power plants were replaced with solar plants (minimum pgen = 250 MW). An optimal fixed structure controller, described

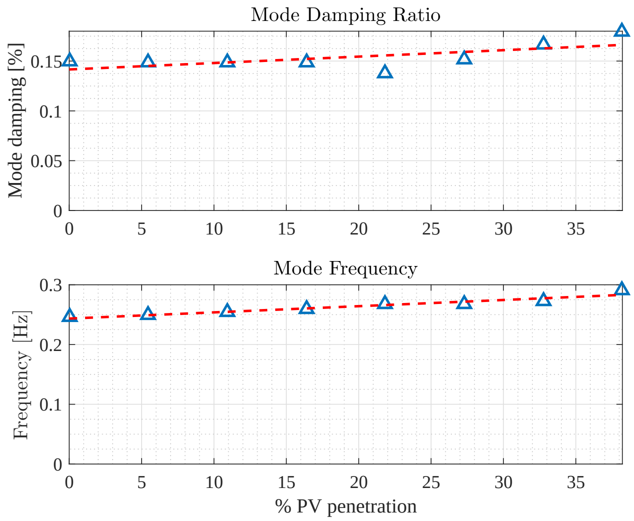

Fig. 1. ERA results, 2016 heavy summer, NS mode A.

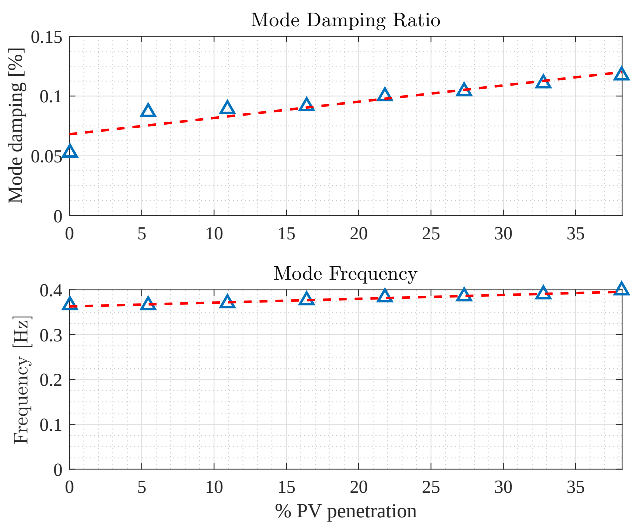

Fig. 2. ERA results, 2016 heavy summer, NS mode B.

in more detail in [17], was designed using the linearized system model from the ERA analysis. The optimal fixed structure controller design methodology attempts to minimize a performance index

$$J = \int_0^T \left(x^T Q x + \sum_{i=1}^{S} \tilde{u}_i^T R_i \tilde{u}_i \right) dt \tag{1}$$

for a linear time invariant system composed of S subsystems [18].

$$\dot{x} = Ax + \sum_{i=1}^{S} \left(\tilde{B}_i \tilde{u}_i \right) \tag{2}$$

For this example, there are 23 subsystems, one for each solar plant. It was assumed that each solar plant had access to the

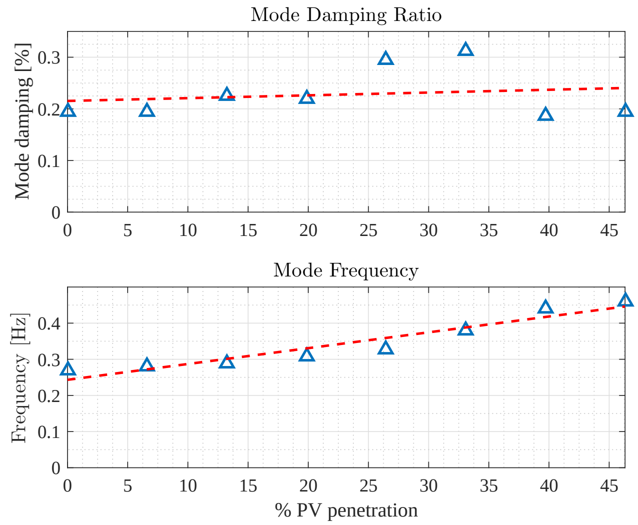

Fig. 3. ERA results, 2022 light spring, NS mode A.

