Replication and identification of causes of grid oscillations

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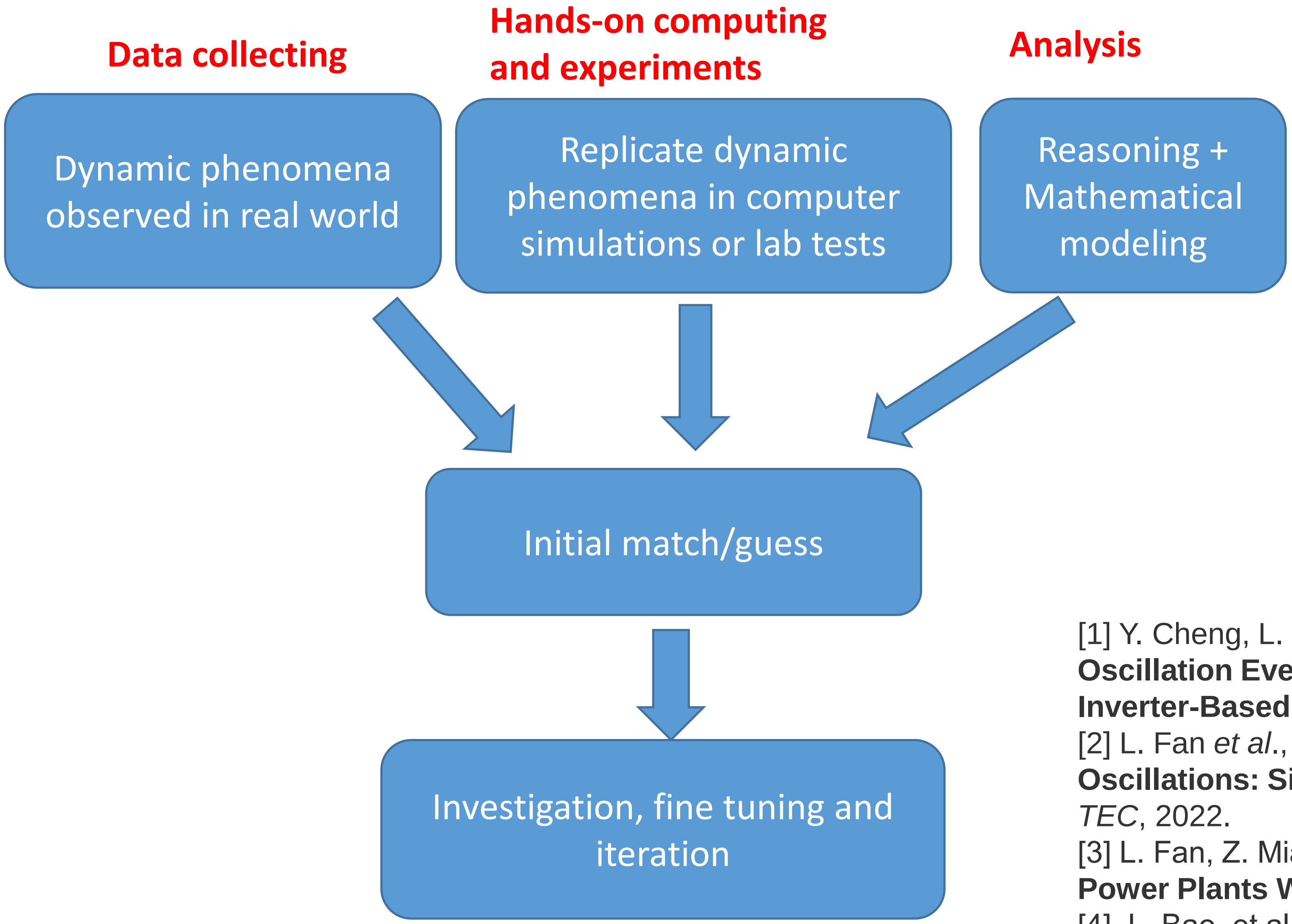
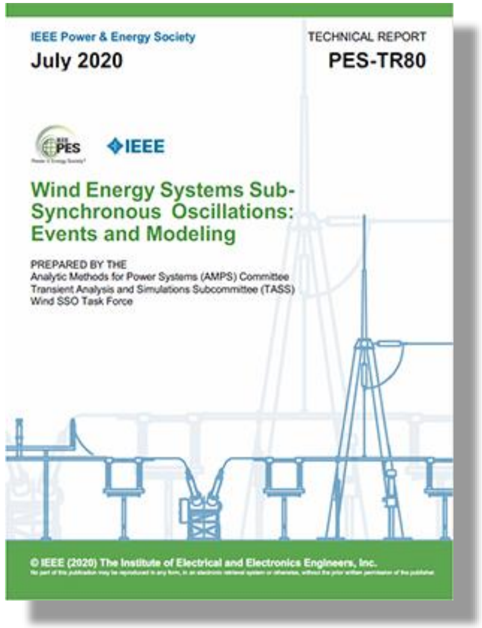
ESIG Fall 2022 Technical Workshop, Minneapolis
October 26, 2022





[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 2022.*
[2] L. Fan *et al*., "**Real-World 20-Hz IBR Subsynchronous Oscillations: Signatures and Mechanism Analysis**," in *IEEE TEC*, 2022.
[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 2021.

