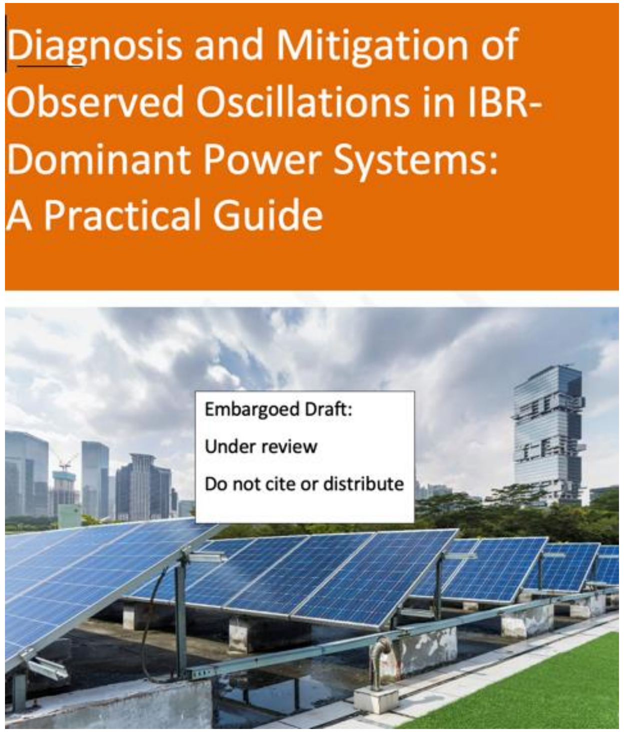
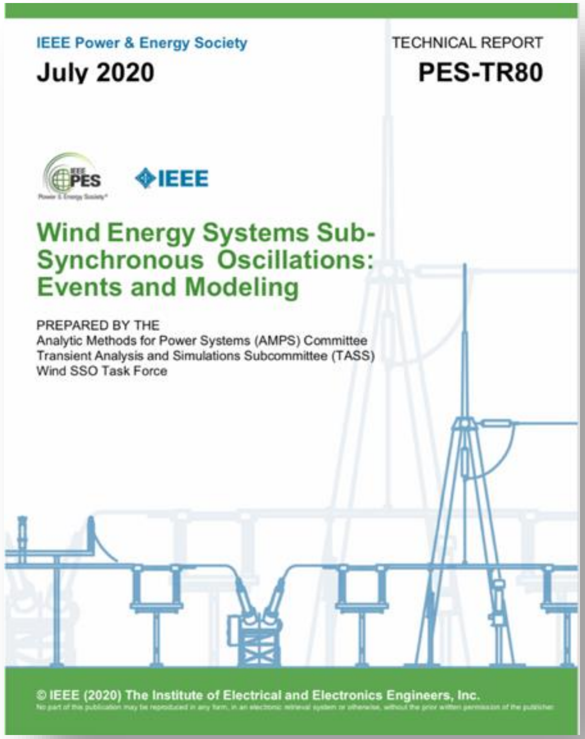
ESIG 2025 Spring Technical Workshop

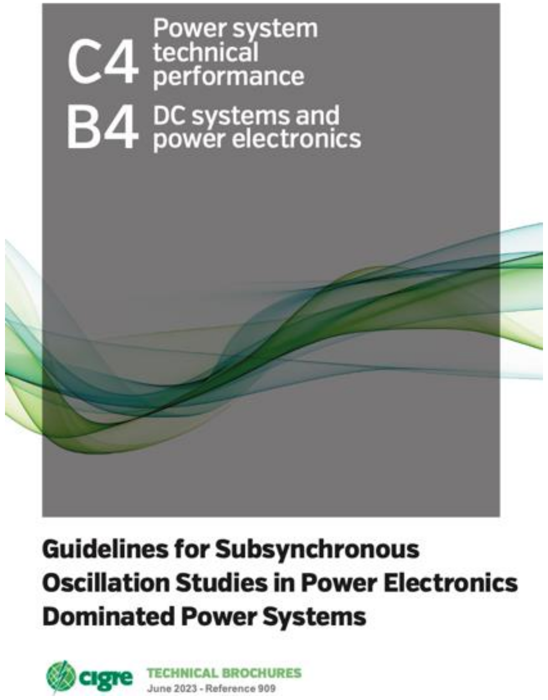
Feedback and Oscillations:
How to conduct effective root cause analysis (RCA)?

Lingling Fan, Professor, FIEEE
University of South Florida
March 19th, 2025

Oscillations, a subgroup of dynamics







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

19 events

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

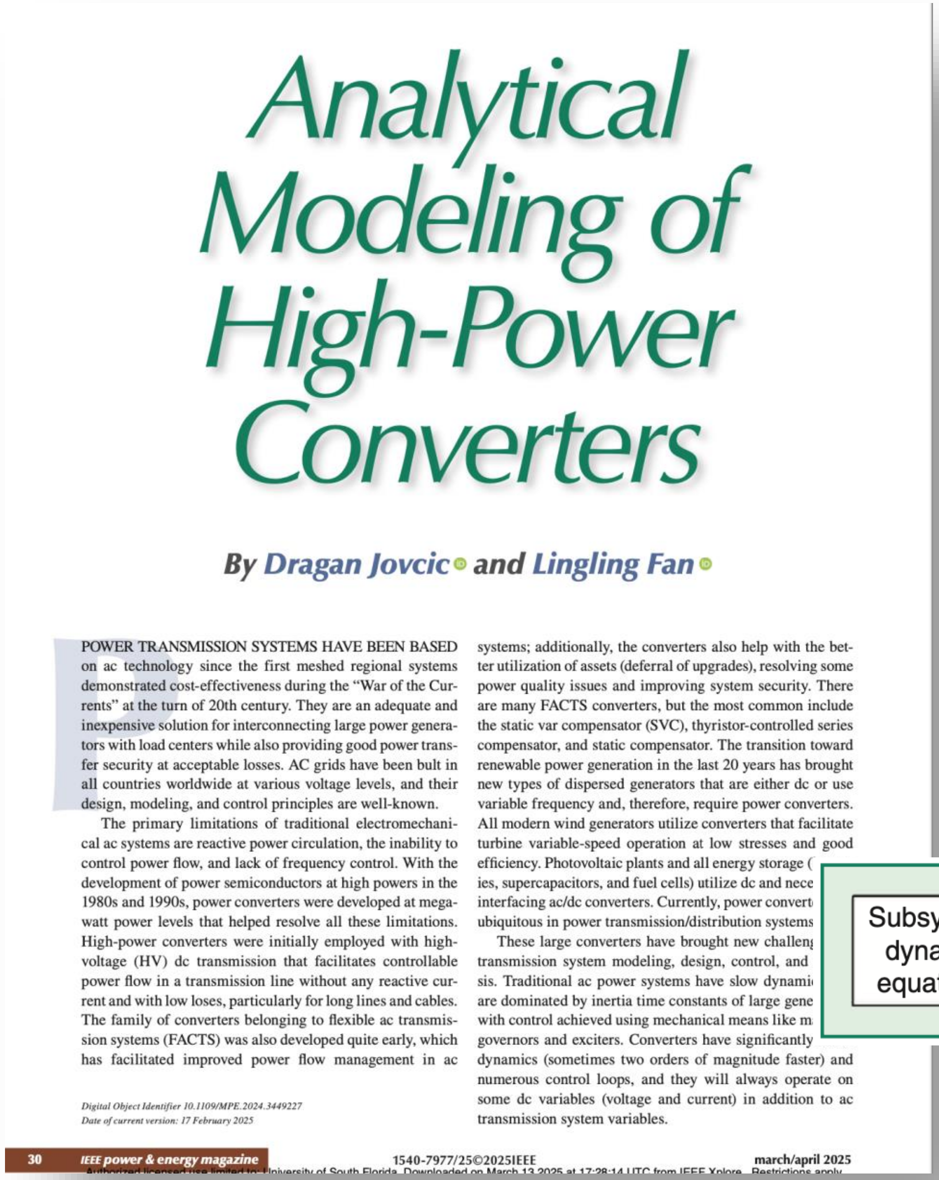
IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 37, NO. 4, DECEMBER 2022 2863

Real-World 20-Hz IBR Subsynchronous Oscillations: Signatures and Mechanism Analysis

Lingling Fan, *Fellow, IEEE*, Zhixin Miao, *Senior Member, IEEE*, Shahil Shah, *Senior Member, IEEE*, Yunzhi Cheng, *Senior Member, IEEE*, Jonathan Rose, *Senior Member, IEEE*, Shun-Hsien Huang, *Senior Member, IEEE*, Bikash Pal, *Fellow, IEEE*, Xiaorong Xie, *Senior Member, IEEE*, Nilesh Modi, *Senior Member, IEEE*, Song Wang, *Senior Member, IEEE*, and Songzhe Zhu, *Senior Member, IEEE*

(IEEE PES IBR SSO Task Force)

