What's on the horizon for mitigation measures:

-Protection, Control, and Operation

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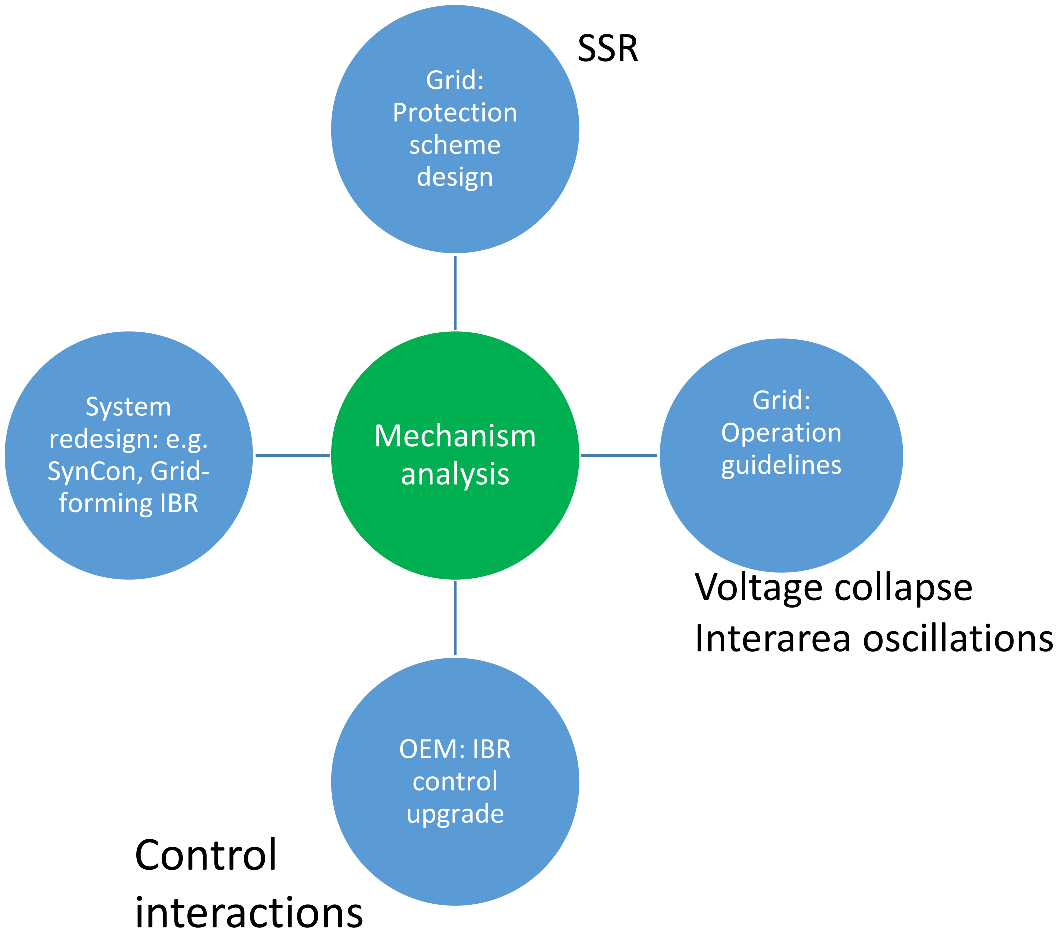
University of South Florida

March 28, 2024

ESIG Spring 2024 Workshop



- **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

Outline

- Traditional oscillation mitigation measures: protection & control
  - SSR Synchronous generator torsional interactions
  - Power grid inter-area oscillations
- Weak grid system redesign: SynCon
  - a measure to enhance voltage and synchronizing stability of inverter-based resources
- Control parameter tuning as oscillation mitigation
  - Grid forming control design

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

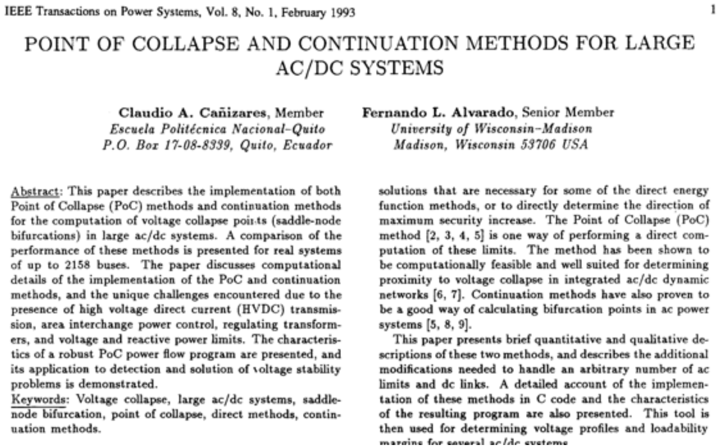
Mariesa L. Crow and Bernard C. Lesieutre

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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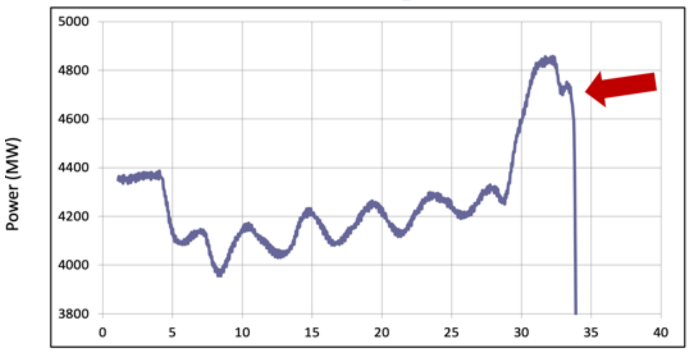
Abstract: This paper describes the implementation of both Point of Collapse (PoC) methods and continuation methods for the computation of voltage collapse points (saddle-node bifurcations) in large ac/dc systems. A comparison of the performance of these methods is presented for real systems of up to 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.