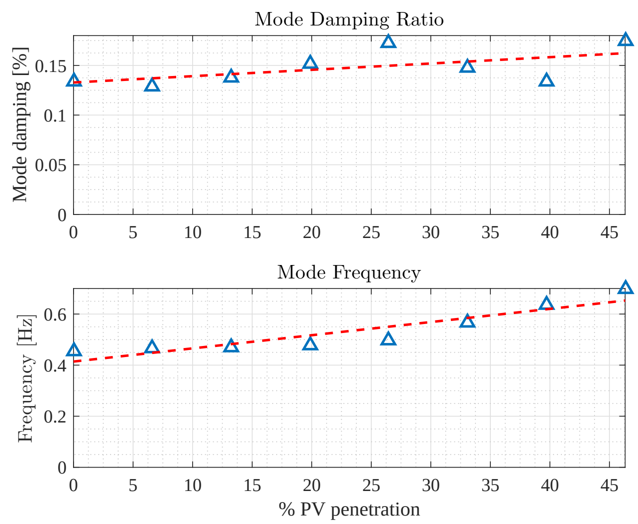

Fig. 4. ERA results, 2022 light spring, NS mode B.

bus frequency measurements at all the plants. The control law at each solar plant is given by:

$$\Delta P(t) = \sum_{i=1}^{N} K_i f_i(t) \tag{3}$$

where K_i is the gain calculated from the optimal fixed structure control algorithm and $f_i(t)$ is the bus frequency measurement at the i^{th} solar plant.

To obtain the linearized system model, the power output of each solar plant was perturbed with a 30 second log-chirp signal with a magnitude of 50 percent of the mva base, and a frequency range of 0.2 to 2.0 Hz. A representative chirp signal is shown in Figure 9. To test the model fit, one of the plant chirp signals was used as an input to the linearized model, and compared to the actual response of the system. The comparison is shown in Figure 10. The order of the system was determined by the ratio of singular values. All modes

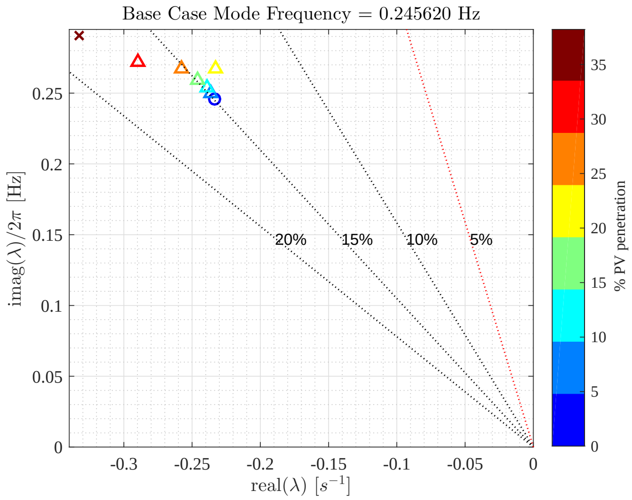

Fig. 5. ERA results, 2016 heavy summer, NS mode A.

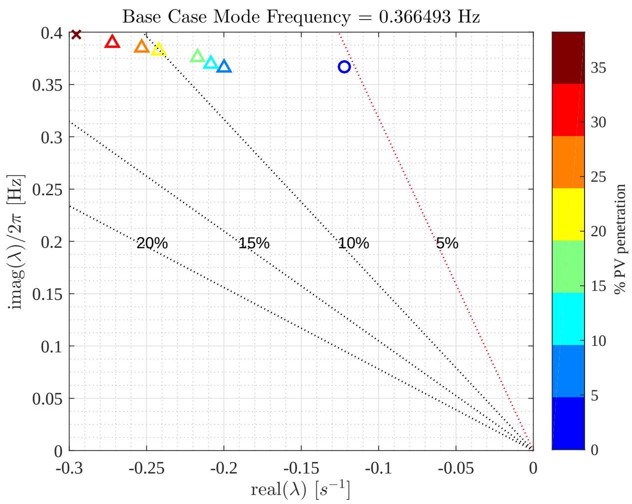

Fig. 6. ERA results, 2016 heavy summer, NS mode B.

