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Impact of High PV Penetration on the Inter-area Oscillations in the U.S. Eastern Interconnection

Shutang You, *Student Member, IEEE*, Gefei Kou,*Member, IEEE,* Yong Liu, *Member, IEEE,* Xuemeng Zhang, *Student Member, IEEE*, Yi Cui, Micah J. Till, *Student Member, IEEE,* Wenxuan Yao,*Student Member, IEEE,* and Yilu Liu, *Fellow, IEEE*

Abstract—**This study explores the impact of high PV penetration on the inter-area oscillation modes of large-scale power grids. A series of dynamic models with various PV penetration levels are developed based on a detailed model representing the U.S. Eastern Interconnection (EI). Transient simulations are performed to investigate the change of inter-area oscillation modes with PV penetration. The impact of PV control strategies and parameter settings on inter-area oscillations is studied. This study finds that as PV increases, the damping of the dominant oscillation mode decreases monotonically. It is also observed that the mode shape varies with the PV control strategy and new oscillation modes may emerge under inappropriate parameter settings in PV plant controls.**

Index Terms—**Large-scale power system oscillation, photovoltaic (PV), oscillation mode, oscillation frequency, inertia**

I. INTRODUCTION

SOLAR photovoltaic (PV) generation grows quickly in the U.S. and worldwide, joining wind power as a major renewable energy technology. While many aspects of wind power's impact on system power grid stability has been investigated, including rotor angle stability [1-3], voltage stability [4], frequency response [5-7], and inter-area oscillations [1, 8-11], the impact of PV generation on power system dynamics has not been given enough attention.

Among all these aspects, inter-area oscillations need special attention from system operators. Poorly damped inter-area oscillations can reduce transmission line capacity, damage system generation and transmission facilities, influence power quality, and lead to cascading failures or blackouts. The impact of PV generation on power system oscillations may be attributed to various aspects. However, the findings of existing literature are not consistent. For example, the New-England and New York test system was used to investigate the PV's impact on its established inter-area oscillation mode; it was found that PV could detrimentally affect the inter-area oscillation mode as PV integration results in larger angular separation among synchronous generators [12]. Furthermore, using small signal analysis and transient simulation, the study in [13] indicated that the increase of utility-scale and residential rooftop PV may decrease damping of inter-area oscillation modes due to reduced system inertia. However, other studies have found it is also possible that PV integration could improve small-signal stability. For example, the study in [14] concluded that PV could increase oscillation damping because PV adds damping to critical modes, and the scattered integration pattern is more beneficial than the concentrated pattern. Other studies that have similar findings include [15] and [16]. Additionally, other literature observed both beneficial and detrimental influence of PV on oscillations. Ref. [17] studied the impact of increased PV on system small signal stability based on a single-machine infinite-bus system. It was found that PV could either have positive or negative impact on oscillation damping. Similar findings can be found in [11] and [18]. The operation limit of PV also plays a significant role on the contribution of PV's damping torque. Ref. [19] studied the impact of distributed PV and large PV farms on system stability and found that damping does not vary significantly with the increase of either PV type.

Obviously, the impact of PV on power system inter-area oscillations is not yet well understood. Since there are so many factors that may play a role in this phenomenon, the impact of PV on inter-area oscillations may need to be studied on a case-by-case basis at this stage. Therefore, the United States Eastern Interconnection (EI) is used as a case study in this paper to investigate the impact of PV generation on a large interconnected power grid. Specifically, by incrementally displacing synchronous generators with PV in the EI dynamic model, how the dynamics of PV affect inter-area oscillation frequency and damping ratio will be illustrated. The following sections present the procedures and details in model development, time-domain dynamic simulation, and analytical analysis.

II. CURRENT OSCILLATION MODE ANALYSIS IN THE EI

Since the EI covers a wide area, inter-area oscillation is an important issue for system operators and planners [20, 21]. Our previous study shows that the inter-area oscillation modes are observable by FNET/GridEye, which is a wide-area measurement system deployed at the distribution level [22, 23]. Before analyzing the impact of PV on oscillations of the U.S. EI, this section analyzes the characteristics of inter-area oscillations in the EI based on FNET/GridEye wide-area measurements during 2013 to 2015 using the Matrix-Pencil method [24]. Fig. 1 shows the frequency distribution

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Gefei Kou is with Dominion Virginia Power, Richmond, VA USA 23220 (kou.utk@gmail.com).

Shutang You, Yong Liu, Xuemeng Zhang, Yi Cui, Wenxuan Yao, Micah J. Till, and Yilu Liu are with the University of Tennessee, Knoxville, TN USA 37996 ({syou3, yliu66, xzhang103, ycui17, wyao3, mtill, liu}@utk.edu). Yilu Liu is also with the Oak Ridge National Laboratory.