3 types of fast control and PLL related 20-Hz oscillation events



Analytical Modeling of High-Power Converters

By Dragan Jovcic and Lingling Fan

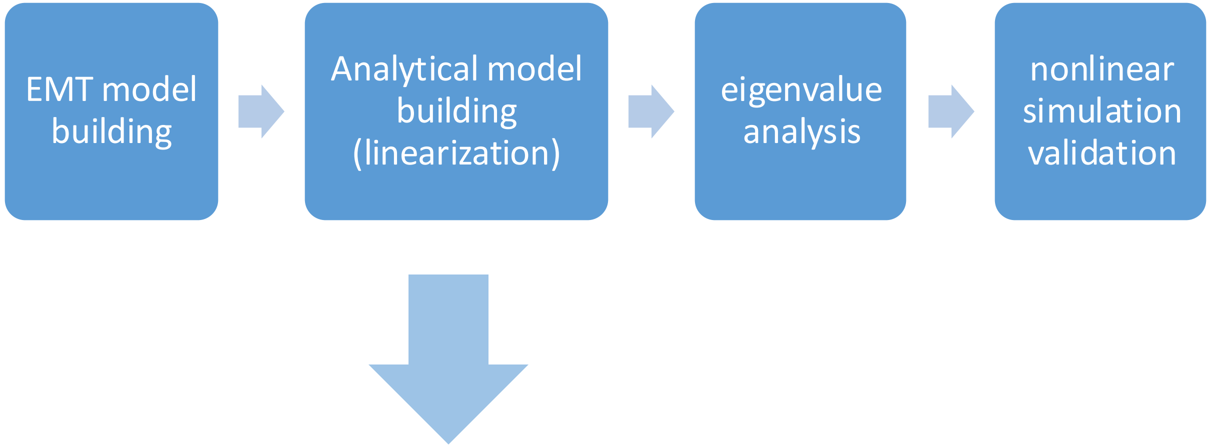
POWER TRANSMISSION SYSTEMS HAVE BEEN BASED on ac technology since the first meshed regional systems demonstrated cost-effectiveness during the "War of the Currents" at the turn of 20th century. They are an adequate and inexpensive solution for interconnecting large power generators with load centers while also providing good power transfer security at acceptable losses. AC grids have been bult in all countries worldwide at various voltage levels, and their design, modeling, and control principles are well-known.

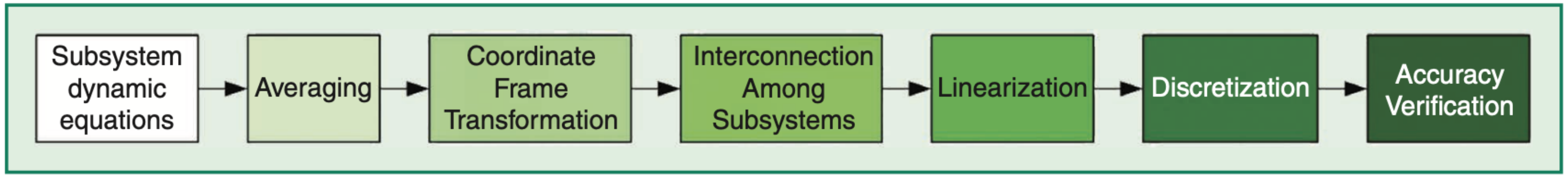
The primary limitations of traditional electromechanical ac systems are reactive power circulation, the inability to control power flow, and lack of frequency control. With the development of power semiconductors at high powers in the 1980s and 1990s, power converters were developed at megawatt power levels that helped resolve all these limitations. High-power converters were initially employed with high-voltage (HV) dc transmission that facilitates controllable power flow in a transmission line without any reactive current and with low loses, particularly for long lines and cables. The family of converters belonging to flexible ac transmission systems (FACTS) was also developed quite early, which has facilitated improved power flow management in ac systems; additionally, the converters also help with the better utilization of assets (deferral of upgrades), resolving some power quality issues and improving system security. There are many FACTS converters, but the most common include the static var compensator (SVC), thyristor-controlled series compensator, and static compensator. The transition toward renewable power generation in the last 20 years has brought new types of dispersed generators that are either dc or use variable frequency and, therefore, require power converters. All modern wind generators utilize converters that facilitate turbine variable-speed operation at low stresses and good efficiency. Photovoltaic plants and all energy storage (
ies, supercapacitors, and fuel cells) utilize dc and nece
interfacing ac/dc converters. Currently, power convert
ubiquitous in power transmission/distribution systems

These large converters have brought new challen
transmission system modeling, design, control, and
sis. Traditional ac power systems have slow dynami
are dominated by inertia time constants of large gene
with control achieved using mechanical means like m
governors and exciters. Converters have significantly
dynamics (sometimes two orders of magnitude faster) and numerous control loops, and they will always operate on some dc variables (voltage and current) in addition to ac transmission system variables.

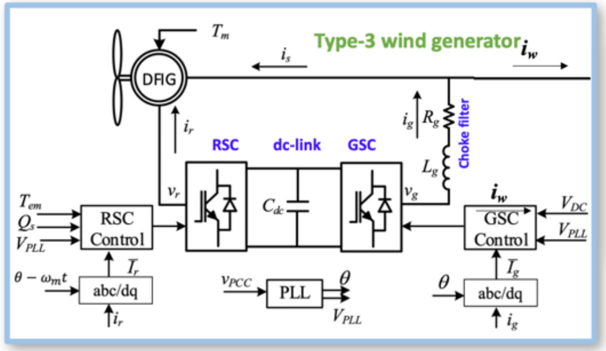
Digital Object Identifier 10.1109/MPE.2024.3449227
Date of current version: 17 February 2025

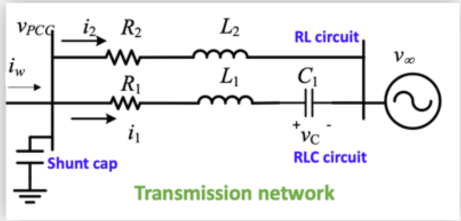
The conventional analysis approach:
analytical model building, and
linear analysis.

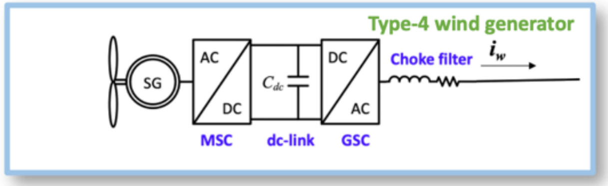


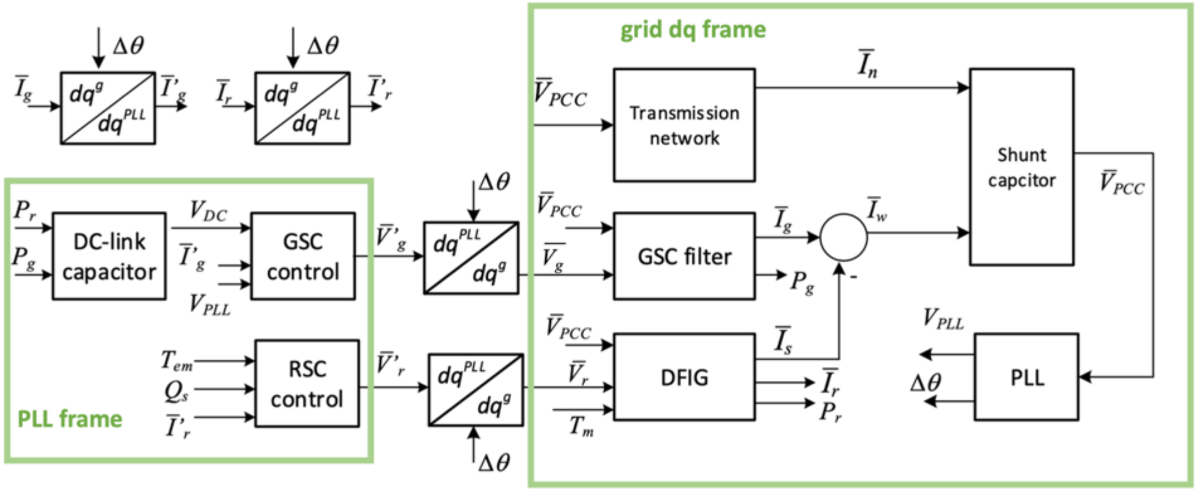


Conventional mechanism analysis: analytical modeling, eigenvalues, sensitivity analysis