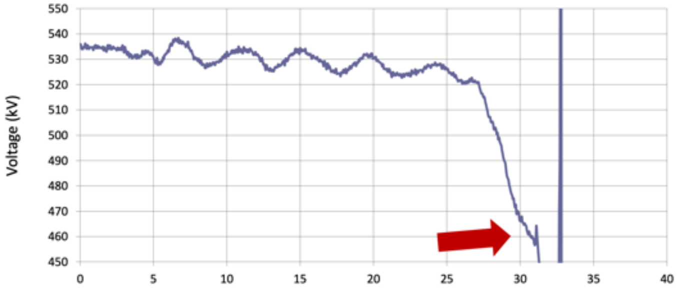
solutions that are necessary for some of the direct energy function methods, or to directly determine the direction of maximum security increase. The Point of Collapse (PoC) method [2, 3, 4, 5] is one way of performing a direct computation of these limits. The method has been shown to be computationally 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.

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



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

Success stories: Interarea oscillations

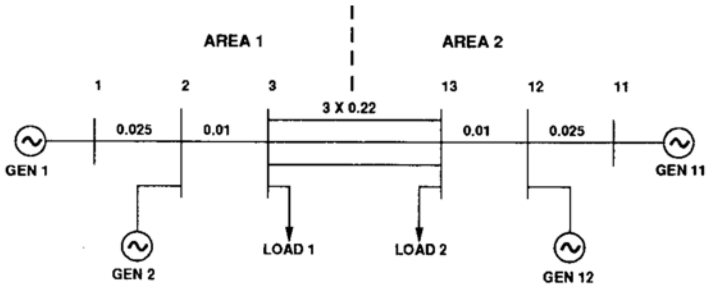


FIGURE 1
Two-Area System

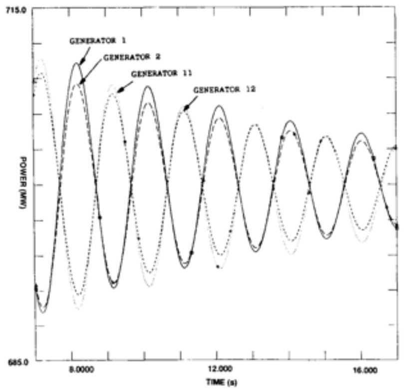
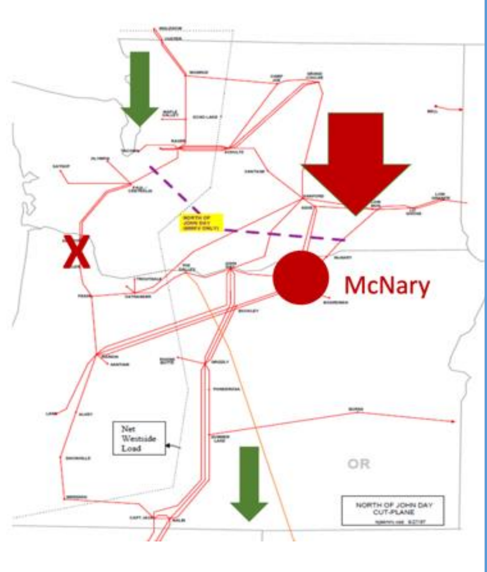
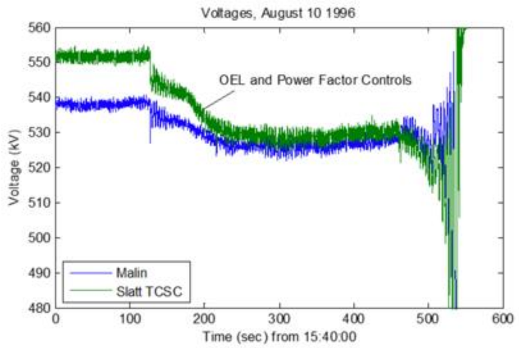


FIGURE 3
Generators' Active Power

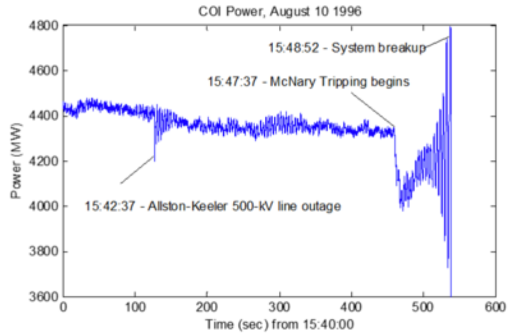
- M. Klein, G. J. Rogers and P. Kundur, "A fundamental study of inter-area oscillations in power systems," in *IEEE Transactions on Power Systems*, vol. 6, no. 3, pp. 914-921, **Aug. 1991,** doi: 10.1109/59.119229.



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:

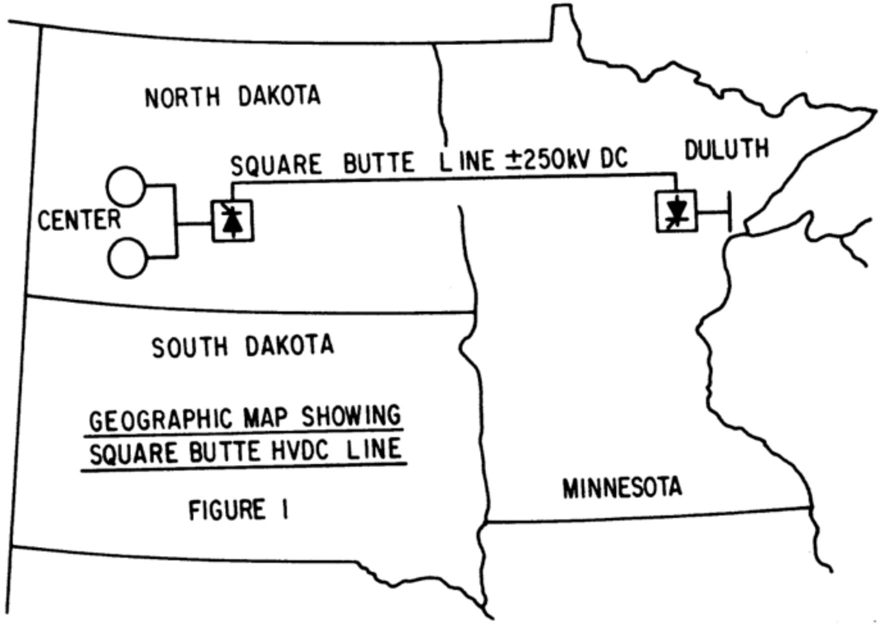
- Interarea oscillation phenomena can be viewed as **dynamic voltage stability**.
- The insight is revealed by use of graph spectrum decomposition technique.

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

Mitigation: Operation guide to reduce power transfer level;

Control: Power system stabilizer (with wide area measurements as input signals)

Success stories: Square Butte HVDC control interactions

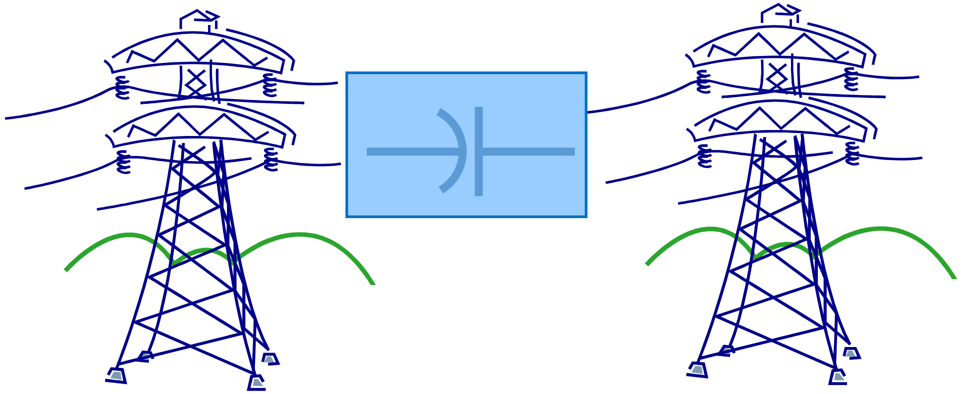


- **Abstract:** Tests on the the modern HVDC system at Square Butte conducted in October 1977 indicated that the HVDC terminal was interacting in an adverse way with **an 11.5-Hz torsional mode of an adjacent turbine-generator unit**. Subsequent analytical work duplicated the field test observations 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: have SSR protection installed.

Subsynchronous resonance (SSR) due to LC resonance

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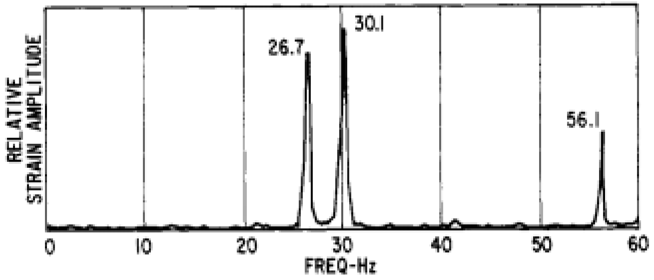
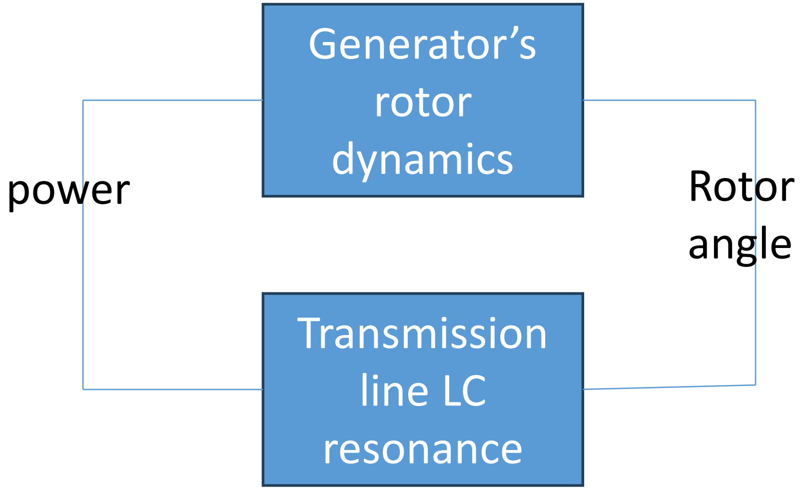


Fig. 7. Synchronization Frequency Analysis

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.

