

Impact of High PV Penetration on Out-of-step Instability and Regional Electromechanical Wave Propagation

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Abstract— The increase of renewable generation is a key feature of current power grids in worldwide. Due to different generator dynamics between synchronous generators and inverter-interfaced generation, the high PV penetration will influence the system out-of-step instability and regional electromechanical wave propagation. To better understand the high-PV impacts on these two issues and improve system reliability under high PV penetration, this paper uses the high PV grid dynamics model developed based on the actual U.S. Eastern Interconnection system to perform a simulation study. The study results found that high PV penetration reduces the stability margin for the FRCC-EI and increases the vulnerability of out-of-step instability. In addition, it is found that the wave propagation speed increases nonlinearly with the decrease of inertia: increasing faster for the same amount of inertia reduction when the system inertia is lower.

Index Terms— Solar PV, power grid, stability, electromechanical wave propagation, inertia.

I. INTRODUCTION

Power grid is the backbone of the modern society and its reliability is critically important [1-9]. The increasing penetration of renewable generation is changing the traditional paradigms of power grid operation. [3, 10-15]. The involving characteristics of power grids due to the increasing renewables and distributed energy resources have also been observed by the high-resolution wide-area power grid monitoring system deployed in the many power grids [16-37]. Some existing efforts have focused on quantifying these changes and developed some strategies to mitigate their impacts on grid reliability [38-52]. These studies have explored different aspects of power grid reliability, including voltage stability, oscillation, frequency stability, and transient stability, etc. However, there is little literature on how the increasing inverter-interfaced renewable generation will influence the system out-of-step instability and regional electromechanical wave propagation. These two issues can influence the grid stability and should be considered in relay set up as the penetration of renewable energy increase.

In this paper, the impact of high PV penetration on the system out-of-step instability and regional electromechanical wave propagation is studied. The out-of-step instability study is based on an actual scenario that exists in the Florida Reliability

Coordinating Council (FRCC) power grids and the rest of the U.S. Eastern Interconnection (EI) grid. The regional electromechanical wave propagation study will be studied based on the PJM regional power grid.

II. : IMPACT OF HIGH PV PENETRATION ON FRCC OUT-OF-STEP STABILITY

As a part of the EI system, FRCC may be separated from the rest of the EI after a large generation loss in Florida if the two 500kV tie-lines connecting FRCC and main EI are already heavily-loaded before the generation loss, causing an out-of-step (OOS) instability issue. The two 500 kV tie-lines (Duval-Hatch and Duval-Thalmann) are shown in Figure 1. This OOS issue occurs because much more power will flow from EI to FRCC after a Florida generation loss and these two lines will likely be overloaded and tripped by line protections. Since this OOS issue will make FRCC lose synchronization and support from EI, TRC suggested to examine the impact of high PV penetration on this issue.

The study model was built based on our previous effort [40]. To replicate the heavily-loaded tie-lines, the original tie-line power flows were increased according to the TRC's suggestions, as shown in Table 1. Then contingencies with different generation loss amounts in FRCC were simulated to examine the OOS issue.

