Dealing with System Oscillation – IBR Interconnection and Operation

Yunzhi Cheng
Manager of Operations Stability Analysis, ERCOT
Co-Chair of IEEE IBR SSO Taskforce

ESIG/G-PST SSO Workshop

March 28, 2024

IEEE IBR SSO Taskforce

Real-World Subsynchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources

Yunzhi Cheng, *Senior Member, IEEE*, Lingling Fan, *Fellow, IEEE*, Jonathan Rose, Shun-Hsien Huang, John Schmall, Xiaoyu Wang, *Senior Member, IEEE*, Xiaorong Xie, *Senior Member, IEEE*, Jan Shair, Jayanth R. Ramamurthy, *Senior Member, IEEE*, Nilesh Modi, Chun Li, *Senior Member, IEEE*, Chen Wang, Shahil Shah, *Senior Member, IEEE*, Bikash Pal, *Fellow, IEEE*, Zhixin Miao, *Senior Member, IEEE*, Andrew Isaacs, Jean Mahseredjian, *Fellow, IEEE*, and Jenny Zhou, *Senior Member, IEEE*

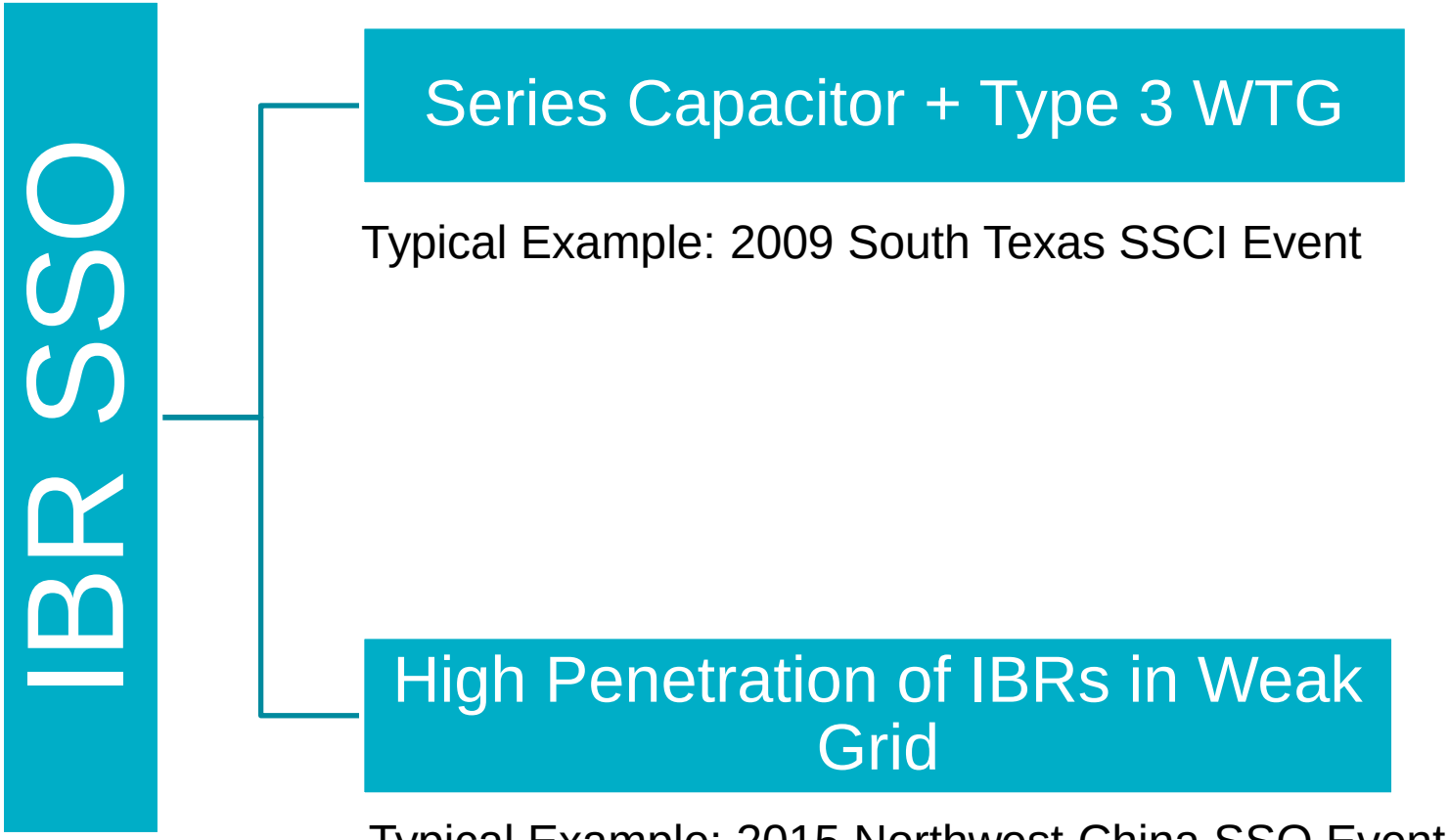
***Abstract*—This paper presents a survey of real-world subsynchronous oscillation events associated with inverter-based resources (IBR) over the past decade. The focus is on those oscillations in the subsynchronous frequency range known to be influenced by power grid characteristics, e.g., series compensation or low system strength. A brief overview of the historical events is presented followed by detailed descriptions of a series of events. This paper also examines causation mechanisms and proposes future research directions to meet grid needs worldwide.**

***Index Terms*—Inverter-based resources, oscillations, stability.**

I. Introduction

PENETRATIONS of inverter-based resources (IBRs) are increasing worldwide. The maximum instantaneous penetration levels of IBRs in South Australia, Texas, Ireland, and Tasmania have reached 150%, 66%, 92%, and 95%, respectively [1]. The operation with such high levels of IBRs has introduced undesirable dynamics, including subcycle overvoltage [2], ac overcurrents [3] and subsynchronous oscillations (SSOs) [4], [5]. Stability issues related to IBRs have caught attention by

IBR SSO



Y. Cheng *et al*., "Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources," in *IEEE Transactions on Power Systems*, 2023

Some Reported IBR SSO Events

Year	Location	Frequency (Hz)	Mechanism
2021	Scotland	8	Offshore WTG + Weak grid (?)
2020 – 2021	West Murray, Australia	15 – 20	IBR + Weak grid (?)
2019	Great Britain	9	Offshore WTG + Weak Grid
2015 – 2019	West Murray, Australia	7	IBR + Weak Grid
2017	First Solar, USA	7	Solar PV + Weak Grid
2015	Northwest China	27 – 34	Type 4 WTG + Weak Grid
2015	Hydro One, Canada	20	Solar PV + Weak Grid
2011	Texas, USA	4	Type 4 WTG + Weak Grid
2023	South Texas, USA	20 – 30	Type 3 WTG + Series Cap.
2017	South Texas, USA	20 – 30	Type 3 WTG + Series Cap.
2012 – 2016	North China	3 – 12	Type 3 WTG + Series Cap.
2009	South Texas, USA	20 – 30	Type 3 WTG + Series Cap.

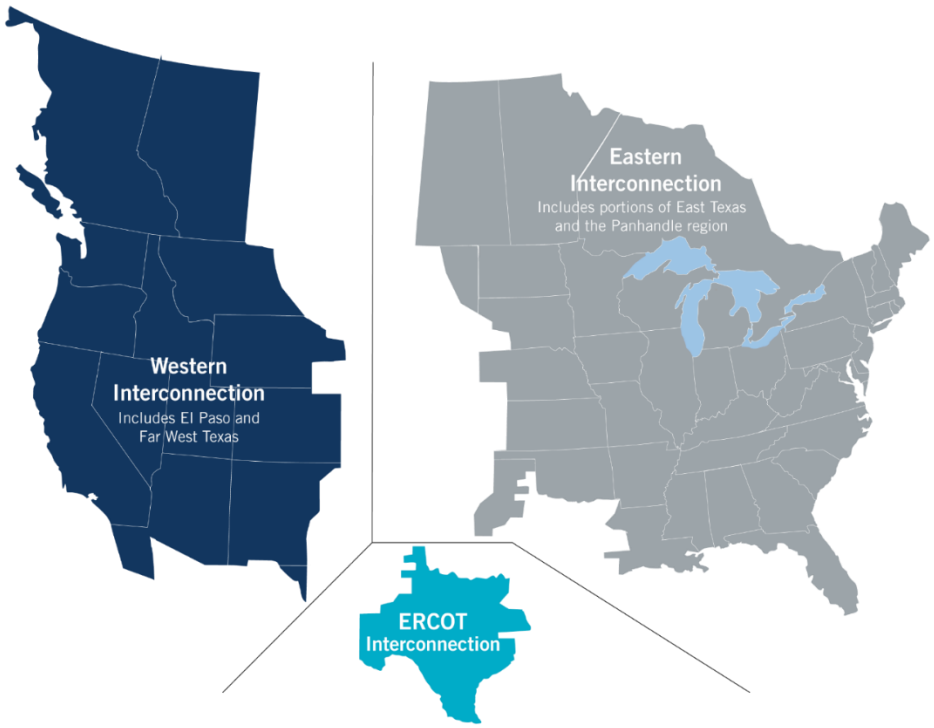
Y. Cheng *et al*., "Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources," in *IEEE Transactions on Power Systems*, 2023

The ERCOT Region

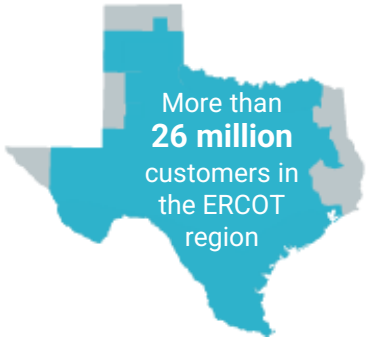
The interconnected electrical system serving most of Texas, with limited external connections

- 90% of Texas electric load; 75% of Texas land
- 85,508 MW peak, August 10, 2023
- More than 54,100 miles of transmission lines
- 1250+ generation units (including PUNs)

ERCOT connections to other grids are limited to ~1,220 MW of direct current (DC) tie capacity