Torsional interaction mechanism and mitigation measures

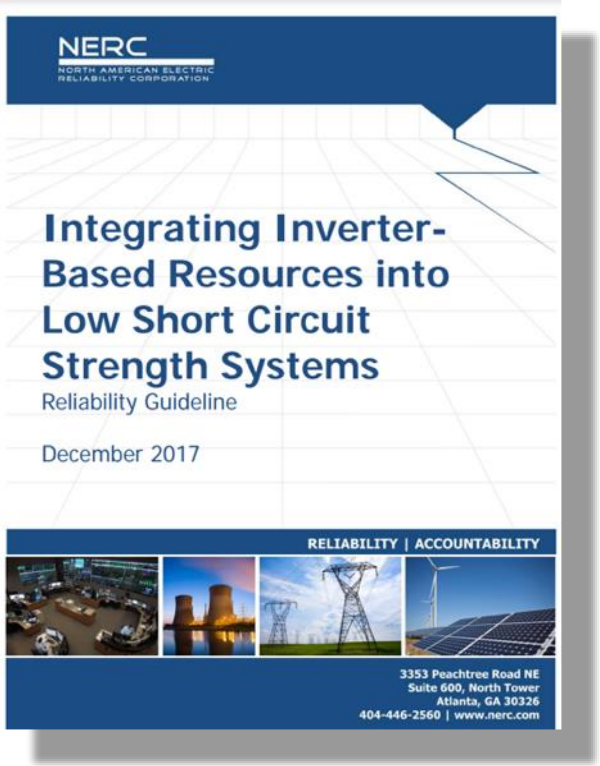


- Mitigation: block the interaction between the two blocks for oscillations in the SSR range
  - 1970s solutions: add a filter in the generator's transformer to block the SSR oscillations.
  - Technology from Tsinghua Xie group: add filters at the generator's terminal

- Torsional interaction mitigation options and cost (ABB to NYISO)
  - #1: SSR Detection at the series capacitor to bypass series capacitor
  - #2: SSR Detection at Generators to Bypass Series Capacitor- $1.3 m
  - #3 RAS – Sort of like operation guide to provide preventive measures. >$1 m
  - #4 SSR Protective Relays at Generators to Trip Generators - $900K (a single relay for the Empire facility)
  - Resonant Blocking Filters installed at the neutral end of GSU high-voltage winding (not provided by ABB)

https://www.nyiso.com/documents/20142/5172540/04f%20AC%20Transmission%20ApnxH%20ABB%20Report.pdf/db176ad7-7c08-5cfe-2e7b-14253256262f

IBR in Weak grids



- 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

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

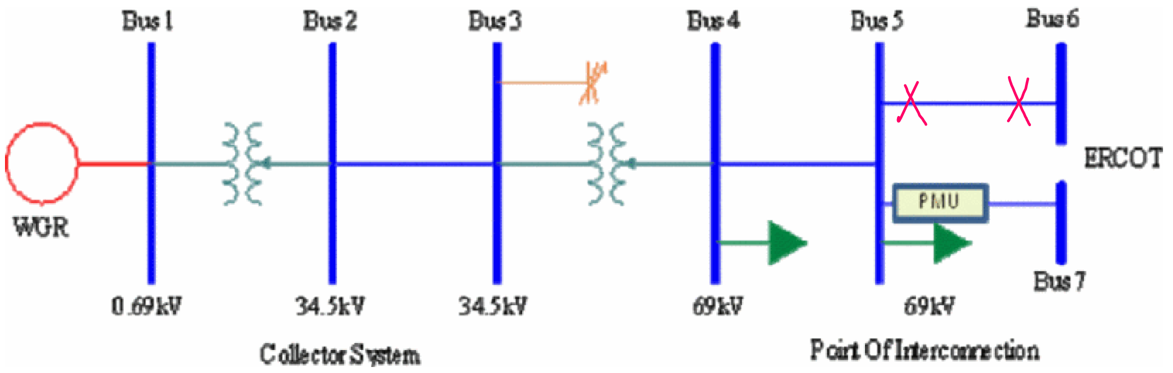
#5 (2011-2014) Since 2011, oscillations were observed by BPA during high wind generation conditions [4]. A 450- MW type-4 WPP located in Oregon was identified as the source. In summer 2013, BPA's phasor measurement unit (PMU) monitoring system identified **5-Hz oscillations in voltage, real and reactive 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**.

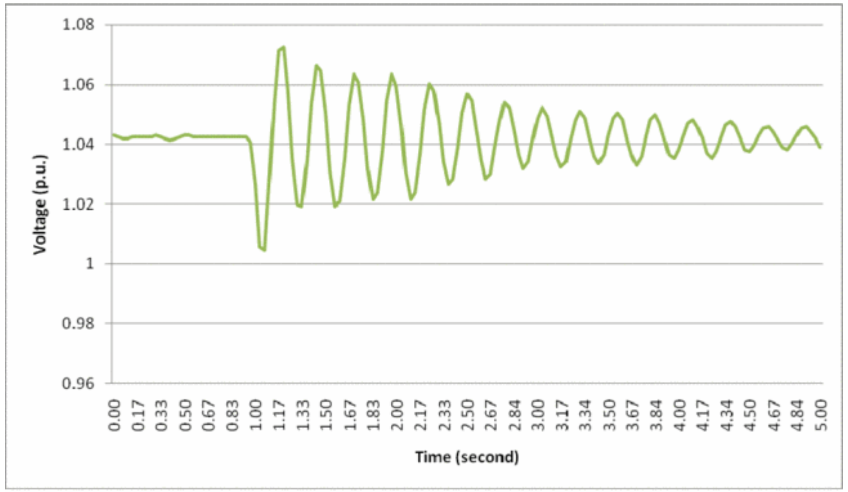
- Y. Cheng *et al*., "Real-World Subsynchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources," in *IEEE Transactions on Power Systems*, vol. 38, no. 1, pp. 316-330, Jan. 2023, doi: 10.1109/TPWRS.2022.3161418.

