SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Mechanism Analysis of Dynamic Phenomena in Power Grids with High Penetrations of Inverter-Based Resources (IBRs)

When IBRs meet Grids

DOE SETO System Integration 2023 Webinar Series

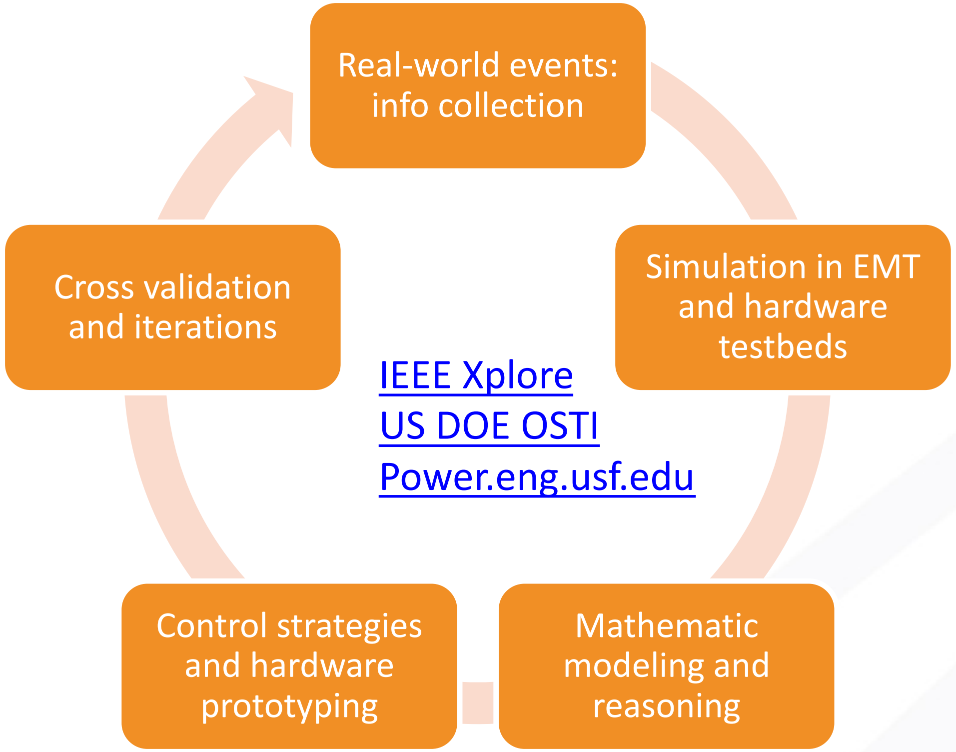
February 22, 2023

Lingling Fan, University of South Florida

Outline

- Overview of power grid dynamic events associated with IBRs
- Why mechanism analysis
- When IBRs meet grids
  - Weak grids & oscillations
  - Shunt compensation & overvoltage
  - Small IBR impedance & overcurrent
  - Series compensation & subsynchronous oscillations
- Concluding remarks

DE-EE-0008771 Modeling and Control of Solar PVs for Large Grid Disturbances and Weak Grids



IEEE Xplore
US DOE OSTI
Power.eng.usf.edu

23 published journal articles since 2019 in the following topics: analytical modeling, data-driven modeling, IBR control design, mechanism analysis, etc.

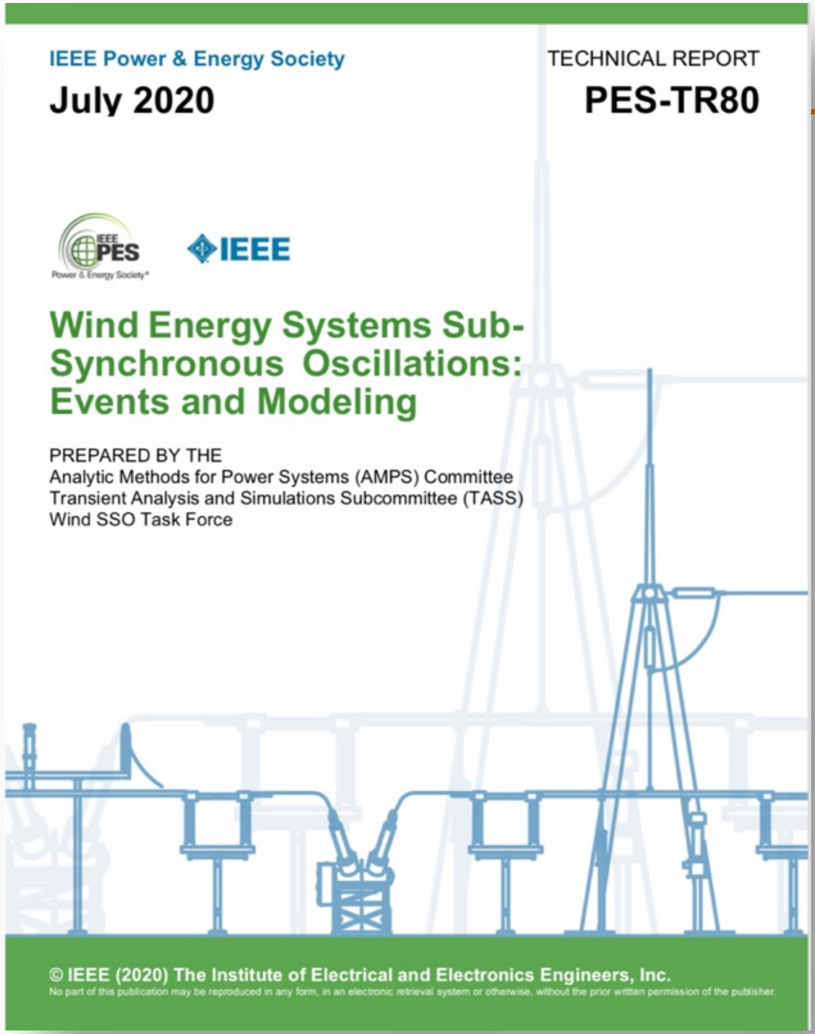
Title	Journal
Admittance-based stability analysis: Bode plots, Nyquist diagrams or Eigenvalue Analysis?	*IEEE trans on Power Systems*
A Tutorial on Data-Driven Eigenvalue Identification: Prony Analysis, Matrix Pencil and Eigensystem Realization Algorithm	*Int Trans Electr Energ Syst.*
Small-Signal Stability Analysis of Type-4 Wind in Series-Compensated Networks	*IEEE trans on Energy Conversion*
Time-Domain Measurement-Based DQ-Frame Admittance Model Identification for Inverter-Based Resources	*IEEE trans on Power Systems*
Subcycle Overvoltage Dynamics in Solar PVs	*IEEE trans on Power Delivery*
Randomized Dynamic Mode Decomposition for Oscillation Modal Analysis	*IEEE trans on Power Systems*
Identifying DQ-Domain Admittance Models of a 2.3-MVA Commercial Grid- Following Inverter Via Frequency-Domain and Time-Domain Data	*IEEE trans on Energy Conversion*
Reduced-Order Analytical Model of Grid-Connected Solar Photovoltaic Systems for Low-Frequency Oscillation Analysis	*IEEE trans on Sustainable Energy*
Root Cause Analysis of AC Overcurrent in July 2020 San Fernando Disturbance	*IEEE trans on Power Systems*
Inter-IBR Oscillation Modes	*IEEE trans on Power Systems*
Stability Enhancement Module for Grid-Following Converters: Hardware Implementation and Validation	*Int Trans on Electr Energy Syst*
From Event Data to Wind Power Plant DQ Admittance and Stability Risk Assessment	*IEEE trans on Power Systems*
The cause of sub-cycle overvoltage: Capacitive Characteristics of Solar PVs	*Electric Power Systems Research*
Data-Driven Dynamic Modeling in Power Systems	*IEEE PEM*
Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources	*IEEE trans on Power Systems*
Real-World 20-Hz IBR Subsynchronous Oscillations: Signatures and Mechanism Analysis	*IEEE trans on Energy Conversion*
Analysis of 0.1-Hz Var Oscillations in Solar Photovoltaic Power Plants	*IEEE trans on Sustainable Energy*
A New Type of Weak Grid IBR Oscillations	*IEEE trans on Power Systems*
Mechanism Analysis of Wind Turbine Var Oscillations	*IEEE trans. Industrial Electronics*
Data-Driven Interarea Oscillation Analysis for a 100% IBR- Penetrated Power Grid,	*IEEE OAJPE*
A Laplace-Domain Circuit Model for Fault and Stability Analysis Considering Unbalanced Topology	*IEEE trans. Power Systems*
Generalized Circuit Representation for a Synchronous Machine,	*IEEE trans. Energy Conversion.*
Solar PV and BESS Plant-Level Voltage Control and Interactions: Experiments and Analysis	*IEEE trans on Power Systems*

Research outcomes: talks

Date	Organization	Title
Jan 6, 2021	NERC	**Root cause analysis of subcycle overvoltage dynamics and ac overcurrent**
Feb 25, 2021	NERC IRPWG	**Simulation and Analyses of Inverter Tripping from NERC Reports**
April 6, 2021	WECC Model building validation subcommittee	**IBR Model Validation & Analysis via Admittances**
June 24, 2021	NERC IRPWG	**Effect of volt-var droop control delay on inverter dynamic performance**
July 22, 2021	NERC IRPWG	**Are solar PVs capacitive?**
Feb 17, 2022	NERC IRPWG	**A new look on IBR interactions and Inter-area Oscillations**
Mar 10, 2022	UC Berkley PES/PELS student chapter	**Analysis of IBR Dynamic Events**
April 22, 2022	NERC IRPWG	**Experiment and Analysis Results of BESS/PV Plant-Level Controls — an examination of volt-var feedback system & oscillations**

Date	Organization	Title
June 16, 2022	NERC IRPS, virtual	**Analysis of Solar Plant Oscillations in SCE Footprint - 0.1-Hz Voltage/Var Oscillations**
June 27, 2022	PNNL, virtual	**Stability Analysis and Control for Power Grids with High Penetrations of Inverter-Based Resources**
July 7, 2022	PES Live webinar, virtual	**Inverter-based resources subsynchronous oscillations: events and mechanisms (833 registrants, 367 attendees)**
July 19, 2022	PESGM 2022, Denver	**Signatures Analysis of IBRs from Measurement Data**
July 20, 2022	PESGM 2022, Denver	**Modal Analysis of a 100% IBR-Penetrated Power Network via Frequency Scans**
Oct 26, 2022	ESIG Technical Workshop, Minneapolis	**Replication and Identification of Causes of Grid Oscillations**
Oct 31, 2022	UNIFI Forum (NREL), virtual	**Analytical model building for IBRs**
Jan 17, 2023	NERC IRPS	**Large PLL angle deviation in Texas Odessa events**

Overview of power grid dynamic events associated with IBRs


IEEE Power & Energy Society

July 2020

TECHNICAL REPORT

PES-TR80

Wind Energy Systems Sub-Synchronous Oscillations: Events and Modeling

PREPARED BY THE
Analytic Methods for Power Systems (AMPS) Committee
Transient Analysis and Simulations Subcommittee (TASS)
Wind SSO Task Force

2007- 2019

Type-3 wind farms: Minnesota, Texas, North China

Type-4 wind farms: Texas, Northwest China, UK

wind farm oscillations

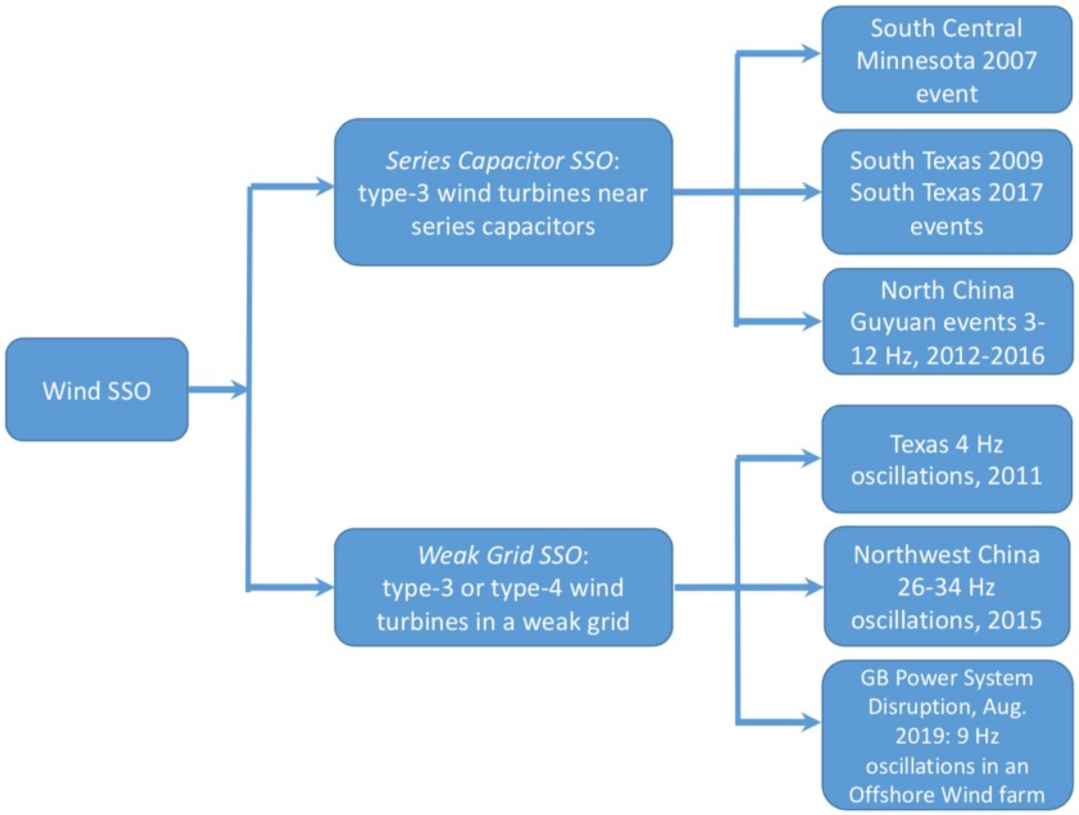


Figure 1.1: Types of oscillations in subsynchronous range for systems with WPPs.

IBR SSO

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

IEEE PES IBR SSO Task Force

2021 Dominion Energy 22-Hz oscillations

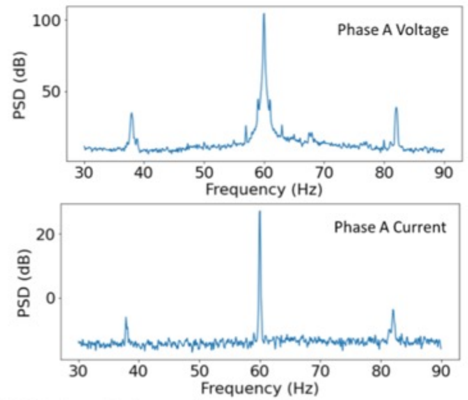


Fig. 17. PSD plots of voltage and current PoW data.

Hydro One 20-Hz/80-Hz oscillations

C. (2015) Hydro One 20-Hz oscillations in solar PVs

Hydro One observed 20-Hz poorly damped oscillations in RMS voltage measurements at a 44-kV distribution feeder upon switching in a 30-Mvar capacitor in a substation [13]. Three 10-MVA solar PV plants were connected to the utility substation through a 30-km feeder. Fault level at the 44-kV point of connection (PoC) is approximately 120 MVA.

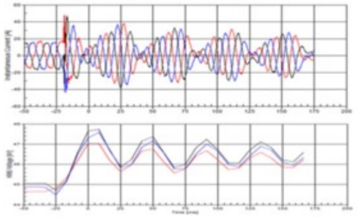


Fig. 11. Hydro One solar PV oscillations. (a) 80-Hz oscillations in the phase current. (b) 20-Hz oscillations in the RMS voltage measurements.

Australia 7-Hz and 19-Hz oscillations

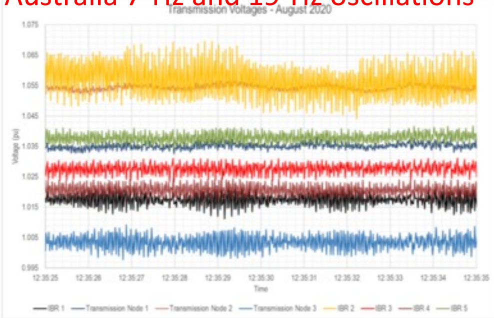


Fig. 15. AEMO 19-Hz oscillations - West Murray area.