ERCOT Quick Facts



90% of Texas Load

75% of load is competitive choice customers

1 MW of electricity can power about 200 Texas homes during periods of peak demand

1,250+
generating units, including PUNs

54,100+
miles of high-voltage transmission

98,000+ MW
of expected capacity for summer 2023 peak demand

$3,3 billion
transmission projects endorsed in 2022

1,873+
active market participants that generate, move, buy, sell or use wholesale electricity

85,508 MW
Record peak demand
(August 10, 2023)

38,694 MW
of installed wind capacity
(as Dec. 31, 2023)

27,548 MW
Wind generation record
(Jan. 7, 2023)

69.15%
Wind penetration record
(April 10, 2022)

85,116 MW
Weekend peak demand record
(August 20, 2023)

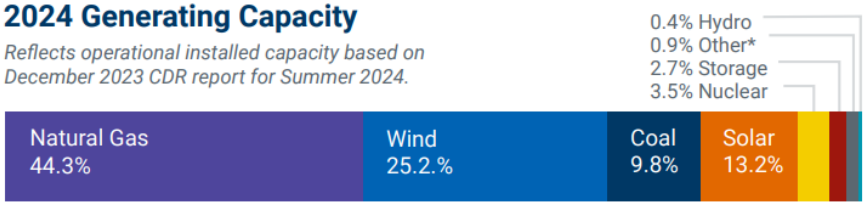
22,258 MW
of installed solar capacity
(as Dec. 31, 2023)

17,201 MW
Solar generation record
(Feb. 19, 2024)

39.94%
Solar penetration record
(Feb. 18, 2024)

2024 Generating Capacity

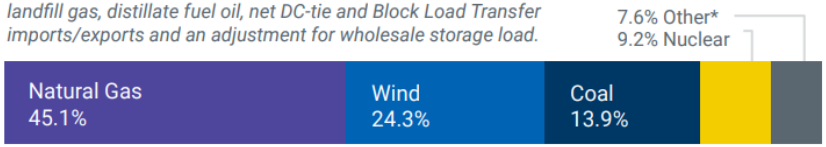
Reflects operational installed capacity based on December 2023 CDR report for Summer 2024.



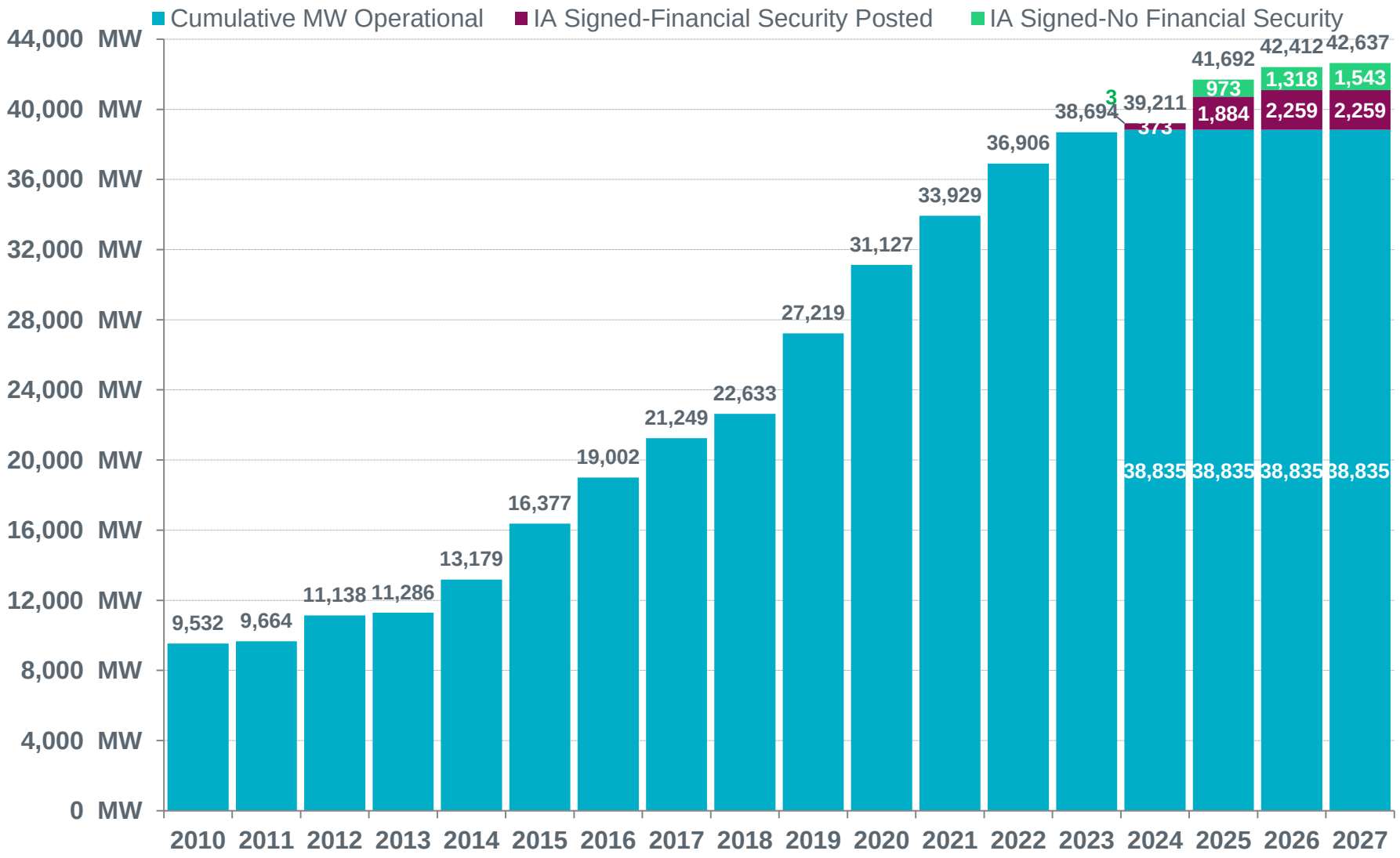
The sum of the percentages may not equal 100% due to rounding.
**Other includes biomass and DC Tie capacity.*

2023 Energy Use

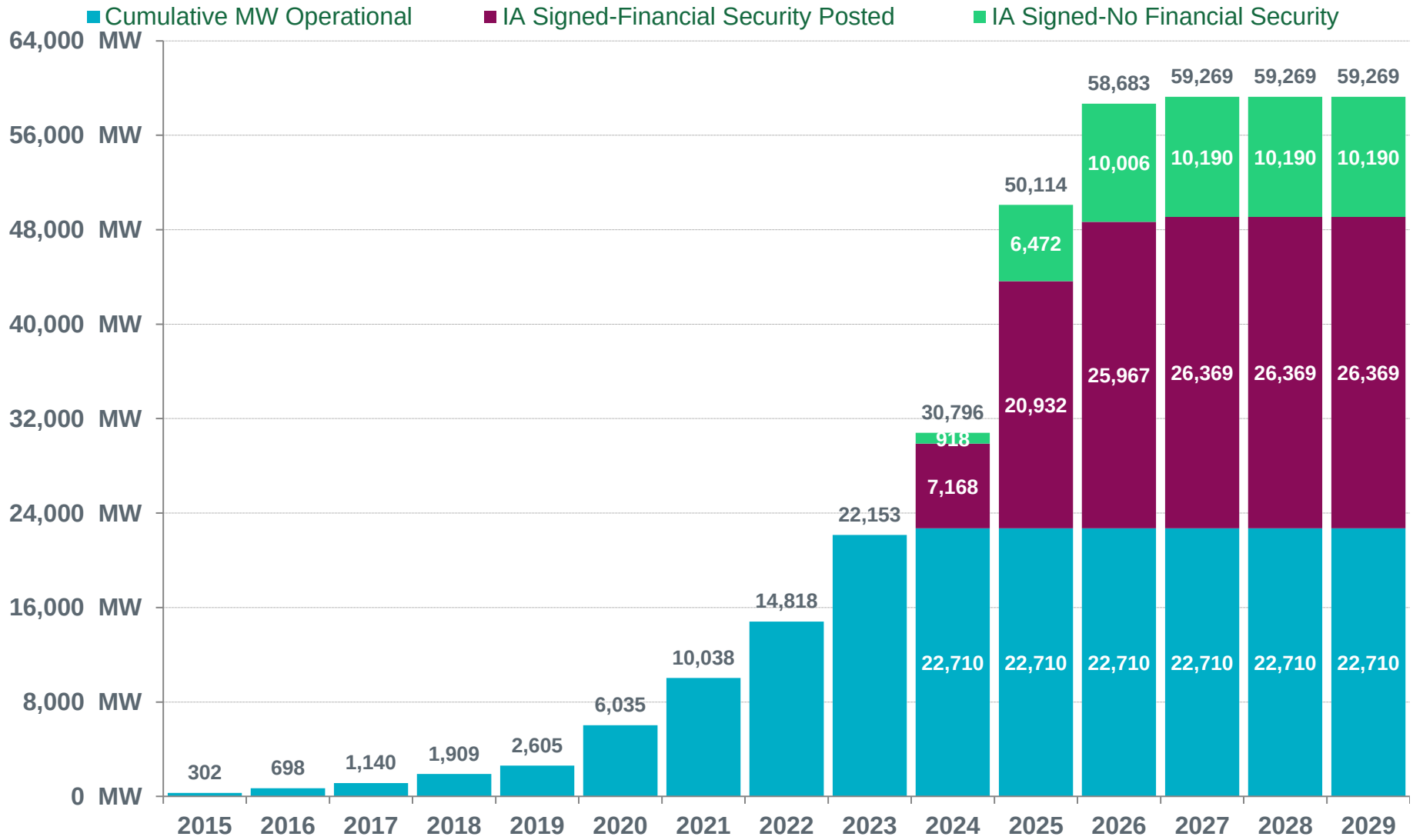
**Other includes solar, hydro, petroleum coke (pet coke), biomass, landfill gas, distillate fuel oil, net DC-tie and Block Load Transfer imports/exports and an adjustment for wholesale storage load.*