Texas 4-Hz oscillations (2011)

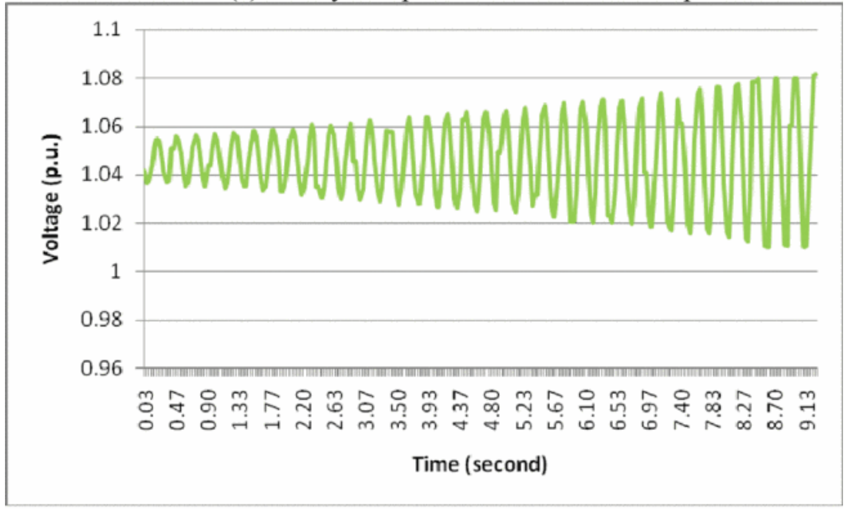


At normal conditions, the WPP was connected to the ERCOT grid through two 69-kV transmission lines. When one 69-kV transmission line was out of service for maintenance, **the SCR reduced below 2** and undamped oscillations appeared. Measurement recordings are presented in Fig. 11.

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.



(a) Poorly-damped oscillation at low output



(b) Un-damped oscillations at high output

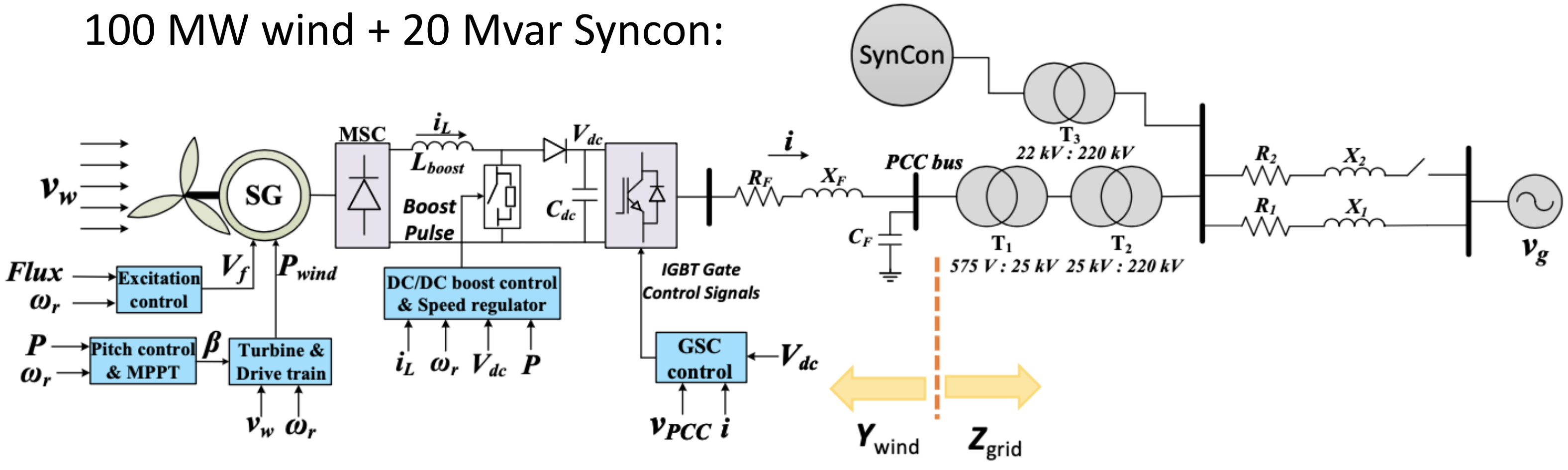
- S. -H. Huang, J. Schmall, J. Conto, J. Adams, Y. Zhang and C. Carter, "Voltage control challenges on weak grids with high penetration of wind generation: ERCOT experience," *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1-7, doi: 10.1109/PESGM.2012.6344713.

System redesign for weak grids

- SynCon: ERCOT, AEMO
  - Two synchronous condensers were installed in 2018 at ERCOT Panhandle to provide the required voltage and system strength support
  - The installation helped increase 400 MW more power exporting level from 3100 MW in 2017.
  - ERCOT is currently evaluating installing SynCons in the west Texas region with 34.5 GW IBRs to avoid similar disturbances as the 2021 Odessa events. It is found that 2.45 GW SynCons can help improve the grid strength by 16%.

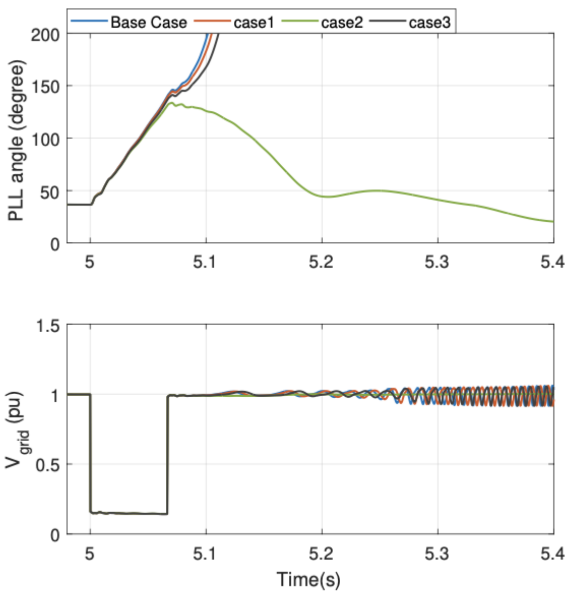
Y. Cheng, S. Hunag, “Strengthening the West Texas Grid to Mitigate Widespread Inverter-Based Events – Operation Assessment Results”, 2023