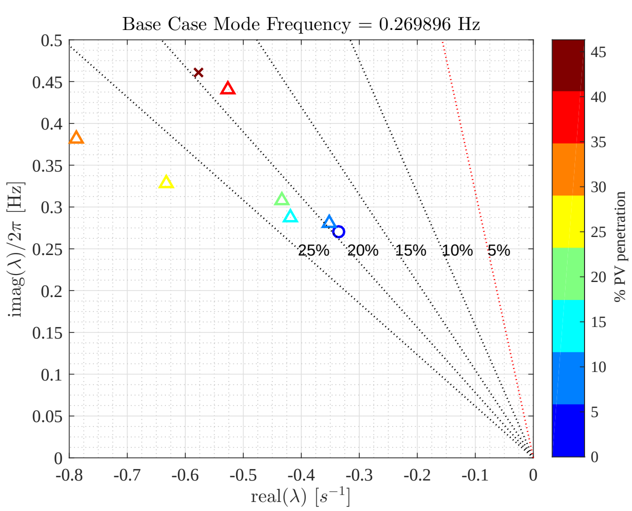

Fig. 7. ERA results, 2022 light spring, NS mode A.

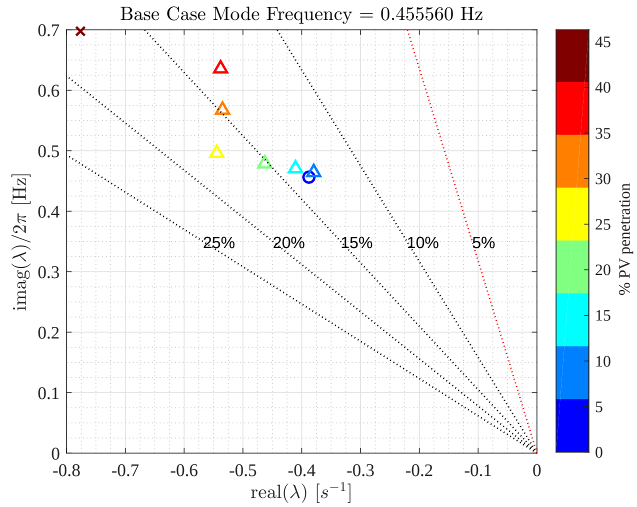

Fig. 8. ERA results, 2022 light spring, NS mode B.

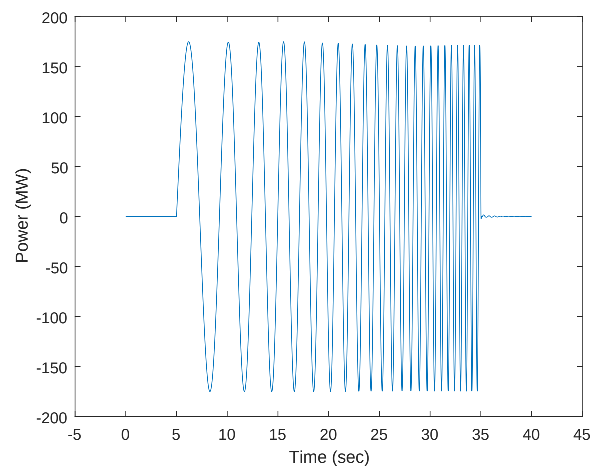

Fig. 9. Solar plant stimulus for system identification.

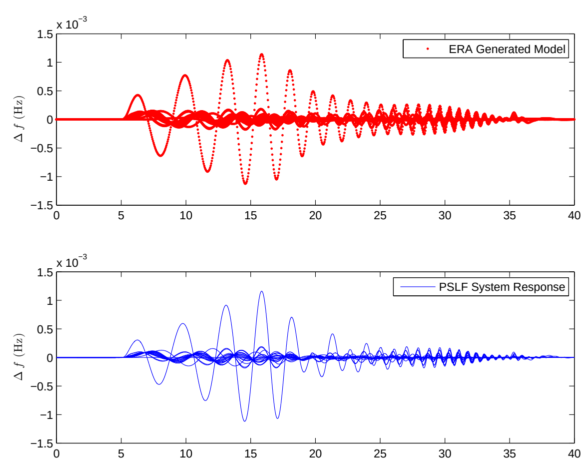

Fig. 10. Comparison of the ERA model system to the actual response of the PSLF model.

with a singular value less than 1 percent of the maximum singular value were discarded. This resulted in a system with 126 states. The eigenvalue movement of the linearized system is shown in Figure 11.

