



# Control System Stability for Converter-Dominated Grids

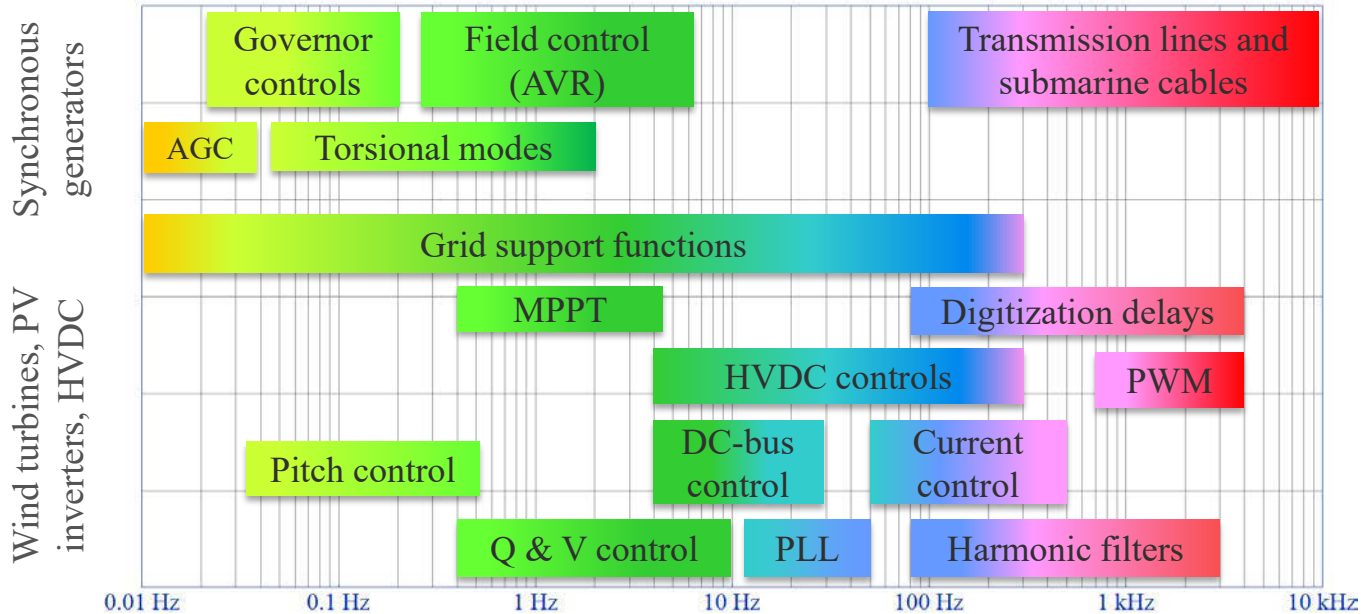
Shahil Shah, Vahan Gevorgian, Przemyslaw Koralewicz, and Robb Wallen

ESIG Spring Technical Workshop (April 28, 2020)

# Outline

- Stability problems in converter-dominated grids
- Impedance-based stability analysis
- A case study:
  - Reactive power oscillations in wind power plants.
- Effect of grid-forming resources on stability:
  - Grid-forming Type III wind turbines
  - Damping of inter-area modes.

# New Stability Problems: Control Interactions



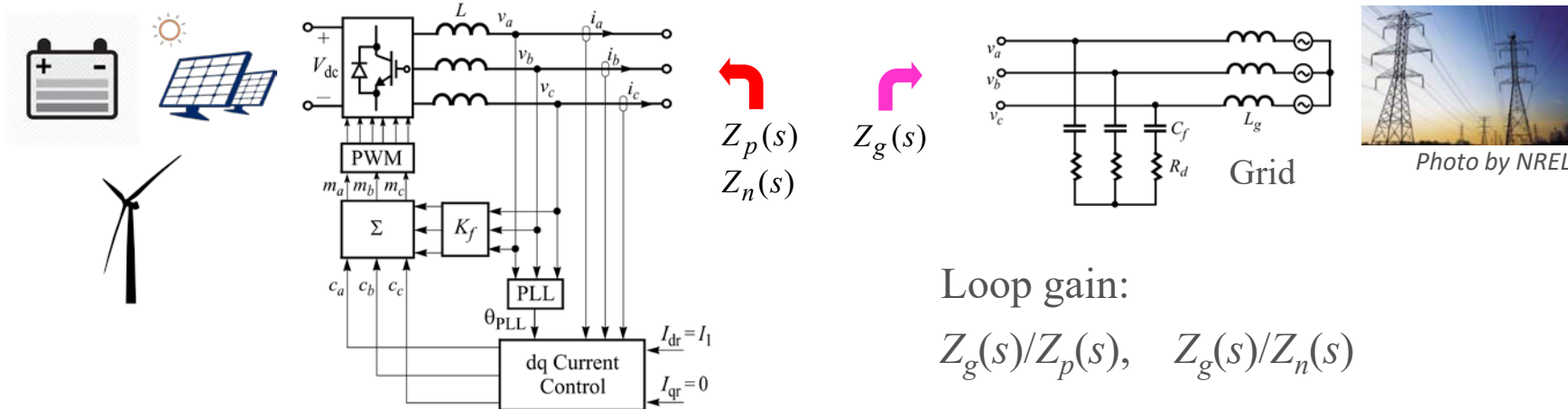
## Resonating variables:

- **Phasor (DC) variables:** *Frequency, voltage magnitude, active and reactive power flow*
- **Phase (AC) variables:** *Phase voltages and currents*

- Major challenges: (1) fast controls, (2) diversity of controls, (3) unavailability of dynamic models, (4) complex dynamics

*SSO in phasor variables is not the same as SSO in phase variables.*

# Impedance-Based Stability Analysis

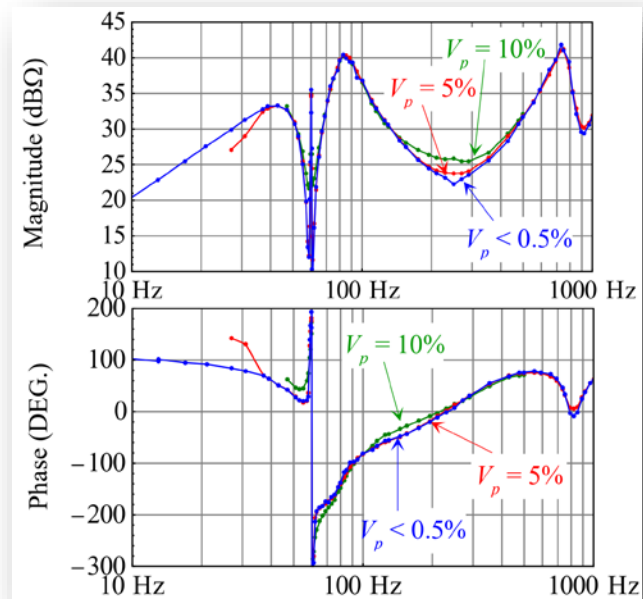


- Impedance responses of two subsystems are compared:
  - Magnitude response intersection points give frequencies of resonance modes.
  - Phase difference at intersection points gives damping.

# Positive-Sequence Impedance of a 4-MW Turbine



Photo by NREL



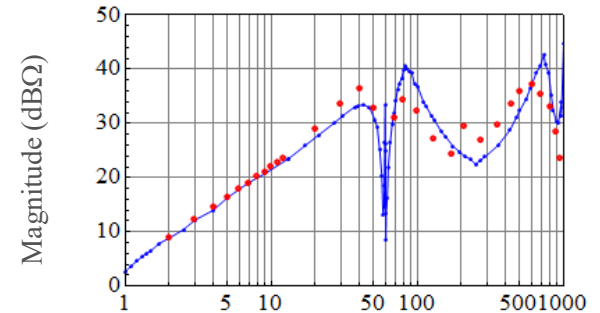
- Automated sequence impedance measurement by a 7-MW grid simulator for different operation conditions