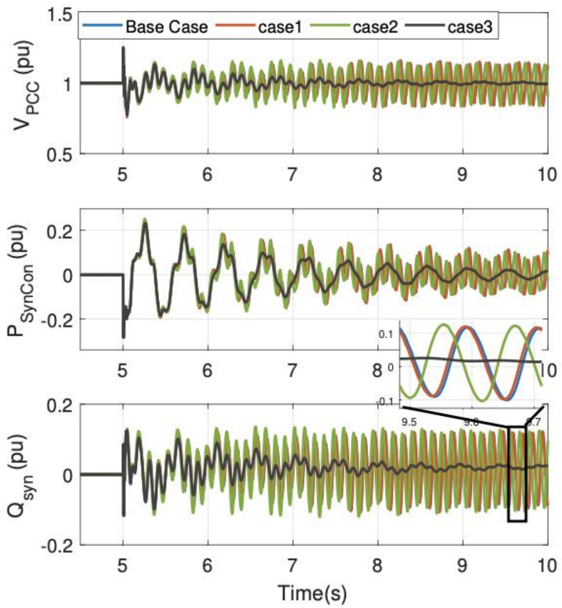
100 MW wind + 20 Mvar Syncon:

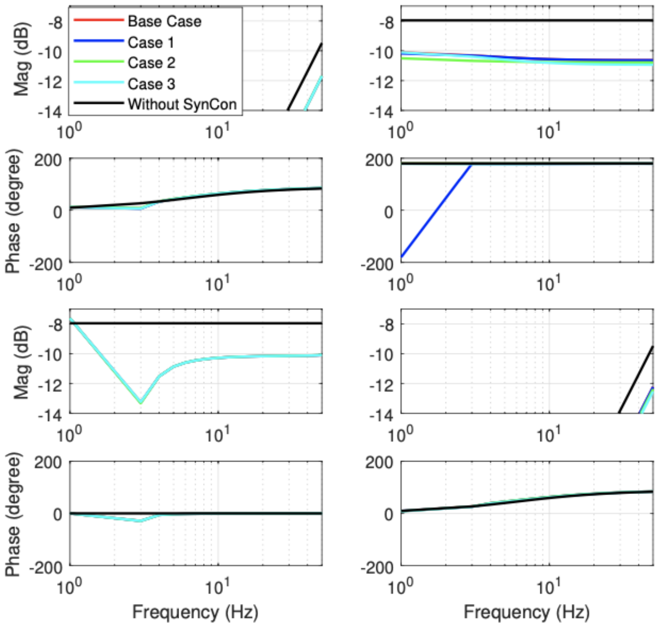


Syncon effectively reduces Thevenin impedance and enhance grid strength

Equivalent grid reactance with or without a syncon



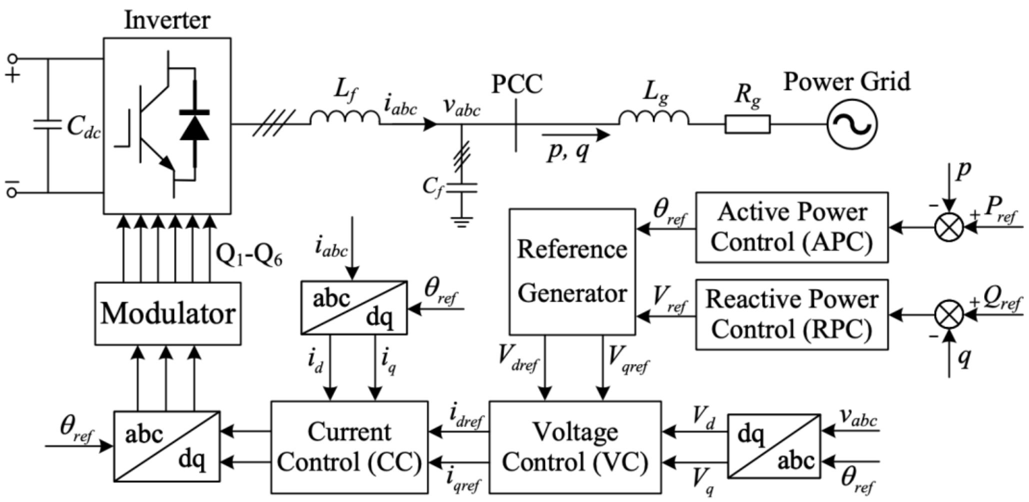




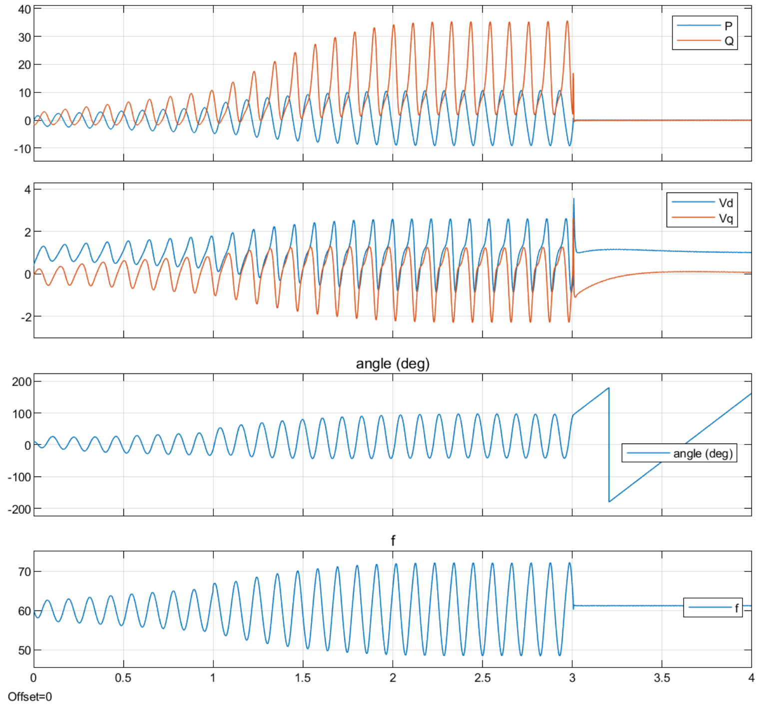
L. Bao, L. Fan, Z. Miao, “Maximizing SynCon’s Capability to Stabilize IBR-Penetrated Grids,” 2nd review, TEC