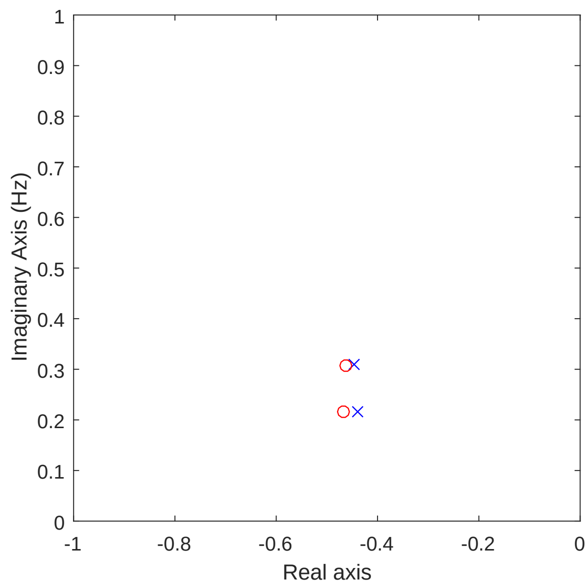

Fig. 11. Eigenvalue movement for the linearized system model with the optimal fixed structure controller. The blue ‘x’ represents the eigenvalues of the open loop linearized system. The red ‘o’ represents the eigenvalues of the closed loop linearized system. Only the two north-south modes are shown.

The next section presents results for the WECC 2016 heavy summer case with 10 GW of solar penetration and time delay on the remote measurement.

IV. ERA Modal Analysis with Distributed Control and Communications Delay

This section presents results for distributed control with communications latency for the 2016 heavy summer case with 10 GW of solar generation. The behavior of the north-south modes were analyzed as the communications delay, T_d was varied from 0 to 4.375 s. The local feedback signal was not delayed. Therefore the control law at the j^{th} plant is given by:

$$\Delta P(t) = \sum_{i \neq j} K_i f_i(t - T_d) + K_j f_j(t) \tag{4}$$

The eigenvalues as a function of communications delay are shown in Figure 12. For the NS-A mode, increased time delay on the remote measurement generally improved the stability margin and had minimal impact on damping. For the NS-B mode, increased time delay decreased the stability margin and damping.

V. Conclusion

As converter-based renewable sources become more prevalent, the characteristics of inter-area oscillations will likely change. The goal of this research was to quantify the impact

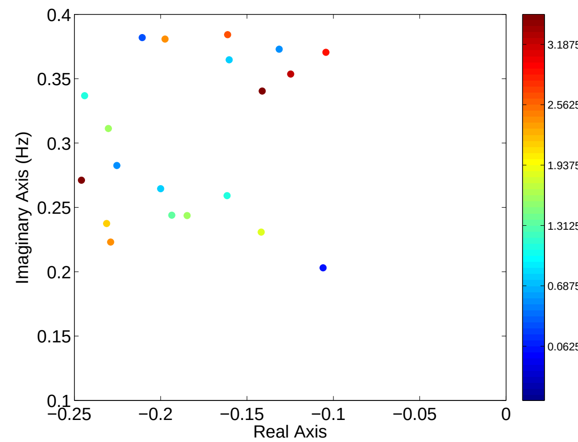

Fig. 12. Eigenvalues as a function of communications time delay for the 2016 heavy summer case with 10 GW of solar penetration.

of high penetrations of wind and photovoltaic generation on inter-area modes in the western North American power system. This paper focused on the two north-south modes which are the most widely observed and widespread. Using ERA analysis and two representative WECC PSLF base cases that were modified to include greater amounts of renewable generation, the modes were found to increase in frequency with relatively constant damping as renewable generation was increased. While the increased renewable generation had no negative effects on the two north-south modes, they offer the opportunity to further improve damping of these modes through active power control. Therefore, an optimal fixed structure control scheme to mitigate the modes was analyzed, as well as the impact of communications delay on the control system performance. Time delay negatively affected the NS-B mode, and improved the stability margin for the lower frequency NS-A mode. These results are preliminary, and future research will focus on studying the effects of time delay on damping control schemes for a wide range of systems with high penetrations of solar generation.

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