# Adoption by Industry

## Root-cause finding; grid codes; control design

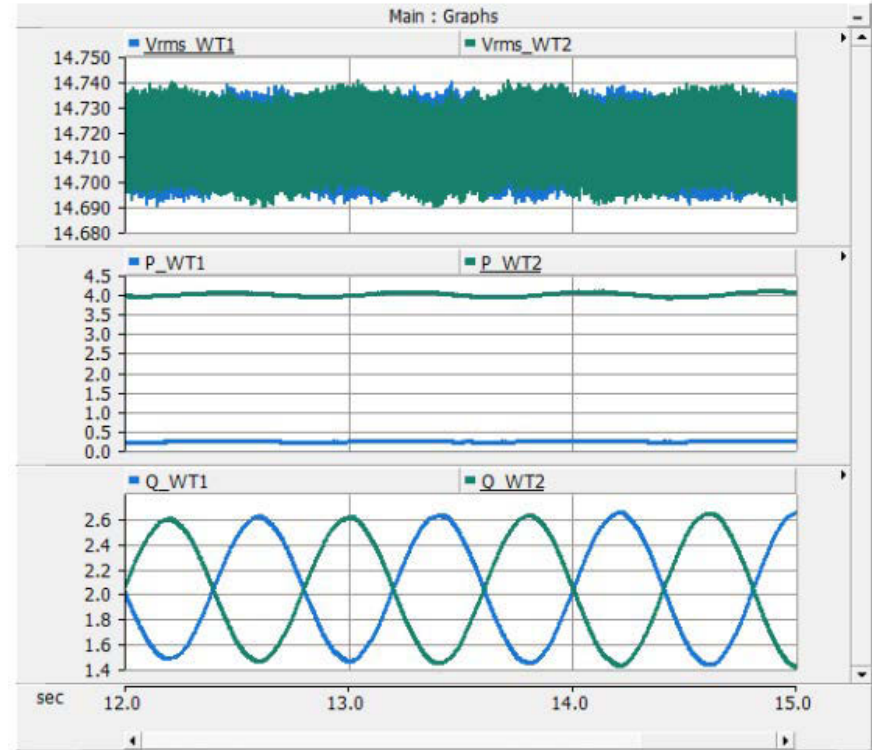
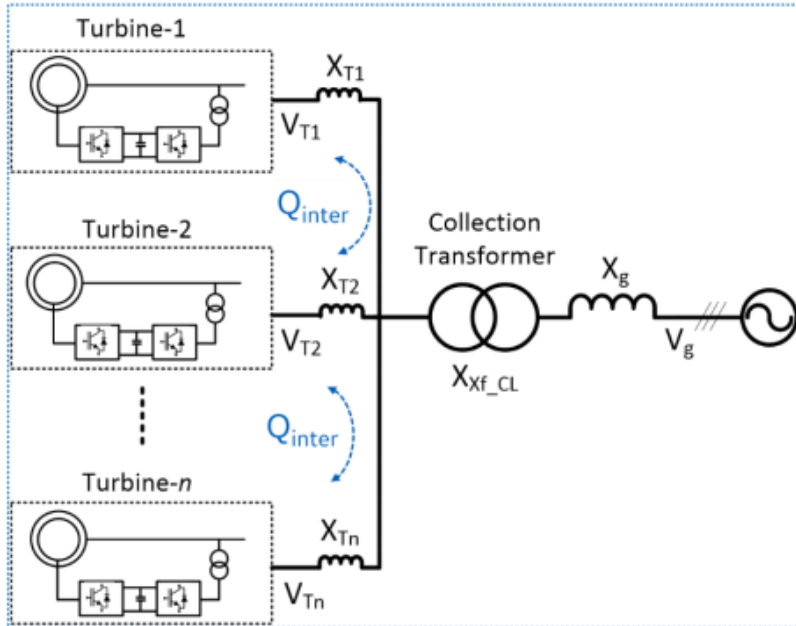
- TenneT (Germany)
  - Wind power plant owner needs to ensure stability and avoid resonance problems.
- ERCOT (United States)
  - Requires new wind projects to conduct SSR studies—impedance scans.
- State Grid (China)
  - CHIL simulation lab of CEPRI
  - Analysis of resonance for new wind power plants
  - Maintain library of impedance models.
- Grid integration studies by utilities.

## • Model validation



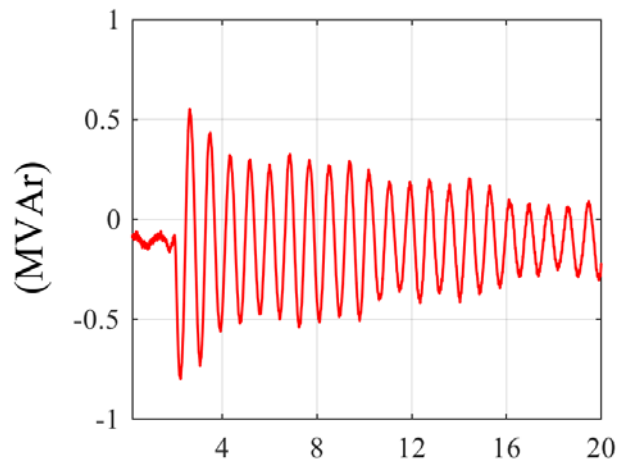
Blue: Measurements of 4-MW DFIG  
Red: PSCAD model from OEM