System redesign for weak grids: GFM

- Some common saying: GFM is good for weak grids but has issues with strong grids
- One lesson learned: GFM needs careful parameter retune if its original design is for standalone operation instead of grid operation
  - Based on a classic GFM design in Yazdani & Iravani's green book, power-frequency droop control is added to regulate frequency. Operating in the grid–connected conditions, the system is subject to oscillations when the grid is strong.
  - The original design does not include the P-f control



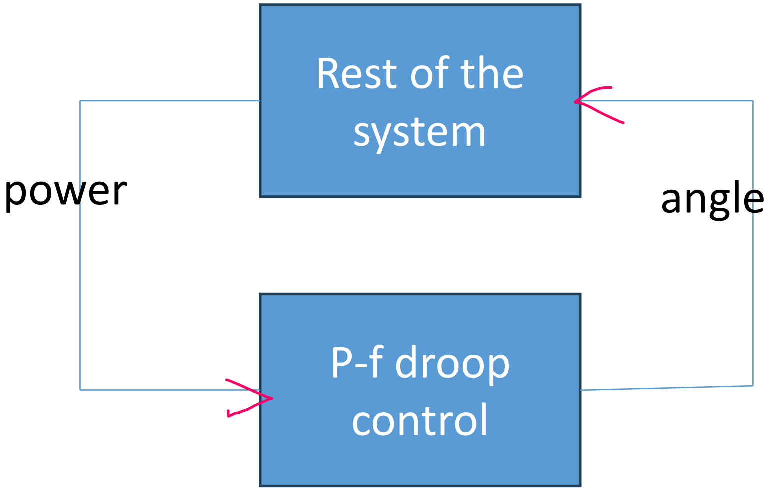
The above figure is from X. Wang, M. G. Taul, H. Wu, Y. Liao, F. Blaabjerg, and L. Harnefors, "Grid-synchronization stability of converter-based resources—an overview," IEEE Open J. Ind. Appl., vol. 1, pp. 115–134, 2020.

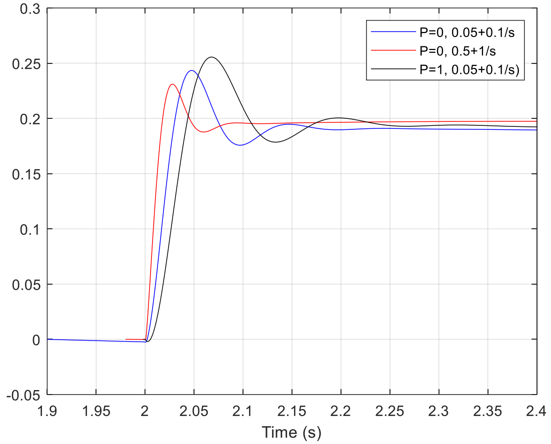


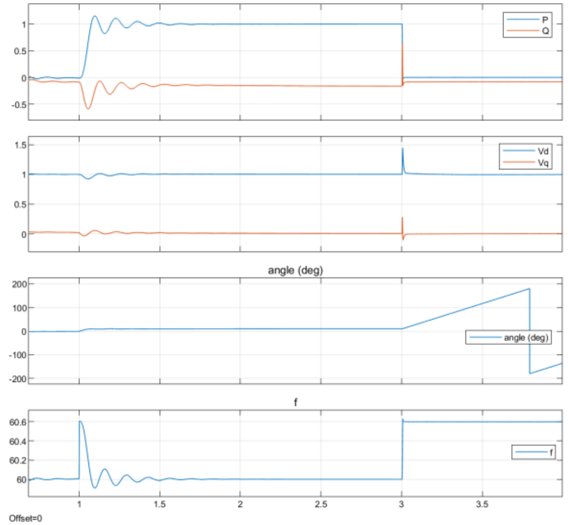
EMT simulation results for Xg = 0.1 pu and typical parameters designed based on the green book philosophy

What is missing?

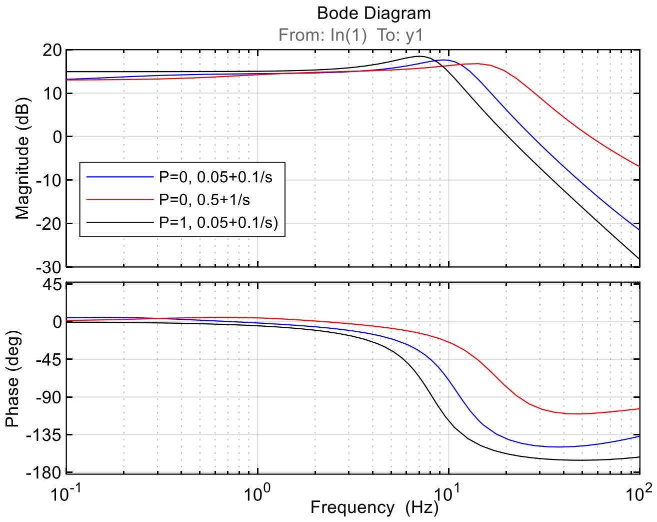
- Check of power-frequency feedback system