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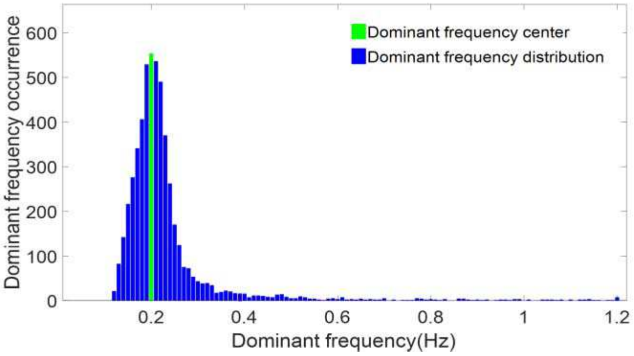

Fig. 1. Dominant frequency distribution of inter-area oscillations.

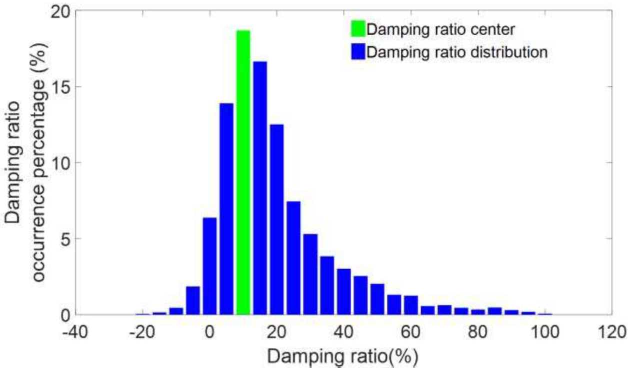

Fig. 2. Damping ratio distribution of inter-area oscillations

TABLE I
OSCILLATION FREQUENCY AND DAMPING RATIO

Year	2013	2014	2015
Dominant frequency center (Hz)	0.21	0.21	0.20
Damping ratio center of the dominant frequency (%)	10	10	10

of the dominant oscillation modes, while Fig. 2 shows the distribution of the damping ratio of the same. It can be seen that the frequency of the dominant oscillation of the EI is around 0.2 Hz and the center of the damping ratio is close to 10%. Additionally, both distributions show patterns with long tails, similar to the Beta distribution. The slight shifting of oscillation frequency and damping can be explained by seasonal and daily load variations.

Table I shows the oscillation frequency and damping ratio of different years. It can be seen that the oscillation characteristics are relatively stable in past years. The frequency center changed slightly from 2014 to 2015 (0.21 Hz to 0.20 Hz). This can be explained by the increase of renewable generation in the EI. Since 0.2 Hz is the dominant oscillation mode in the EI, this mode will be the study focus in the rest of this paper.

III. EI MODELLING APPROACH FOR HIGH PV

High PV penetration. model development, time-domain transient simulation, and oscillation analysis are conducted to investigate the change of the 0.2 Hz oscillation mode with the increase of PV. In this section, high PV penetration model development is introduced.

A. Base Model Introduction

This study is based on the detailed power flow scenario for the EI in year 2030, which was originally developed by the Eastern Interconnection Planning Collaborative (EIPC) [25]. This power flow model depicts a scenario in which wind generation provides 15% instantaneous power and some transmission network upgrades are built to facilitate wind power transfer, primarily from west to east within the EI. Earlier efforts also include the development of corresponding dynamic models, including synchronous generators, excitation systems, turbine governors, and dynamic load models. Extensive sanity checks and contingency simulations are conducted to represent the actual detailed dynamics of existing components, as well as ensuring numerical convergence and simulation accuracy. More detailed information on this dynamic modeling effort can be found in [26]. Some statistic values on this model are shown in Table II.

B. High PV Penetration Model Development

Before developing the high PV power system models, this study must define the PV penetration rates for the to-be-developed high PV simulation scenarios. Based on the results of a survey involving electric utilities, national labs and research institutes, the renewable generation mix of the to-be-developed high PV simulation scenarios are defined as 5%, 25%, 45%, and 65% PV penetration (as shown in Table III), plus 15% wind at the interconnection level [27]. The rest is conventional generation including hydro, nuclear, and thermal power plants.

The development of high PV penetration models includes two major steps: 1) Generate PV distribution. 2) Incorporate the dynamic models of PV and wind into the system model.