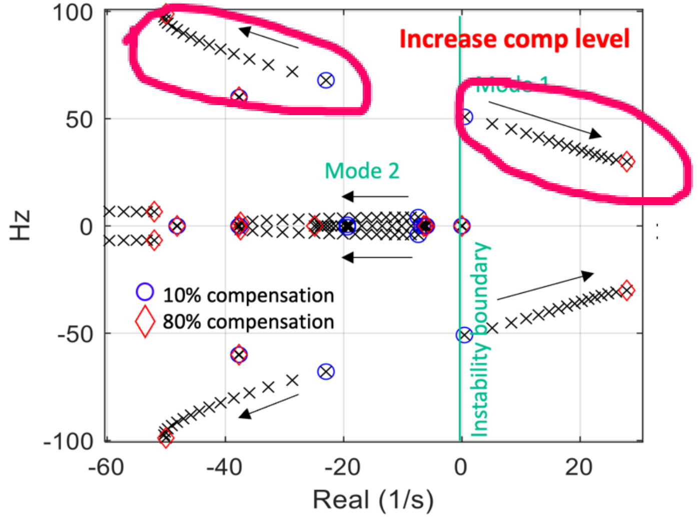








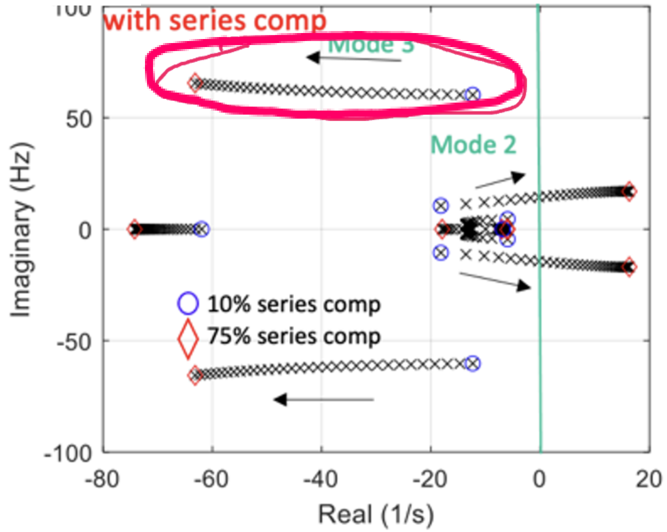
there are 2 modes: sub and super sync.



Type 3 vs Type-4 wind

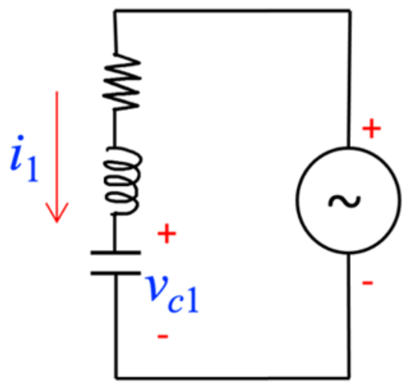
with radial connection to a cap

there is only a 60-Hz mode.



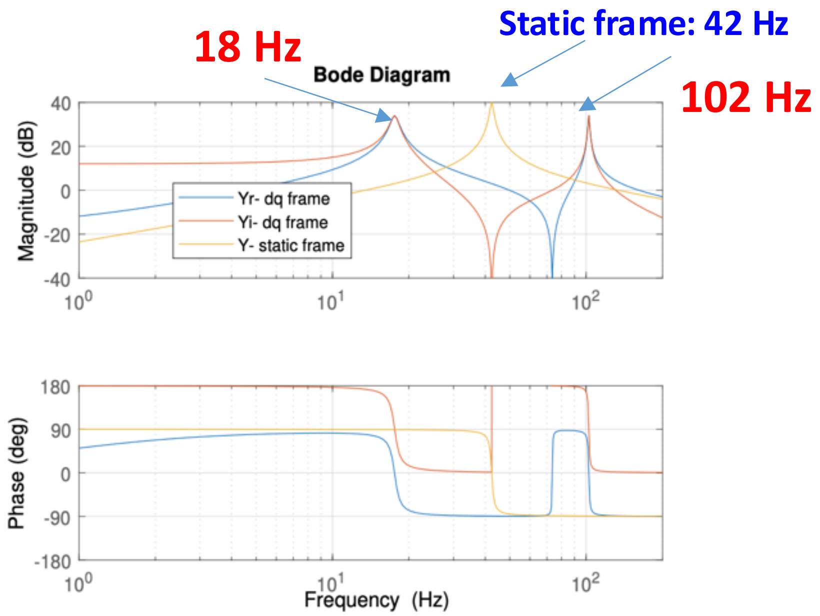
Eigenvalue analysis is powerful. Yet just eigenvalue analysis cannot explain **mechanism**, e.g.: **why the difference?**

Simplification & frequency-domain analysis:



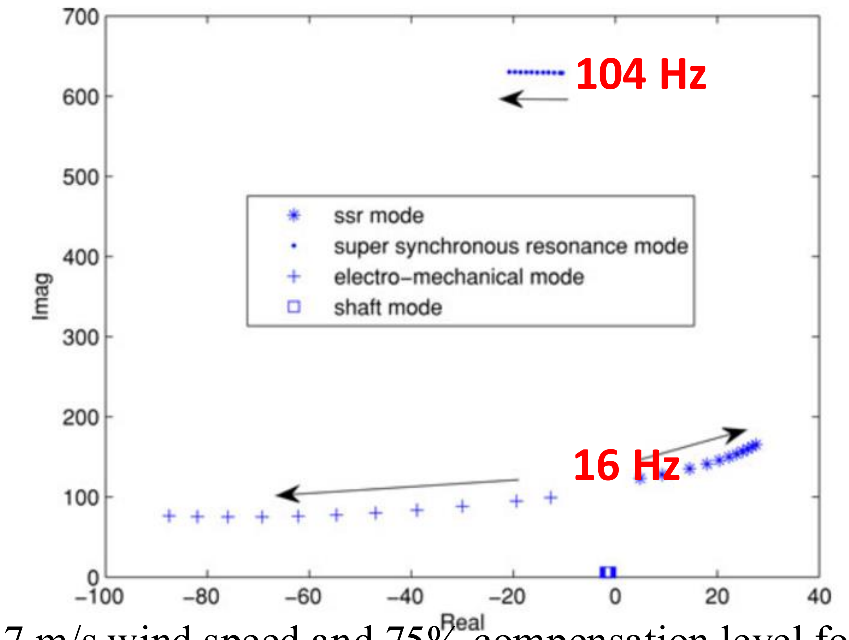
$$\frac{i_L}{v_s} = \frac{1}{R + sL + \frac{1}{sC}}.$$

$$Y_1(s) = \frac{\bar{I}_L}{\bar{V}_s} = \frac{1}{R + (s + j\omega)L + \frac{1}{(s+j\omega)C}}.$$



50% compensation level ➔ SSR at sqrt(0.5)*60 Hz = 42 Hz

With rotor resistance increased, sub mode becomes worse, sup mode becomes better.



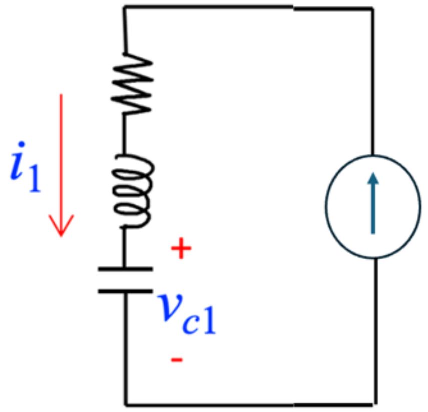
7 m/s wind speed and 75% compensation level for increasing rotor resistance(R_r = 0.00549 to 0.1).

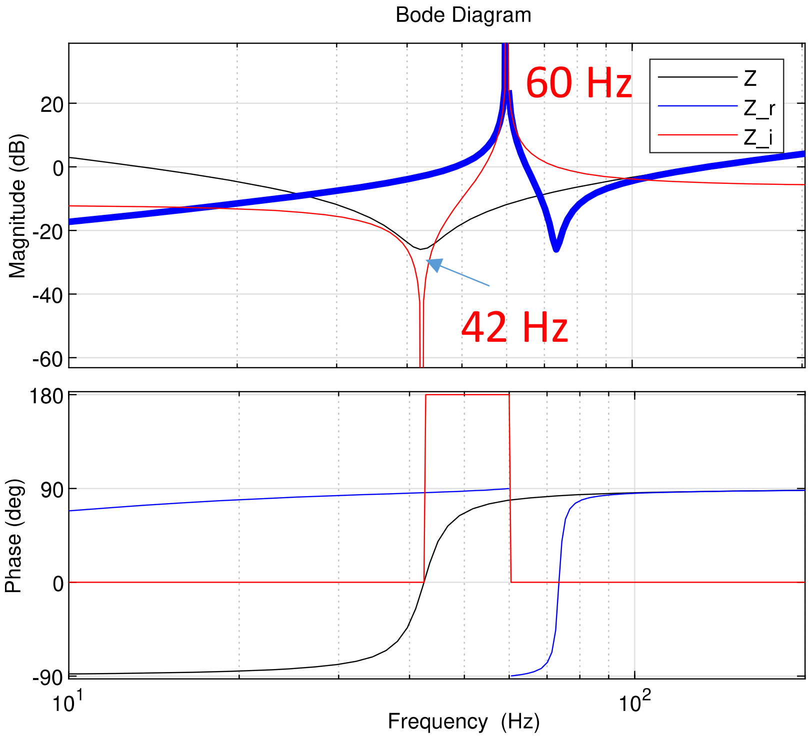
Ref: L. Fan, C. Zhu, Z. Miao and M. Hu, "Modal Analysis of a DFIG-Based Wind Farm Interfaced With a Series Compensated Network," TEC 2011

If the RLC circuit is powered by a voltage source, we expect to see sub- and super-sync modes in the dq frame, or in power.