Data collecting

wind farm oscillations

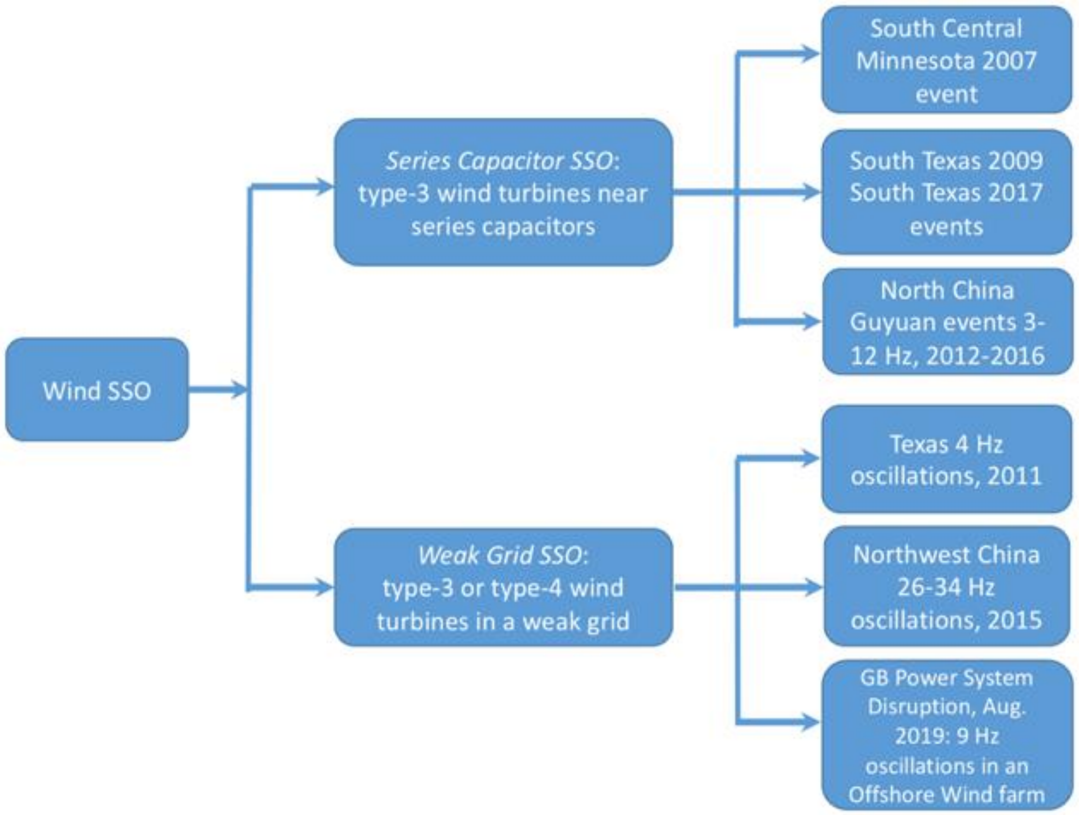


Figure 1.1: Types of oscillations in subsynchronous range for systems with WPPs.

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

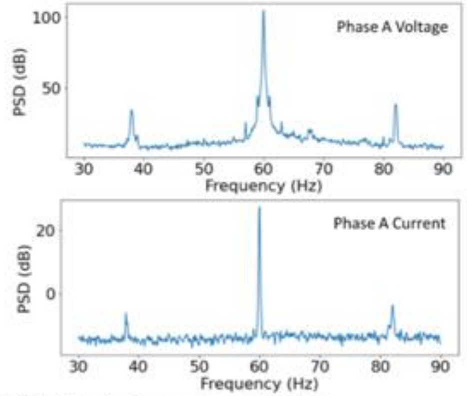


Fig. 17. PSD plots of voltage and current PoW data.

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.

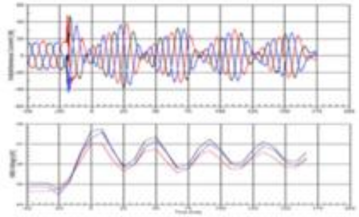


Fig. 11. Hydro One solar PV oscillations. (a) 80-Hz oscillations in the phase current. (b) 20-Hz oscillations in the RMS voltage measurements.

Australia 7-Hz and 19-Hz oscillations

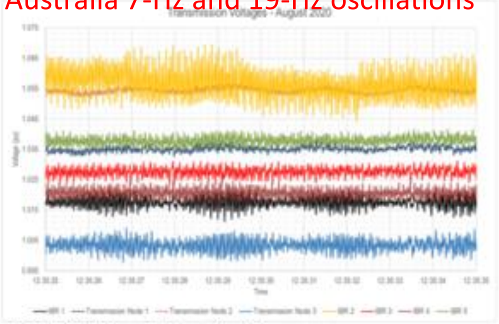


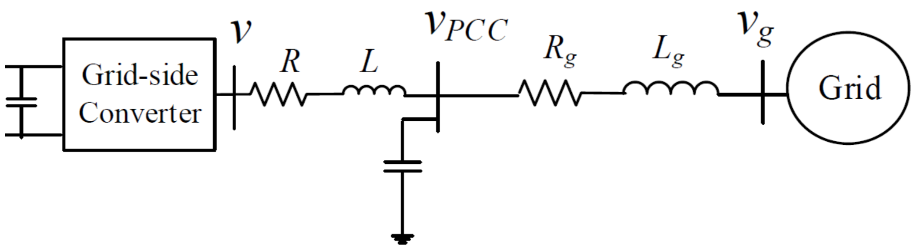
Fig. 15. AEMO 19-Hz oscillations - West Murray area.