In the first step, the guideline for PV plant siting is to optimize the distribution of PV based on various impact factors, including existing generation and transmission infrastructure, load forecasts, solar radiation, fuel price forecasts, carbon emission, PV price forecasts, PV site land price, etc. The horizon of this PV projection features a PV growth primarily driven by a high carbon-emission price curve as predicted in [28]. A summary of the sources of input data in the PLEXOS optimization model[1] is shown in Table IV [29]. Using these parameters as inputs, a PV projection model is applied to optimize the PV distribution to minimize the total cost in the projected high PV scenarios.

The optimization problem is solved by a commercial mixed-integer programming solver (Xpress-XP). The optimized result is the projected PV capacity distribution in each region for each PV penetration level.

Fig. 4 shows the PV distributions for the four renewable penetration levels. Following the PV distribution optimization,

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[1] PLEXOS uses a bubble/pipe model representing 24 partitioned regions in the EI and the interfaces between them These regions represent utilities, regional transmission operators, coordinating authorities, independent system operators, and other natural groupings based on the structure of the EI.

TABLE II

BASIC INFORMATION OF THE EI MODEL

EI model statistics	Value
Total bus number	68309
Generator number	8337
Branch number	58784
Load	560 GW

TABLE III

PV AND WIND PENETRATION RATES FOR ALL EI SCENARIOS

Scenario	Instantaneous PV penetration level
Scenario 1	5%
Scenario 2	25%
Scenario 3	45%
Scenario 4	65%

TABLE IV

PLEXOS MODEL INPUT DATA SOURCES

PLEXOS model input	Data sources
Existing generation and transmission infrastructure Load forecast Solar radiation Fuel price forecast Carbon emission price forecast	The Eastern Interconnection Planning Collaborative (EIPC) dataset[2] [28, 30-32]
PV price forecast	North American PV Outlook [33]
PV siting land price	Land Value 2015 Summary [34]

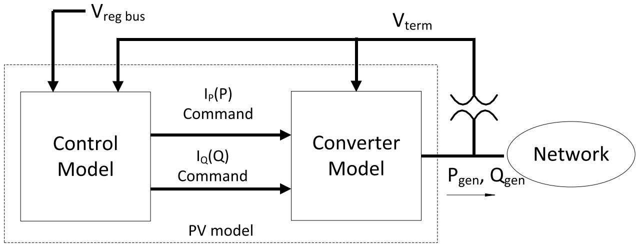
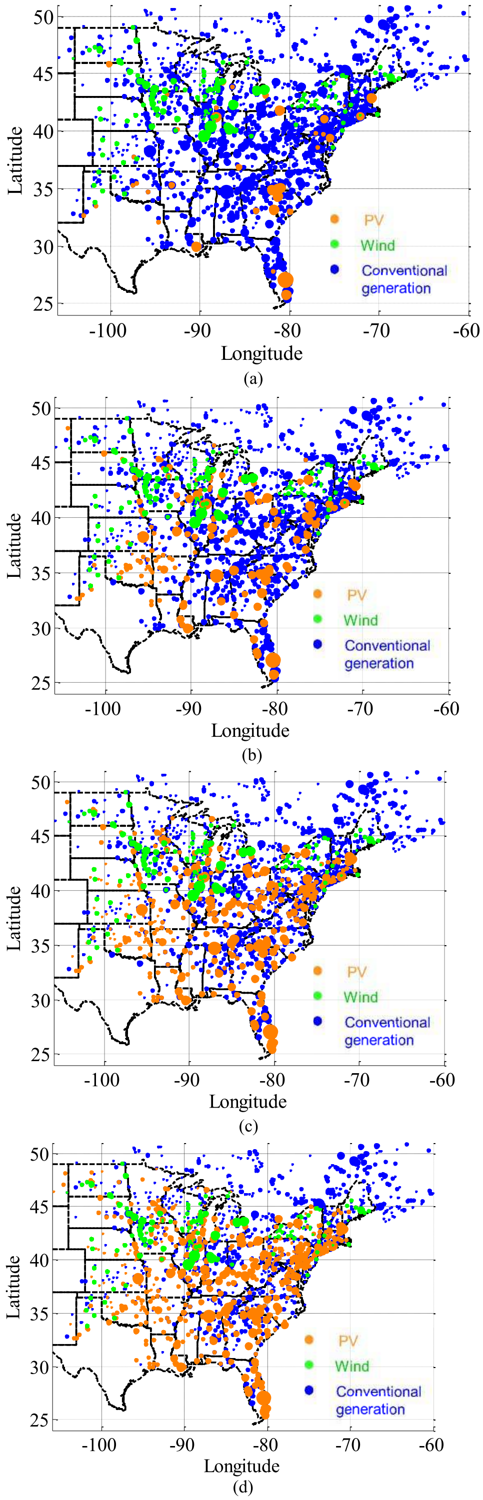