19 events

North America solar PV related large disturbances

freq meas. error	subcycle overvoltage	subcycle overvoltage	Instantaneous overcurrent	PLL loss of synch

NERC

1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California 8/16/2016 Event

June 2017

RELIABILITY | ACCOUNTABILITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

NERC

900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California Event: October 9, 2017
Joint NERC and WECC Staff Report

February 2018

RELIABILITY | ACCOUNTABILITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

NERC

April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report

Southern California Events: April 20, 2018 and May 11, 2018
Joint NERC and WECC Staff Report

January 2019

RELIABILITY | ACCOUNTABILITY

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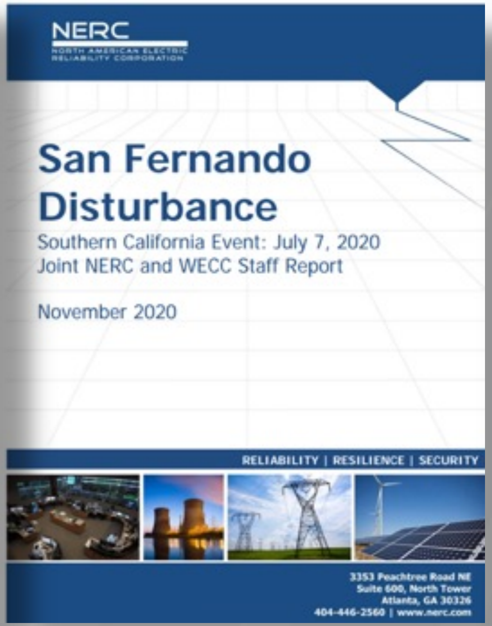
404-446-2560 | www.nerc.com



NERC

San Fernando Disturbance

Southern California Event: July 7, 2020
Joint NERC and WECC Staff Report

November 2020

RELIABILITY | RESILIENCE | SECURITY

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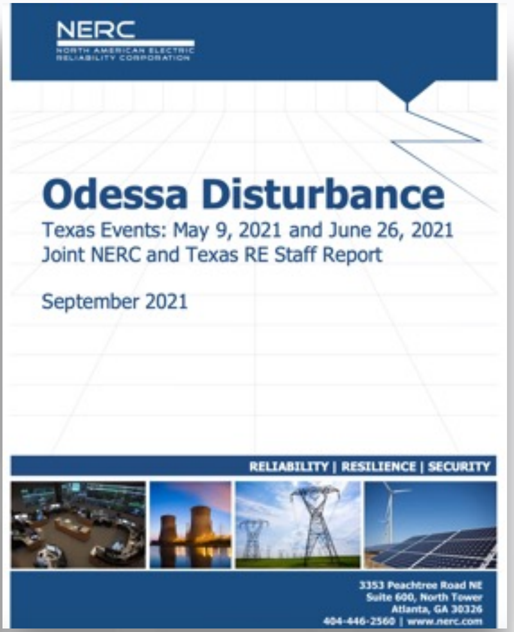


NERC

Odessa Disturbance

Texas Events: May 9, 2021 and June 26, 2021
Joint NERC and Texas RE Staff Report

September 2021

RELIABILITY | RESILIENCE | SECURITY

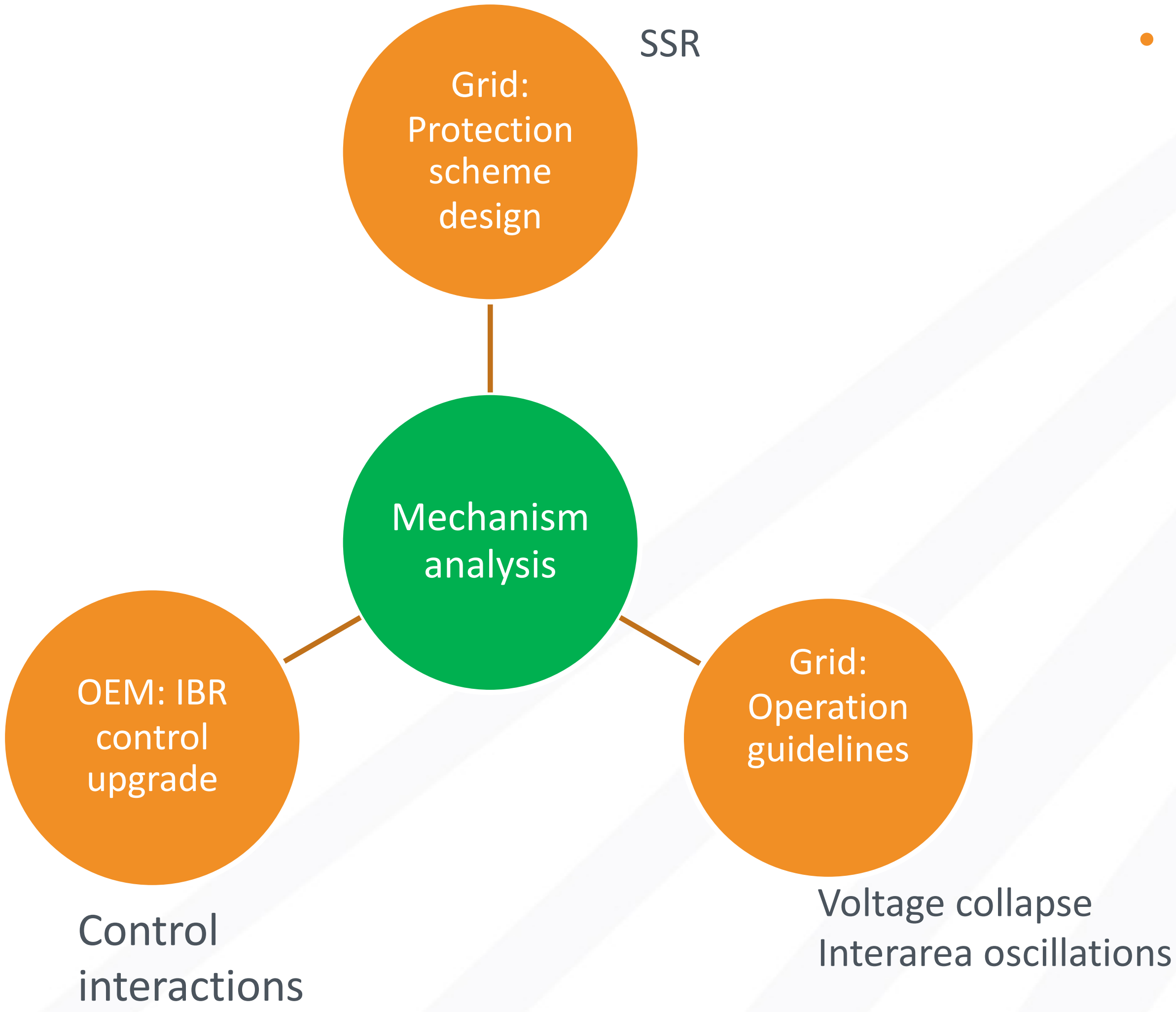
3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

2016 California	2017 California	2018 California	2020 California	2021 Texas

- L. Fan, Z. Miao and M. Zhang, "**Subcycle Overvoltage Dynamics in Solar PVs**," in *IEEE TPWRD, 2021*
- L. Fan, Z. Miao, *"***The cause of Subcycle overvoltage: the capacitive nature of solar PVs***", Electric Power Systems Research 2022.*
- L. Fan, Z. Miao, "**Root Cause Analysis of AC Overcurrent in July 2020 San Fernando Disturbance**", *IEEE TPWRS 2021.*
- L. Fan, Z. Wang, Z. Miao, "**Large PLL angle deviation in the Texas Odessa Events**", submitted Feb. 2023.

Why mechanism analysis?

Why Mechanism Analysis?



- **Success stories:**
  - Voltage collapse
  - Quarter Hz interarea oscillations
  - Synchronous generator torsional interaction with series LC mode (1971 Mohave power plant events) or HVDC control (1977 Square Butte event)
  - Induction generator effect: when machines interact with series LC mode
  - Supplementary control in synchronous generator’s excitation systems – power system stabilizer

Success stories: Voltage stability

- Cause of 1996 WECC blackout, 2003 Northeast blackout, etc.
- **Mechanics**: a power grid has steady state limits -- voltage sensitivity becomes extremely high.
- **Industry practice**: **PV curves, QV curves have been used to compute maximum loadability.**

[1994 IEEE Potentials](#)
[M.L. Crow](#); [B.C. Lesieutre](#)

Voltage collapse

An engineering challenge

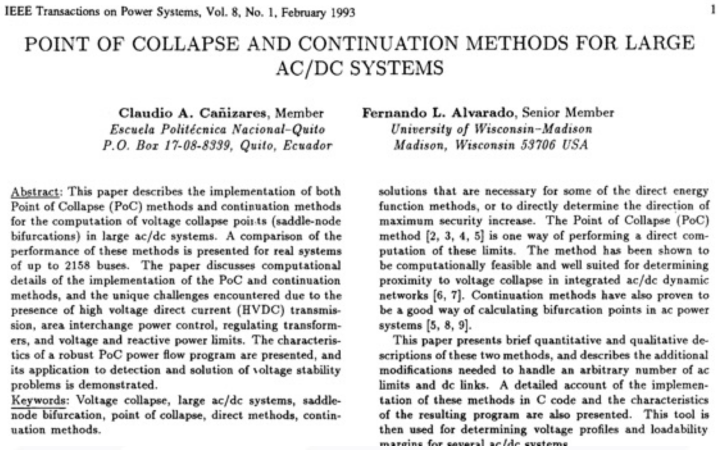
Mariesa L. Crow and Bernard C. Lesieutre

Recent blackouts in major cities throughout the world, including Tokyo and New York City, have raised concerns about a relatively new phenomenon in power system behavior: voltage collapse. This type of event is characterized by a loss of control of the voltage levels in a power system. Often, the initial voltage decay is so gradual, system operators are un-aware that the declining voltages are symptomatic of

Tokyo — The Image Bank/Andy Caulfield

small fraction of the additional power required by 2010. The largest shortfall of power will occur in highly populated areas, where older facilities are being retired but not replaced. To compensate for this deficiency, the necessary additional power must be imported from other utilities as well as non-utility sources, often over considerable distances. This causes considerable stress on the remaining facilities, as well as the power

[1993 IEEE trans. Power Systems](#)
[Claudio Canizares, F.L. Alvarado](#)



IEEE Transactions on Power Systems, Vol. 8, No. 1, February 1993 1

POINT OF COLLAPSE AND CONTINUATION METHODS FOR LARGE AC/DC SYSTEMS

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Escuela Politécnica Nacional-Quito
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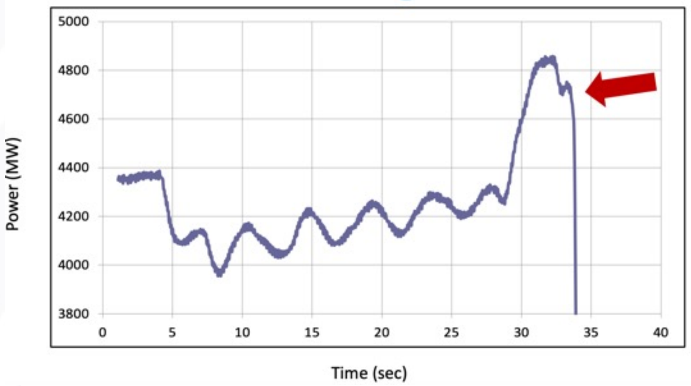
Abstract: This paper describes the implementation of both Point of Collapse (PoC) methods and continuation methods for the computation of voltage collapse points (saddle-node bifurcations) in large ac/dc systems. A comparison of the performance of these methods is presented for real systems of up to 2158 buses. The paper discusses computational details of the implementation of the PoC and continuation methods, and the unique challenges encountered due to the presence of high voltage direct current (HVDC) transmission, area interchange power control, regulating transformers, and voltage and reactive power limits. The characteristics of a robust PoC power flow program are presented, and its application to detection and solution of voltage stability problems is demonstrated.
Keywords: Voltage collapse, large ac/dc systems, saddle-node bifurcation, point of collapse, direct methods, continuation methods.

solutions that are necessary for some of the direct energy function methods, or to directly determine the direction of maximum security increase. The Point of Collapse (PoC) method [2, 3, 4, 5] is one way of performing a direct computation of these limits. The method has been shown to be computationally feasible and well suited for determining proximity to voltage collapse in integrated ac/dc dynamic networks [6, 7]. Continuation methods have also proven to be a good way of calculating bifurcation points in ac power systems [5, 8, 9].

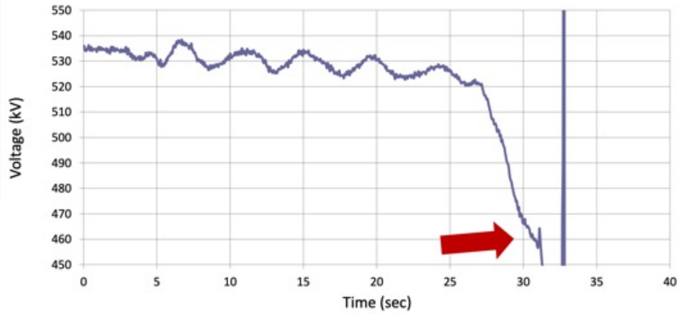
This paper presents brief quantitative and qualitative descriptions of these two methods, and describes the additional modifications needed to handle an arbitrary number of ac limits and dc links. A detailed account of the implementation of these methods in C code and the characteristics of the resulting program are also presented. This tool is then used for determining voltage profiles and loadability margins for several ac/dc systems.

Source: Dmitry Kosterev
BPA, WECC presentation, Nov. 2021

July 2 1996 – 500-kV Voltage on California kV Voltage on California kV Voltage on California-Oregon Border



Voltages on California - Oregon Intertie during July 2 1996 Event



Success stories: Interarea oscillations

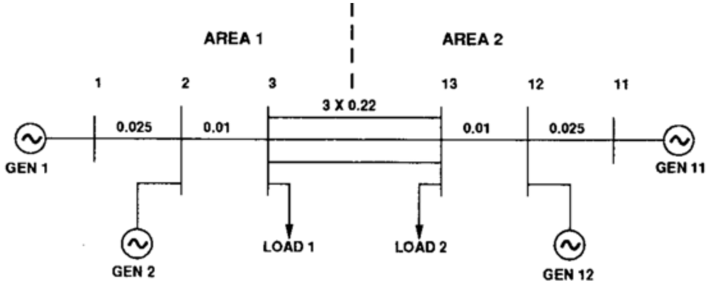


FIGURE 1
Two-Area System

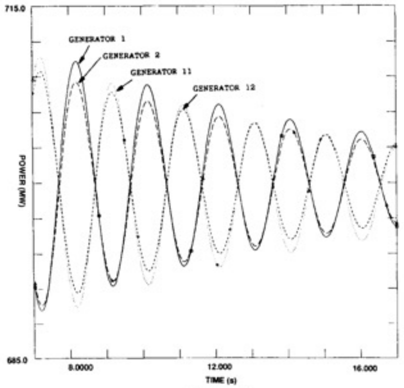
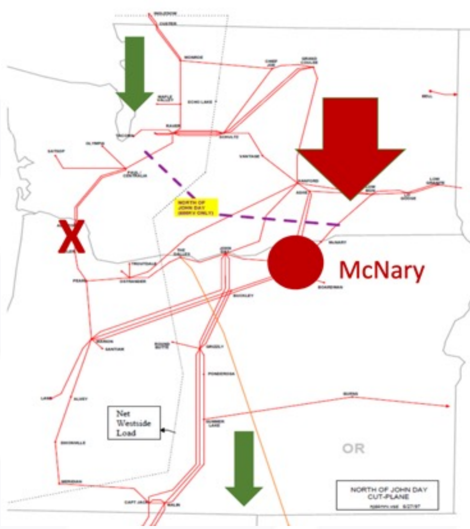
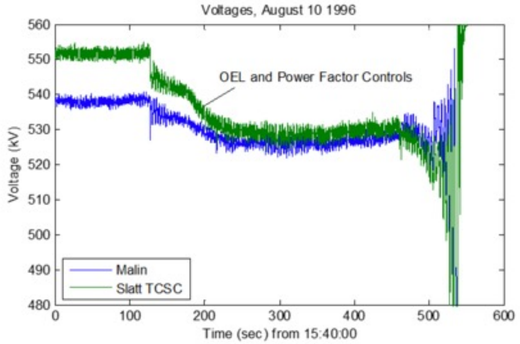


FIGURE 3
Generators' Active Power

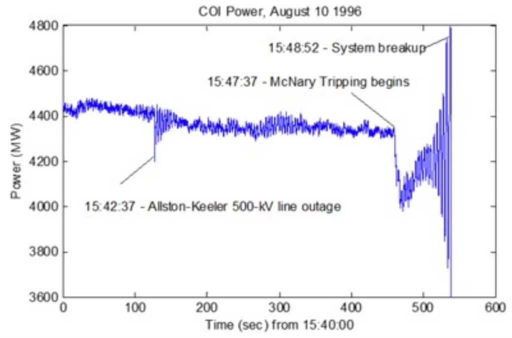
- M. Klein, G. J. Rogers and P. Kundur, "A fundamental study of inter-area oscillations in power systems," in *IEEE Transactions on Power Systems*, vol. 6, no. 3, pp. 914-921, **Aug. 1991**, doi: 10.1109/59.119229.