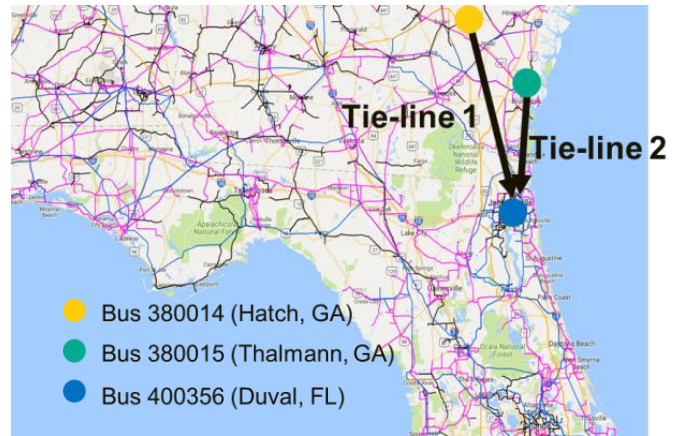


Figure 1. Two 500kV tie lines between FRCC and main EI

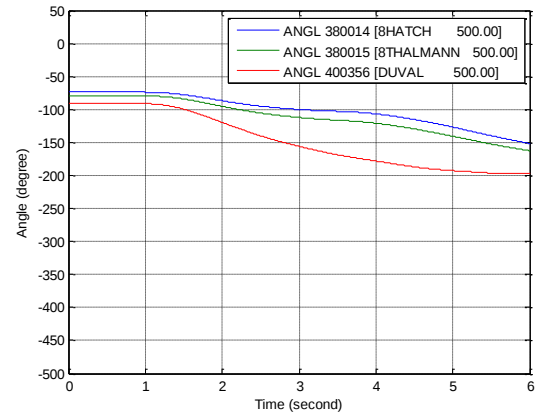
This work was also supported by U.S. Department of Energy Solar Energy Technologies Office under award number 30844. This work made use of Engineering Research Center shared facilities supported by the Engineering

Research Center Program of the National Science Foundation and the Department of Energy under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

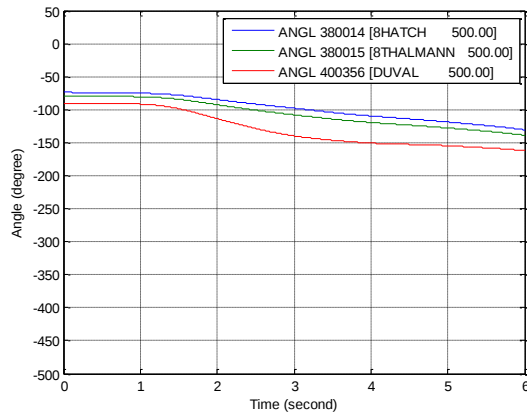
Table 1. Increased tie-line flows

Tie line	Tie-line Flow when heavily-loaded
Line 1 (Duval-Hatch 500kV)	1,150MW
Line 2 (Duval-Thalmann 500 kV)	1,250MW

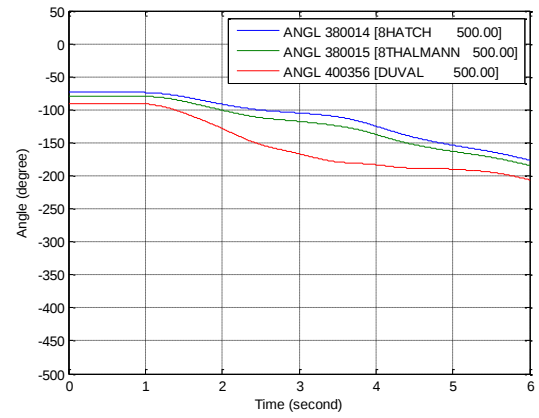
Figure 2 (a) through (e) show the voltage phase angles of Hatch, Thalmann, and Duval buses after a 2.0 GW generation loss event in FRCC. It can be seen that for this event, FRCC keeps synchronism with the rest of EI when the PV penetration is no more than 45%. When the PV penetration increases to 65%, FRCC (including Duval) will lose synchronism with the rest of the EI (including Hatch and Thalmann) after a 2.0 GW generation loss.