Fig. 3. PV dynamic model connectivity

the second step is to incorporate PV dynamic models into each scenario. The connectivity diagram of the PV dynamic model is shown in Fig. 3. Details about the converter and control models of a PV power plant can be found in [35]. In this step, the distribution of PV is kept consistent with the PV siting optimization result. Since these are future scenarios, generic dynamic parameters of PV power plants are adopted for the models [35]. Table V shows the two typical control strategies for PV power plants in North America [36]. As the normal configuration, the Volt/Var control with SolarControl (Strategy 1) is selected as the base strategy.

IV. IMPACT OF HIGH PV ON EI OSCILLATION MODES

The EI is a geographically dispersed power grid. To capture its inter-area oscillation modes, multiple observation locations across the EI are necessary to mitigate the impact of local



(a)

(b)

(c)

(d)

Fig. 4. PV distribution in different scenarios

oscillations and obtain more reliable results from inter-area oscillation analysis. The observation locations in this study are shown in Fig. 5. To analyze the oscillations observed at each observation point, the Matrix Pencil method is applied to the bus frequency at each location [37]. The oscillation analysis results from all observation locations are combined to form a more complete picture of oscillation trends. These

TABLE V

PV PLANTS CONTROL STRATEGIES [35]

PV control strategies	Description
Strategy 1: Volt/Var control with SolarControl[3]	Current configuration of North American PV plants
Strategy 2: Volt/Var control without SolarControl	SolarControl turned off and a slow reset of reactive power

Fig. 5. Observation locations in the U.S. EI

procedures are conducted under four scenarios, specifically 5%, 25%, 45%, and 65% PV penetration.

A. Impact on Frequency and Damping Ratios

To observe oscillations, a test disturbance is applied to the system and the frequency response is recorded at multiple locations. This disturbance is a three-phase fault on a 500 kV bus located in the central EI lasting for two cycles. Using Matrix Pencil analysis to analyze the oscillation modes at multiple locations, the frequency and damping ratios of the 0.2 Hz inter-area oscillation mode at each observation location are calculated. The change of oscillation frequency and damping ratios with PV penetration are shown in Fig. 6 and Fig. 7, respectively. It can be noted that as PV penetration increases from 5% to 65%, the oscillation frequency increases almost linearly from 0.20 Hz to 0.28 Hz, and the damping ratio decreases from around 9% to 6%. The distribution of the damping ratio

Fig. 8 and Fig. 9 shows the frequency profiles of two different locations: Connecticut (CT) and Tennessee (TN), respectively. It can be seen from Fig. 8 that the oscillation frequency increases, but the amplitude and damping decreases as PV penetration increases. In TN (IV-B), while the change of this inter-area oscillation mode is similar to that of Connecticut, there is an obvious local oscillation as well due to the proximity of the disturbance location. The frequency of this local oscillation is around 15 Hz for the 65% PV penetration scenario. It can be noted that this oscillation frequency increases with PV penetration, indicating that this oscillation mode change is related to the reduction of system inertia.