August 10 1996 – Voltages



August 10 1996 – COI Power



Source: Dmitry Kosterev
BPA, WECC presentation, Nov. 2021

Lessons learned:

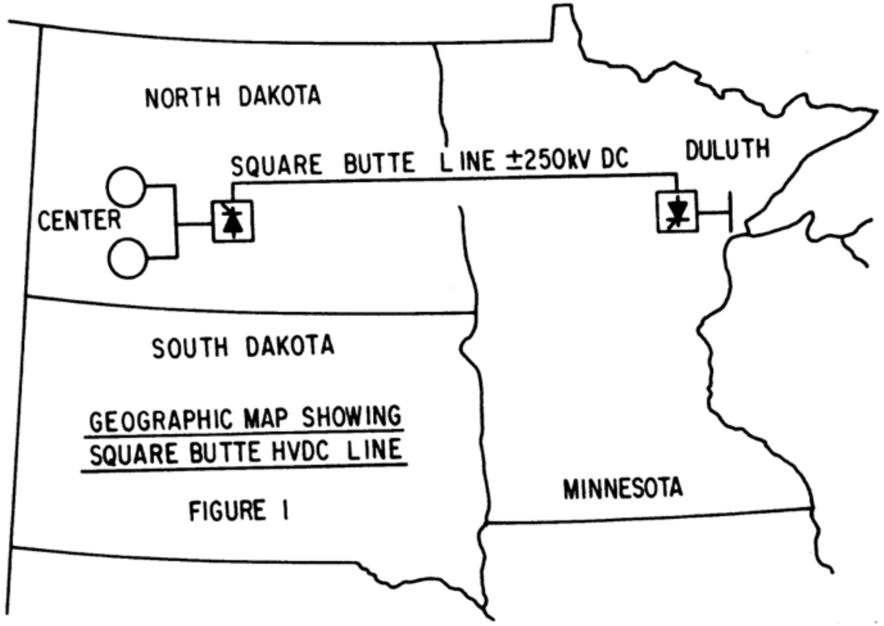
- **High power transfer can lead to interarea oscillations**
  - **A system has loading limits!**
- **Better monitoring systems**
- **Better modeling practice**

New insights:

- Interarea oscillation phenomena can be viewed as **dynamic voltage stability**.
- The insight is revealed by use of graph spectrum decomposition technique.

[1] L. Fan, "Interarea oscillations revisited," IEEE TWPRS, 2017

Success stories: Square Butte HVDC control interactions

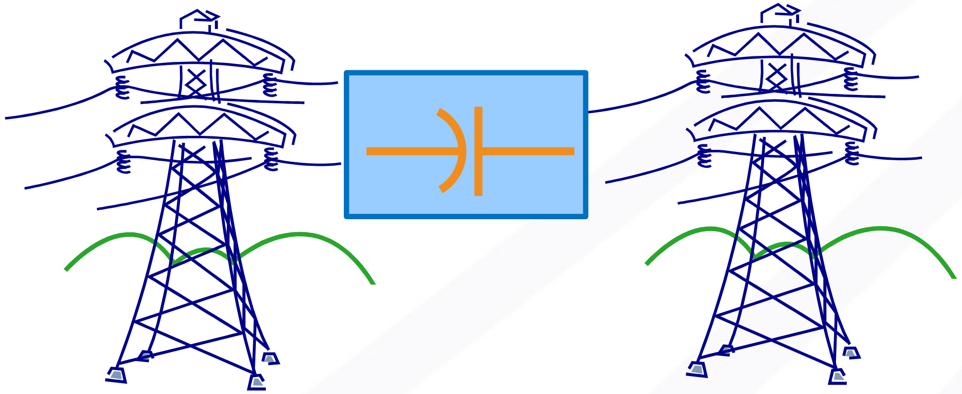


- **Abstract:** Tests on the the modern HVDC system at Square Butte conducted in October 1977 indicated that the HVDC terminal was interacting in an adverse way with **an 11.5-Hz torsional mode of an adjacent turbine-generator unit**. Subsequent analytical work duplicated the field test observations and was used to **develop an understanding** of the HVDC-torsional interaction phenomena. As a result of the analytical work, **the control system of the HVDC terminal was modified** and subsequent tests showed that the changes resulted in stable operation. The paper includes significant field test and analytical results.

Ref: Bahrman, M. P., Einar Vaughn Larsen, Richard Piwko and Hiteshkumar Patel. "Experience with HVDC - Turbine-Generator Torsional Interaction at Square Butte." *IEEE Transactions on Power Apparatus and Systems* PAS-99 (1980): 966-975.

Success stories: Subsynchronous resonance (SSR) due to LC resonance

- It happened before in 1970s at Nevada's Mohave power plant.
- One of the power plant (1,580 MW)'s synchronous generator experienced growing vibration in its shaft, causing damage ➔
- Reason: 30.1 Hz oscillations in the mechanical side triggered by LC resonance from the electrical side.
- If the **electric LC frequency + shaft mode frequency = 60 Hz**, **torsional interaction may occur**.



Series capacitors can introduce LC resonances.

Source: Jonathan Rose, ERCOT and the following two references

D. Baker, G. Boukarim, "Subsynchronous Resonance Studies and Mitigation Methods for Series Capacitor Applications," IEEE 2005.
D. Walker, D. Hodges, "Results of Subsynchronous Resonance Test At Mohave," IEEE 1975.

Solution: Generators have SSR protection installed.

There are many other success stories.

To be collected …

The New Era of Power Grids:
→When IBRs meet grids

IBR control design stage: a strong grid is assumed

"Grid-following control is inherited from vector control of ac motor drives. "

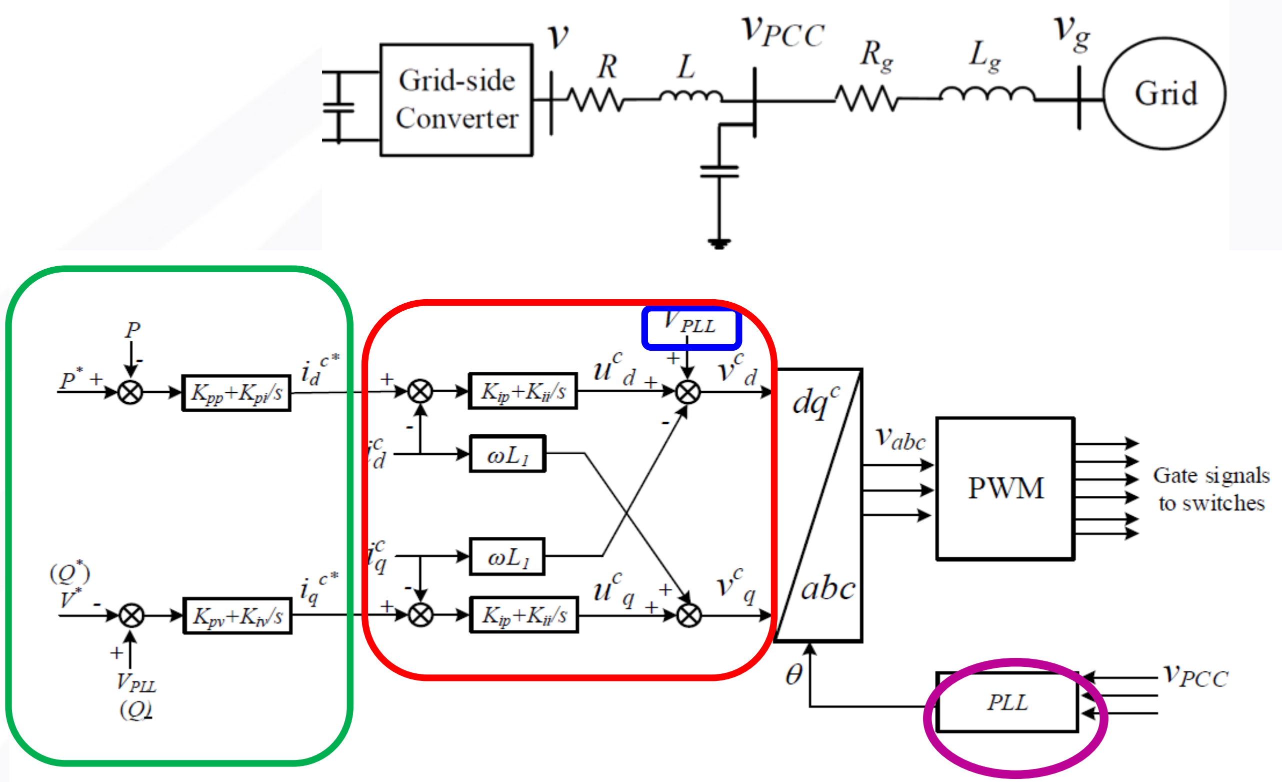
-Lennart Harnefors, ABB Sweden

Voltage source converter control design has considered the following aspects:

- converter current limit (very fast current control)
- decoupling from grid (voltage feedforward)
- decoupled real power and reactive power control **(vector control)**
- Voltage-based synchronization (**Phase-locked-loop: PLL**)

Grid perspective:

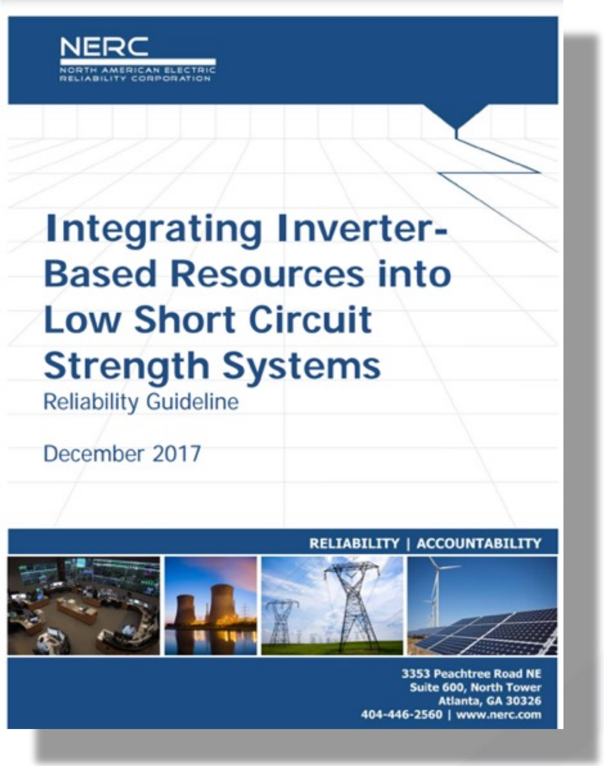
➢ An IBR works as a current source with voltage-based synchronization.



Textbook: Yazdani, Amirnaser, and Reza Iravani. *Voltage-sourced converters in power systems: modeling, control, and applications*. John Wiley & Sons, 2010.

When IBRs meet grids: Weak Grid Strength

Weak grid impact on voltage



- Sebastian Achilles (General Electric)
- Andrew Isaacs (Electranix)
- Jason MacDowell (General Electric)
- Charlie Smith (UVIG)

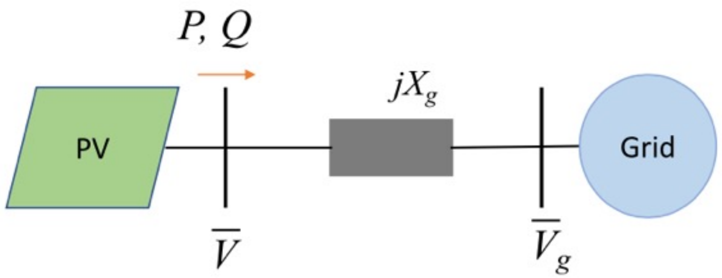
Name	Entity
Sebastian Achilles	General Electric
Andrew Isaacs	Electranix
Jason MacDowell	General Electric
Jose Conto	Electric Reliability Council of Texas
Shih-Min Hsu	Southern Company
Hamody Hindi	Bonneville Power Administration
Al McBride	ISO New England
Mohamed Osman	North American Electric Reliability Corporation
Ryan Quint	North American Electric Reliability Corporation

"electrical system strength refers to the **sensitivity of the resource's terminal voltage** to variations of current injections. In a "strong" system, voltage and angle are relatively insensitive to changes in current injection from the inverter-based resource, while this sensitivity is higher in a "weak" system."

"Weak grids experience a **high sensitivity of voltage to changes in power (i.e., higher dV/dP, dV/dQ)**, and are more prone to potential voltage collapse conditions. **Attempting to push active current during low voltage conditions could further degrade system voltage and result in collapse**. Reactive current should be given priority during fault conditions in these weak grid conditions; however, studies should ensure that reactive current contribution during fault conditions does not cause voltage overshoot or other problems that could trip the inverters. "

Index of grid strength:
short circuit ratio (SCR) = 1/Xg
Grid impedance: Xg

Quantitative analysis: influence of current injection on voltage

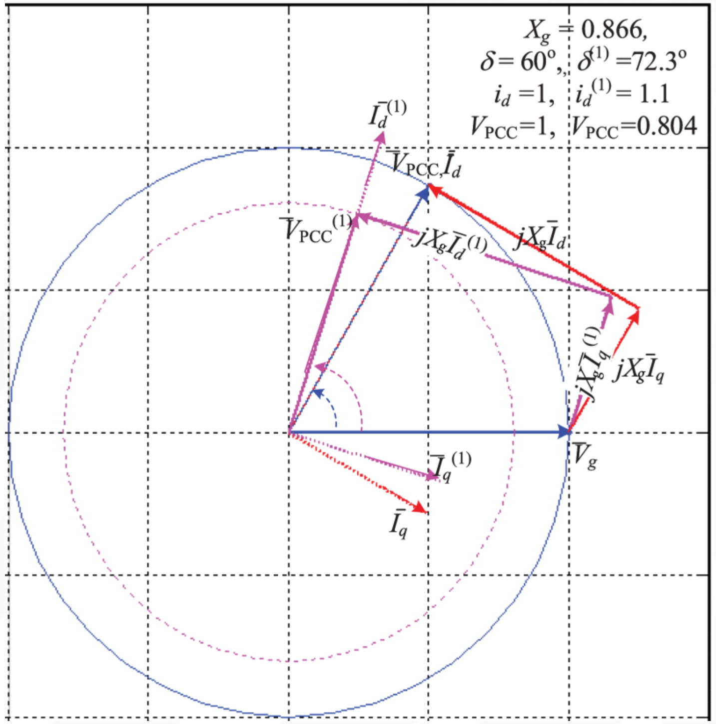


$$v_d + jv_q = (jX_g)(i_d + ji_q) + \bar{V}_\infty$$

⇩

$$\Delta V = \Delta v_d = -X_g \Delta i_q - \frac{X_g}{\underbrace{\sqrt{\left(\frac{V_\infty}{X i_d}\right)^2 - 1}}_{c}} \Delta i_d$$

An increase in d-axis (pushing more real current/power) leads to decrease in voltage.