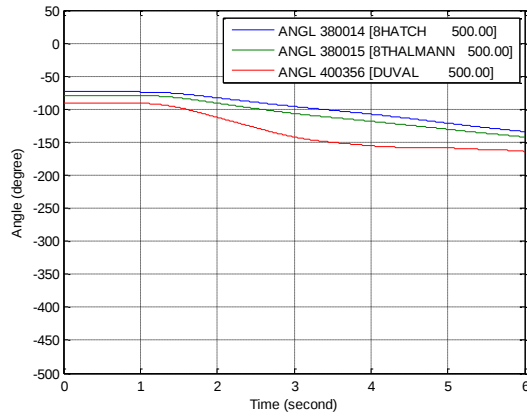
(c) 25%PV +15%WT



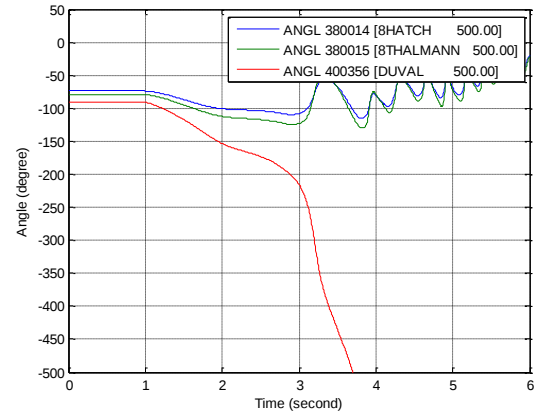
(a) Base Case



(d) 45%PV +15%WT



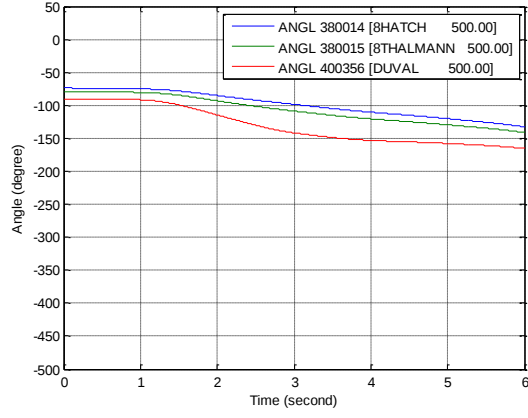
(b) 5%PV +15%WT



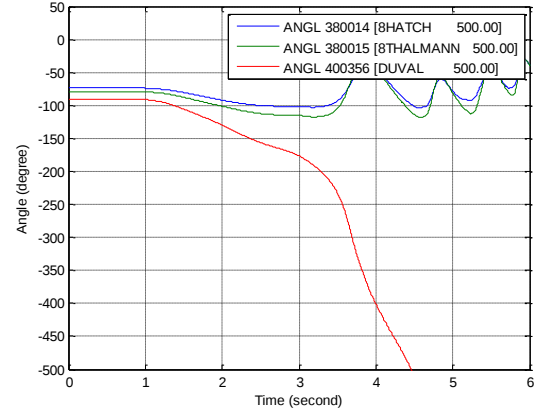
(e) 65%PV +15%WT

Figure 2. The voltage phase angles of Hatch, Thalmann, and Duval buses after a 2.0 GW Gen Loss in FRCC

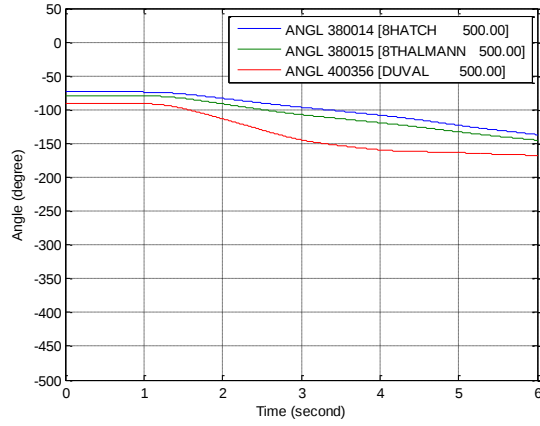
Figure 3 (a) through (e) show the voltage phase angles of Hatch, Thalmann, and Duval buses after a 2.1 GW generation loss in FRCC. It can be seen that the FRCC power grid can not keep synchronization when the PV penetration increases to 25%. This indicates that the increase of PV penetration in FRCC reduces the transient stability limit in this study case.