# Reactive Power Oscillations Between Wind Turbines



# Reactive Power Oscillations in Wind

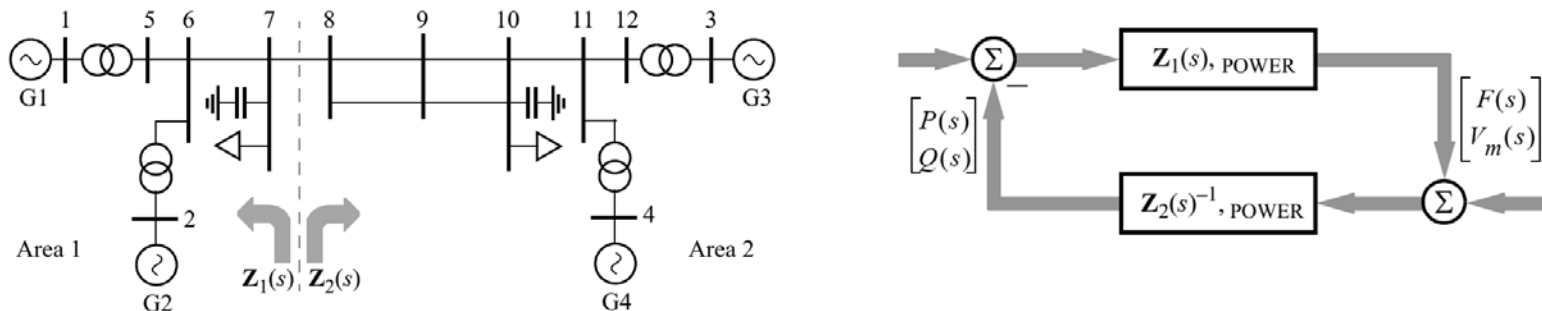
- 4-MW wind turbine at NREL:
  - Turbine reactive power output had 1.2-Hz oscillations following a small (1%) step change in voltage.



- Hornsea wind power plant in the United Kingdom:
  - Hornsea experienced reactive power oscillations before the major blackout event in the United Kingdom grid in August 2019.
  - The wind power plant reactive power output had 8.5-Hz oscillations following a small (2%) step change in voltage.



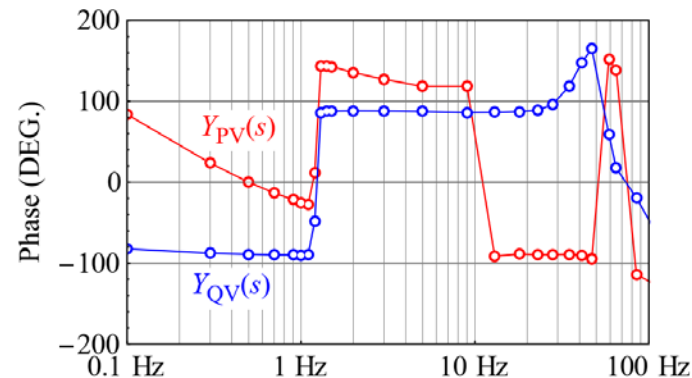
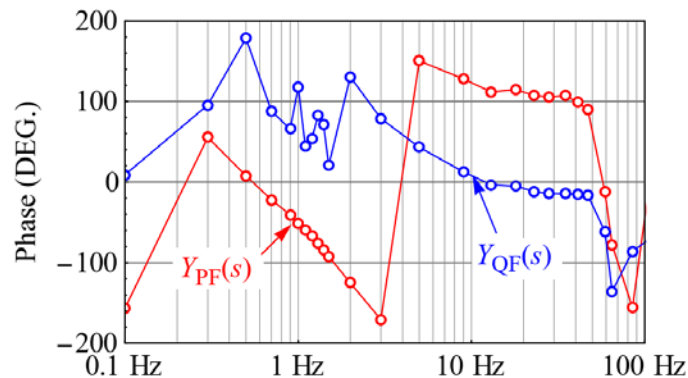
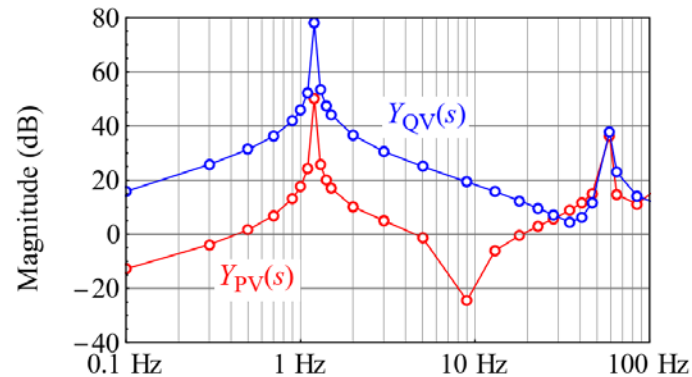
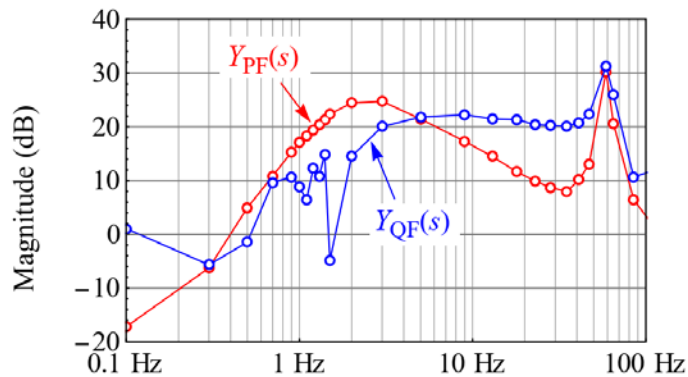
# Power Domain Impedance Theory