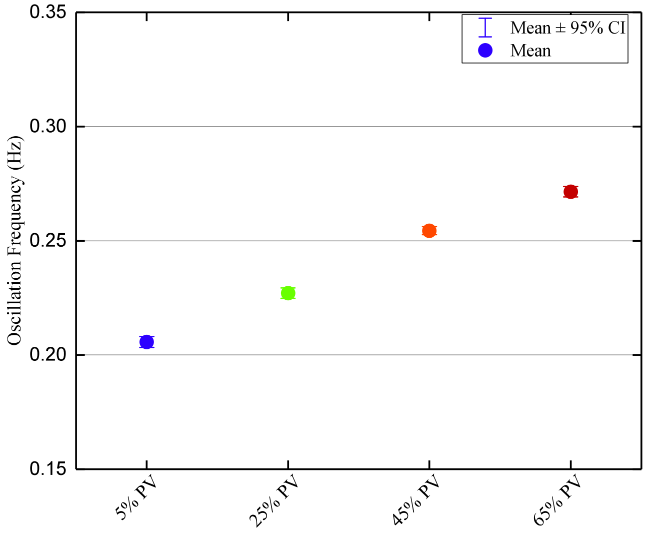


Fig. 6. Oscillation frequency change as PV penetration increases

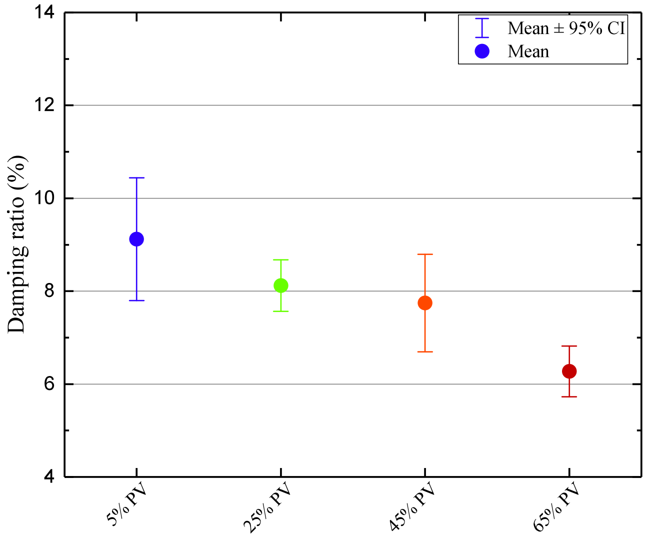


Fig. 7. Oscillation damping ratio change as PV penetration increases

B. Impact on Mode Shape

The mode shape describes the angular information of an oscillation mode and can be used to design additional damping controls. Fig. 10 shows the oscillation mode under different PV penetration levels. It can be seen that the 0.2 Hz inter-area oscillation mode has two main coherent groups: Northeastern EI (NY, PA, CT, and NJ, etc.) and Western EI (MB, MN, and KS, etc). As PV penetration increases, the angular difference between buses within each group decreases, indicating the increase of coherence between generators within each group due to the decrease of conventional generation.

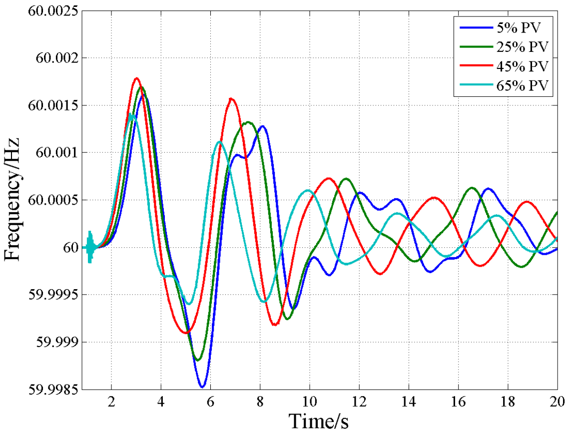


Fig. 8. Oscillation frequency change as PV penetration increases (CT)

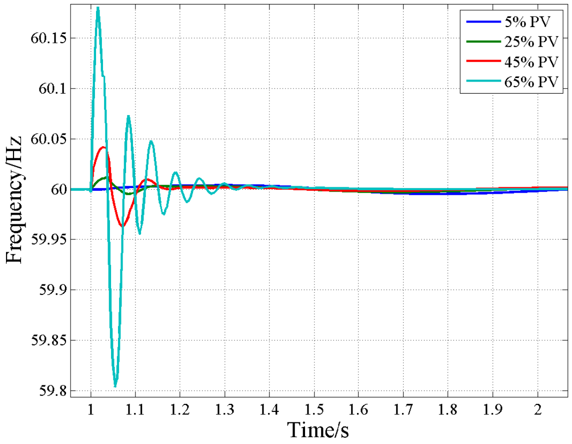
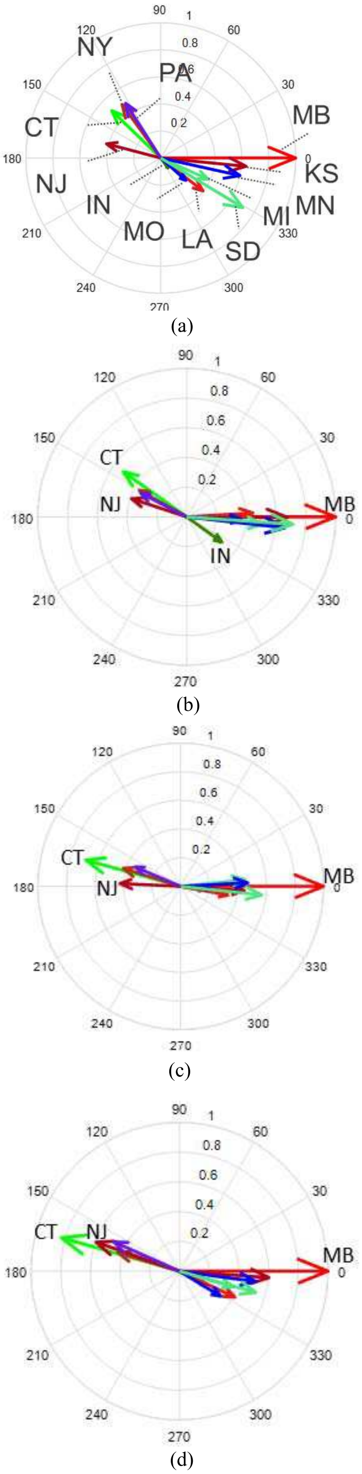