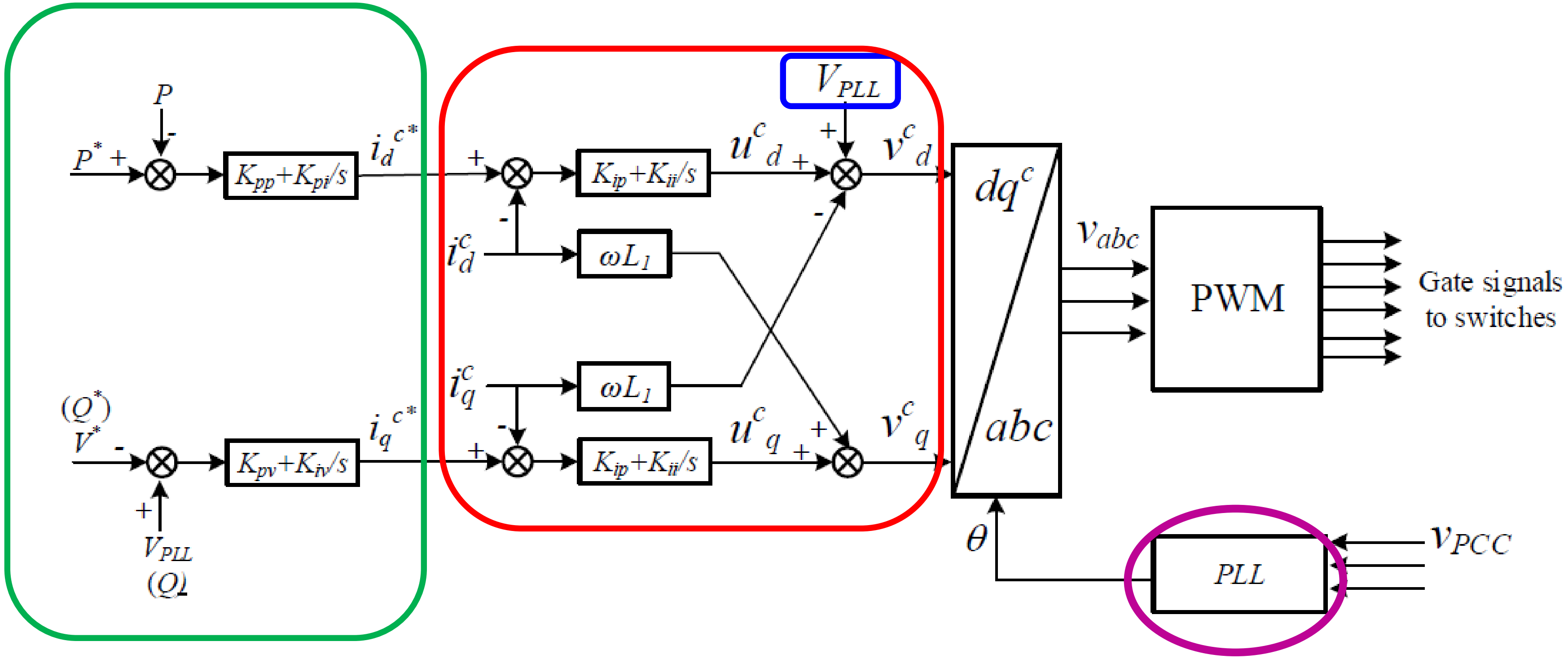
19 events

Understand the fundamentals of converter control (inverter-level)

Voltage source converter control design has considered the following aspects:

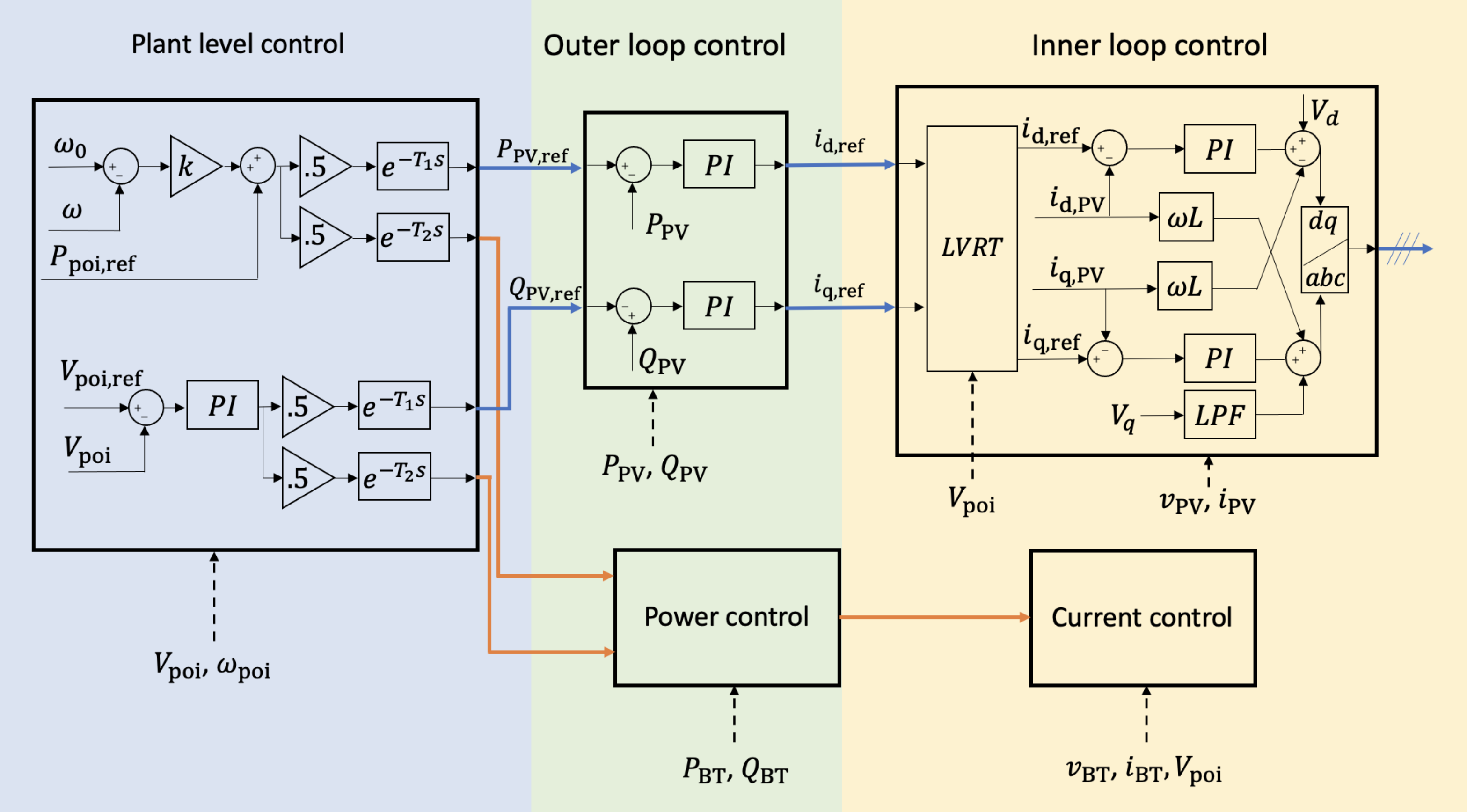
- converter current limit (very fast current control)
- decoupling from grid (voltage feedforward)
- decoupled real power and reactive power control **(vector control)**