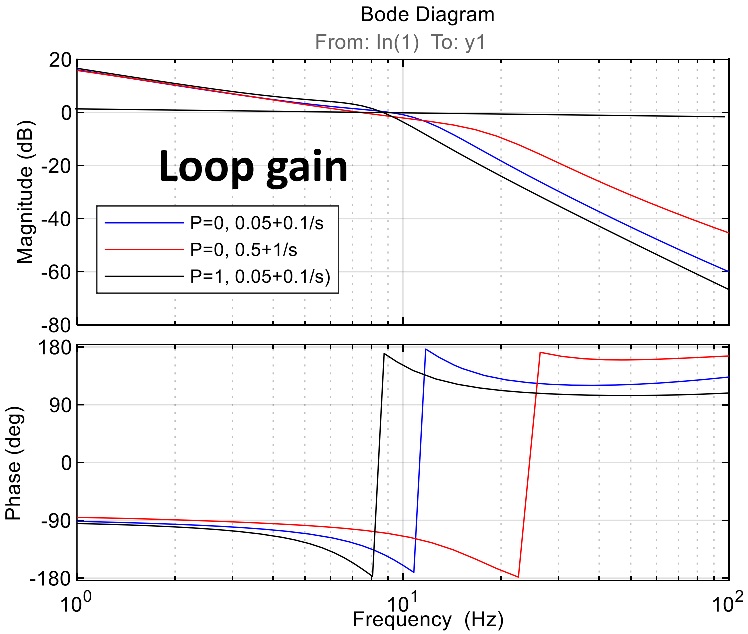






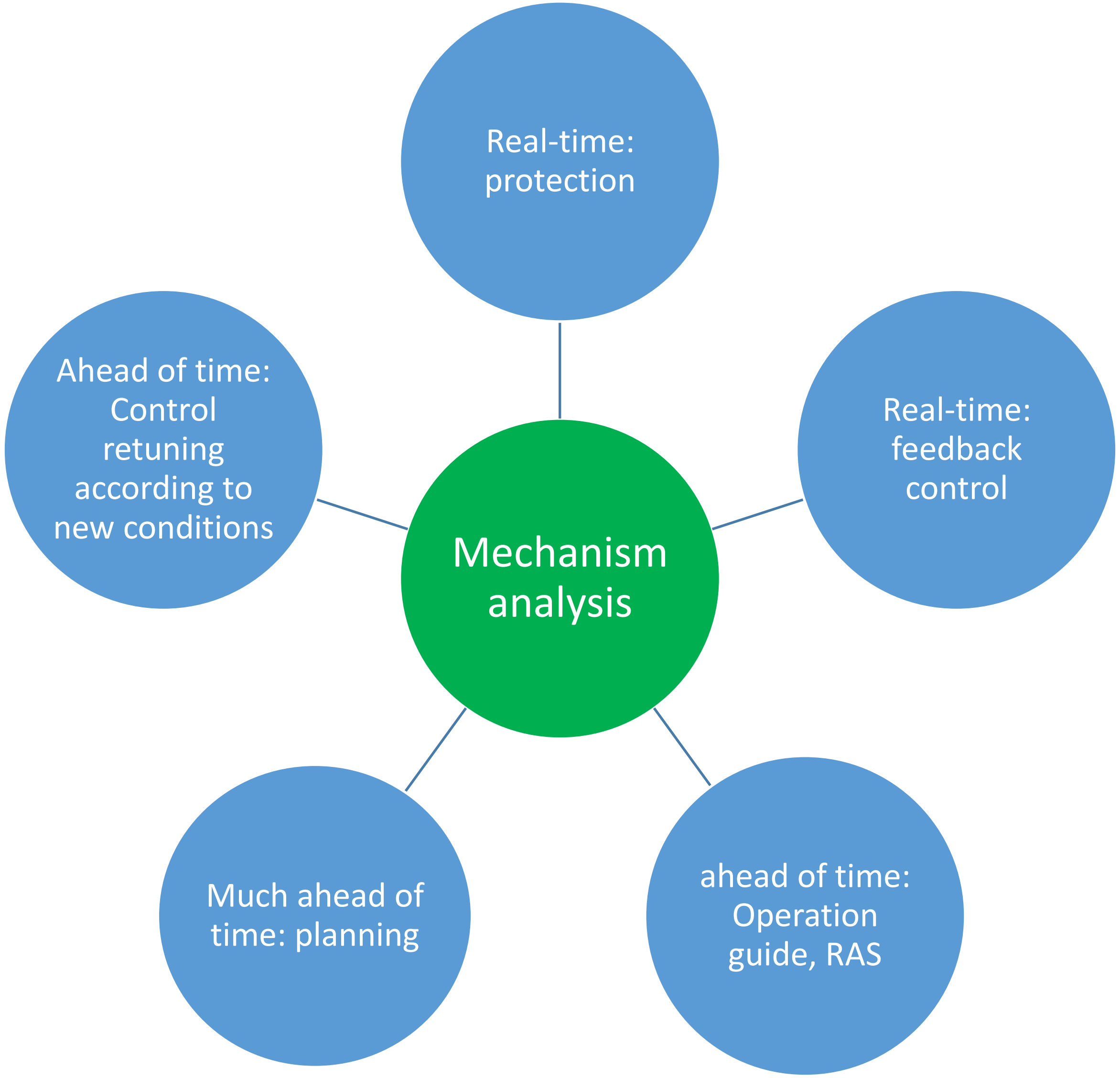
Rest of the system





It is found that using the original parameters lead to slow power response upon a change in the synchronizing angle. Adding the effect of P-f droop control, oscillatory instability occurs.

Mitigation: Make power response to angle change faster; or make the PCC angle track the synchronizing angle faster. Identify the related control block & Increase the gain of that control. Issue solved!


Real-time: protection
Ahead of time: Control retuning according to new conditions
Real-time: feedback control
Mechanism analysis
Much ahead of time: planning
ahead of time: Operation guide, RAS