The detailed analytical model-based eigenvalue analysis results confirm the existence of sub- and super-sync modes.

Simplification & frequency-domain analysis:





Z in the dq frame has a peak at 60 Hz. This implicates a 60-Hz mode as a pole.

This explains why in the type-3 wind farm, the LC mode is dominant; while in the type-4 wind, the LC mode is not a pole.

In the subsynchronous frequency range, **a type-3 wind farm should be viewed as a voltage source**; while **a type-4 wind farm may be viewed as a current source.**

In the static frame:

Z = $R + sL + \frac{1}{sC}$

In the dq frame:

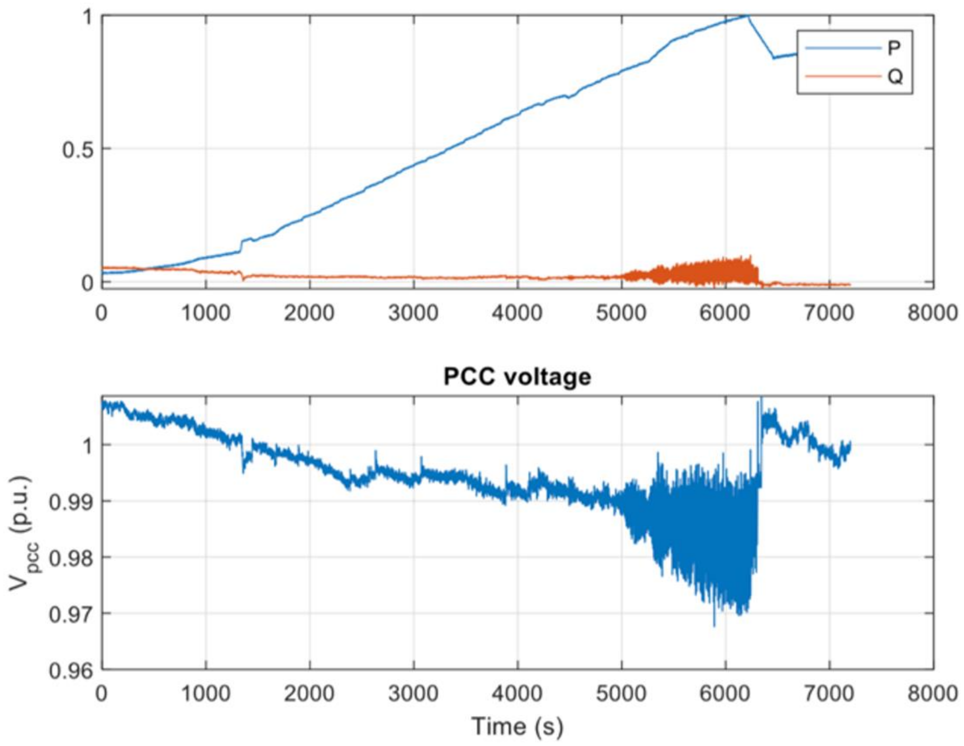
Z = $R + (s + j\omega)L + \frac{1}{(s+j\omega)C}$

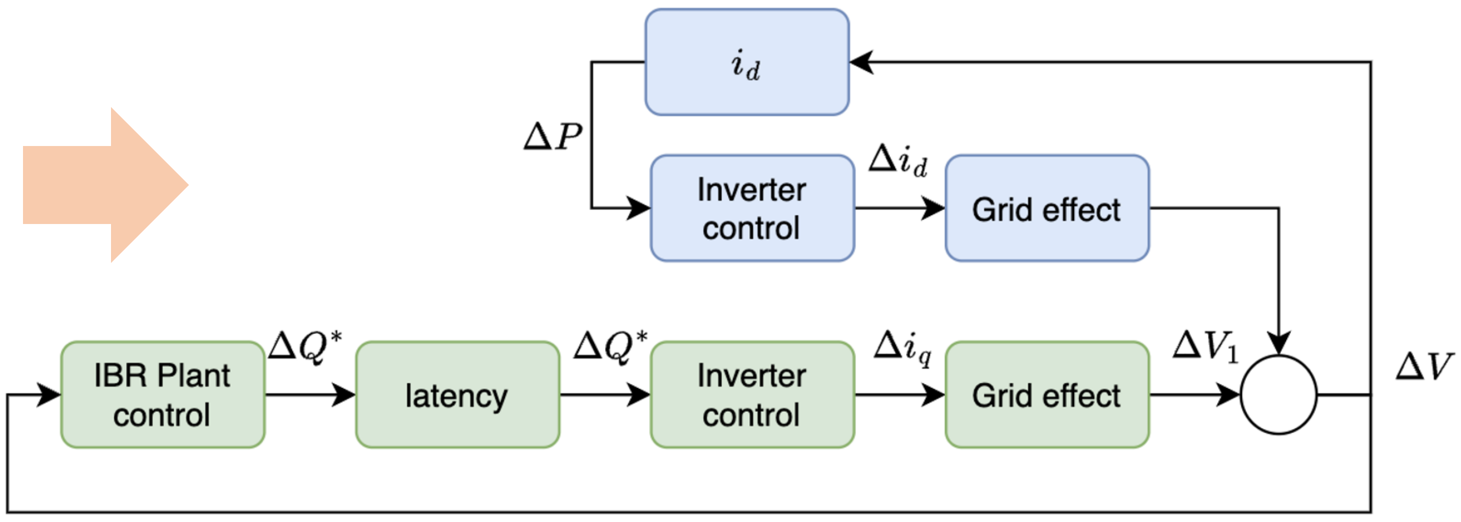
If the RLC circuit is powered by a current source, we expect to see a 60-Hz mode in the dq frame, or in power.

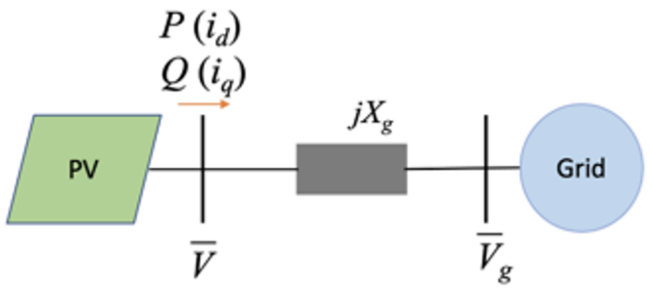
RCA analysis via simplified feedback systems

- Simplification and frequency-domain analysis directly lead us to mechanism. Therefore, RCA may focus on constructing feedback systems consisting of blocks.
- Methodology:
  - Speculate the cause by examining measurement data and construct relevant feedback systems
  - **Example 1**: For voltage oscillations: **volt-var loop**
  - **Example 2**: For PLL related dynamics: **synchronization loop (angle to angle)**
  - **Example 3**: For SSTI: **synchronization loop (power to angle)**