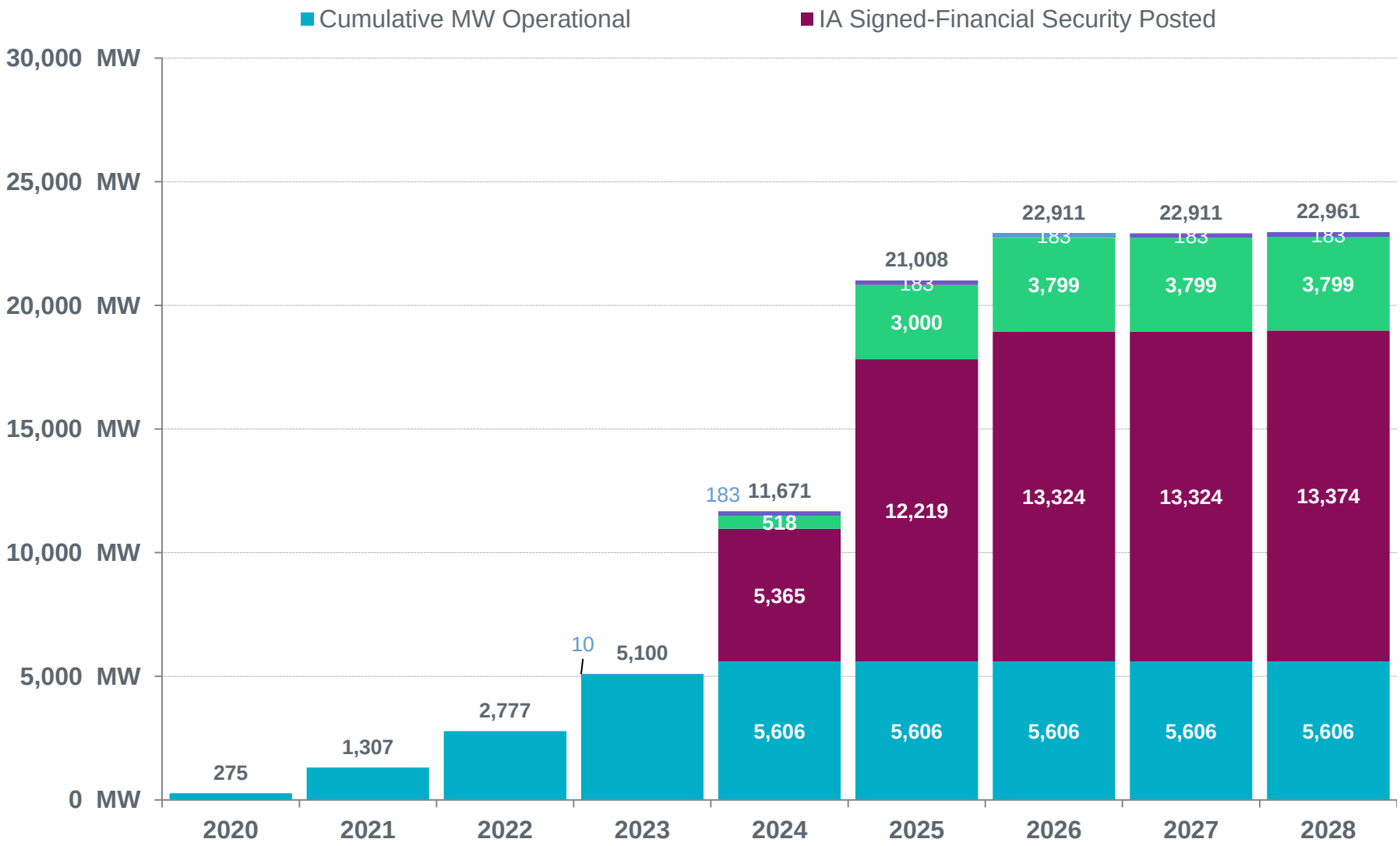
ERCOT Wind Additions by Year (as of Feb. 29, 2024)



ERCOT Solar Additions by Year (as of Feb. 29, 2024)

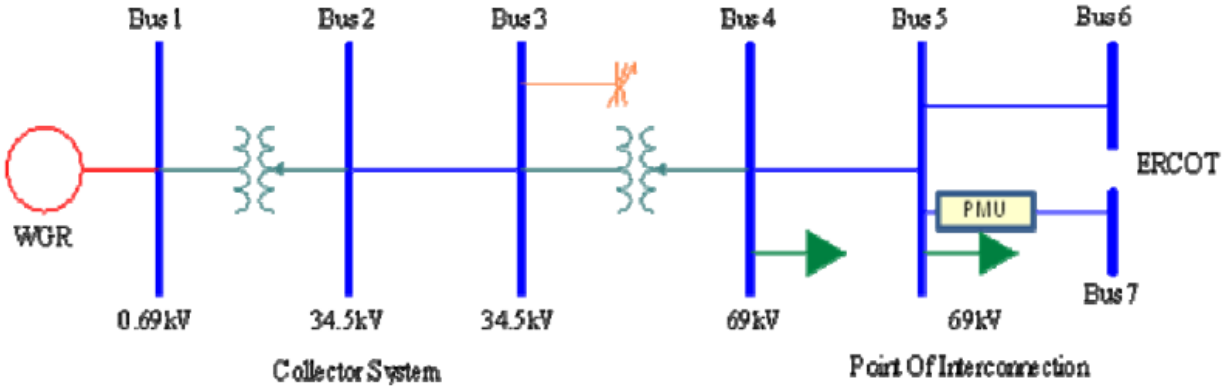


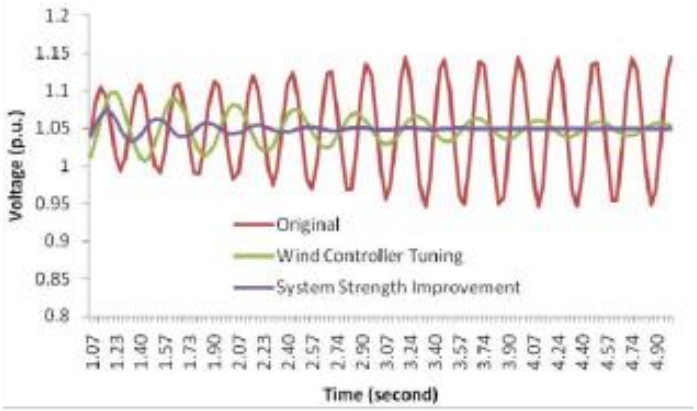
ERCOT Battery Additions by Year (as of Feb. 29, 2024)



Weak Grid related SSO Event in ERCOT

- Local SSO event in 2011
- Undamped oscillation (~4 Hz) was observed at high wind speed with the line of Bus 5 – 6 in outage (SCR dropped to 2)





Reference: Shun-Hsien (Fred) Huang, etc., "Voltage Control Challenges on Weak Grids with High Penetration of Wind Generation: ERCOT Experience", 2012 IEEE PES GM

System Strength (Weak Grid)

- System strength identified in the simulation of Panhandle area
  - Far away from load centers
  - No synchronous generators
  - No Load
  - All the resources are IBRs (~5GW)

- Two synchronous condensers (175MVA each) were added to Panhandle
- ERCOT proposed the concept of WSCR (Weighted Short Circuit Ratio) to measure the Panhandle system strength based on actual output of the Panhandle IBRs

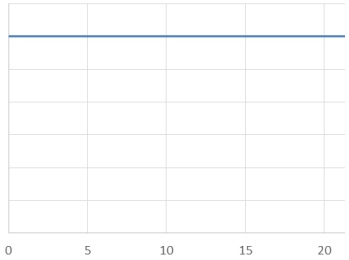
$$WSCR = \frac{\sum_i^N S_{SCMVAi} * P_i}{\left(\sum_i^N P_i\right)^2}$$

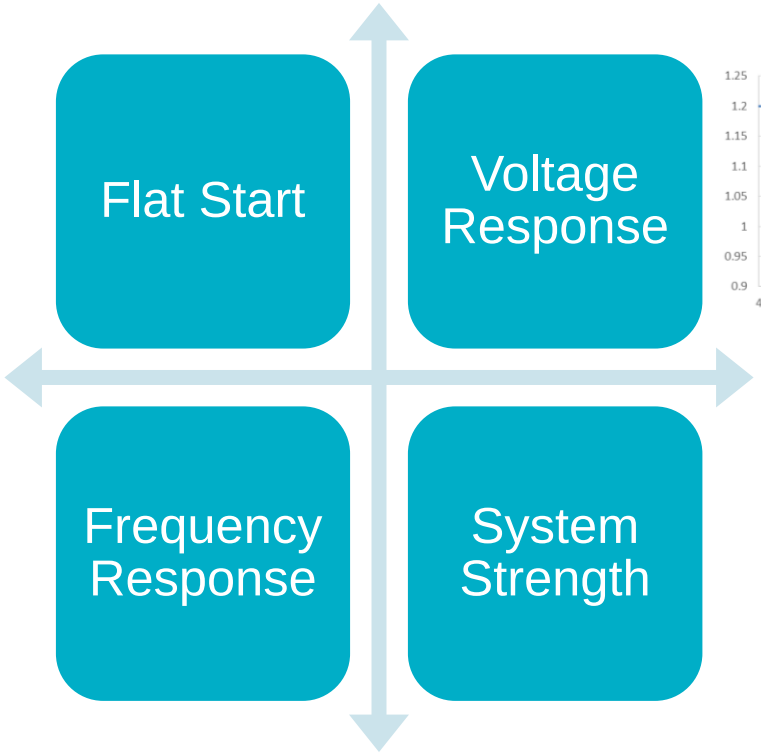
- WSCR=1.5 was proposed as the minimum pre-contingency system strength and implemented in real time operations to limit the Panhandle IBRs output based on the system strength
- WSCR index was retried in 2021 with transmission system upgrade in Panhandle

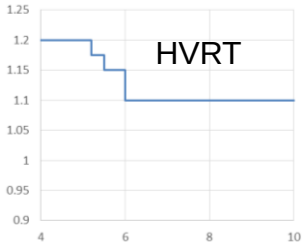
Y. Zhang, etc., "*Evaluating System Strength for Large-Scale Wind Plant Integration*," in Power and Energy Society General Meeting, 2014 IEEE