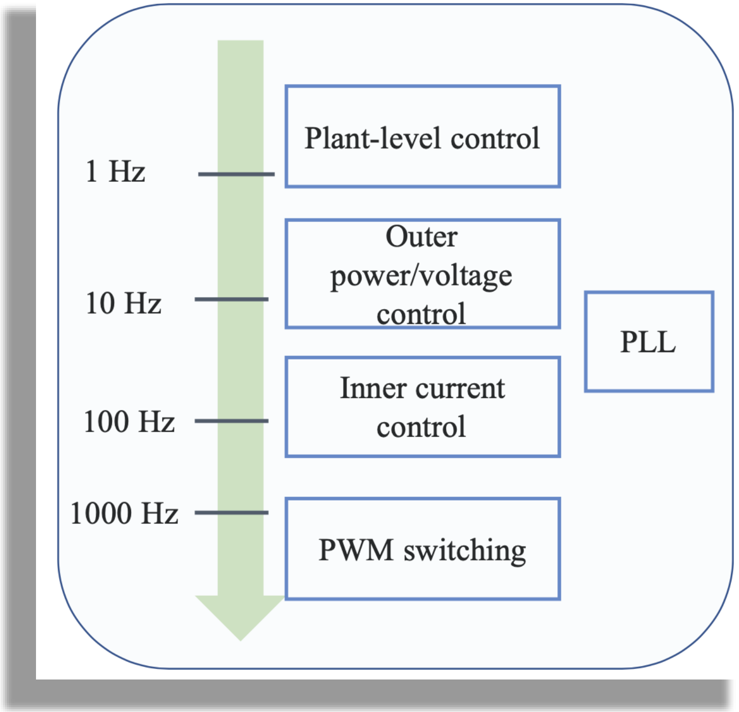


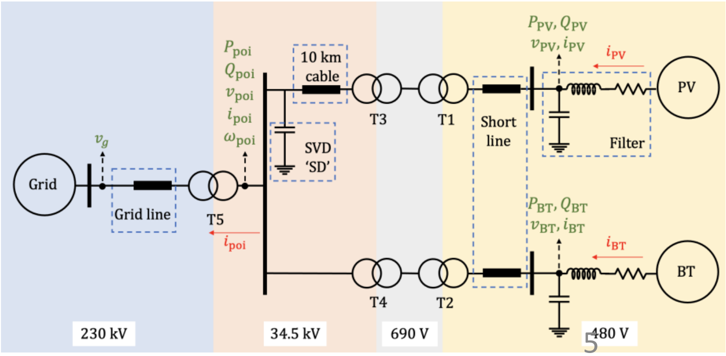


Textbook on VSC:
A. Yazdani, R. Iravani, Voltage-Sourced Converters in Power Systems, IEEE Wiley 2010

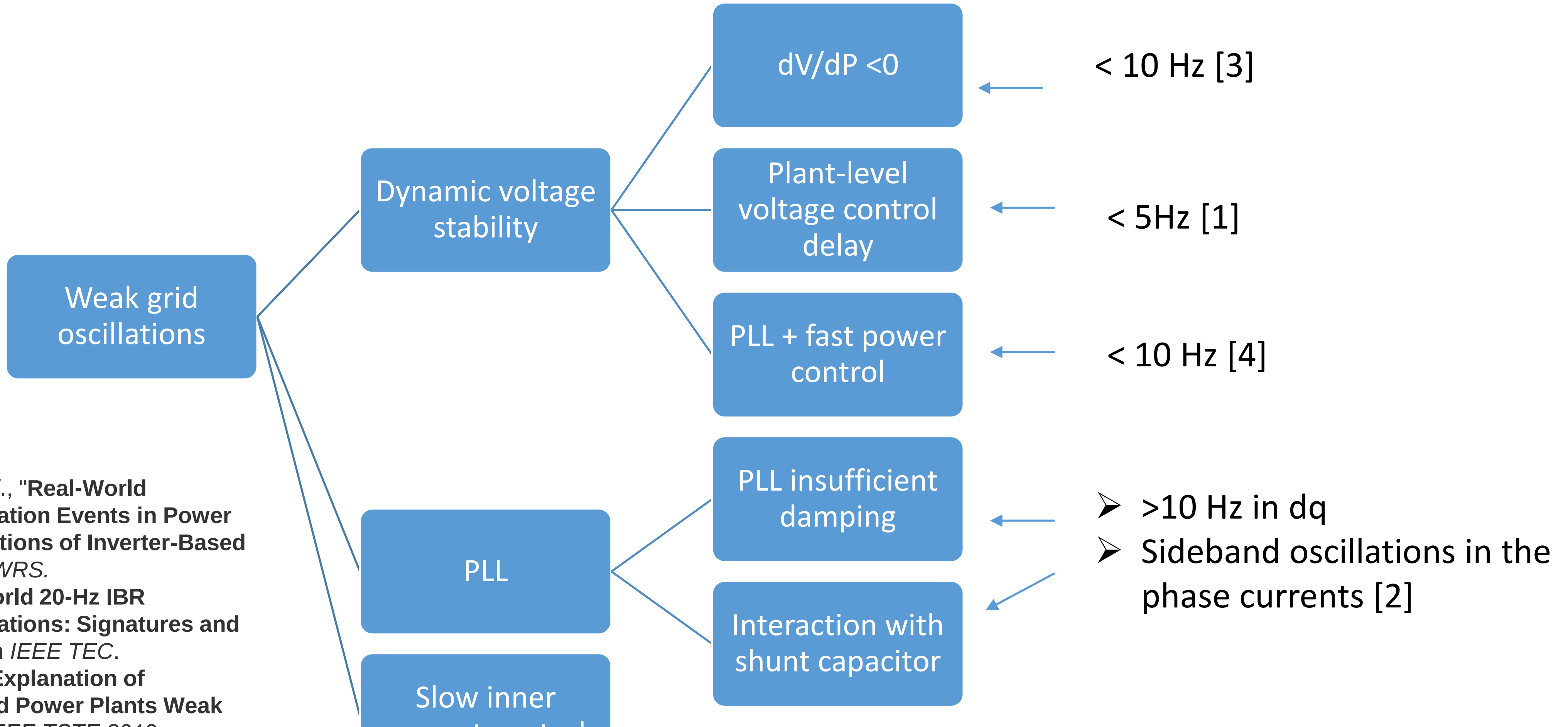
Understand the fundamentals of IBR plant control (plant-level)