Example 1: Oscillations in voltage and reactive power

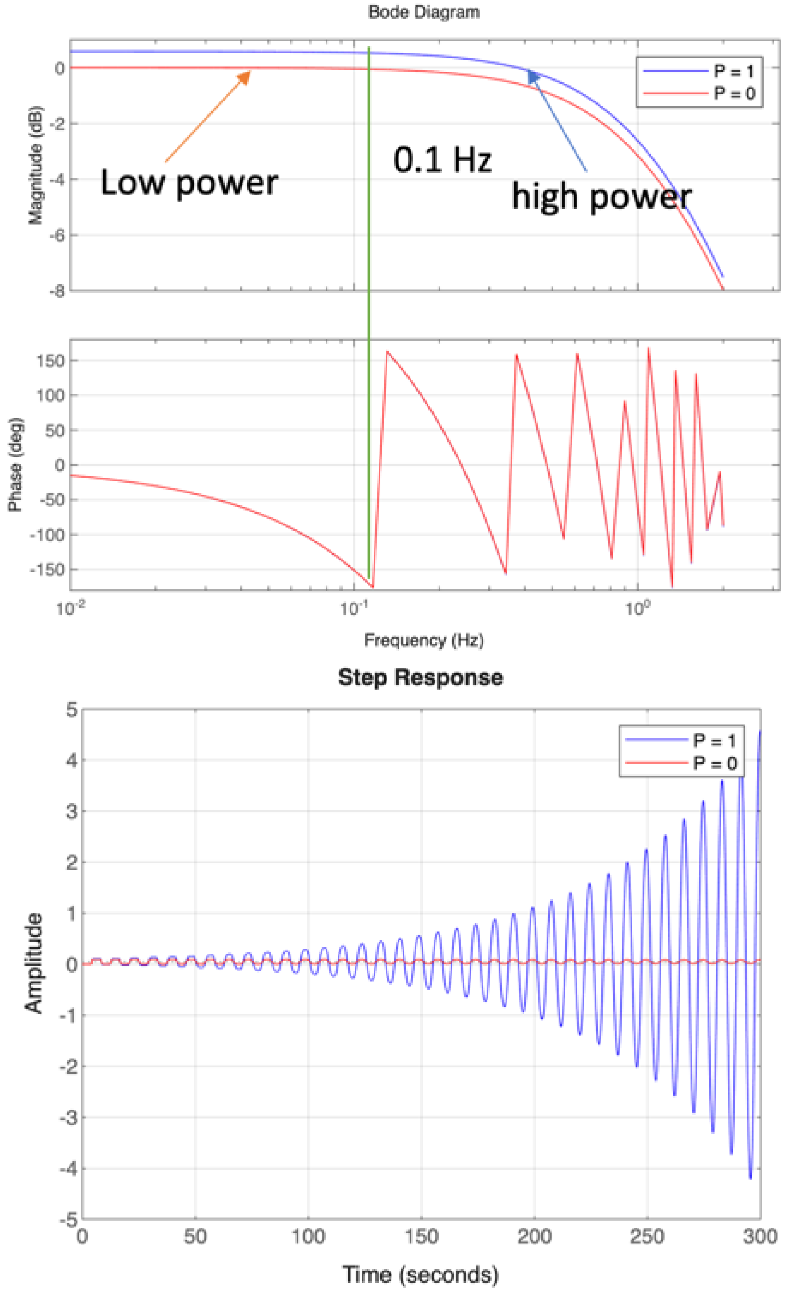


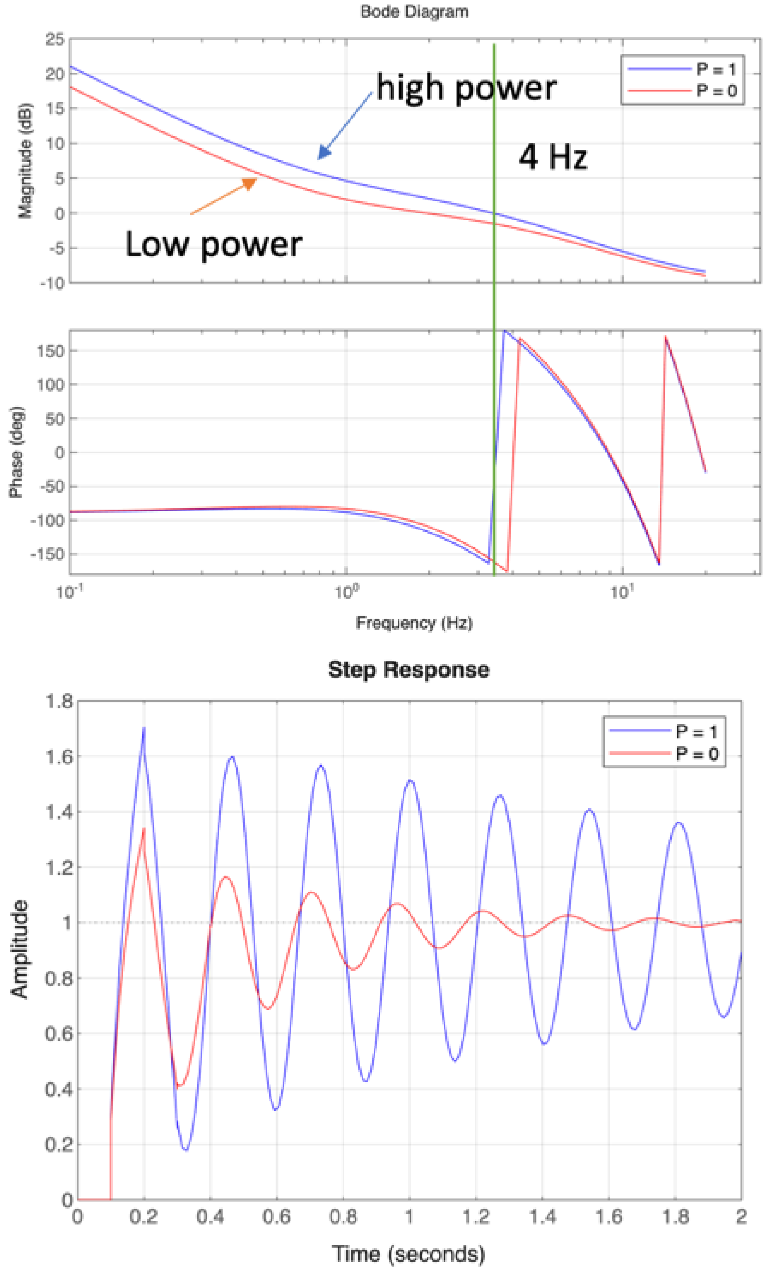




When the real power ramps to a certain level, voltage and reactive power show 0.1-Hz oscillations.

- Major feedback: voltage-reactive power
- Fine tuning: real power also has influences.





Case 1: **0.1-Hz** oscillations
Case 2: **4-Hz** oscillations

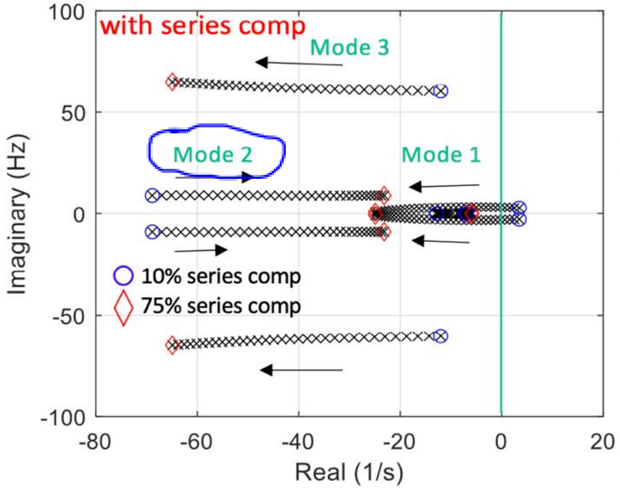
Oscillation frequency is dependent on the **communication delay.**

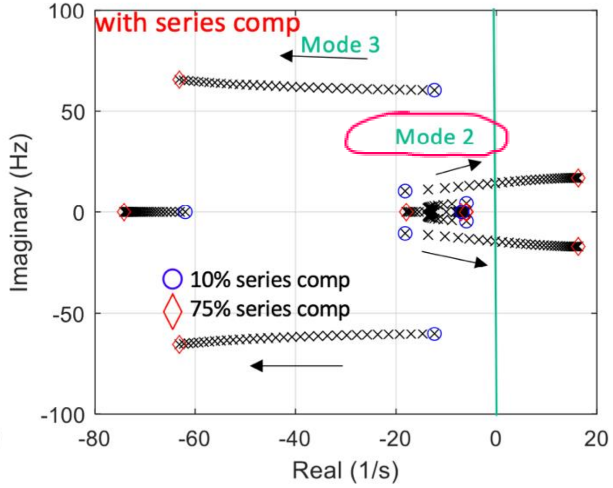
High power,
large voltage control gain,
weak grid strength,
large communication delay
may lead to oscillations.

Example 2: Series/shunt compensation makes PLL-induced oscillations worse

Type-3 wind with radial connection to a series capacitor is known to cause SSO. For IBRs with grid-connected converters,

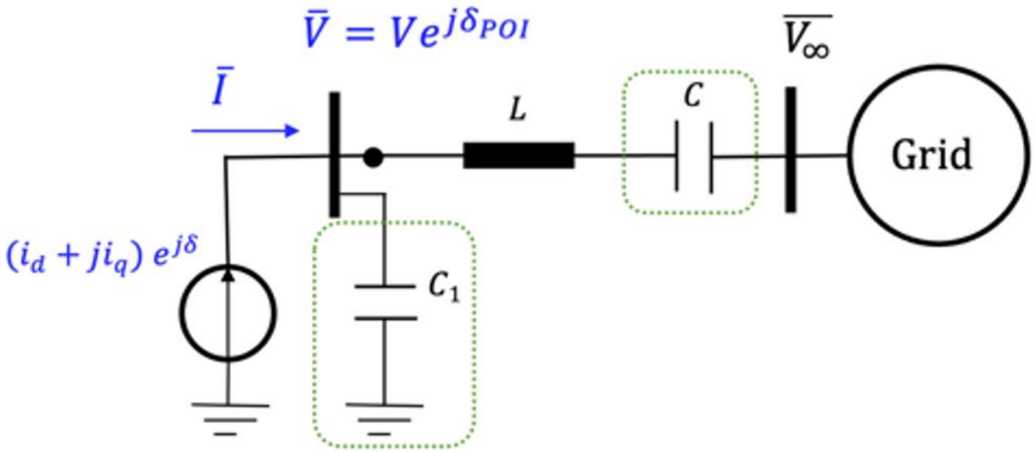
- Will series compensation cause SSO for type-4 wind?
- Will shunt compensation cause SSO for solar PV and type-4 wind?
- Why shunt compensation makes IBRs lose stability?
  - If there is no shunt cap, an IBR can operate in a weak grid. With shunt, it can no longer operate in such a grid.