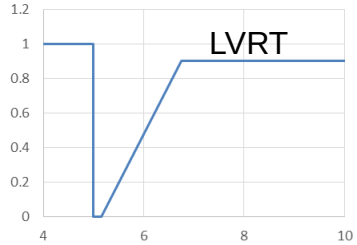
Weak Grid related SSO Analysis in ERCOT

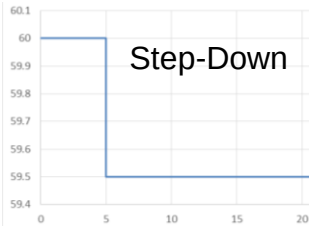
- Model Quality Test (MQT)
  - System Strength (SCR) Test with minimum requirement of SCR = 1.5
  - DMView tool available at https://sites.google.com/view/dmview/home
  - PMView tool available at https://sites.google.com/view/pmview/home

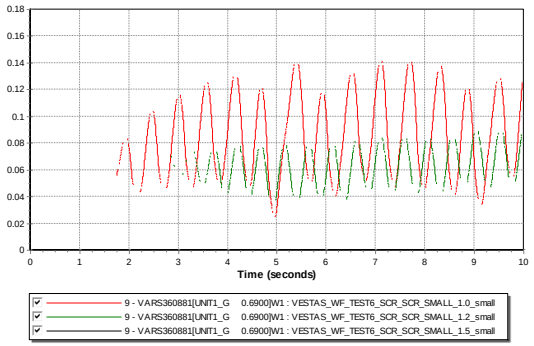






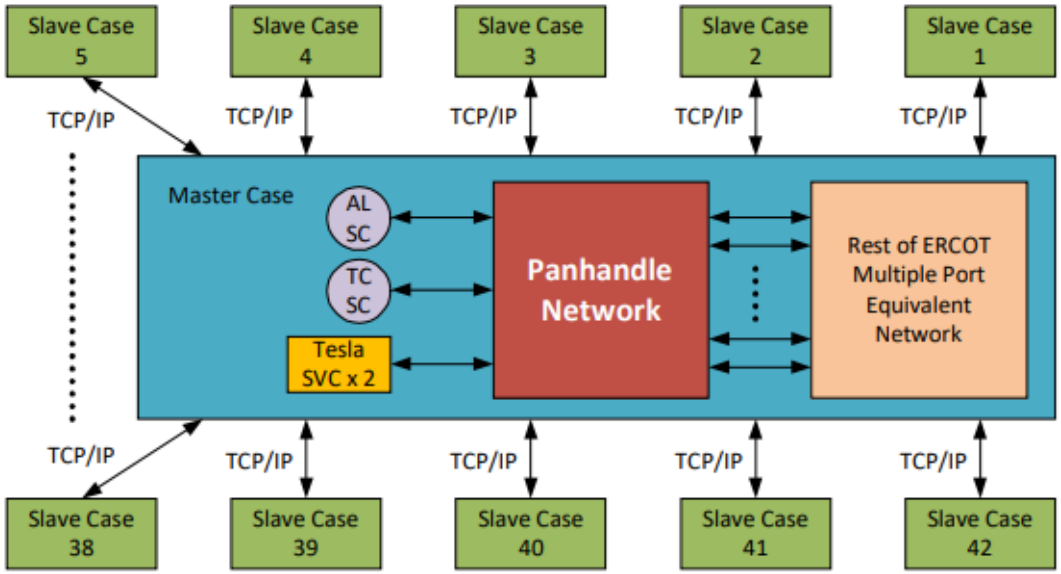






Large Scale PSCAD Simulation

- 2020 Panhandle Study (PSS/e & PSCAD)
  - 46 IBR projects (>10GW)
  - 43 PSCAD cases created for parallel simulation
  - ETRAN Plus tool is used for PSCAD parallel simulation

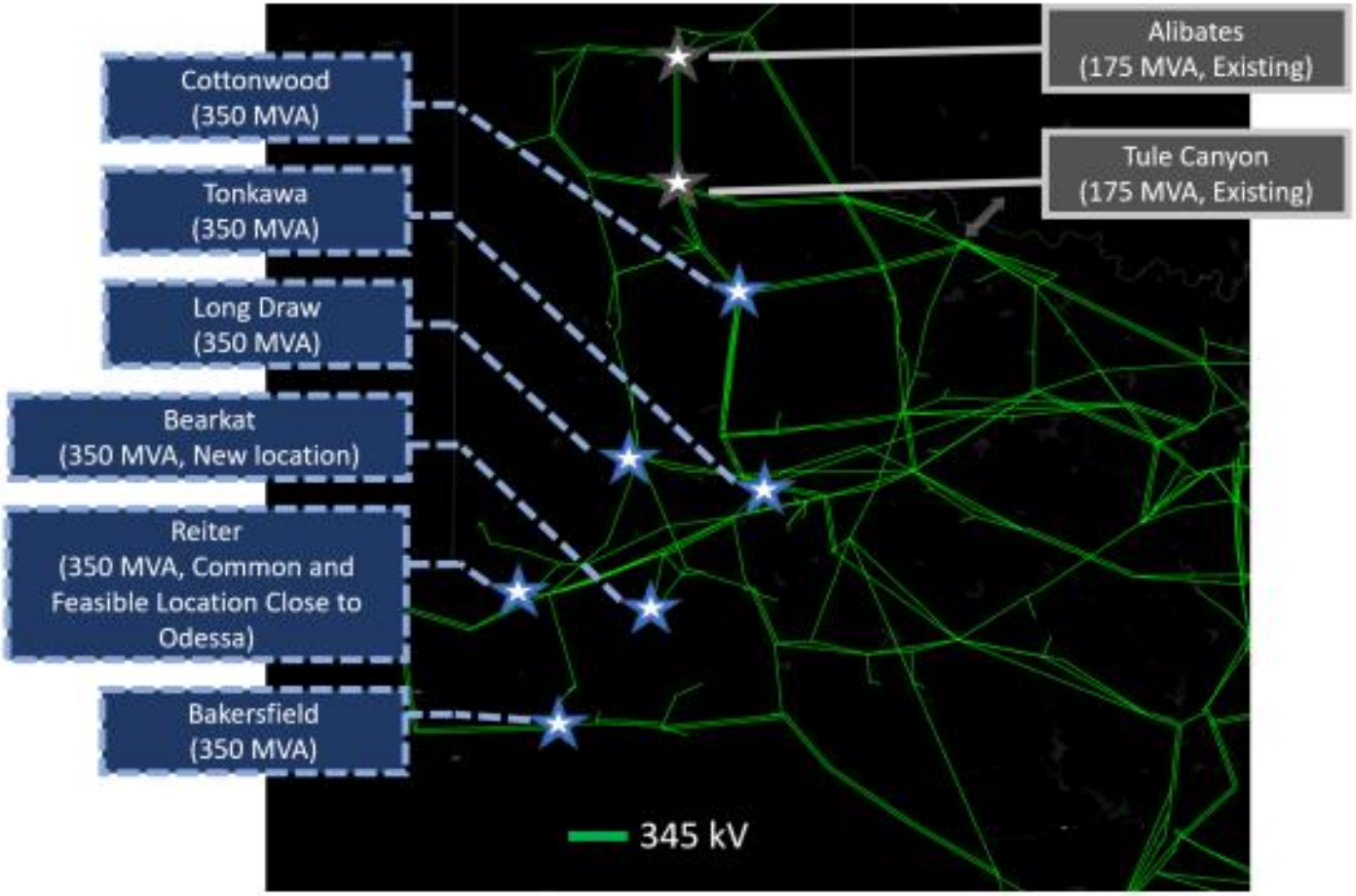


  - For the stable scenarios, the overall performances from PSCAD simulations were consistent with that from PSS/e simulations
  - PSCAD studies are necessary to evaluate potential control stability issues

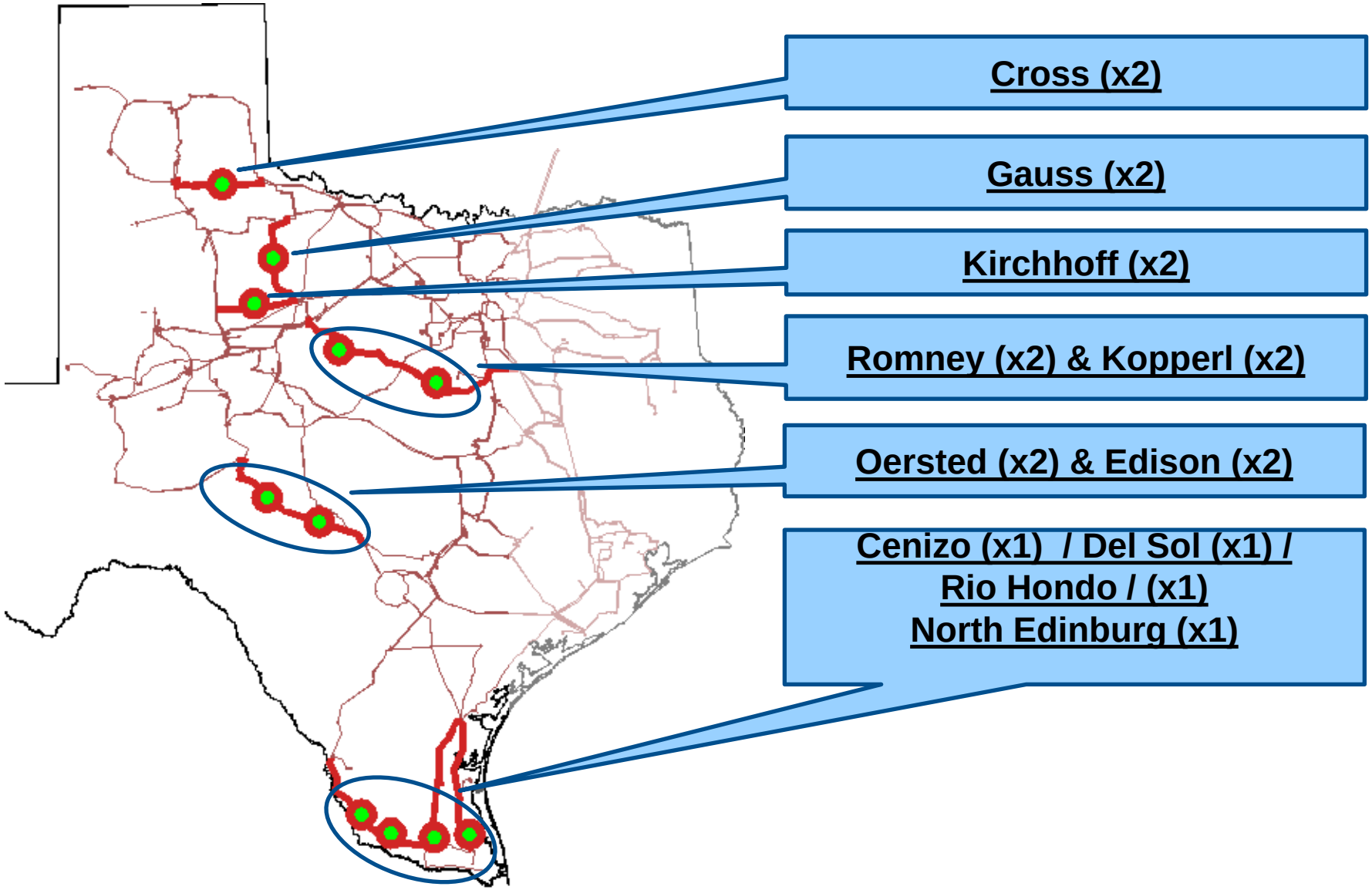
"2020 Panhandle Regional Stability Study, available at "https://www.ercot.com/files/docs/2020/11/27/2020_PanhandleStudy_public_final__004_.pdf