Fig. 9. Local oscillation changes as PV penetration increases (TN)

C. *Impact of PV Plant Control Strategies on Inter-area Oscillations*

The control strategies of PV power plants impact inter-area oscillation modes. For a comparison with Control Strategy 1, Control Strategy 2 (Volt/Var control without SolarControl) is applied to all PV plants. Fig. 10 contrasts the frequency profile of a bus in CT under both control strategies in the 65% penetration scenario. It can be seen that the system oscillation frequencies under the two control strategies are close, but Control Strategy 2 has a smaller oscillation amplitude and damping ratio, due to the slower reset of reactive power from PV plants after the disturbance.

Fig. 12 shows the oscillation mode shape under Control Strategy 2. It can be seen that the oscillation mode shape also includes two separate groups, similar to Control Strategy 1 (Fig. 10 (d)). but with some differences in phase angles, especially at grid edges such as New Jersey and Manitoba, Canada. This oscillation mode shape difference is due to the discrepancy in reactive power output under the two PV control strategies.



(a)

(b)

(c)

(d)

Fig. 10. Mode shape change with PV penetration

D. *Introduction of New Inter-area Oscillation Modes under Certain PV Plant Control Settings*

Certain control parameters can introduce new oscillation modes. The initial reactive power regulator gain value is increased from 0.1 to 0.5 in Control Strategy 1. Applying the same disturbance as before, the frequency profiles at a 138 kV bus in Illinois (IL) for the 65% PV scenario under the

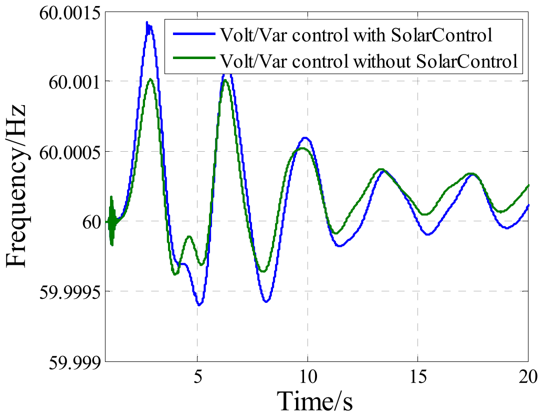


Fig. 11. Oscillation frequency in CT under different PV power plant control strategies (65% PV)