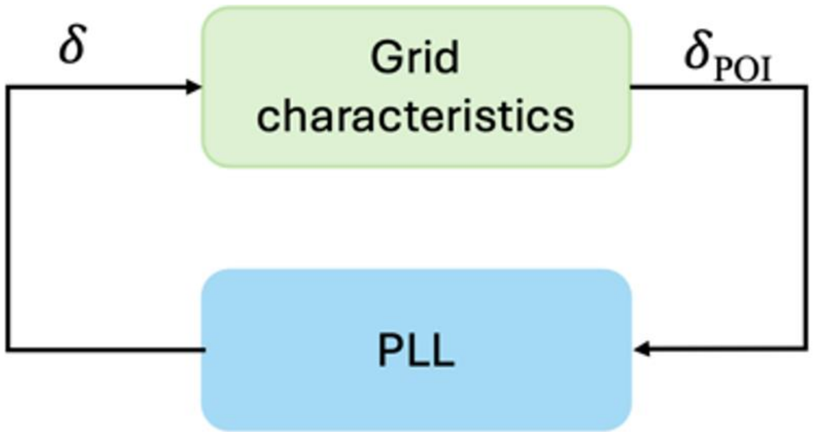


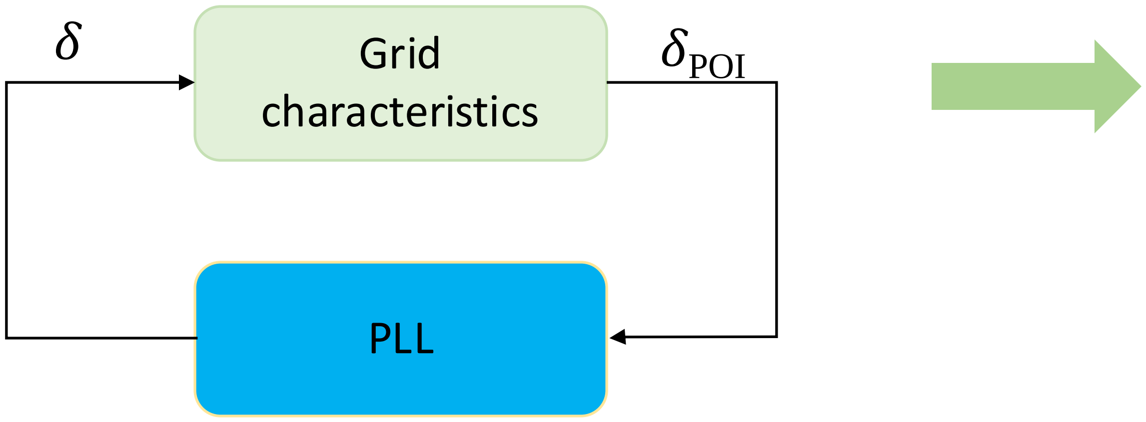


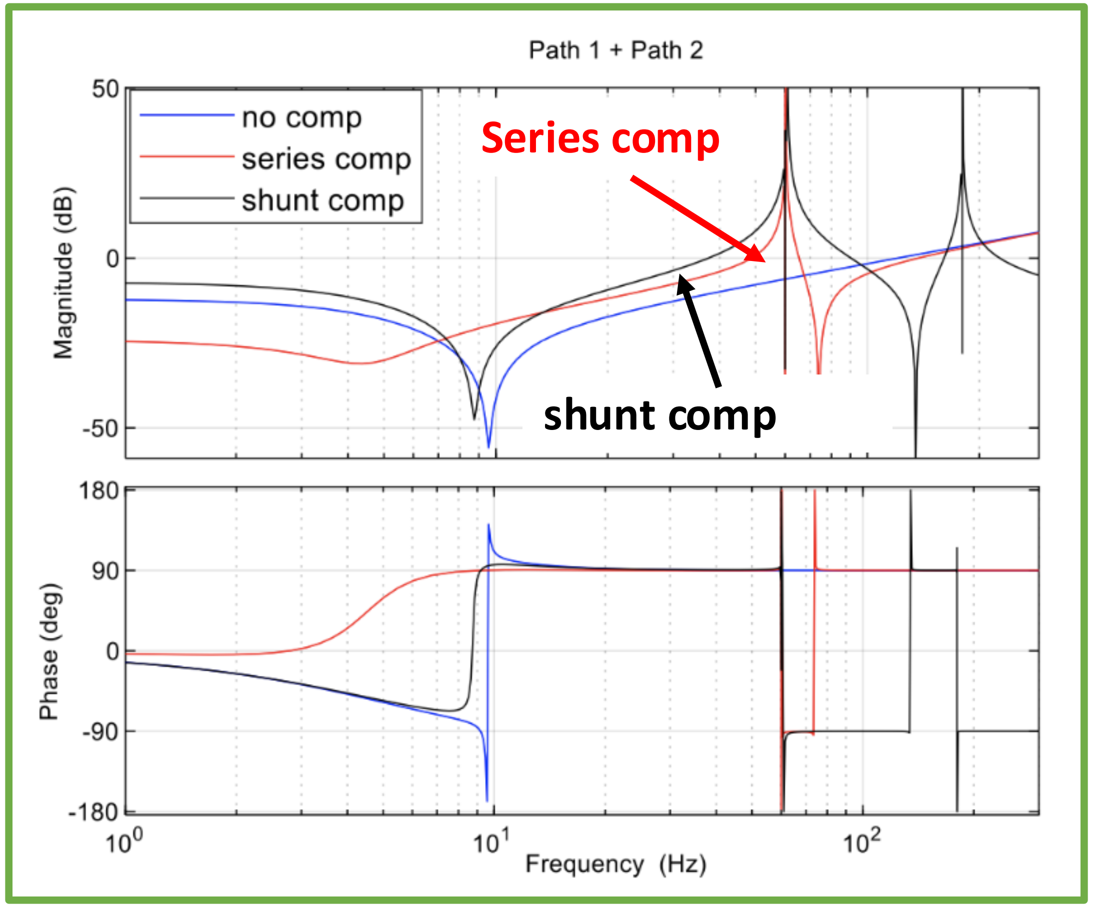
Eigenvalue analysis results based on an analytical model (including a grid-following converter's inner current control, outer power/voltage control, PLL, and the grid electromagnetic transients) show:
Increasing compensation level, a mode sensitive to PLL's parameter (mode 2) may move to the RHP.

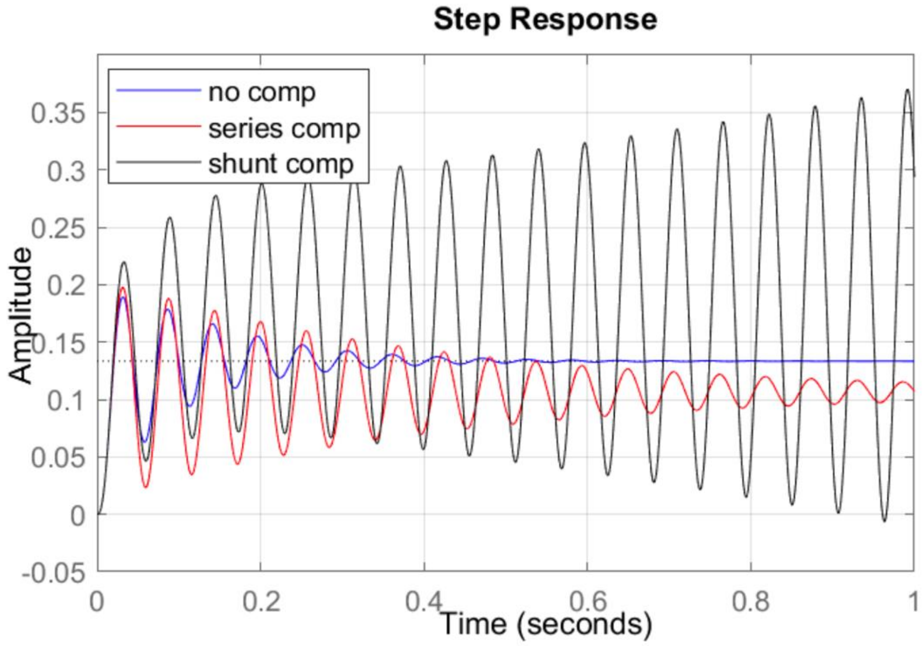
Reasonable to single out the PLL block and construct a feedback system of synchronization.