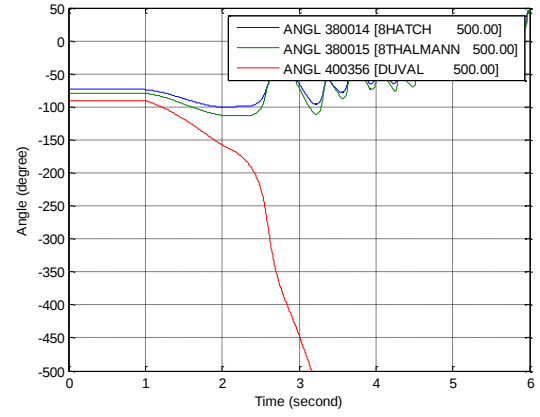
(a) Base Case



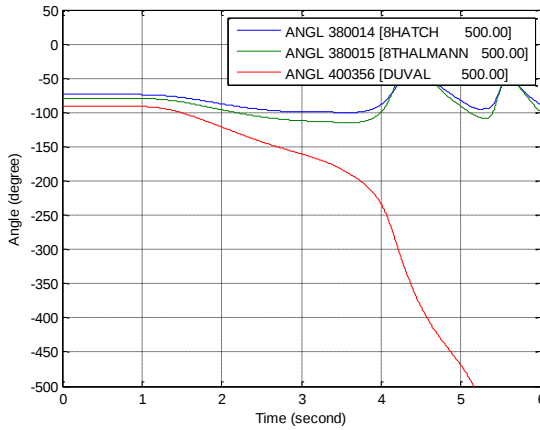
(d) 45%PV +15%WT



(b) 5%PV +15%WT



(e) 65%PV +15%WT



(c) 25%PV +15%WT

Figure 3. The voltage phase angles of Hatch, Thalmann, and Duval buses after a 2.1 GW Gen Loss in FRCC

Table 2 summarizes the OOS results at different MW loss in FRCC and different PV penetration scenarios. As shown in Table 2, for the base case, the system can withstand 2.5 GW generation loss in FRCC. When the PV penetration increases to 40% to 60%, this limit decreases to around 2.1 GW. As the PV penetration increases further to 80%, this limit reduces to 2.0 GW. These results indicate that, with the increasing PV penetration level, FRCC becomes more vulnerable to the OOS instability issue. This can be explained by that FRCC will gradually lose its own frequency regulation capability due to the reduction of synchronous units and rely more on the power imports from the two tie-lines. Countermeasures to mitigate this OOS issue may include engaging PV plants in FRCC frequency control and strengthening the tie-lines between FRCC and main EI.

Table 2. FRCC OOS test results with increased tie-line flows

Contingency Magnitude	Base Case	20% Renewable (8.4% PV within FRCC)	40% Renewable (29.4% PV within FRCC)	60% Renewable (52.4% PV within FRCC)	80% Renewable (69.7% PV within FRCC)
3.5 GW	OOS	OOS	OOS	OOS	OOS
2.5 GW	OOS	OOS	OOS	OOS	OOS
2.1 GW	No OOS	No OOS	OOS	OOS	OOS

2.0 GW	No OOS	No OOS	No OOS	No OOS	OOS
1.8 GW	No OOS	No OOS	No OOS	No OOS	No OOS

III. IMPACT OF HIGH PV PENETRATION ($\geq 100\%$ PEAK LOAD) ON REGIONAL ELECTROMECHANICAL WAVE PROPAGATION

It has been noticed that high PV penetration will increase the average propagation speed of electromechanical waves of an interconnection grid. How the high PV penetration will influence the wave propagation speed at the regional level is unknown. This section investigates the relation between the regional electromechanical wave propagation speed and local high PV penetration.

As the future renewable penetration in PJM_ROM may increase to 100% based on our previous projection study [40], PJM_ROM is used for the regional wave propagation study. Renewable distribution outside the PJM_ROM region is kept the same as the 80% interconnection-level penetration scenario, while the renewable penetration in PJM_ROM was intentionally varied from 0% to 100%. The electromechanical wave arrival time of two monitoring buses were recorded to calculate the propagation speed in the PJM_ROM region. Locations of the two monitoring buses are shown in Figure 4.