Converter-driven oscillations: based on simulation and experiments



- >10 Hz in dq
- Dominant supersynchronous oscillations. [2]

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An example of oscillation replication and mechanism analysis

- Data collection
- EMT/hardware experiments
- Analysis & simulation results matching the real-world observations:
    - Reasoning, analysis, mathematic model building

Data collecting: voltage stability related issues [1]

#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].

#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.

Line tripping
High power
Voltage control

Hardware demonstration: weak grid oscillations

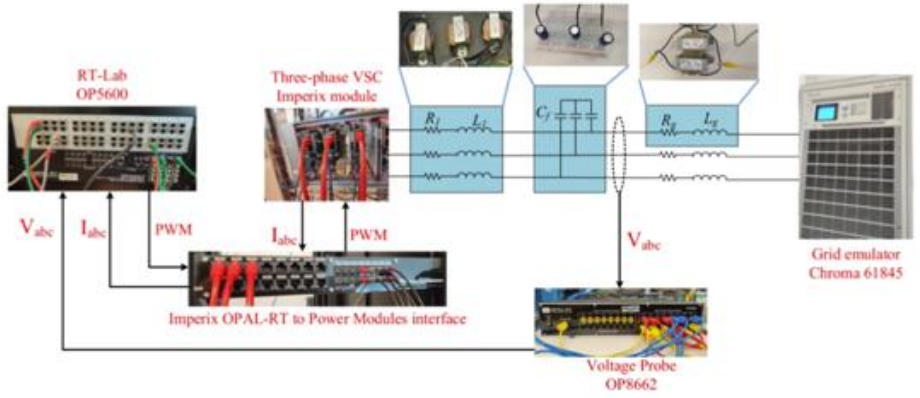


Fig. 19: Configuration of the hardware test bed at University of South Florida [49].

For well-tuned control parameters, if P/Q control mode is adopted, the system loses stability without oscillations. If P/V is adopted, the system loses stability with oscillations.

Ref: L. Bao, L. Fan, Z. Miao, and Z. Wang, "Hardware demonstration of weak grid oscillations in grid-following converters," *the 53rd NAPS*, 2021.

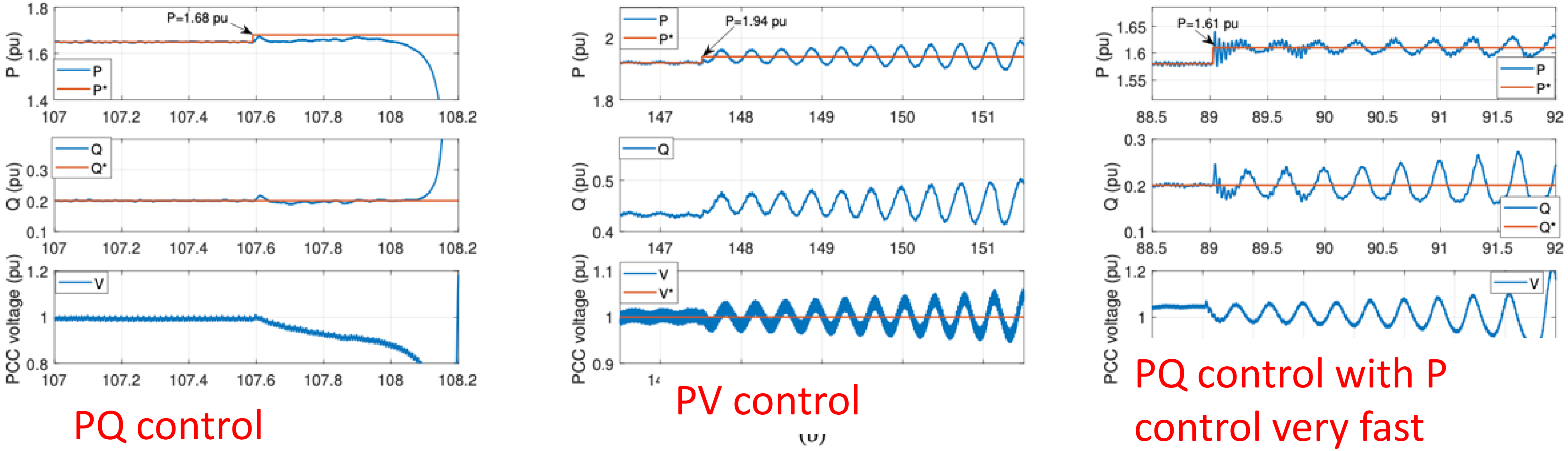


Fig. 20: Hardware experiment results [49] (The responses of P, Q and voltage when P is given a step change) demonstrating weak grid instability. (a) PQ control mode (slow P control): losing stability without subject to oscillations. (b) PV control mode (slow P control): oscillations. (c) PQ control (fast P control): oscillations appear when the power control becomes fast.