Six Synchronous Condensers (SynCons) in WTX

- A total of six new SynCons (2100MVA) were identified to increase the system strength of WTX (>40GW IBRs)

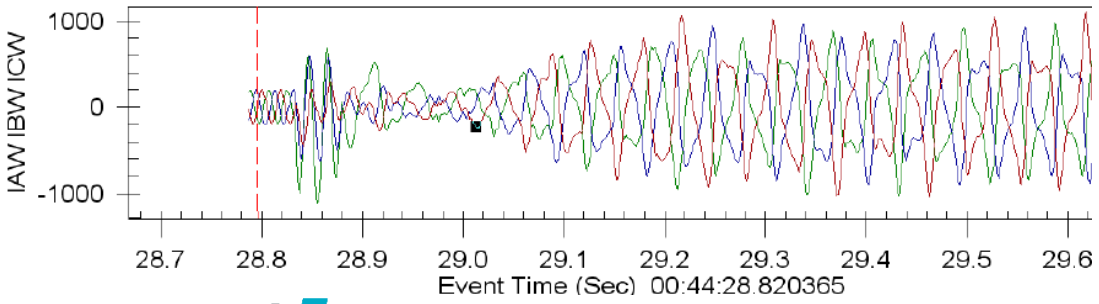


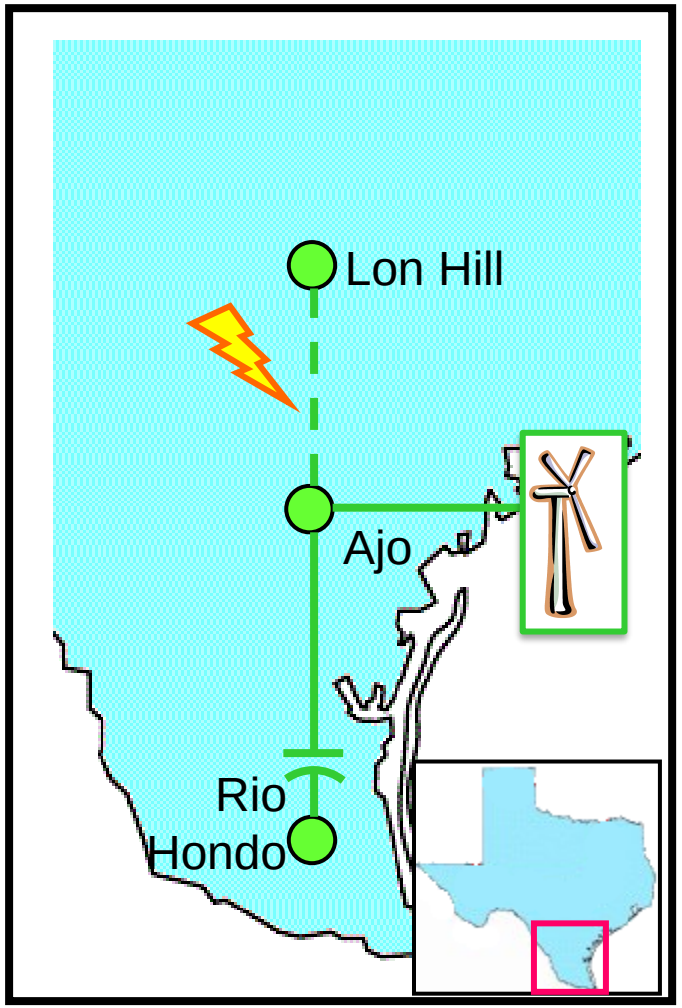
Series Capacitors in ERCOT



South Texas 2009 Event

- Series capacitors installed on long 345 kV line in South Texas.
- A cluster of wind farms (DFIG) connected to Ajo.
- In 2009, a fault caused LonHill – Ajo line to trip, leaving wind radially connected to series caps.
- Very high currents resulted in damage.



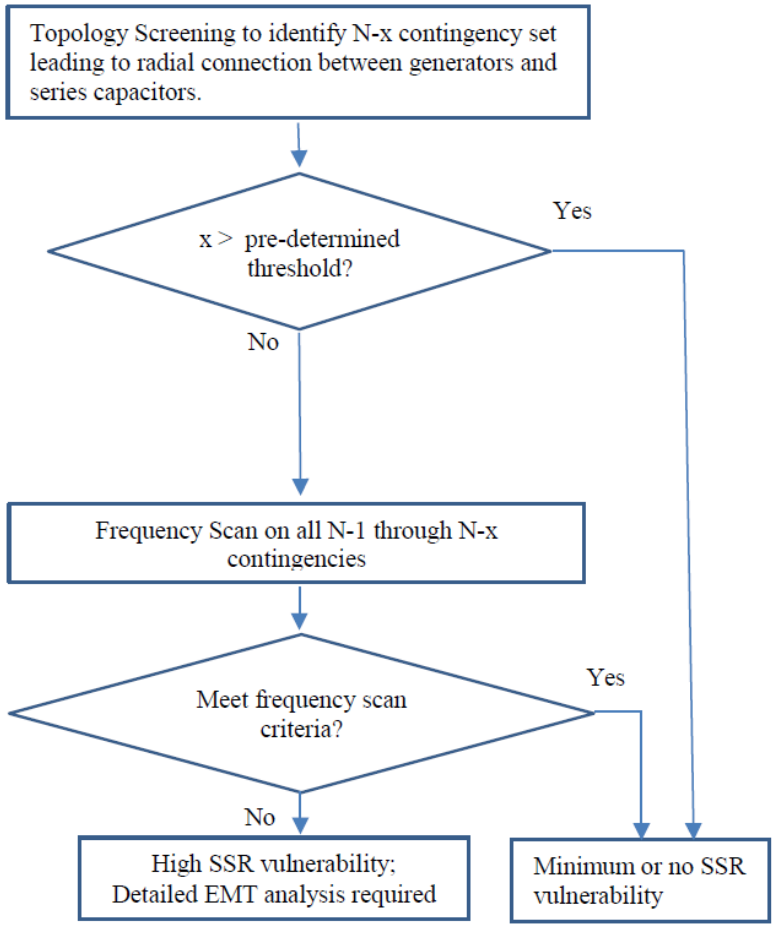


SSR Studies – Series Capacitor related SSO

- SSR studies are tedious!
- Layered onion approach

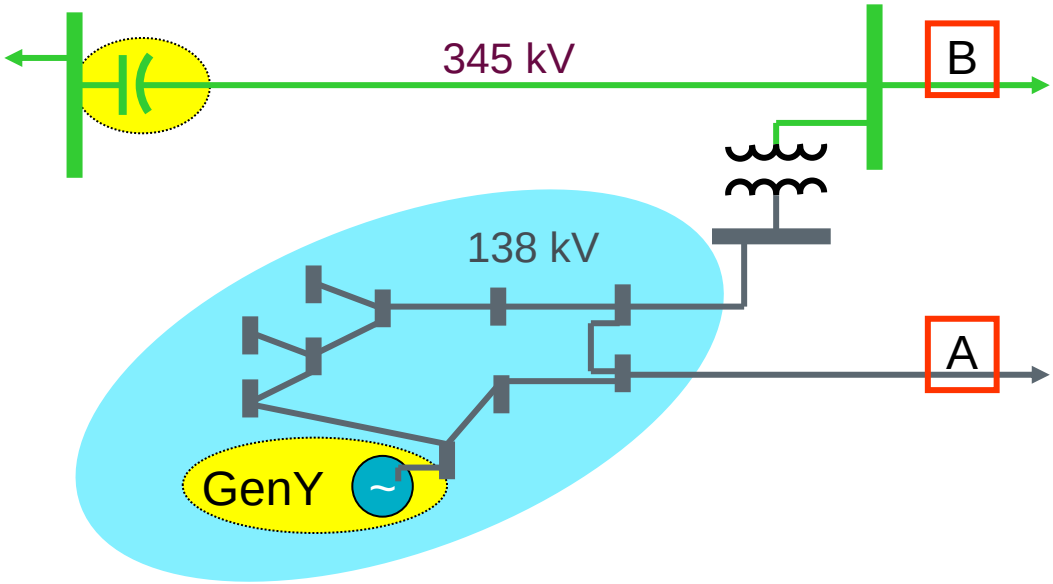
ERCOT SSR Study Framework

- Step 1: Topology Screening
  - Identify N-x contingency set leading to radial connection
- Step 2: Frequency Scan (FS)
  - Run frequency scan and compare with the FS criteria
- Step 3: EMT analysis
  - Run PSCAD simulation for limited contingencies as identified in FS



Reference: Yunzhi Cheng, etc, "Subsynchronous Resonance Assessment for A Large System with Multiple Series Compensated Transmission Circuits", IET Renewable Power Generation, vol. 1, no. 1, 2019.