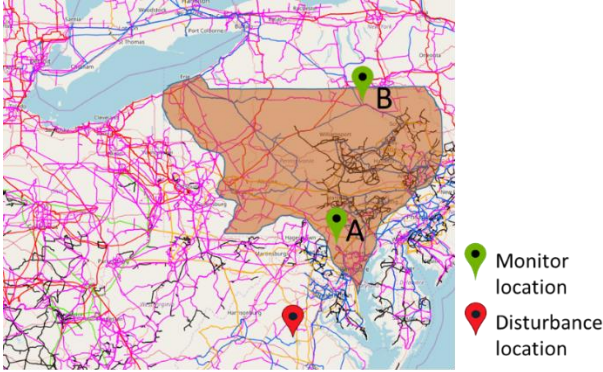


Figure 4. Locations of disturbance and monitoring buses

To excite an electromechanical wave, a generation trip event was simulated outside PJM_ROM (shown by the red pin in Figure 4). The time delays of arrival (TDOAs) at the two monitoring buses are shown in Table 3. Then the wave propagation speed in the PJM_ROM area can be calculated based on the TDOAs and the distance between the two monitoring buses. The average electromechanical wave propagation speed in PJM_ROM for each renewable penetration scenario is shown in Figure 5. The average propagation speed increases from 464 mile/s in the base case to 3,750 mile/s for the 100% renewable penetration in PJM_ROM. It is also noticeable that the average wave propagation speed in PJM_ROM is higher than the interconnection-average speed for 60% and 80% renewable penetrations. This discrepancy is due to the differences in network topologies, line impedances, and generation distributions etc.

Table 3. TDOA at different locations

	Renewable penetration rate					
	0%	20%	40%	60%	80%	100%
TDOA at Bus A T_a (s)	0.036	0.032	0.032	0.032	0.028	0.028
TDOAs at Bus B T_b (s)	0.424	0.368	0.244	0.160	0.108	0.076
ΔT (s)	0.388	0.336	0.212	0.128	0.080	0.048

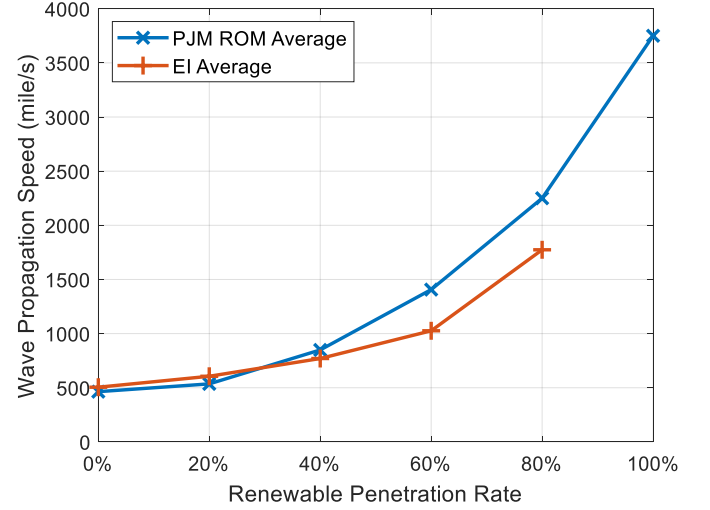


Figure 5. Change of electromagnetic wave propagation speed in PJM-ROM and the EI

IV. CONCLUSIONS

This paper studied the impact of high PV penetration on the system out-of-step instability and the regional electromechanical wave propagation. This study is based on a high renewable case model developed from based on the actual U.S. EI system. The study result shows that high PV penetration will reduce the stability margin and make the system more vulnerable to out-of-step instability in the FRCC-EI separation case. In addition, the regional electromechanical wave propagation speed is directly influenced by the high PV penetration in a nonlinear relation. These results indicate that the system remedial action schemes and relay settings may need to be adjusted to accommodate the increasing renewable generation and ensure system reliability.

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