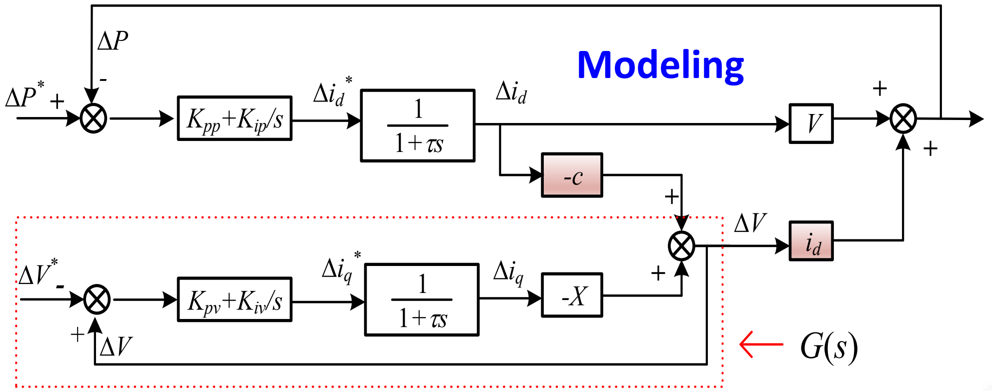


A numerical example:

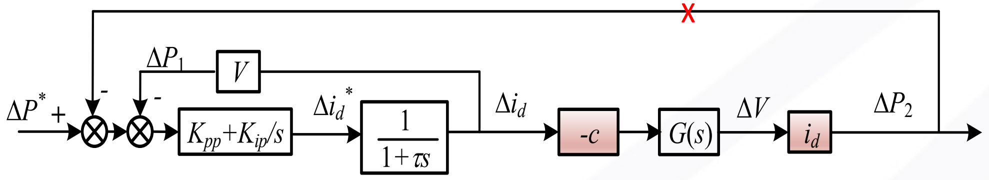
Pushing 10% more real current leads to 20% reduction in voltage when the short circuit ratio is 1.15.

- L. Fan and Z. Miao, "An Explanation of Oscillations Due to Wind Power Plants Weak Grid Interconnection," IEEE TSTE,2018.
- Y. Li, L. Fan and Z. Miao, "Stability Control for Wind in Weak Grids," in IEEE Transactions on Sustainable Energy, vol. 10, no. 4, pp. 2094-2103, Oct. 2019,

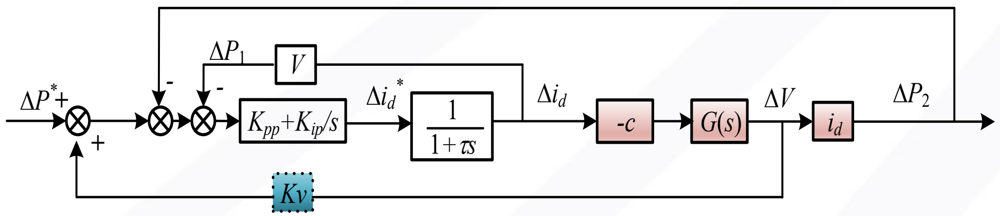
Analysis: effect of IBR's vector control



Modeling



Instability mechanism



Control solution

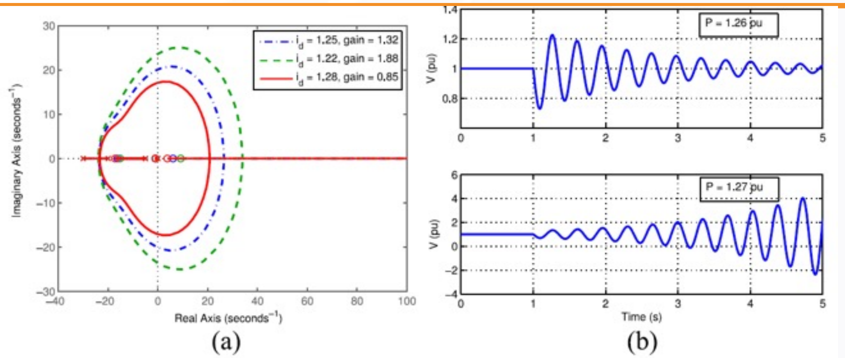


Fig. 3. (a) Effect of P or i_d on root loci. (b) Simulation results. When i_d = 1.28 pu, the closed-loop system is unstable. Other parameters: $\tau = 0.05$ s, $X = 0.75$, $K_p = 1$, $K_i = 1$, $K_{pv} = 1$, $K_{iv} = 10$, $V = v_d = 1$.

Insights:

- High power transfer and weak grid strength lead to instability
- Fast voltage control is beneficial
- Slow power control is beneficial
- "Decoupling" V and P can improve voltage stability

Events documented in the IEEE IBR SSO TF paper

#3: (2010) Oklahoma Gas & Electric (OG&E) observed 13- Hz oscillations at two nearby WPPs [4]. The oscillations occurred when wind farm output was above 80 percent of its rated level and the magnitude of oscillation reached 5% of the 138-kV voltage. OG&E **curtailed the plant's output** until the manufacturer made modifications to the wind power conversion system.

#4: (2011) 4-Hz oscillations were observed at a type-4 WPP in Texas region after a transmission line tripped [18].

Line tripping
High power
Voltage control

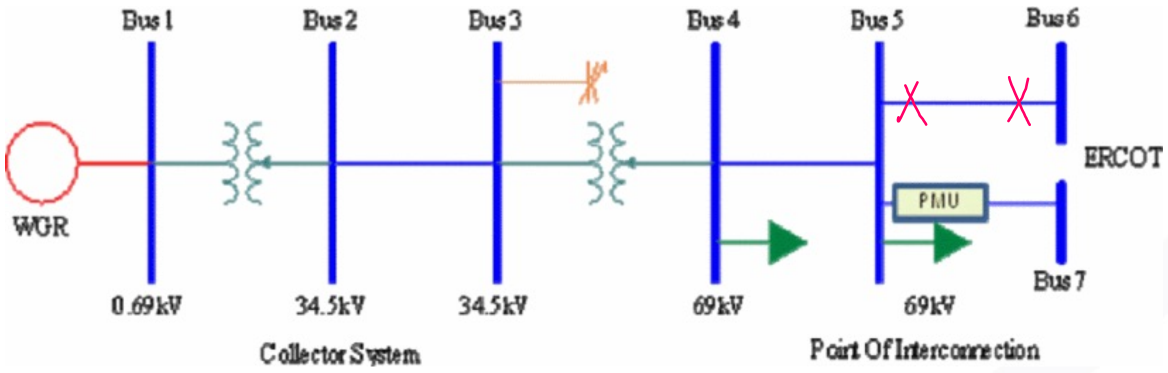
#5 (2011-2014) Since 2011, oscillations were observed by BPA during high wind generation conditions [4]. A 450- MW type-4 WPP located in Oregon was identified as the source. In summer 2013, BPA's phasor measurement unit (PMU) monitoring system identified **5-Hz oscillations in voltage, real and reactive power**. In early 2014, BPA detected 14-Hz oscillations. Reactive power oscillations reached 80 Mvar peak to peak **while power reached 85% of the rated level**. The wind generator manufacturer upgraded their **voltage control** and no oscillations have been detected since.

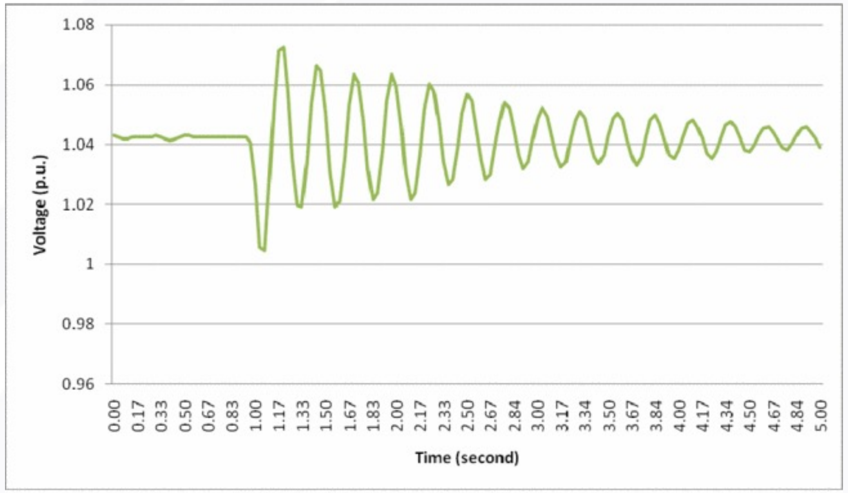
#6 (2011-2012) OG&E reported two wind oscillation events, one in December 2011 and another one in December 2012. **Both were triggered due to line outage.** For the 2012 event, 3-Hz oscillations appeared at a 60-MW WPP after a line outage [4**].** **Curtailing the power** helped restore the system. OG&E worked with the WPP manufacturer to **tune the WPP control parameters,** resolving the issue.

#15 (2019) Hydro One 3.5-Hz oscillations were observed **in real power and reactive power** measurement for two 230-kV type-4 WPPs in Hydro One after a planned 230-kV bus outage. The outage caused a significant **reduction in system strength viewed from the WPPs**. A nearby 150-kV solar PV also reported undamped **reactive power oscillations**.

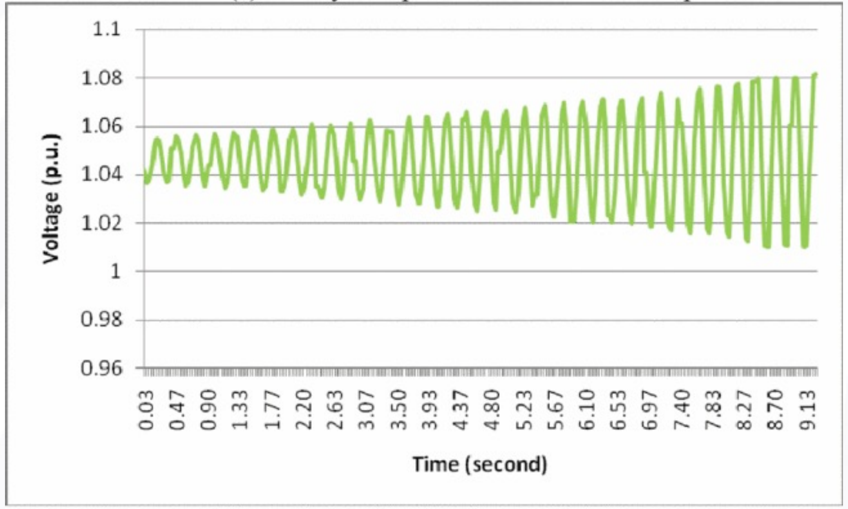
- Y. Cheng *et al.*, "Real-World Subsynchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources," in *IEEE Transactions on Power Systems*, vol. 38, no. 1, pp. 316-330, Jan. 2023, doi: 10.1109/TPWRS.2022.3161418.

Texas 4-Hz oscillations (2011)





(a) Poorly-damped oscillation at low output



(b) Un-damped oscillations at high output

At normal conditions, the WPP was connected to the ERCOT grid through two 69-kV transmission lines. When one 69-kV transmission line was out of service for maintenance, **the SCR reduced below 2** and undamped oscillations appeared. Measurement recordings are presented in Fig. 11.

ERCOT successfully replicated the oscillation events in the study. The oscillations was identified to be associated with the WPP's voltage control. **Slowing down the voltage control** can help mitigate the oscillations.

➢ S. -H. Huang, J. Schmall, J. Conto, J. Adams, Y. Zhang and C. Carter, "Voltage control challenges on weak grids with high penetration of wind generation: ERCOT experience," *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1-7, doi: 10.1109/PESGM.2012.6344713.

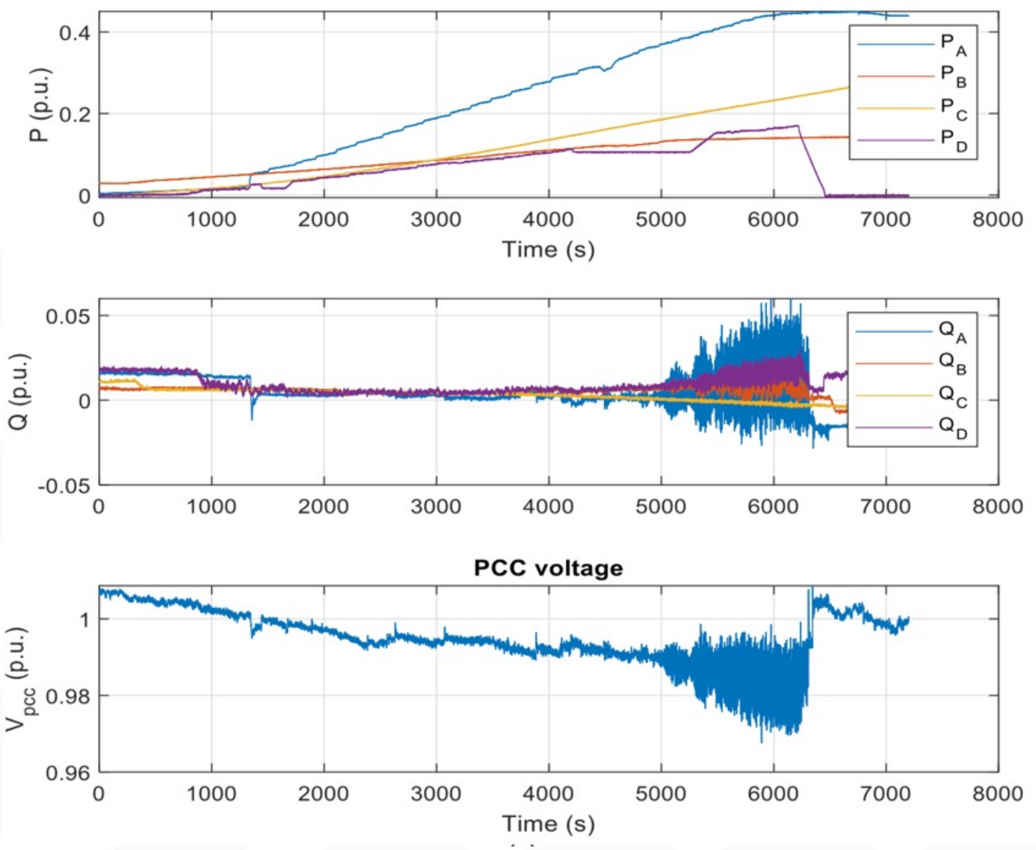
0.1-Hz solar PV plant volt-var oscillations (2020)

1,000 MW solar PV plants are connected to the same POI bus at 230 kV. Close-by, there is another 1000 MW PV plant. Short circuit capacity is **8,000** MVA.

When solar PV power ramps up to about 80% nominal power, 0.1-Hz oscillations appear in voltage and var, invisible in real power.