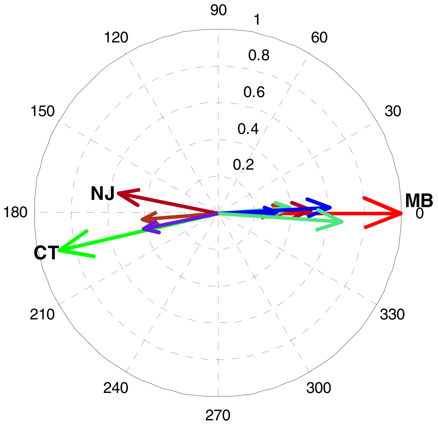


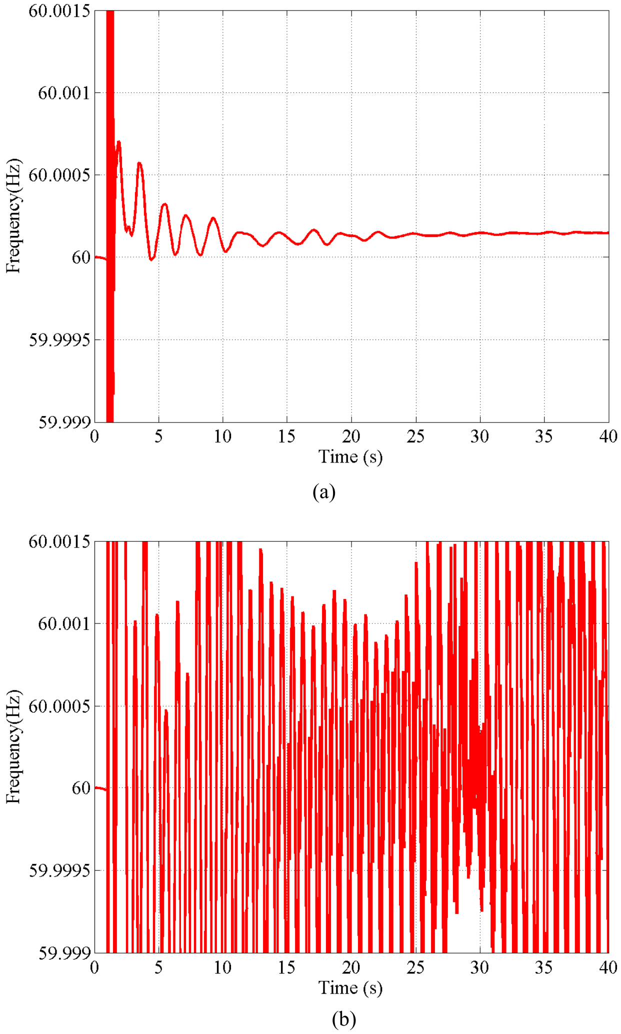
Fig. 12. Oscillation mode shape at 65% PV (Control Strategy 2)

two different settings are shown in Fig. 13. A 1.2 Hz inter-area oscillation mode can be easily seen after the disturbance for the case with a higher reactive power gain. Fig. 14 shows the mode shape of the 1.2 Hz oscillation mode. It can be noted that large oscillation locations include MI, IL, and VA.

Fig. 15 and Fig. 16 show the changes in frequency and damping ratios of this new oscillation mode for multiple PV penetration levels. Unlike the 0.2 Hz mode, the frequency and damping ratios of the 1.2 Hz mode barely change with PV penetration. This insensitivity is seen because the PV controllers, which are not influenced by time constants related to system inertia, cause this oscillation mode.

V. CONCLUSIONS

Based on detailed dynamic system models, this paper studied the impact of high PV penetration on the inter-area oscillation modes of the U.S. EI. The analytical procedures include dynamic model development, PV plant siting, time-domain transient simulation, and Matrix Pencil analysis. Changes in oscillation frequencies, damping, and mode shapes, as well as the introduction of new oscillation modes, are studied by varying PV penetration levels, control strategies and parameters. It is found that oscillation damping decreases as PV penetration increases in the system, indicating that additional operation and planning consideration may be required to increase oscillation damping as PV penetration increases in the future. Variations in PV control strategies and parameters are found to impact mode shape and can create new oscillation modes. These results can help system operators and planners



(a)

(b)

Fig. 13. Frequency profile at IL under different PV control paramter settings (65% PV)

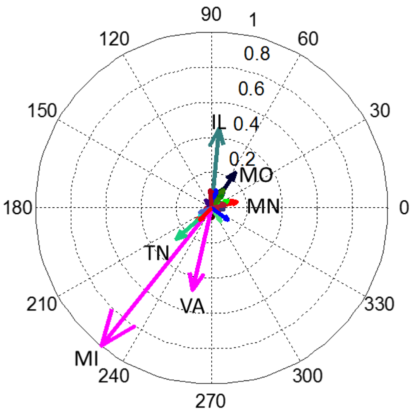


Fig. 14. Mode shape of the 1.2 Hz Inter-area mode (65% PV)

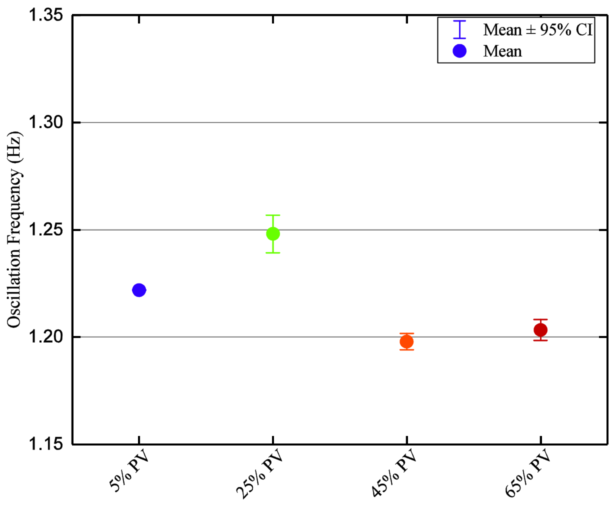


Fig. 15. Oscillation frequency change with PV penetration (1.2 Hz mode)