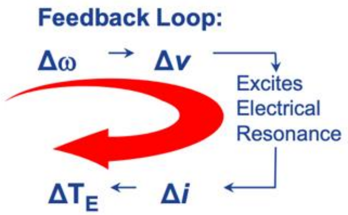


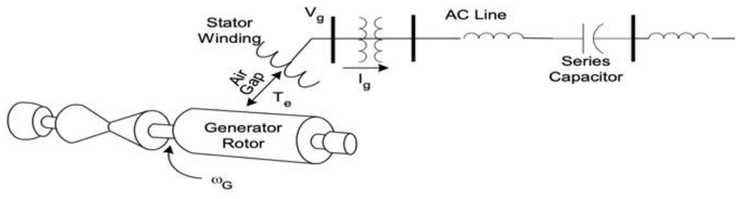
Remarks:

- Series/shunt compensation **makes the sensitivity of the voltage angle towards the synchronizing angle much more sensitive in the region of 10 Hz -60 Hz, and**
- **more vulnerable to the interactions of PLL.**

Example 3: Subsynchronous Torsional Interaction (SSTI)

Mechanics of Interaction With Series Capacitors





$$\Delta v = \Phi \Delta \omega$$

$$\Delta i = \frac{\Delta v}{Z} \Rightarrow \frac{\Delta i}{\Delta v} = G + jB$$

$$\Delta T_E = \Phi \Delta i$$

$$\frac{\Delta T_E}{\Delta \omega} \Rightarrow \frac{\Phi \Delta i}{\Phi \Delta v} \Rightarrow D_E + jS_E$$

D_E = damping torque (in-phase with Δω)

S_E = synchronizing torque (90° out of phase with Δω)

https://www.gevernova.com/content/dam/Energy_Consulting/global/en_US/pdfs/GE_-_SSO_Risk_Analysis_Protection_and_Mitigation_Techniques.pdf

Industry perspective (Bruce English)
SSTI is due to the interaction of **torque mechanical dynamics,** while torque is influenced by the grid characteristics.

GE Energy Consulting Involvement in SSR

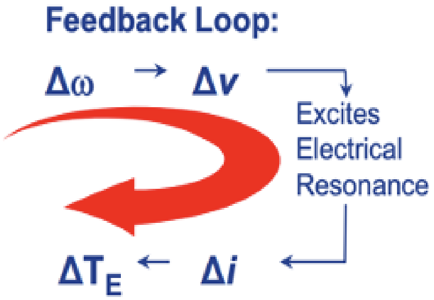
Mohave: 1st SSR event involving series caps
- Unit was radial on-line with 7 of 8 SC modules
- 30 Hz oscillation grow over many seconds until shaft failure occurred : Dec '70 & Oct '71
- GE EC team determined root cause & solution

Over the past 40 years GE EC has:
- Developed analysis tools, protection and mitigation concepts
- Performed SSR analysis on over well over 100 turbine-generators
- Designed protection and mitigation systems for a full range of SSR issues
- Analysis and solutions provided for GE and non-GE units world-wide


Failed Rotor at Mohave


Tuoketuo Power Plant, China

The generator is viewed as a voltage source and the current is influenced by the LC resonance which further influences the torque.

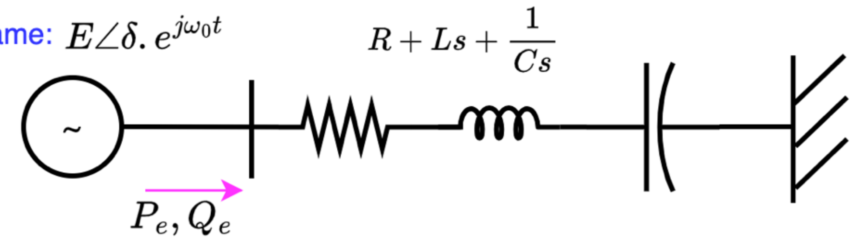


The tricky things of quantitative modeling:
- Which frame? **Static** or **dq frame**?
- **Simplification:** A voltage phasor has a magnitude and an **angle. Which is influenced more by mechanical dynamics?**

Form a feedback system with two blocks:

1. **Mechanical dynamics**
2. **Electrical dynamics**

static frame: $E\angle\delta.\, e^{j\omega_0 t}$

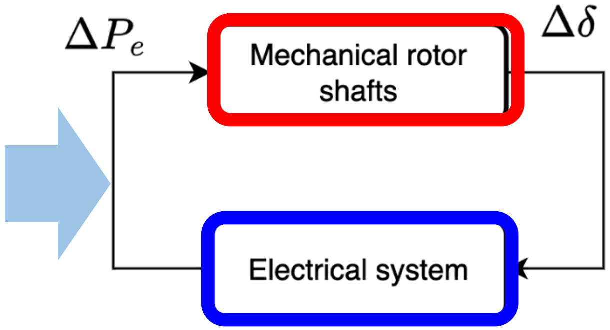


$$Z(s) = R + L(s + j\omega_0) + \frac{1}{C(s + j\omega_0)}$$

dq frame: $E\angle\delta$

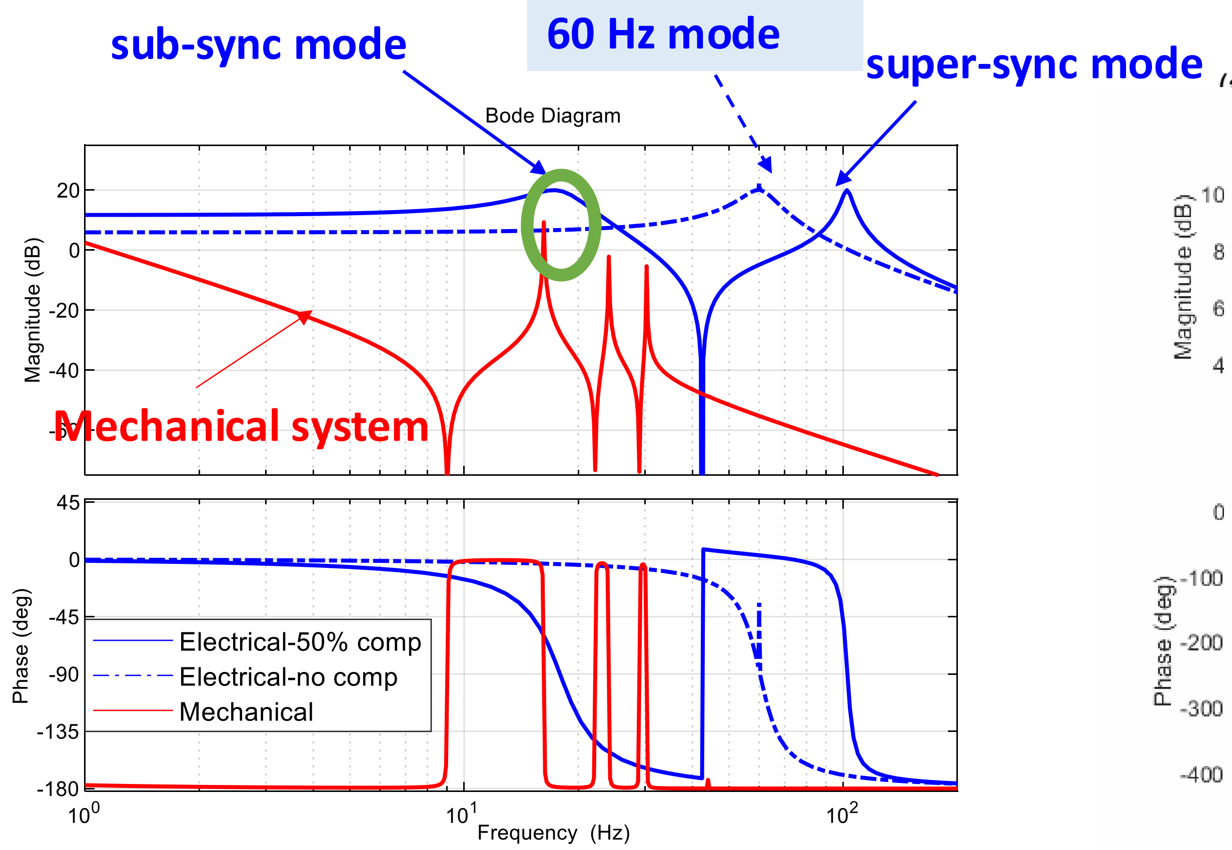
$$Y(s) = \frac{C(s + j\omega_0)}{LC(s + j\omega_0)^2 + RC(s + j\omega_0) + 1}$$