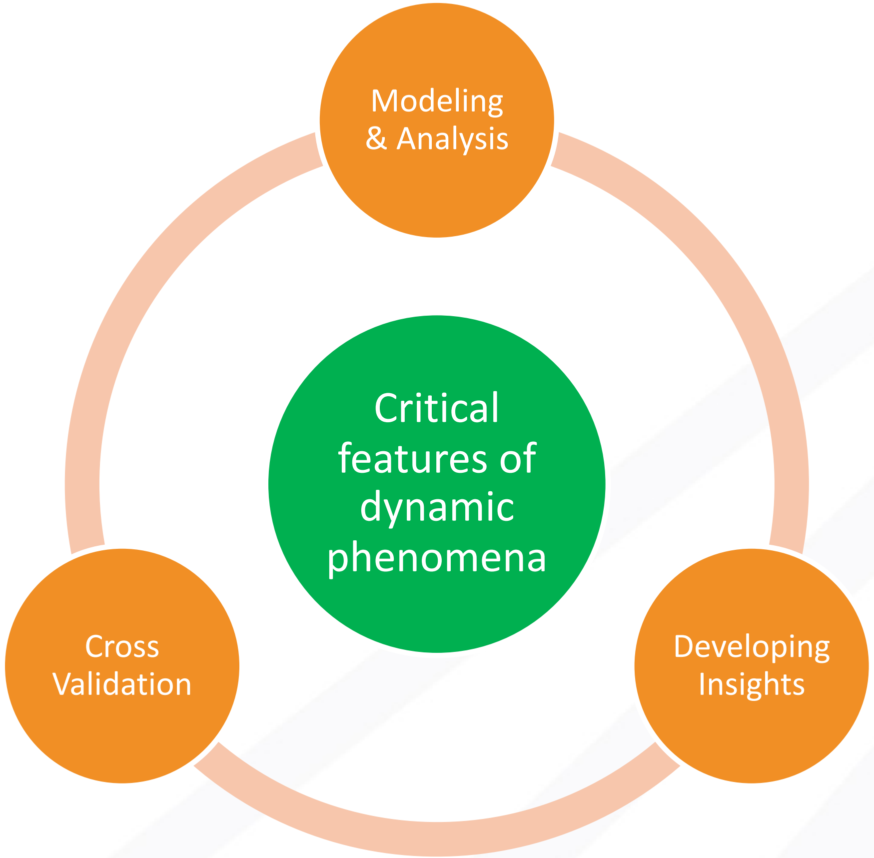
Other features:

- **Oscillations in volt and var**



➢ L. Fan, et al, "**Analysis of 0.1-Hz Var Oscillations in Solar Photovoltaic Power Plants**," IEEE TSTE Jan 2023.

Weak grid oscillations: Mechanism Analysis

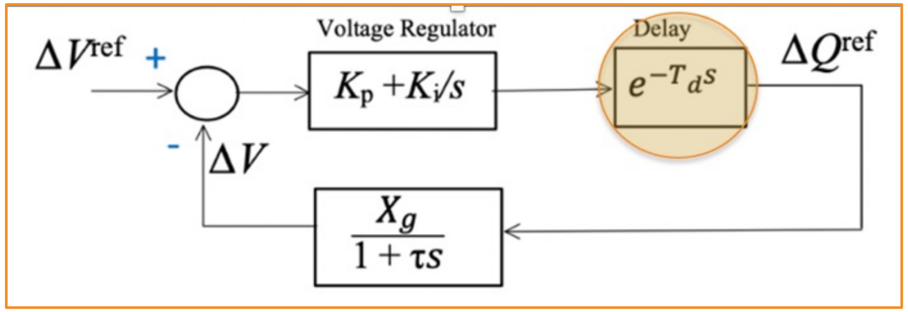


Critical features:

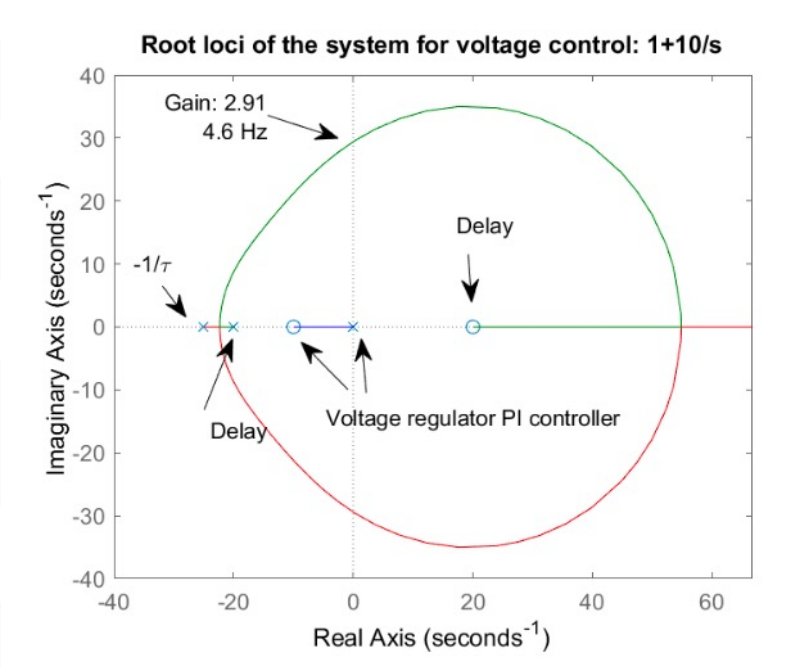
- When grid strength reduces, oscillations may appear.
- High power exporting makes stability worse.
- Have to do with plant-level voltage control; **slowing down voltage control mitigated oscillations (ERCOT experience)**
- Generally observable in voltage, real power and reactive power. Sometimes not observable in real power.

Real-world experience contradicts analysis results.

Revisit the assumptions: Plant-level control vs. inverter level control



- It is crucial to consider the delay effect
  - ➢ Oscillations are due to plant-level voltage control with delay. Larger gains make oscillations worse.
  - ➢ If the voltage control is implemented in inverter level, larger voltage gains make stability better.



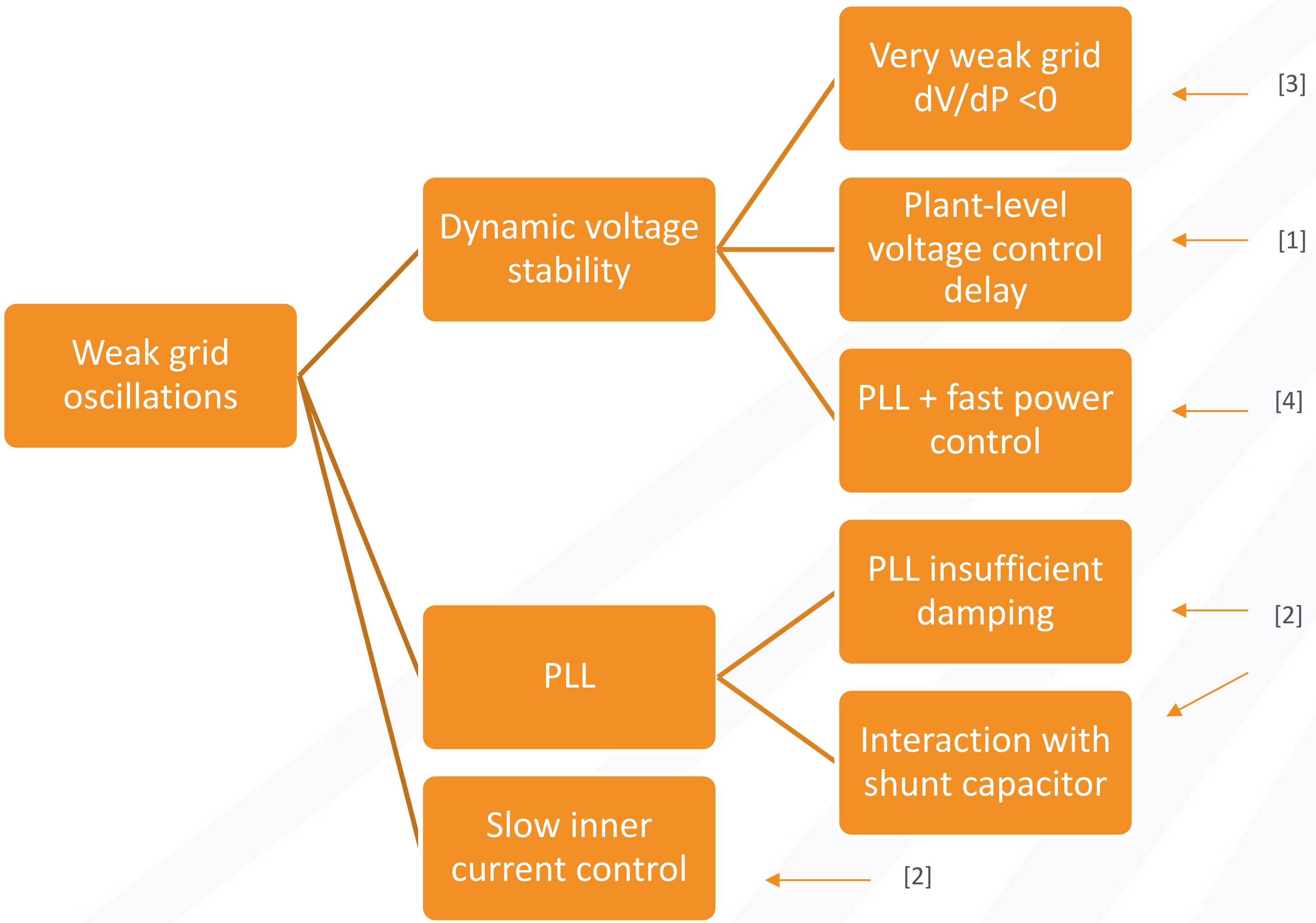
4-Hz oscillations at SCR = 2.

Lessons learned:

- ➢ Fast voltage control at inverter-level is beneficial.
- ➢ Fast voltage control at plant-level may cause issues at weak grid condition.

➢ IEEE PES IBR SSO TF paper --- Y. Cheng, *et al.*, "Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources," in *IEEE TPWRS 2023.*

Weak grid oscillations: variety of root causes



- [1] Y. Cheng, L. Fan, *et al.*, "Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources," in *IEEE TPWRS.*
- [2] L. Fan *et al.*, "Real-World 20-Hz IBR Subsynchronous Oscillations: Signatures and Mechanism Analysis," in *IEEE TEC*.
- [3] L. Fan, Z. Miao, " An Explanation of Oscillations Due to Wind Power Plants Weak Grid Interconnection," IEEE TSTE 2018
- [4] L. Bao et al, "Hardware Demonstration of Weak Grid Oscillations in Grid-Following Converters," NAPS 202

Control upgrade: AEMO 7-Hz event (2015-2019)

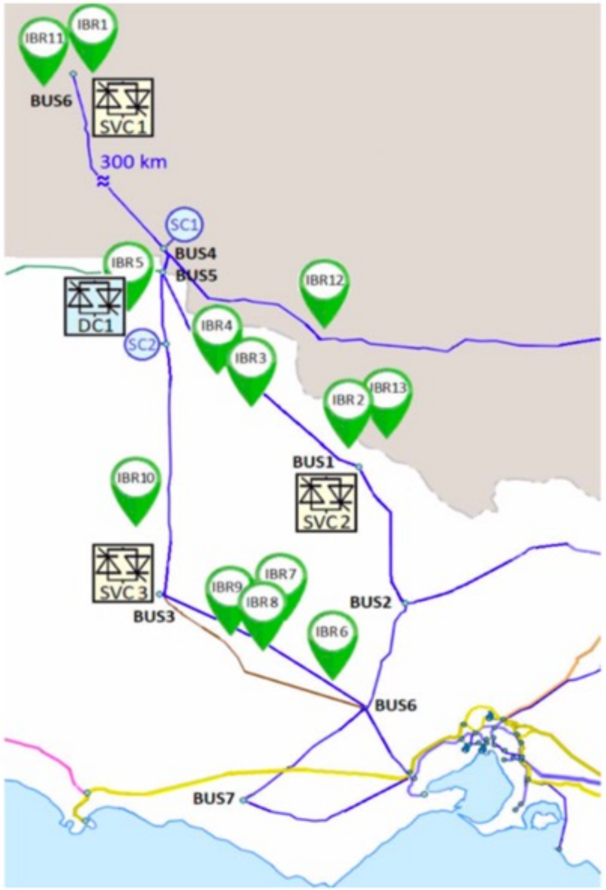


Fig. 14: West Murray region. Source: AEMO; used with permission.

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

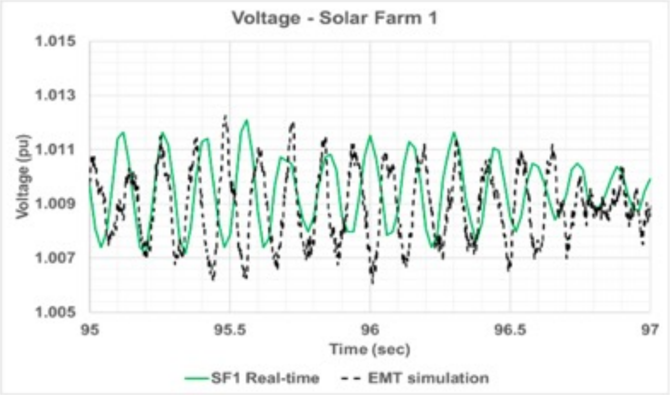
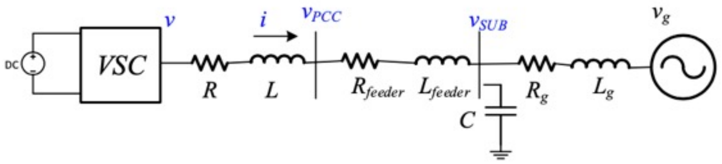


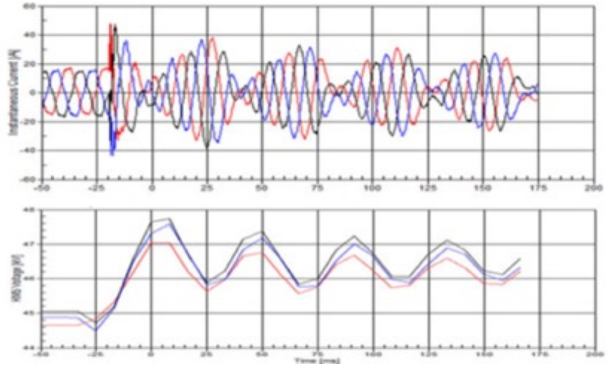
Fig. 15: AEMO 7-Hz oscillations. Voltage after a disturbance. Source: AEMO; used with permission.

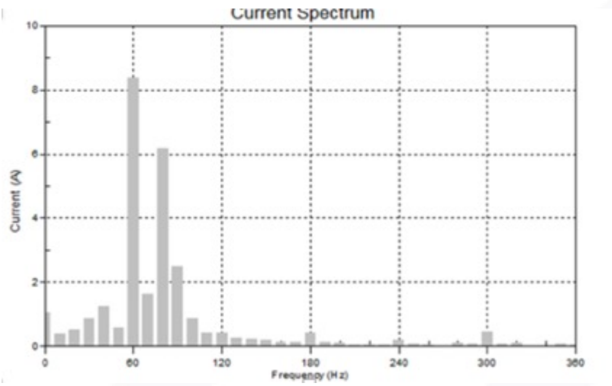
For mitigation via IBR control system parameter tuning, **inverter-level control upgrade** has been conducted by the OEM. The upgrade includes **PLL parameter tuning,** introduction of a **fast reactive current compensation loop**, **plant-level voltage control tuning**.

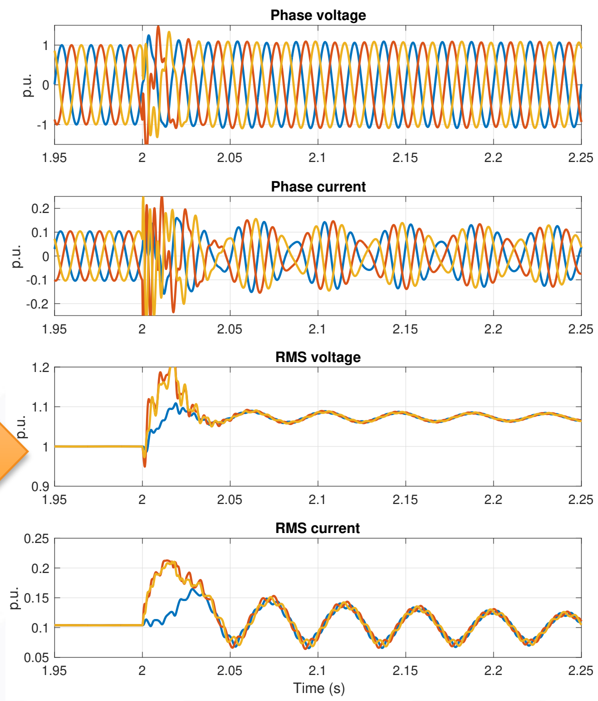
- A. Jalali, B. Badrzadeh, J. Lu, N. Modi, and M. Gordon, “System strength challenges and solutions developed for a remote area of australian power system with high penetration of inverter-based resources,” CIGRE SCIENCE & ENGINEERING, vol. 20, pp. 27–37, Feb 2021.