- We have demonstrated weak grid oscillations. When grid strength reduces, oscillations may appear. High power exporting makes stability worse.
- Those features match the real-world observations, **except:**
- **Fast voltage control in our experiments is good for stability.**

[5] Li, Y., Fan, L. and Miao, Z., 2018. **Stability control for wind in weak grids**. IEEE Transactions on Sustainable Energy, 10(4), pp.2094-2103.

[6] Ramasubramanian, D., Baker, W., Matevosyan, J., Pant, S. and Achilles, S., 2022. **Asking for fast terminal voltage control in grid following plants could provide benefits of grid forming behavior**. IET Generation, Transmission & Distribution.

Then, how to understand the real-world observation:

Slowing down voltage control mitigates the 4-Hz oscillations in ERCOT

Why?

The two voltage controls are different:

Inverter-level control

Plant-level control (delay)

Mechanism: delay in plant-level voltage control

The previous voltage stability example: SCR →1.04. In Texas 4-Hz case, **SCR is 2**.

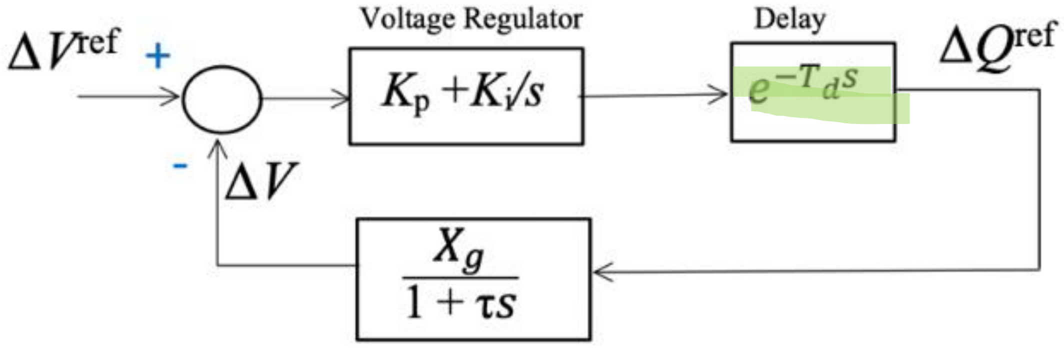
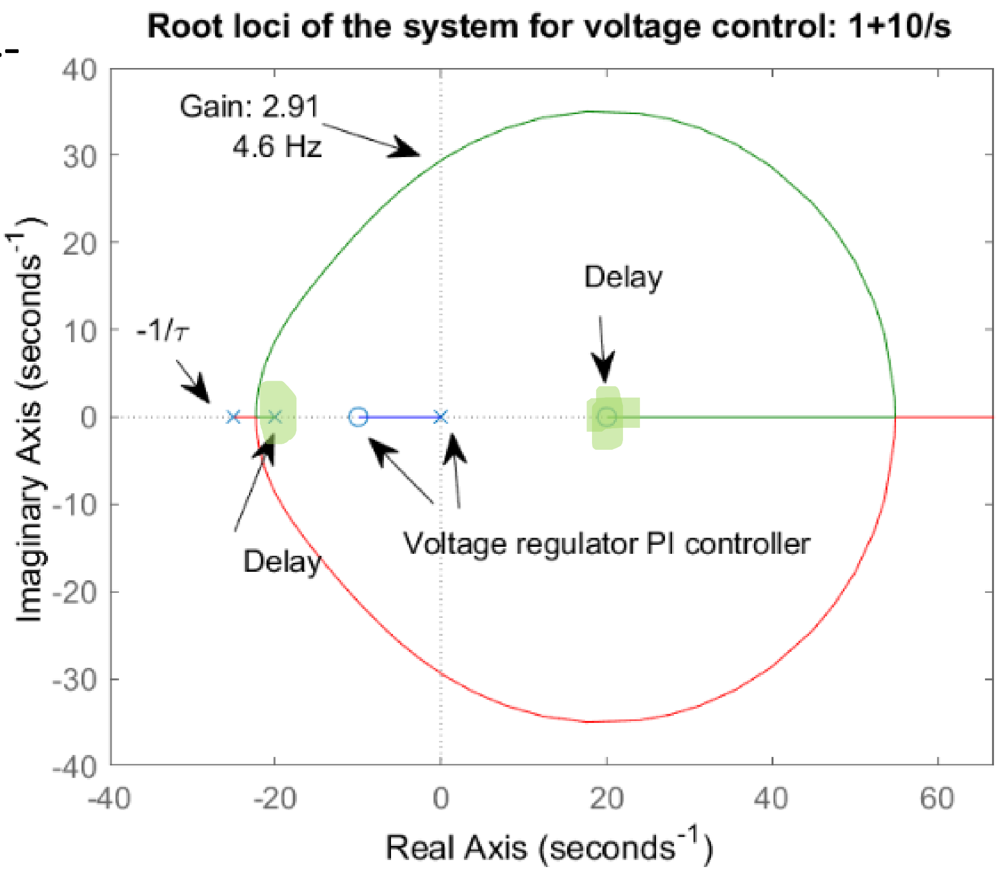


Fig. 21: Voltage control closed-loop system. $K_p = 0$ or 1, $K_i = 10$, $T_d = 0.1$ s, $\tau = 0.04$, $X_g = 0.5$.