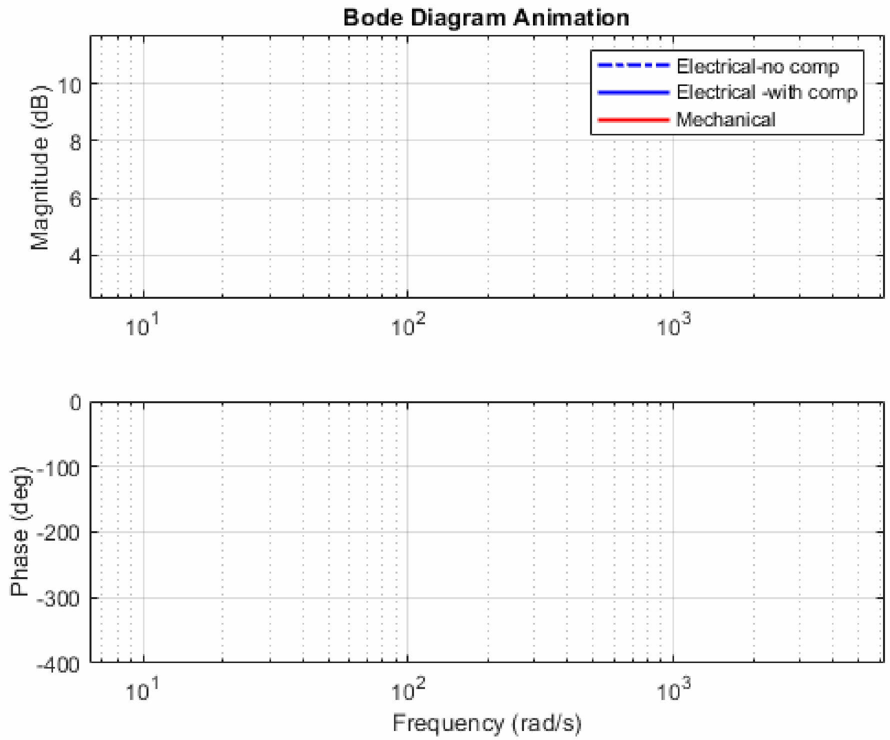
(a)



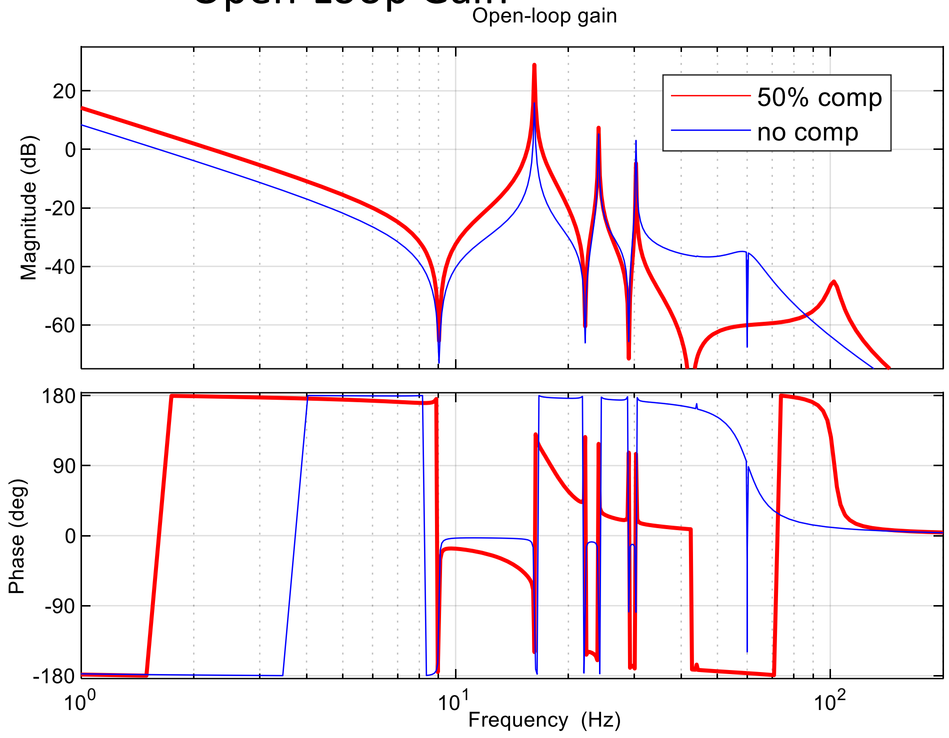
$Y_{\text{imag}}(s)E^2 - Q_e$

(b)

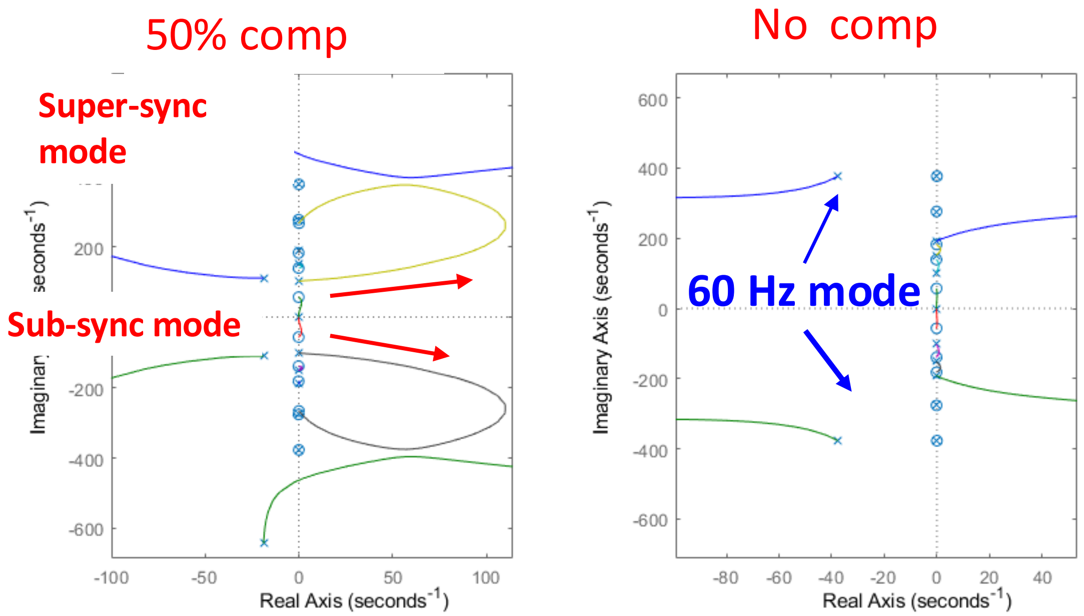


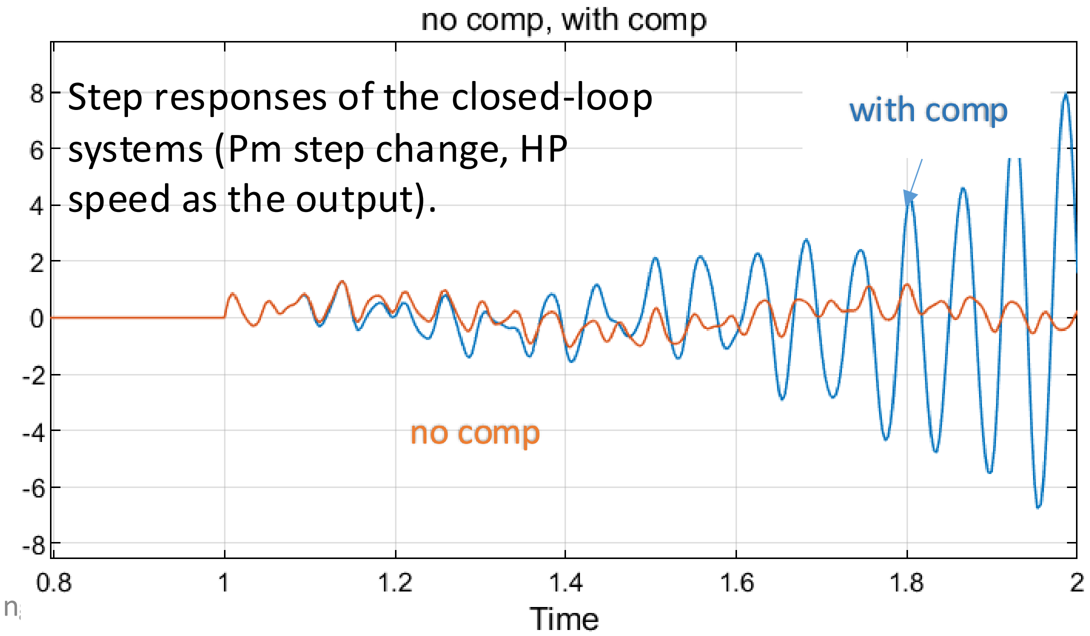


Open-Loop Gain



Root locus diagrams





- The loop gain (product of the two blocks) shows the peak at 16 Hz.
- Series compensation makes the peak more severe.
- The root locus diagrams show the sub-syn mode pushes the 16-Hz mechanical mode to instability.

Concluding remarks: Computing ≠ intelligence

- **RD Middlebrook**: Computers are a very useful tool, but they are not going to do your thinking for you.
- **Charles Concordia**: Sometimes I think they take too much into account, … **People hate to miss anything**.
- **When giants walk the earth:** In the early days, there were no handy computing tools (EMT simulation, cloud computing, etc.) to use to model and replicate dynamics. Yet, brilliant engineers made the power grid work reliably.
- Human brain vs. computers (or AI): **make abstraction & reasoning**; ignore less important details while focusing on most important elements.
- This talk shows that mechanism analysis for oscillations requires more than computing. **Simplifying and constructing feedback systems** help reveal the underlying mechanisms.