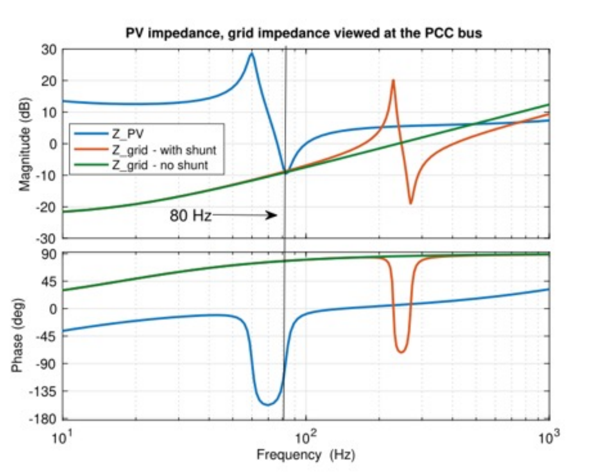
Circuit upgrade: Hydro One 20-Hz/80-Hz event (2015)











SCR = 4, stability issue
If SCR is greater, no stability issue

Replication study shows that 80 Hz oscillations appear in abc frame while 20-Hz oscillations appear in RMS.

Solution: Close a tie breaker to reduce the grid impedance (or improve grid strength)

- Li, Chun. "Unstable operation of photovoltaic inverter from field experiences." IEEE TPWRD 2017.

When IBRs meet grids:

Shunt Compensation & Overvoltage

Sub-cycle overvoltage: Canyon 2 event


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California Event: October 9, 2017
Joint NERC and WECC Staff Report

February 2018

RELIABILITY | ACCOUNTABILITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report

Southern California Events: April 20, 2018 and May 11, 2018
Joint NERC and WECC Staff Report

January 2019

RELIABILITY | ACCOUNTABILITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
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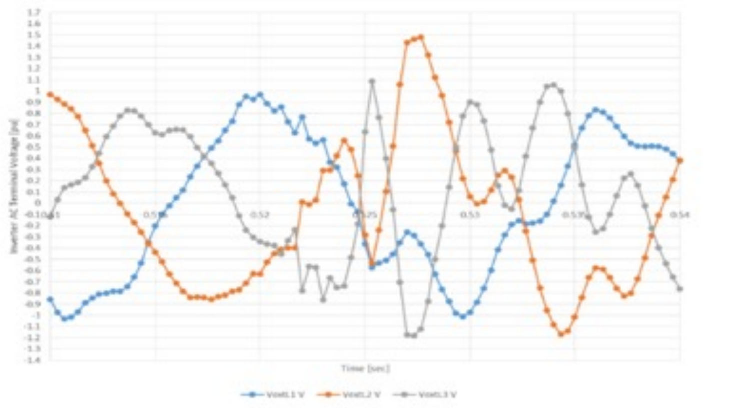


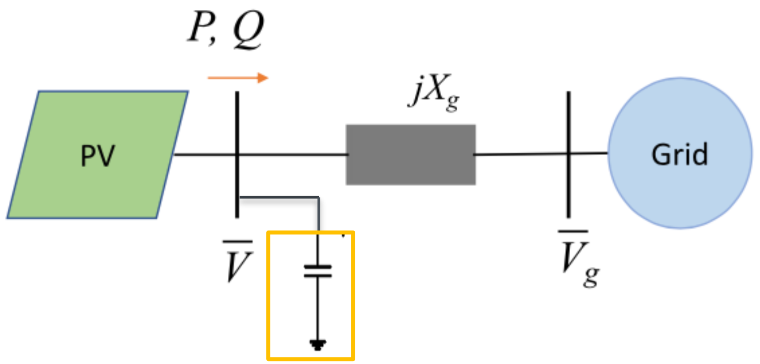
Figure 2.3: Phase Voltages during On-Fault Conditions

Key Finding: During fault events, there appears to be an interrelationship between momentary cessation, **in-plant shunt compensation**, and transient overvoltage conditions that result in inverter tripping. While this has been observed at multiple locations for multiple events, the causes and effects are not well understood and require detailed EMT simulations for further investigation.

Recommendation: EMT studies should be performed by the affected GOPs, in coordination with their TO(s), to better understand the cause of transient overvoltages resulting in inverter tripping. These studies should also identify why the observed inverter terminal voltages are much higher than the voltage at the point of measurement (POM), and any protection coordination needed to ride through these types of voltage conditions.

NERC report page 18

Analysis: the LC mode due to the shunt capacitor

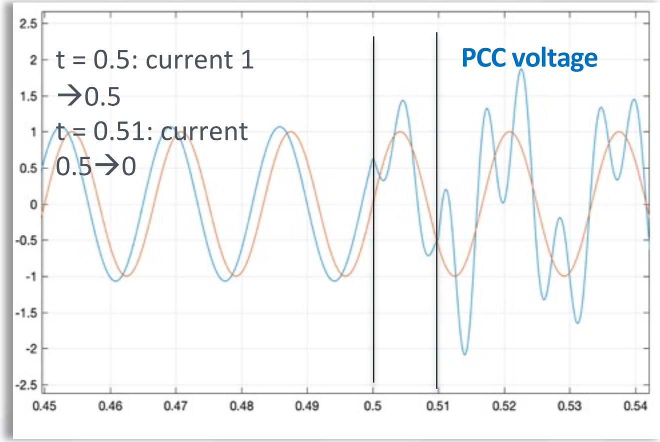


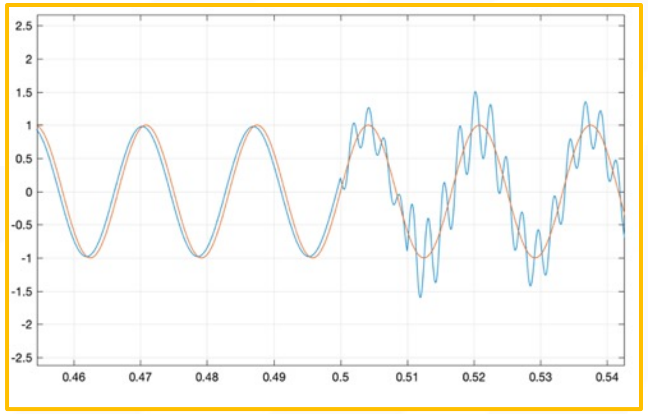
$$i(s) = \left(Cs + \frac{1}{R+Ls}\right) v_{\mathrm{PCC}}(s)$$

$$v_{\mathrm{PCC}}(s) = \frac{1}{LC}\cdot\frac{Ls+R}{s^2+\frac{R}{L}s+\frac{1}{LC}}\cdot i(s)$$

$$s^2 + (R/X)\omega_0 s + \frac{\omega_0^2}{X\cdot B} = 0$$

$$s^2 + 0.1\omega_0 s + \left(\frac{\omega_0}{\sqrt{0.6\times 0.2}}\right)^2 = 0$$





For X = 0.6 pu (SCR about 2), shunt compensation 0.2 pu, the oscillation frequency is about 2.88*60 = 173 Hz.

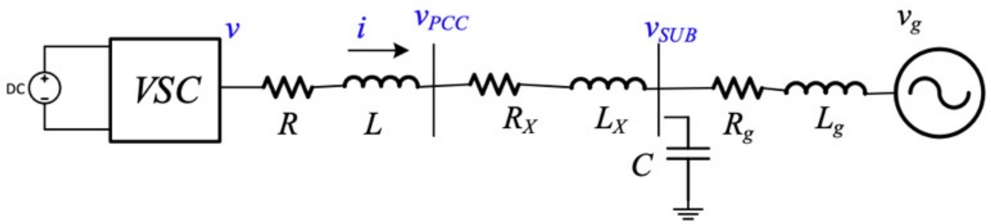
X (line) = 0.2, B (shunt) = 0.1→420 Hz

- **Overvoltage has to do with the LC mode determined by the grid impedance and shunt compensation**
- **current source reduction (momentary cessation) excited such modes and created overvoltage.**

❑ L. Fan, Z. Miao, M. Zhang “**Subcycle Overvoltage Dynamics in solar PVs**,” *IEEE TPWRD* 2020.

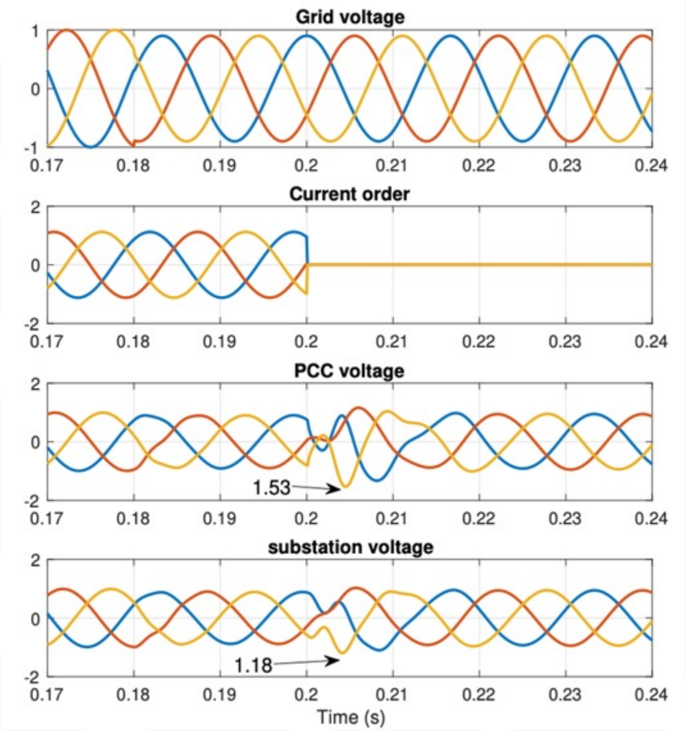
Analysis: more severe overvoltage in the solar PV terminal bus

- Modeling assumption revised:



❖ A solar PV may show **capacitive with negative resistance due to feedforward unit and delay**. **This leads to more severe overvoltage at its terminal bus.**

❖ **Solution**: to avoid solar PV tripping, filtered voltage is used for solar PV protection.



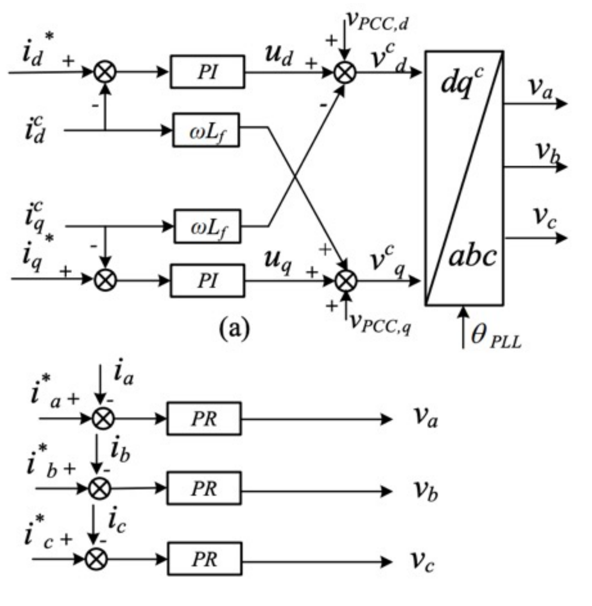
Upon current order ramping down, the PCC shows more severe overvoltage compared to the substation bus.

➢ L. Fan, Z. Miao, "The Cause of Sub-Cycle Overvoltage: Capacitive Characteristics of Solar PVs," 2022 *Electric Power Systems Research*.

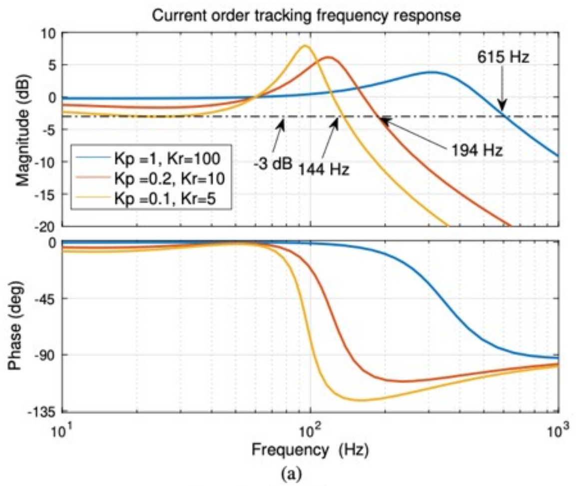
When IBRs meet grids:

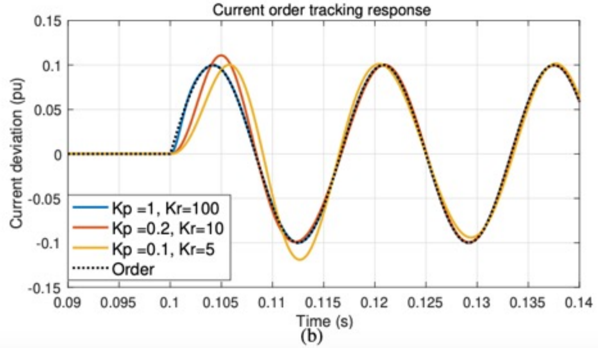
Small IBR impedance & Overcurrent

Causes of small IBR impedance

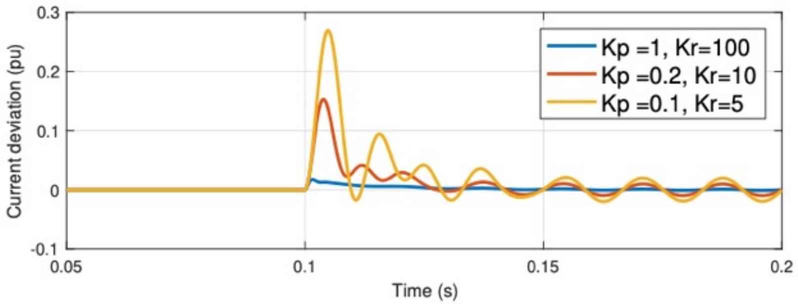


(b)





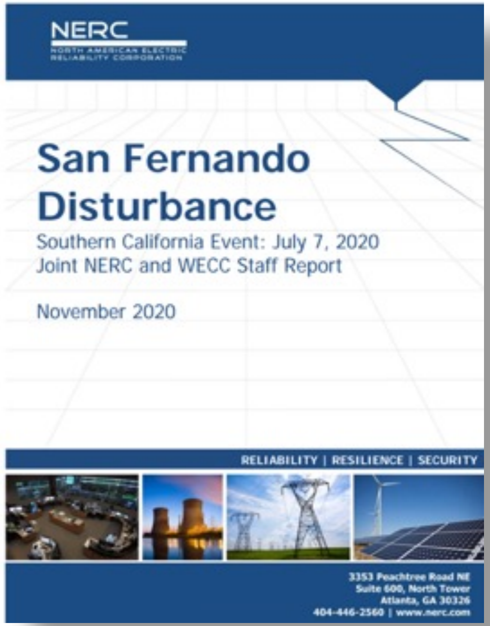
10% change in grid voltage



From control to dynamic performance

- ✓ Small control gain, ineffective feedforward unit, and large delay all slow down current control
- ✓ In summary, slow current control manifests as small IBR impedance
- ✓ Solution: control upgrade

➢ L. Fan, Z. Miao, **"Root Cause Analysis of AC Overcurrent in July 2020 San Fernando Disturbance,"** *IEEE TPWRS, 2022*.