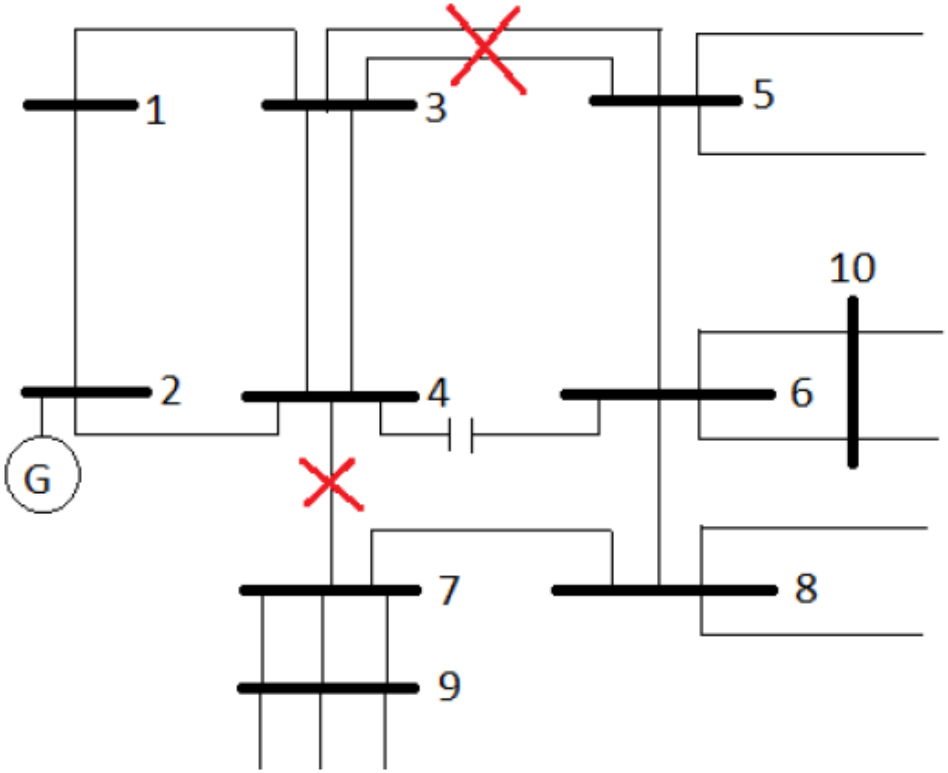
Topology Screening



Outages “A” and “B” make the generator “*radial*” to the series capacitor

Topology Screening

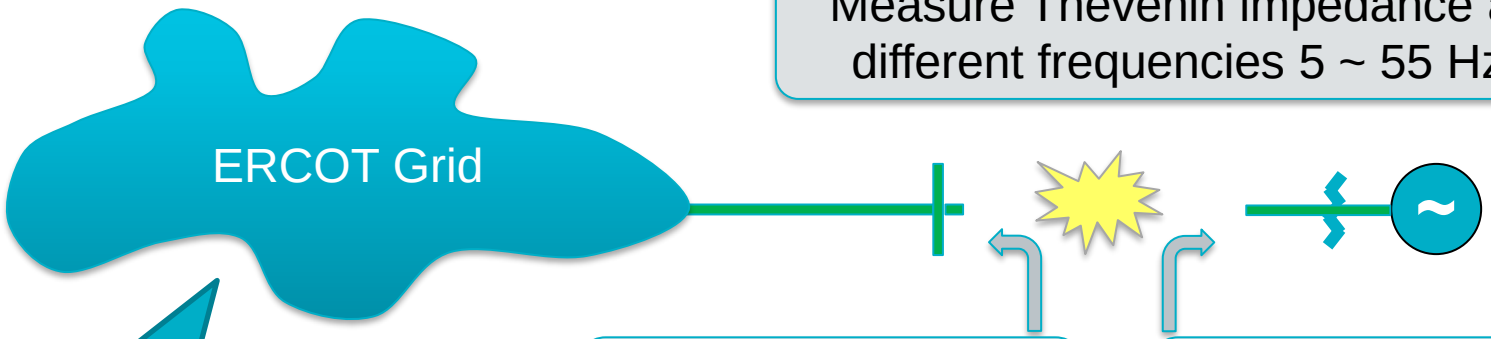
- The classic Ford-Fulkerson max-flow min-cut theorem can be utilized to identify the N-x contingency set leading to radial connection



Reference: Yunzhi Cheng, etc, “Subsynchronous Resonance Assessment for A Large System with Multiple Series Compensated Transmission Circuits”, IET Renewable Power Generation, vol. 1, no. 1, 2019.

Frequency Scan

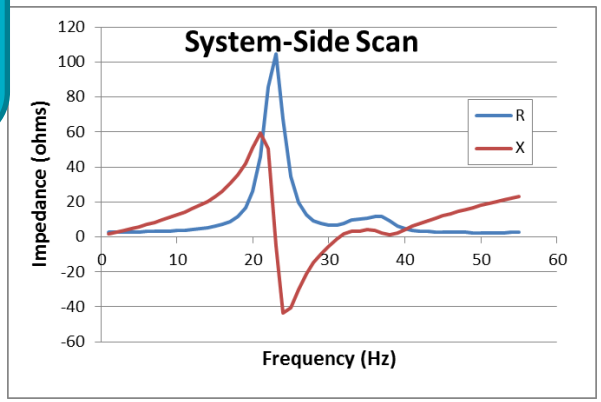
Measure Thevenin impedance at different frequencies 5 ~ 55 Hz

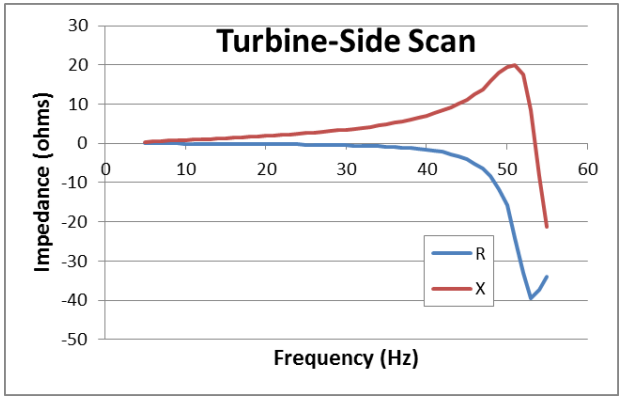


Don't forget to simulate contingencies!

System-Side Frequency Scan (PSS/e)

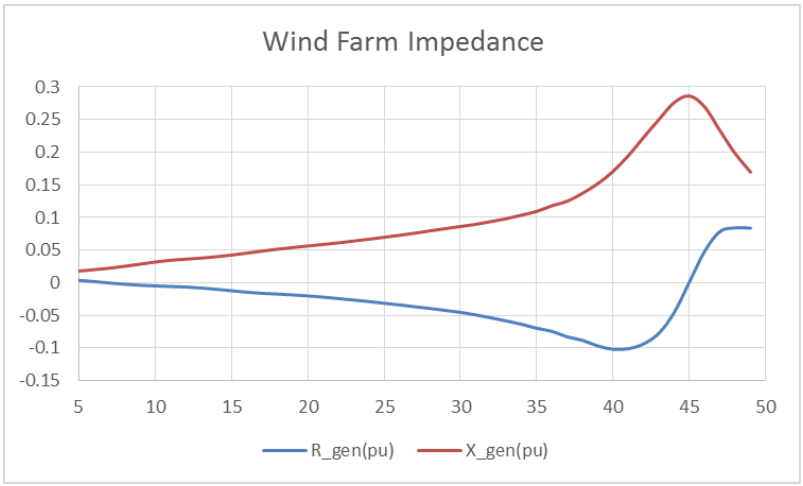
Generator-Side Frequency Scan (PSCAD)

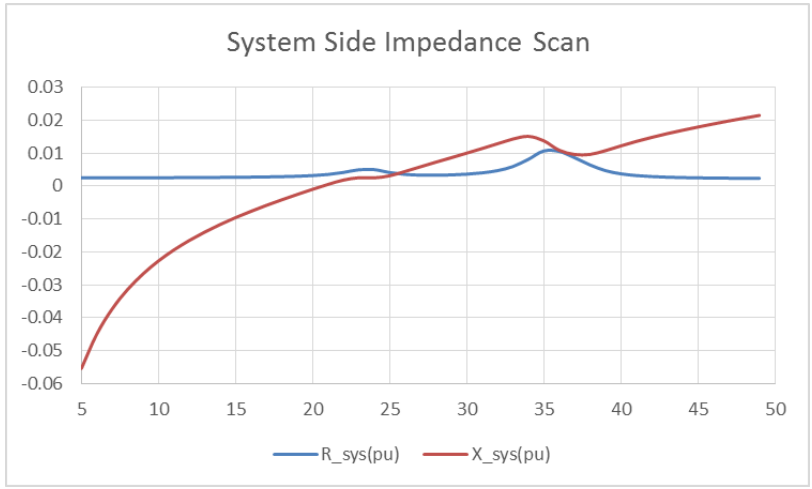


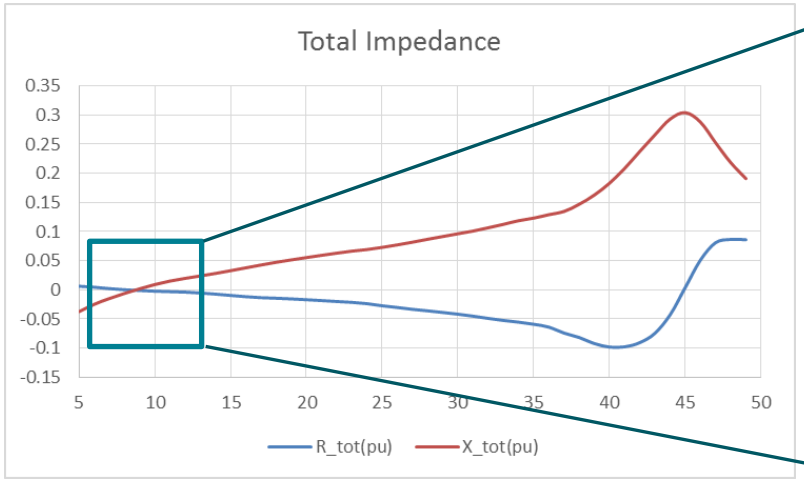


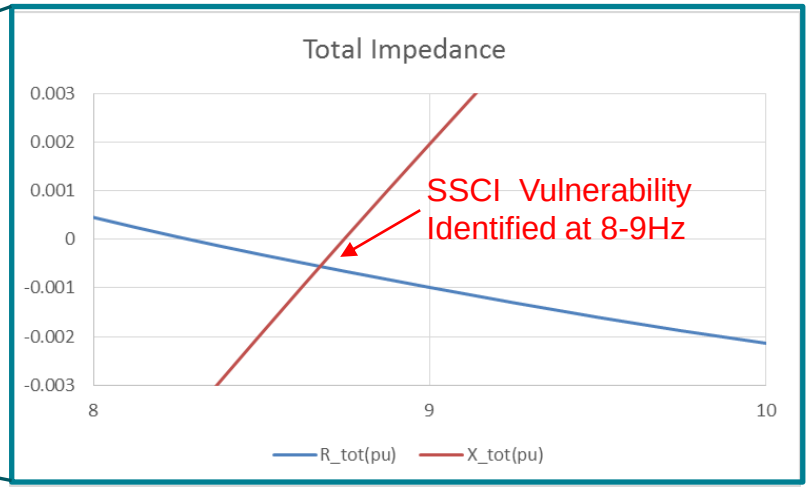
Reference:
B. Badrzadeh, M. Sahni, Y. Zhou, D. Muthumuni, and A. Gole, "General Methodology for Analysis of Sub-Synchronous Interaction in Wind Power Plants", *IEEE Trans. On Power Systems,* vol. 28, no. 2, May 2013
Yunzhi Cheng, etc, "Reactance Scan Crossover-Based Approach for Investigating SSCI Concerns for DFIG-Based Wind Turbines", IEEE Transactions on Power Delivery, Vol. 28, No. 2, 2013