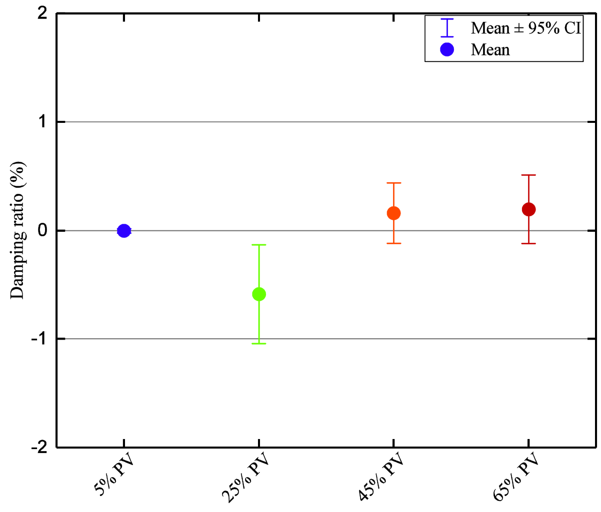


Fig. 16. Damping ratio change with PV penetration (1.2 Hz mode)

understand system oscillation behaviors and design mitigation methods for future high PV generation portfolios. The basic analysis procedures are generic and can be applied to other large-scale power systems.

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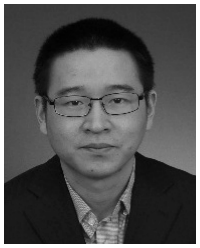


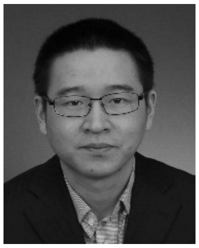
Shutang You (S'13) is a Ph.D. candidate in the Power IT Lab at the University of Tennessee, Knoxville. He received the B.S. and M.S. degree in 2011 and 2014 in Power Engineering at Xi'an Jiaotong University, China. His research interests include power grid dynamics and sychronous measurement.

Gefei Kou (S'14-M'17) is a senior system protection engineer with Dominion Virginia Power. He received his Ph.D and M.S. in Electrical Engineering from the University of Tennessee, Knoxville, in 2016 and 2014, and the B.S. degree from Tianjin University in 2011. His research interests include power system dynamics and synchrophasors.

Yong Liu (S'10-M'15) is currently a research assistant professor at the Department of Electrical Engineering and Computer Science at the University of Tennessee, Knoxville. He is also a member of the DOE/NSF-cofunded engineering research center CURENT. He received his B.S. and M.S. degree of Electrical Engineering from Shandong University in 2007 and 2010 respectively and obtained his Ph.D. degree from University of Tennessee, Knoxville, in 2013. His research interests include power system wide-area measurement, renewable energy integration, and power system dynamic modeling and analysis.

Xuemeng Zhang (S'16) received the B.S. degree from Zhejiang University in 2015. She is currently working towards her Ph.D. degree in electrical engineering at the University of Tennessee, Knoxville. Her research interests include the impact of renewable energy generation such as wind and PV on bulk power grid frequency response, the advanced renewable generation active power control for frequency response improvement, and measurement-based power system model reduction techniques.

Yi Cui (S'12-M'16) is currently a research associate at Power IT Lab at the University of Tennessee, Knoxville. He received the B.Sc.(Engg.) and M.Sc.(Engg.) degrees in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 2009 and 2012, respectively, and the Ph.D. degree in the School of Information Technology and Electrical Engineering, from the University of Queensland, Brisbane, Australia in 2016. His research interests include power system oscilation, power transformers condition assessment and fault diagnosis.



Wenxuan Yao (S'14) received his B.S degreee in electrical engineering from Hunan University, Changsha, China, in 2011, where he is working toward the Ph. D. degree. He is also pursuing the Ph.D. degree in the Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville. His research interests are wide-area power system measurement and digital signal process.

Micah J. Till (S'13) received his B.S.E.E. degree from Tennessee Technological University, Cookeville, in 2011. He is currently working toward his Ph.D. in the Department of Electrical Engineering and Computer Science at the University of Tennessee, Knoxville.

Yilu Liu (S'88-M'89-SM'99-F'04) is currently the Governor's Chair at the University of Tennessee, Knoxville and Oak Ridge National Laboratory. Prior to joining UTK/ORNL, she was a Professor at Virginia Tech. She received her M.S. and Ph.D. degrees from the Ohio State University, Columbus, in 1986 and 1989. She led the effort to create the North American power grid Frequency Monitoring Network (FNET) at Virginia Tech, which is now operated at UTK and ORNL as GridEye. Her current research interests include power system wide-area monitoring and control, large interconnection-level dynamic simulations, electromagnetic transient analysis, and power transformer modeling and diagnosis. She is a member of the U.S. National Academy of Engineering.