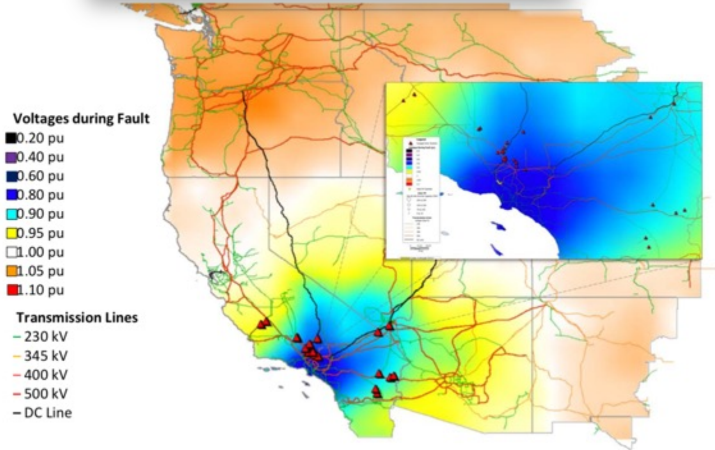


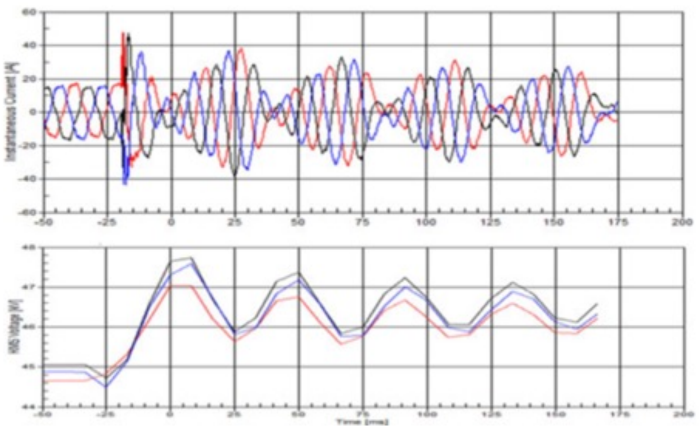
Figure I.1: Map of the Fault Location and Affected Facilities

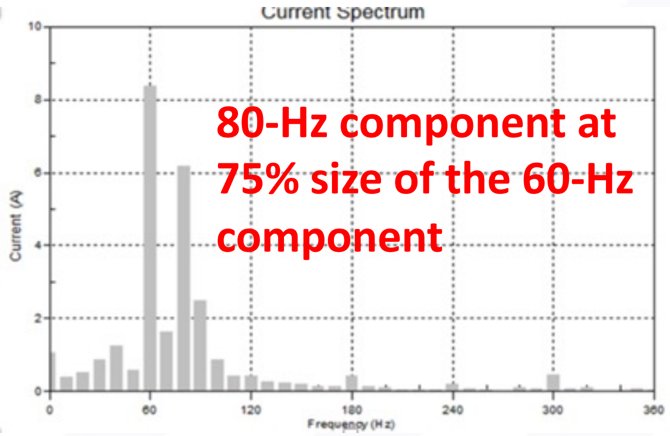
Causes of Inverter Tripping

Three types of inverter tripping were identified in this disturbance: ac overcurrent tripping, dc low voltage tripping, and ac low voltage tripping. Multiple inverter models from one inverter manufacturer had ac overcurrent and dc low voltage tripping attributed to them. Multiple solar PV facilities had partial tripping of inverters for both reasons; however, the ac overcurrent tripping was more common. Brief descriptions of the observed tripping are provided below:

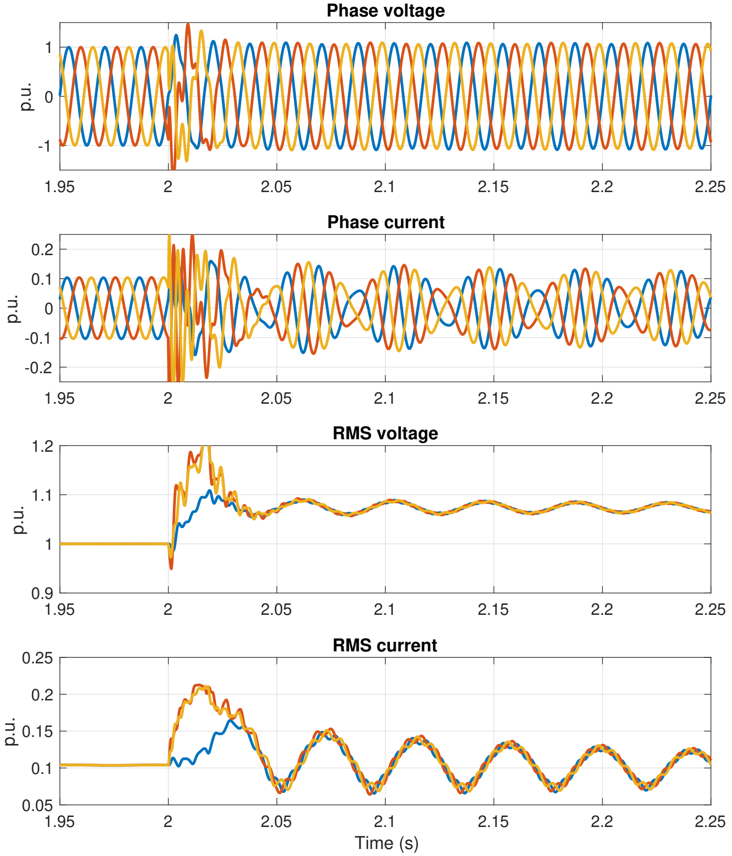
- **AC Overcurrent:** The most prominent inverter tripping occurred when inverter ac currents exceeded 150% of rated current or when ac output power exceeded dc input power. This type of tripping was observed at facilities that exhibited momentary cessation (older models of inverter) as well as at facilities that exhibited current injection during the disturbance. Follow up with other inverter manufacturers highlighted that this type of tripping may occur if the electronic switches (i.e., insulated-gate bipolar transistors (IGBTs)) within the inverter are not tightly controlled at the time of a large ac-side system faults such that uncontrolled current is injected into the low ac voltage conditions and can lead to instantaneous overcurrent conditions. GOPs were unable to provide details regarding this type of tripping since it is based on inverter control topology.
- **DC Low Voltage:** During this disturbance, dc low voltage tripping was also observed. Settings were provided for this trip threshold and were set fairly robustly but with a very short time delay since dc voltage must be strictly controlled. However, if the power electronic switches within the inverter are not appropriately controlling current when an ac-side severe low voltage occurs along the same lines as described above, current injection into a short-circuit condition will deplete the dc bus energy supply, and the voltage will drop rapidly. It is believed that these two trip mechanisms are related, especially since inverters of similar make and model exhibited similar behavior at different facilities.
- **AC Low Voltage:** One solar PV resource experienced "Fast AC Low Voltage" tripping that initiates a trip when voltage falls below a defined low voltage threshold for a predetermined period of time. In this case, the GO reported that the plant experienced voltage below an undefined trip threshold for more than 10 cycles. However, the fault only persisted for less than 3 cycles, so it is unlikely that POI voltage for this facility remained low for 10 cycles. However, since high-speed data is not available from the inverters or from the plant POI, further investigation to better understand any discrepancies was not possible.

80-Hz oscillations in three 10-MW solar PVs (2015)

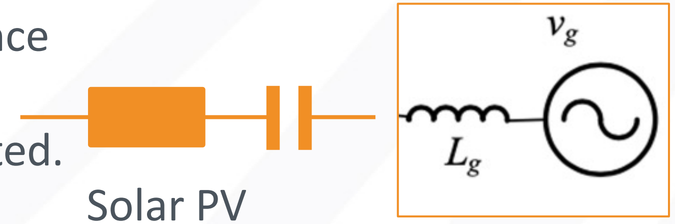




EMT replication study:



- ✓ IBR appears as a capacitive impedance with negative resistance and has a **small size**:
- ✓ A series LC mode at 80 Hz is created.



Solar PV

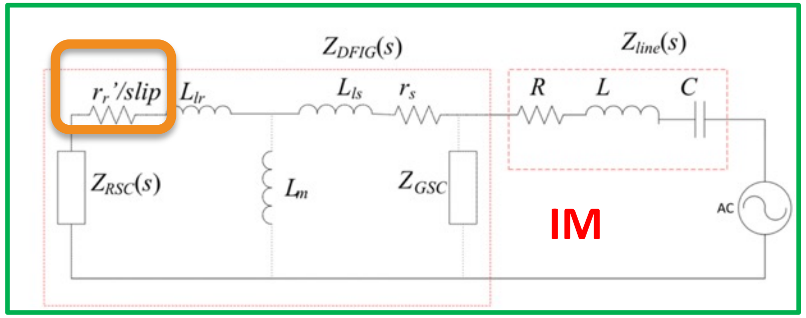
- ✓ **Alternative solution: Control upgrade**

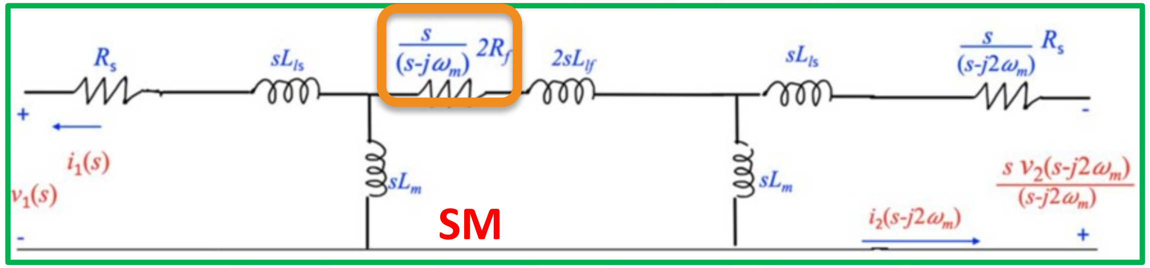
❑ L. Fan, et al, “Real-World 20-Hz IBR Subsynchronous Oscillations: Signatures and Mechanism Analysis” IEEE TEC 2022

When IBRs meet grids:

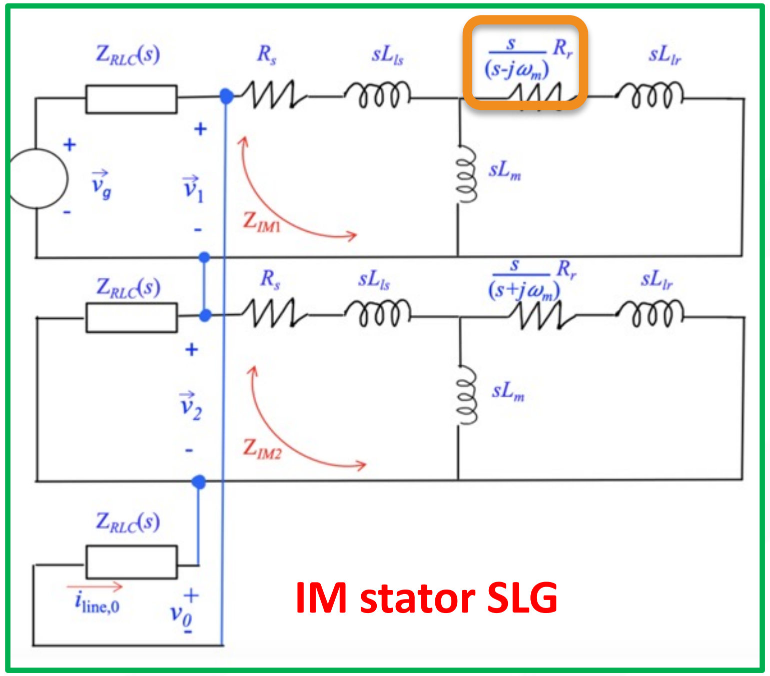
Series Compensation: IGE effect

Mechanism Analysis: Induction generator effect





- Z. Miao and L. Fan, "Generalized Circuit Representation for a Synchronous Machine," in IEEE Transactions on Energy Conversion, doi: 10.1109/TEC.2023.3240584.



- Z. Miao and L. Fan, "A Laplace-Domain Circuit Model for Fault and Stability Analysis Considering Unbalanced Topology," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2022.3230564.

✓ An induction (or synchronous) machine has negative resistance at subsynchronous frequency region.

✓ Unbalanced grid condition mitigates the negative resistance, thus improving stability

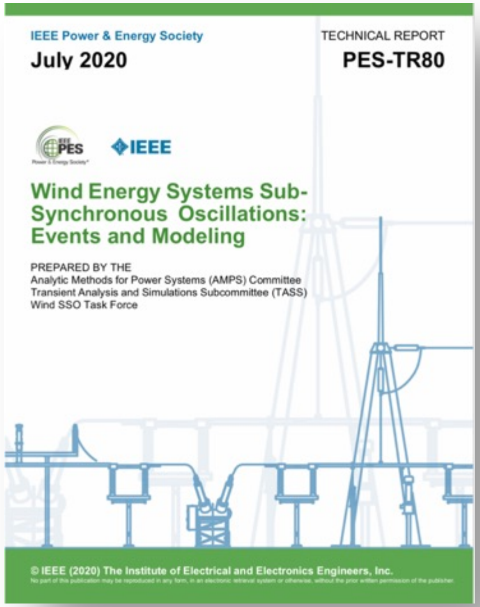
Modeling & Mechanism Analysis:

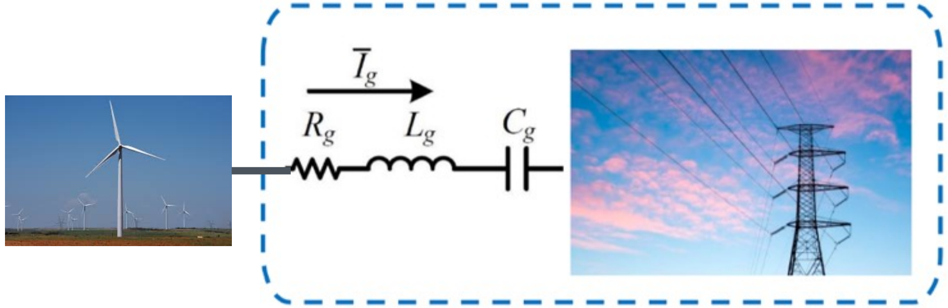
- L. Fan and Z. Miao, “Nyquist-stability-criterion-based SSR explanation for type-3 wind generators,” IEEE trans. Energy Conversion, vol. 27, no. 3, pp. 807–809, 2012.
- Miao Z. Impedance-model-based SSR analysis for type 3 wind generator and series-compensated network. IEEE Transactions on Energy Conversion. 2012 Aug 23;27(4):984-91.
- L. Fan, Z. Miao, “Analytical model building for Type-3 wind farm subsynchronous oscillation analysis”. Electric Power Systems Research, 2021, p.107566.

Control solutions:

- L. Fan, Z. Miao. "Mitigating SSR using DFIG-based wind generation." *IEEE TSTE 2012*
- Y. Li, L. Fan, Z. Miao. "Replicating real-world wind farm SSR events." IEEE TPWRD 2018

2007 Minnesota 9.4 Hz SSO: type-3 wind





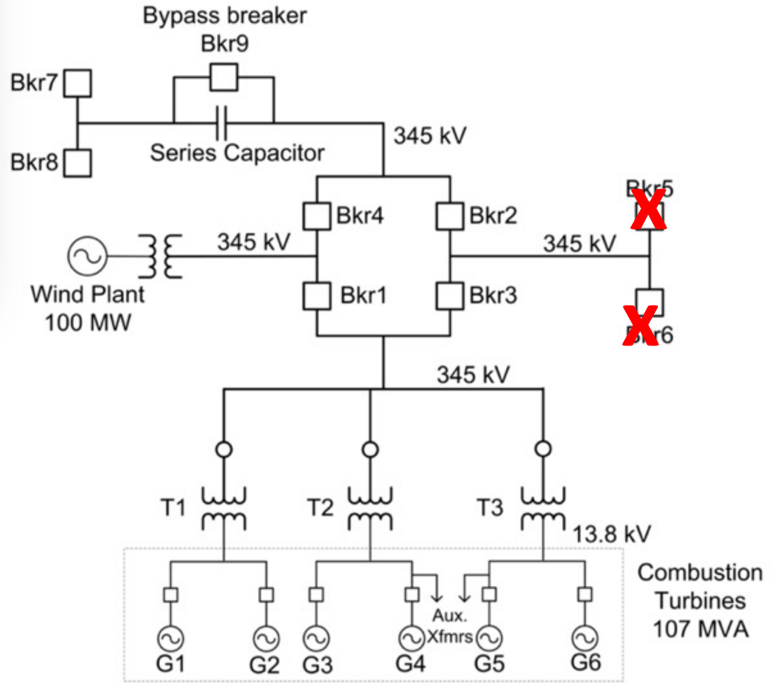


Figure 2.1: 345-kV Transmission system one-line including series compensation.