Frequency Scan Example



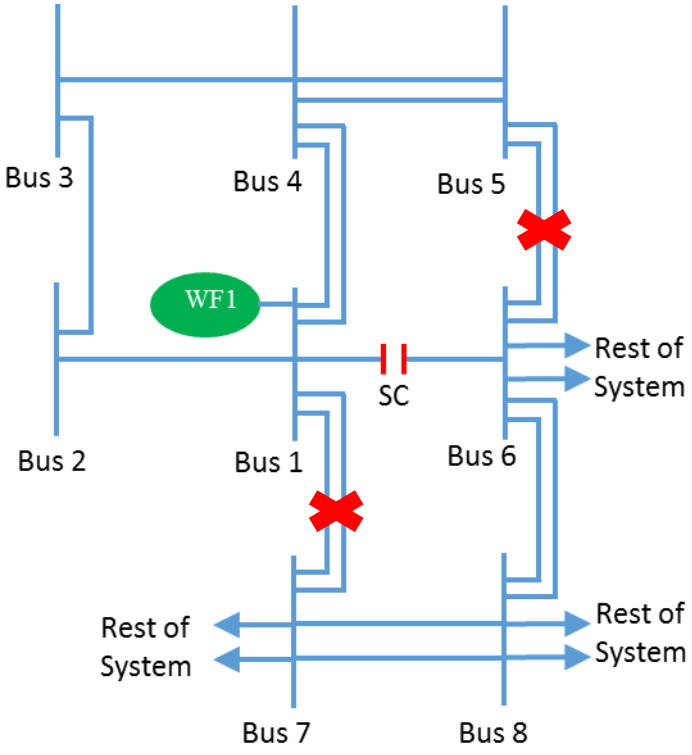






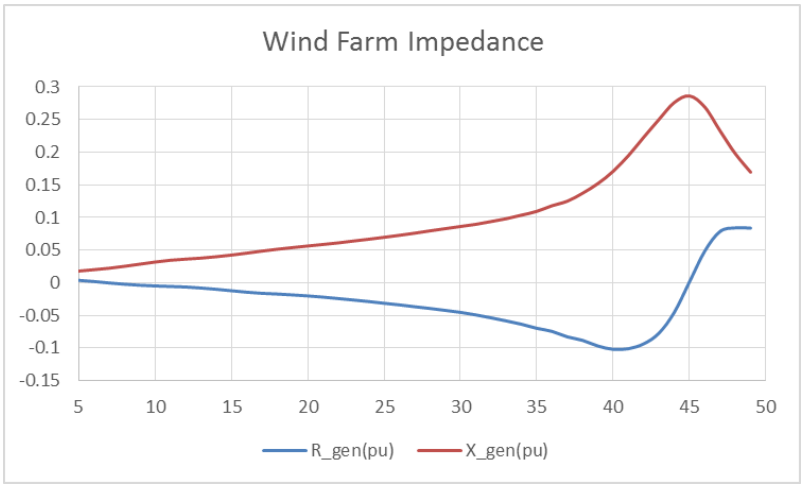
ERCOT's Tool and An Example

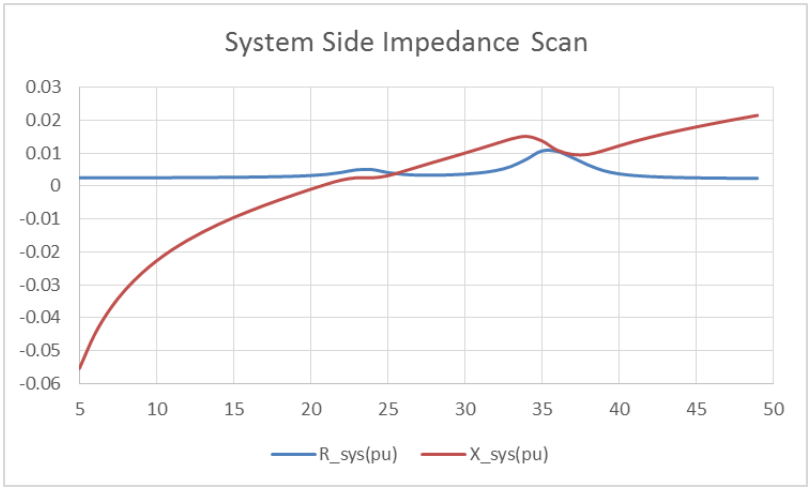
- ERCOT has developed a FS tool and run it for hundreds of SSCI studies
- An example of a DFIG based wind farm (WF1, 290MW) connected to a series compensated transmission network
  - Compensation level is set at 25%
  - An N-4 outage is studied:
    - » Loss of double circuit line of Bus 5 – Bus 6
    - » Loss of double circuit line of Bus 1 – Bus 7
    - » Radial connection between WF1 and SC under this outage

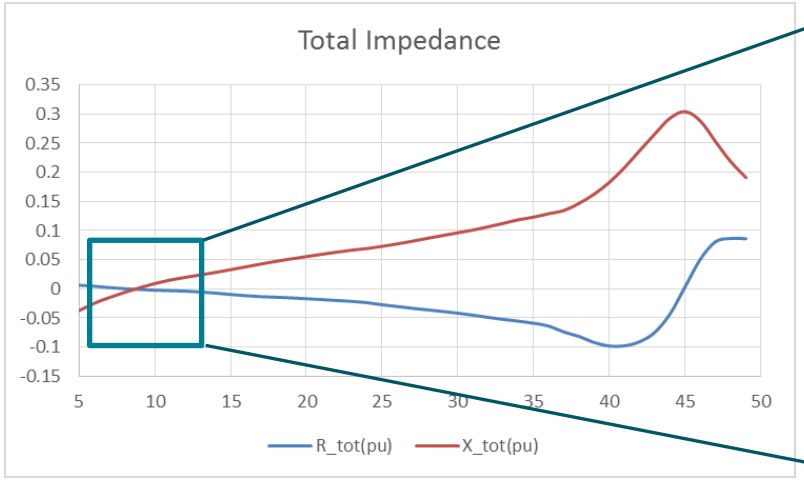


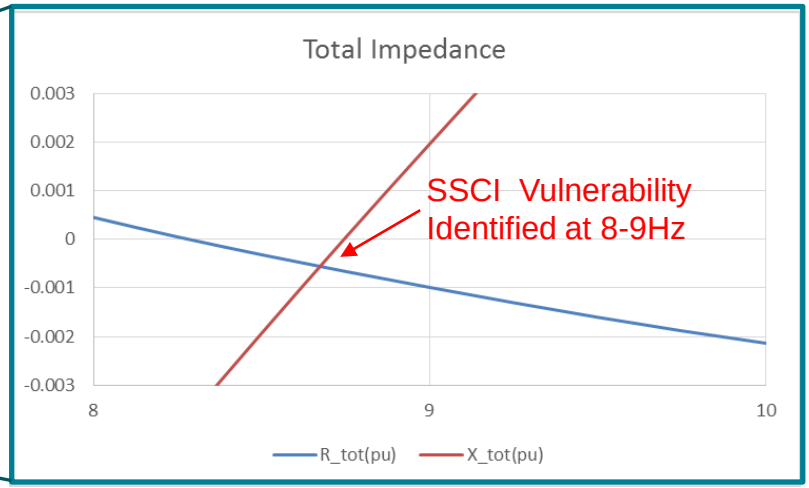
Reference: Yunzhi Cheng, etc, "ERCOT Subsynchronous Resonance Topology and Frequency Scan Tool Development", IEEE PES General Meeting, 2016.