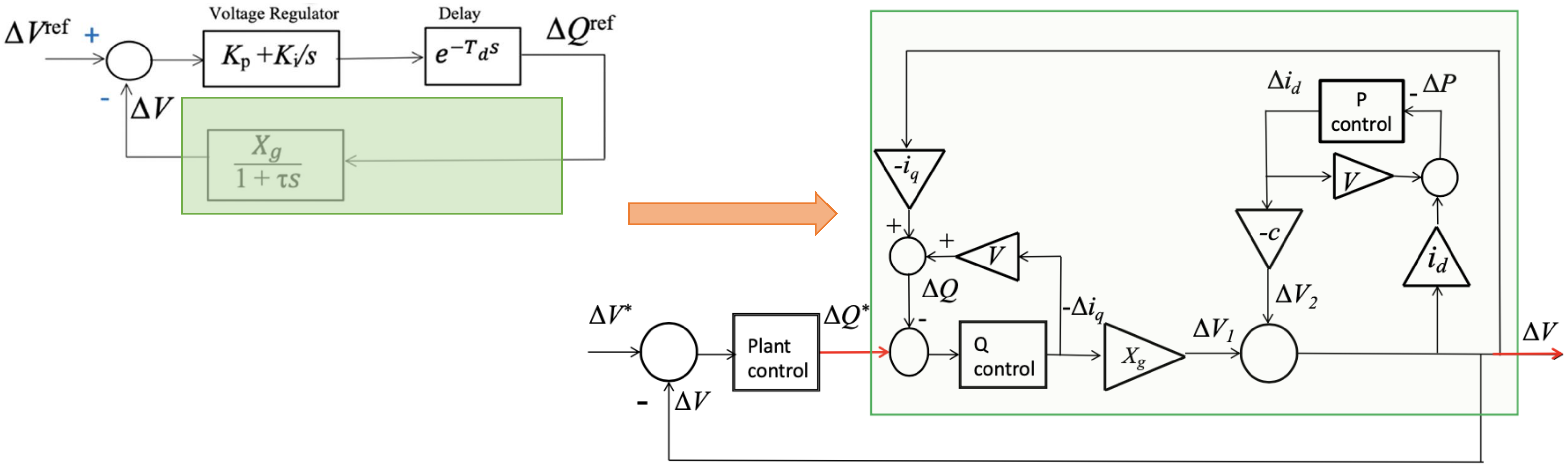
Oscillations are due to plant-level voltage control with delay. Larger gains make oscillations worse.

If the voltage control is implemented in inverter level, larger voltage gains make stability better.



Texas 4-Hz oscillations

Mechanism: full picture to consider the real power effect



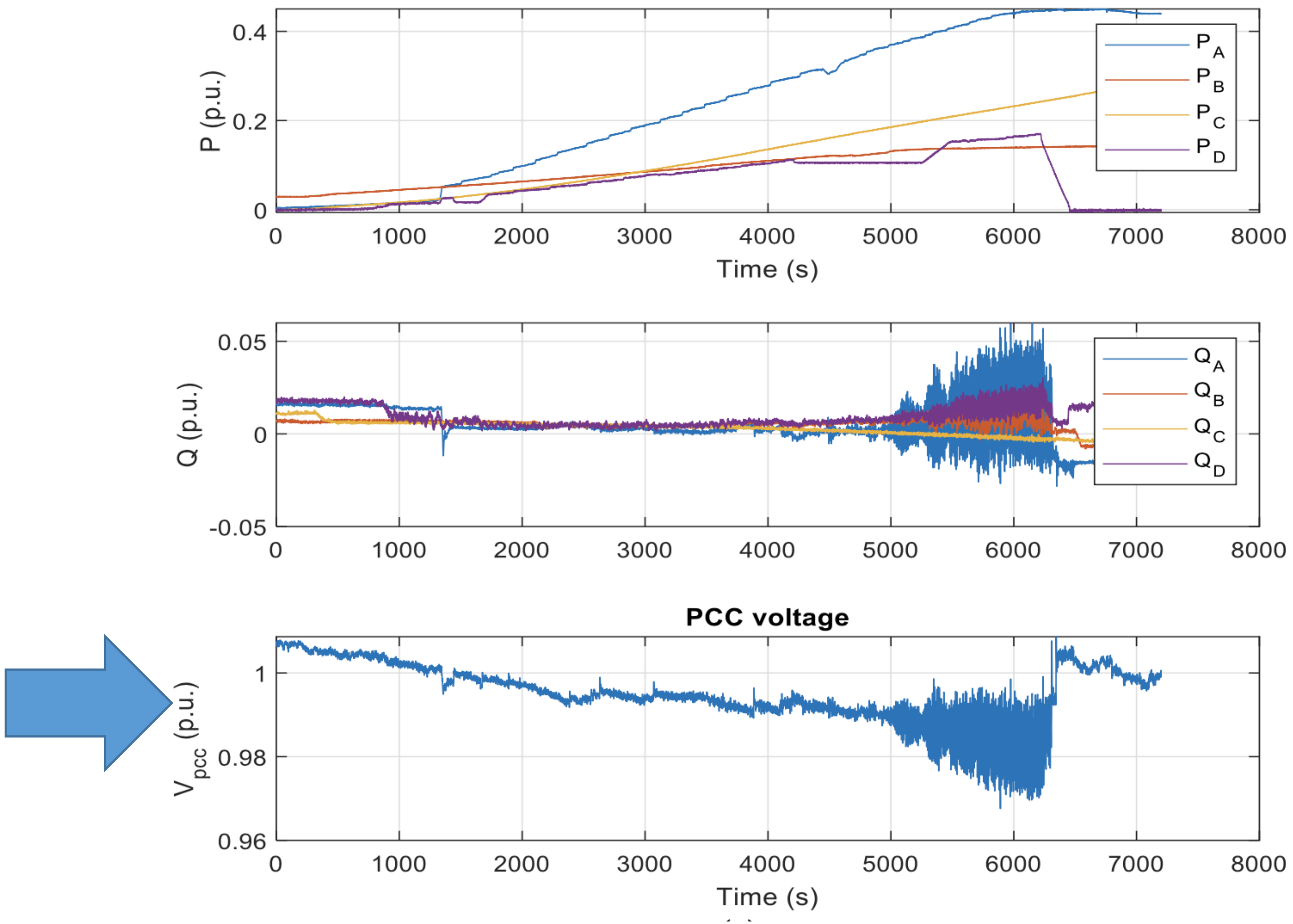
This block diagram can explain the critical features of Texas 4-Hz oscillations:

1. High power makes oscillations worse
2. Weak grid makes oscillations worse
3. Large plant-level voltage control gains make oscillations worse

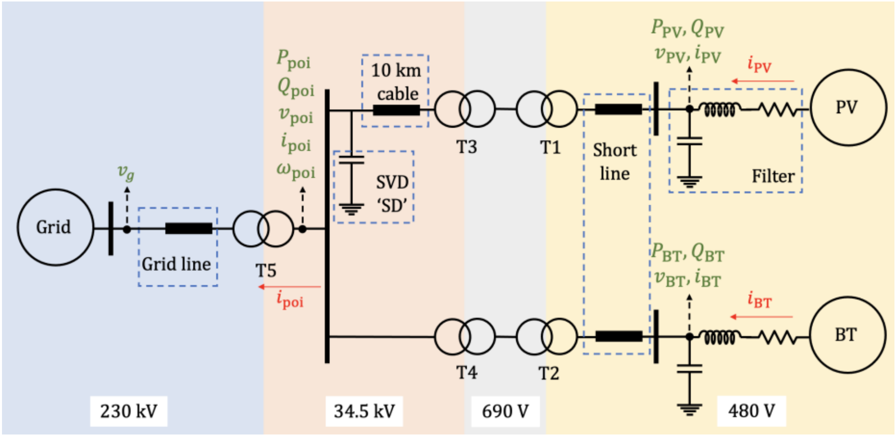
More insights from the previous model:

Real power / voltage has a very small gain at low frequency.

Real-world observation: 0.1-Hz oscillations shown in voltage and reactive power, but not in real power.

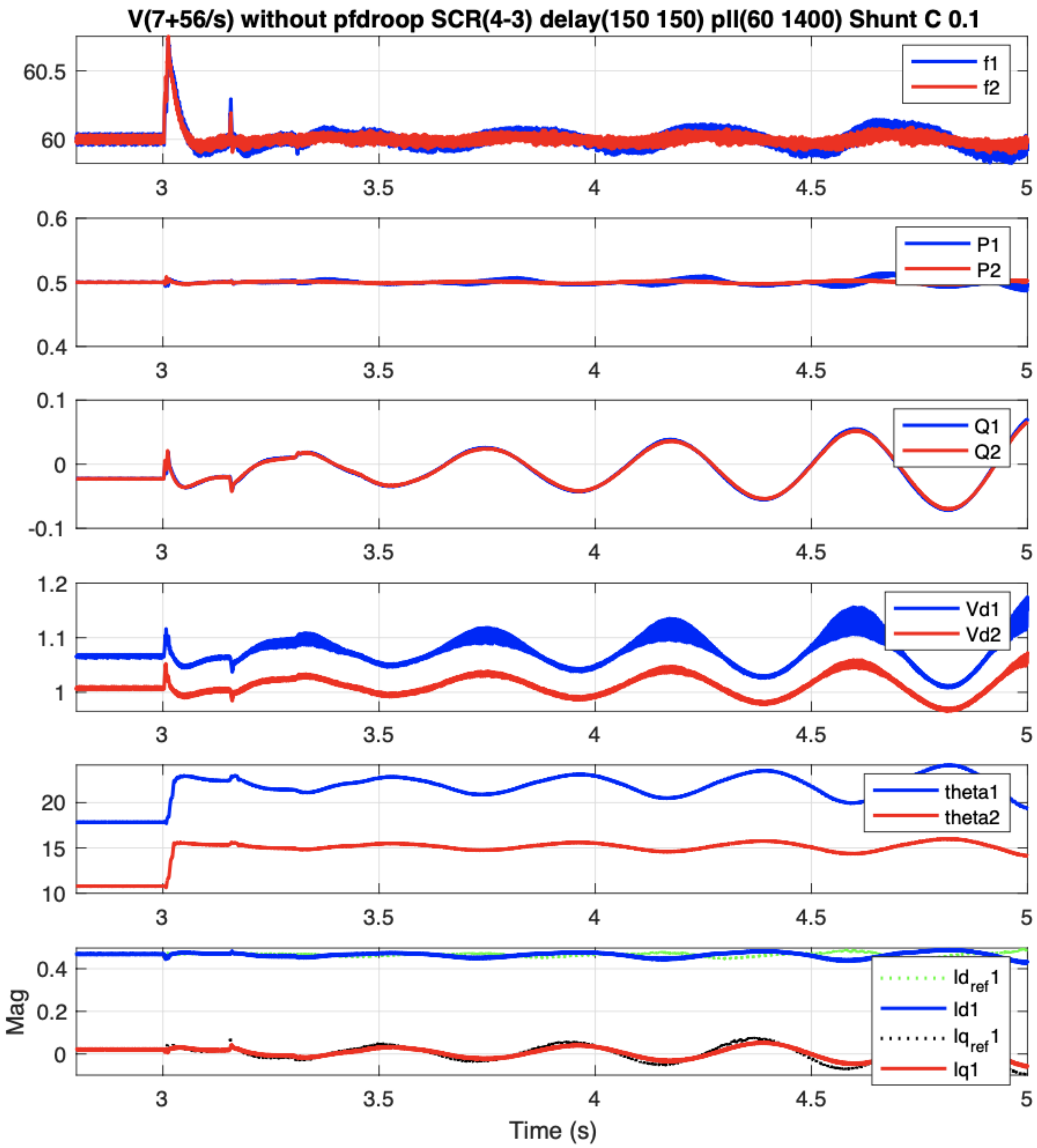


Computer simulation



A line tripping event causes SCR reduction. 2-Hz oscillations appear in voltage and reactive power.

Note the oscillations in real power are less significant.



Concluding remarks

- Grid oscillations have various causes.
- As a first step, it is suggested to collect sufficient information of generators, grid, and oscillations' critical features, and
  - Influence of power, grid strength, series compensation, shunt compensation, voltage control, etc.
- Replication and mechanism analysis require
  - Hands-on computing and/or experiments
  - Reasoning and analysis
  - And iterations