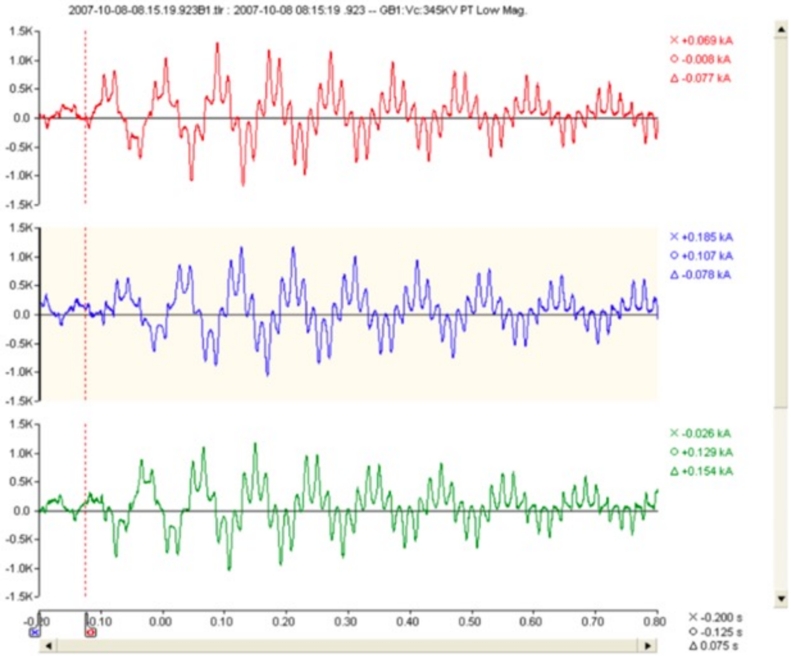
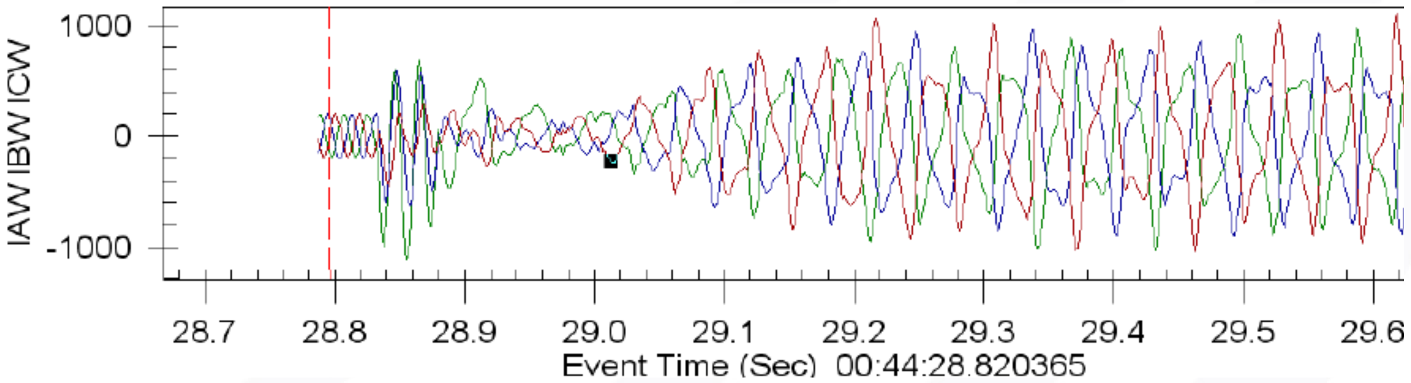


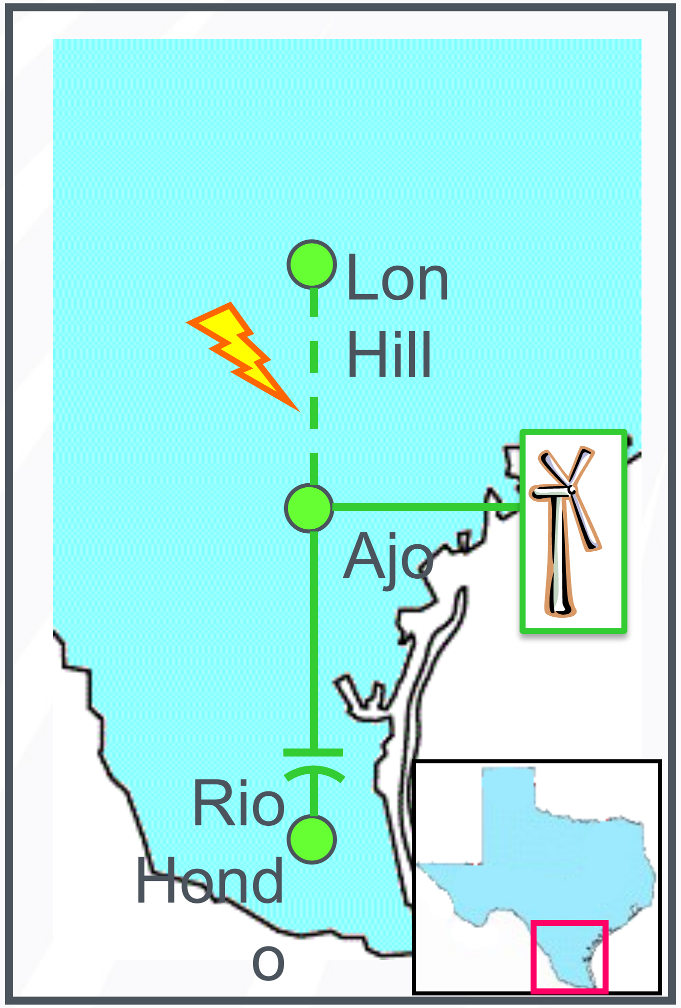
Figure 2.2: WPP Phase A, B, C, currents obtained from DFR, y-axis in Amps and x-axis in Seconds

Source: PES TR-80

South Texas 2009 Event

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

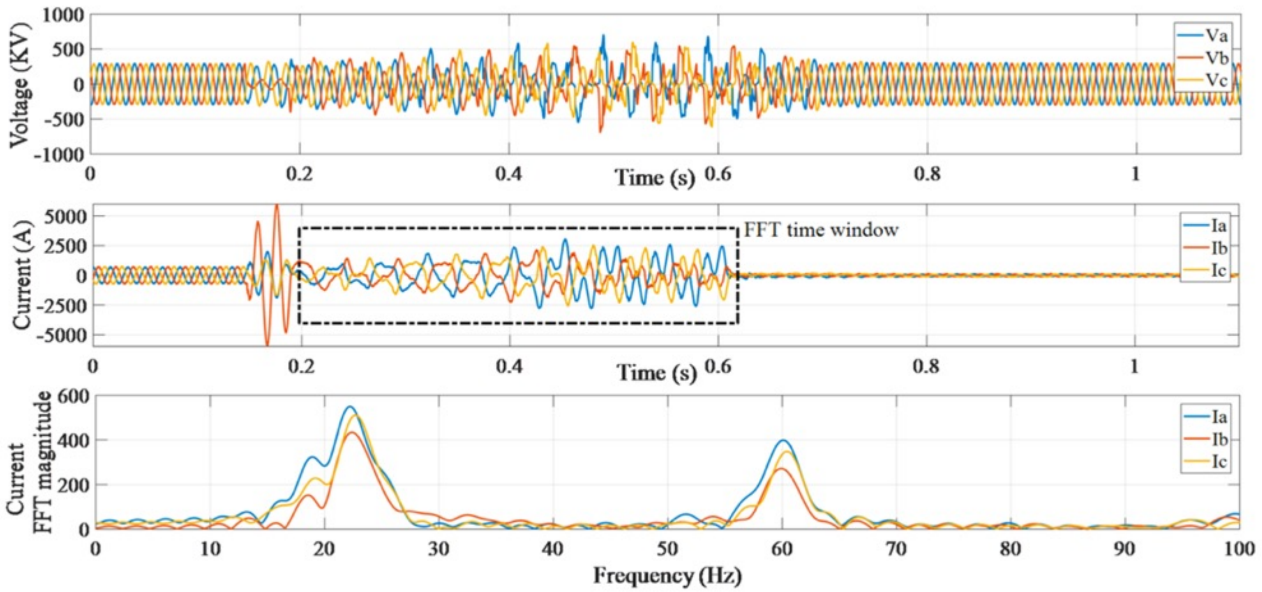


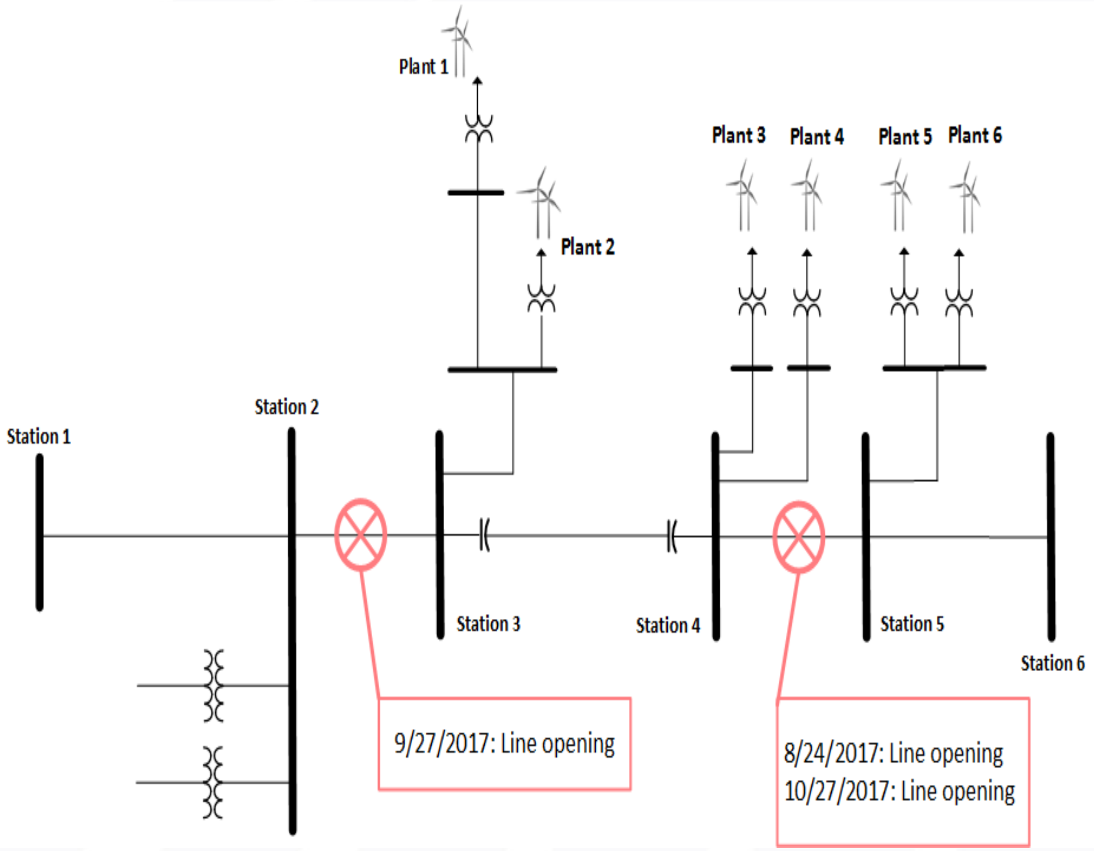


Reference: Chapter 2.2, Task Force Report from IEEE PES Task Force Modeling Subsynchronous Oscillations in Wind Energy Interconnected Systems (Wind SSO TF), by Yunzhi Cheng, Jonathan Rose, John Schmall and Fred Huang

South Texas 2017 Events

- Three type-3 wind SSR events occurred in South Texas in 2017
- Wind plants (DFIG) tripped by SSR protection
- Challenges: The original SSR study failed to capture the SSR risk

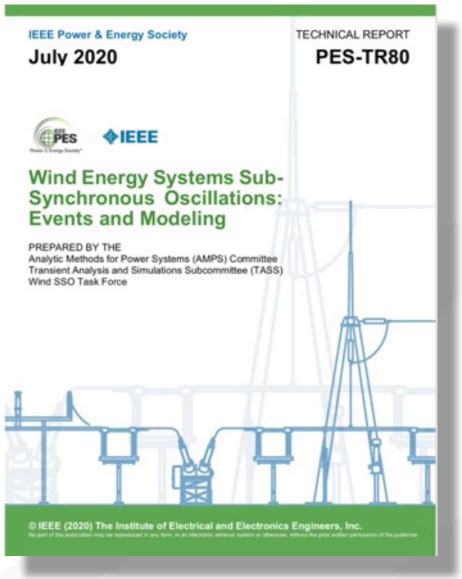


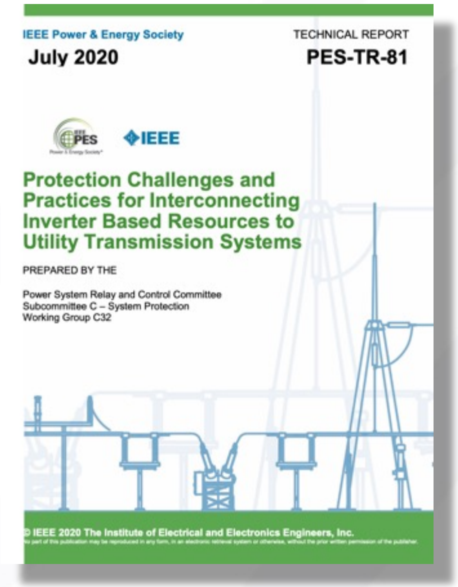


Reference: Chapter 2.2, Task Force Report from IEEE PES Task Force Modeling Subsynchronous Oscillations in Wind Energy Interconnected Systems (Wind SSO TF), by Yunzhi Cheng, Jonathan Rose, John Schmall and Fred Huang

Solutions:

1. Grid operation: avoid radial connection to a series compensated line
2. Protection: bypass the series capacitors if oscillations were detected; wind turbine protection
3. OEM control upgrade





Quotes from E.V. Larsen

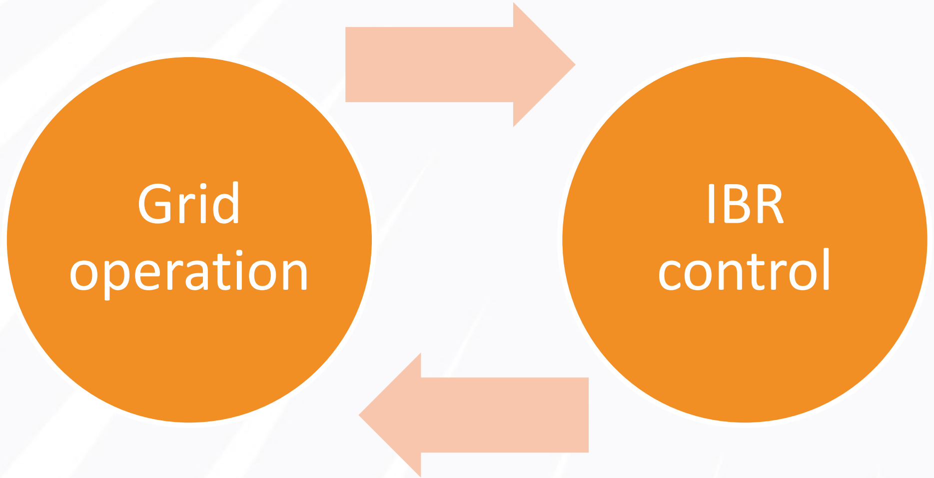
- Special control within the wind generators
- Resonance-damping equipment at the series capacitors
- Resonance-damping equipment at the windfarms
- Transfer-trip schemes to avoid grid configurations that may be unstable

Each project will involve tradeoffs in cost and responsibility that lead to a final design. Arriving at a final design is a complex task involving multiple entities, **including OEMs for the wind generators, wind power developers, transmission owners, and grid operators.**

E. V. Larsen, “Wind generators and series-compensated ac transmission lines,” in *Proc. IEEE PES Td*, 2012, pp. 1–4.

Concluding remarks

- Reliable operation of grids with high penetrations of IBRs requires close collaboration of the grid industry and original equipment manufacturing (OEM) industry.
- Through this DOE project, our team achieves the goals of providing
  - fundamental understandings of IBR dynamic performance under grid disturbances and in weak grids;
  - reliability improving strategies through IBR controls.



Q&A

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