ERCOT's Tool and An Example



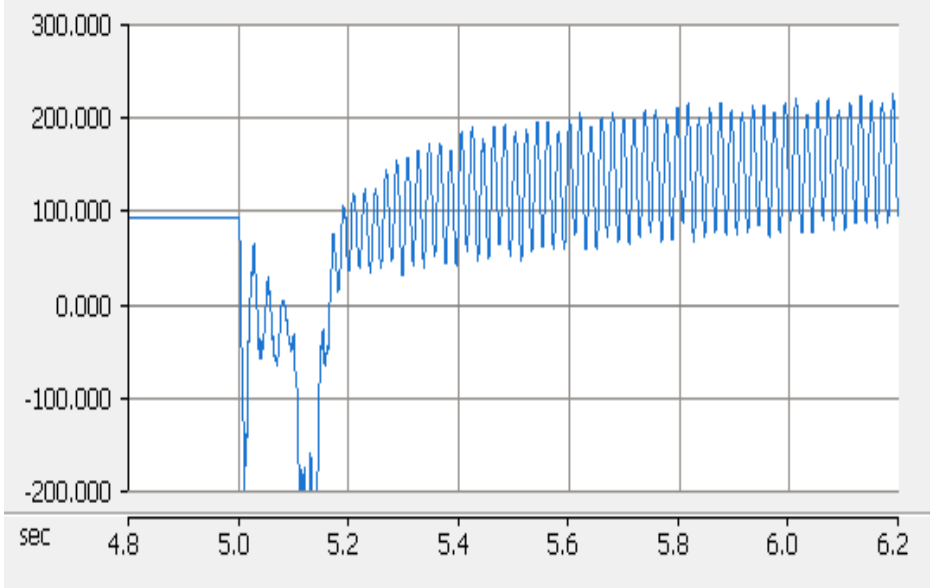




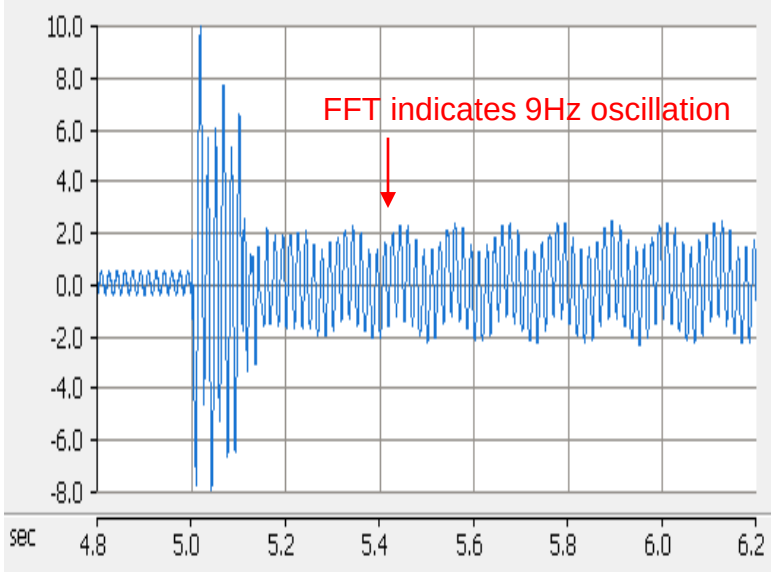


ERCOT's Tool and An Example

Active power (MW)



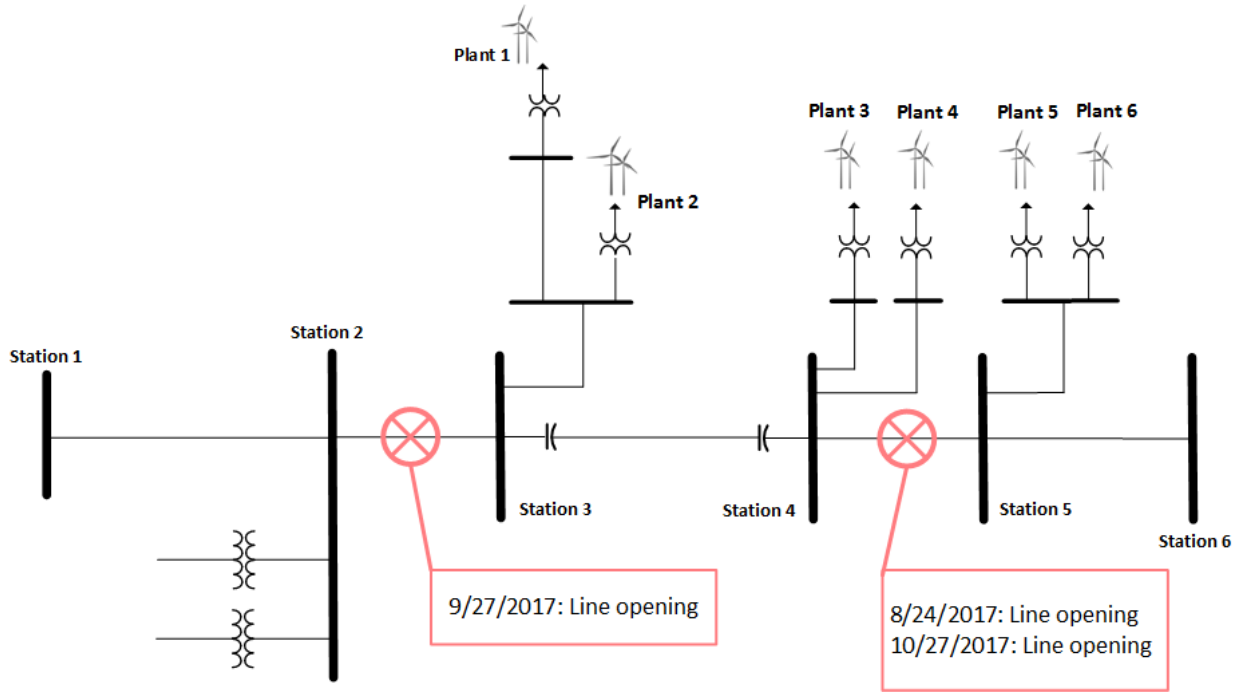
Current (kA)



Active power and Current on the series capacitor
(PSCAD Simulation Results)

ERCOT 2017 Events

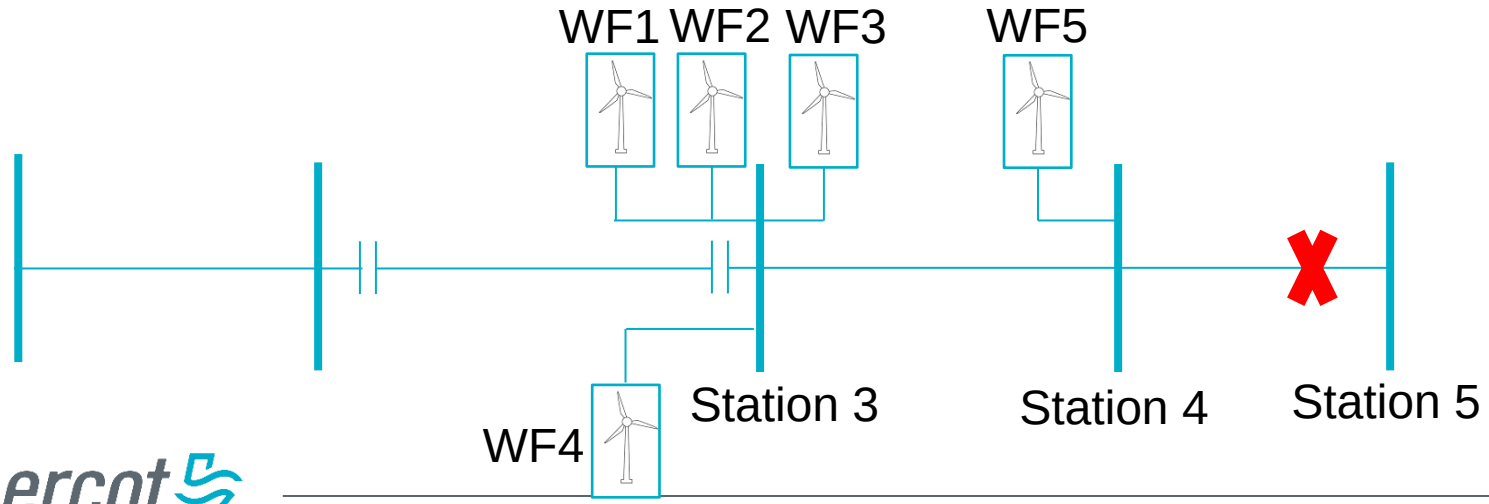
- Three SSCI events occurred in South Texas in 2017
  - All SSCI events are related to DFIG based wind farms radially connected to series capacitors after outages
  - Both undamped SSCI (20-30Hz) and damped SSCI (20-30Hz) were observed. WTGs were tripped during undamped SSCI events.



http://www.ercot.com/content/wcm/key_documents_lists/139265/10._South_Texas_SSR_ERCOT_ROS_May_2018_rev1.pdf

South Texas 2023 SSO Event (3/10/2023)

- Five wind farms (total 1140MW) interconnecting to the other end of series caps
  - DFIG/Type 3: WF2, WF3 and WF5
  - Full converter/Type 4: WF1 and WF4
- 345kV line of Station 4 – Station 5 faulted and tripped leaving WF1–5 radial to two series caps; SSO occurred immediately with the frequency of ~30Hz; Both series caps automatically bypassed by their protection about 1.2-1.3 seconds after fault clearing, WF4 tripped later.



Conclusions

- Weak Grid SSO
  - System strength test (SCR) as part of Model Quality Test
  - Curtailment may be needed based on SCR metrics or dynamic simulation
  - Advanced control such as Grid-Forming has the potential to improve IBR SSO performance under weak grid condition
  - Add SynCons to increase the system strength
- Series Capacitor SSO (SSCI)
  - Tuning the IBR SSCI mitigation control is very complex
  - Avoid radial connection between IBRs and series capacitors under normal condition and credible contingencies
  - Avoid direct connection of IBRs to series capacitors

References

- “ERCOT SSR Study Scope Guidelines”, available at: https://www.ercot.com/files/docs/2020/12/04/ERCOT_SSR_Study_Scope_Guideline_10-27-2020-external.docx
- Y. Cheng *et al*., "Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources," in *IEEE Transactions on Power Systems*, 2023
- Y. Cheng et al., "A Series Capacitor Based Frequency Scan Method for SSR Studies," in *IEEE Transactions on Power Delivery*, vol. 34, no. 6, 2019.
- Y. Cheng et al., “Subsynchronous Resonance Assessment for A Large System with Multiple Series Compensated Transmission Circuits”, *IET Renewable Power Generation*, vol. 1, no. 1, 2019
- Y. Cheng, et al., "ERCOT subsynchronous resonance topology and frequency scan tool development," *2016 IEEE Power and Energy Society General Meeting (PESGM)*
- Y. Cheng, et al., "Reactance Scan Crossover-Based Approach for Investigating SSCI Concerns for DFIG-Based Wind Turbines," in *IEEE Transactions on Power Delivery*, vol. 28, no. 2, 2013
- X. Xie, et al., "Investigation of SSR in Practical DFIG-Based Wind Farms Connected to a Series-Compensated Power System," in *IEEE Transactions on Power Systems*, vol. 30, no. 5, 2015
- B. Badrzadeh, et al., "General Methodology for Analysis of Sub-Synchronous Interaction in Wind Power Plants," in *IEEE Transactions on Power Systems*, vol. 28, no. 2, 2013