- Definition of power domain impedance:

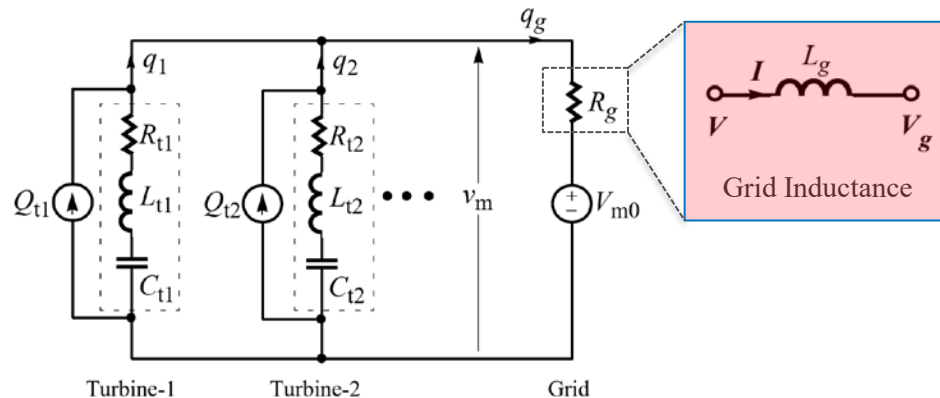
$$\begin{bmatrix} F(s) \\ V_m(s) \end{bmatrix} = \begin{bmatrix} Z_{FP}(s) & Z_{FQ}(s) \\ Z_{VP}(s) & Z_{VQ}(s) \end{bmatrix} \begin{bmatrix} P(s) \\ Q(s) \end{bmatrix} \quad \begin{bmatrix} P(s) \\ Q(s) \end{bmatrix} = \begin{bmatrix} Y_{PF}(s) & Y_{PV}(s) \\ Y_{QF}(s) & Y_{QV}(s) \end{bmatrix} \begin{bmatrix} F(s) \\ V_m(s) \end{bmatrix}$$

# Power Domain Admittance of 4-MW Turbine



# Analysis of Reactive Power Dynamics

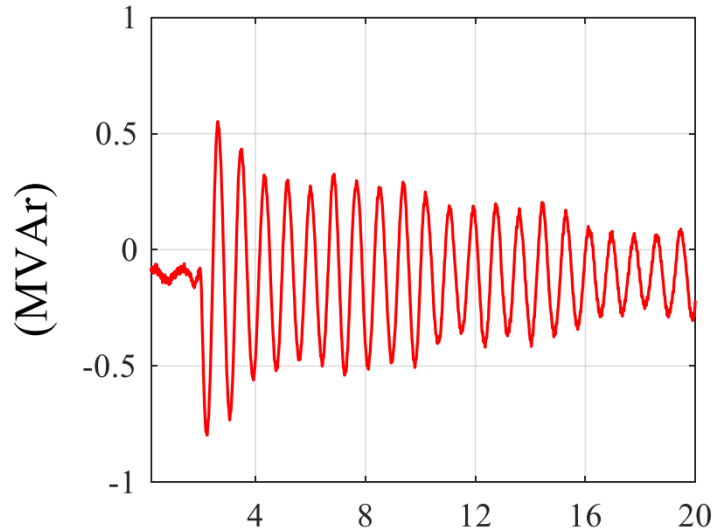
- Equivalent circuit:
  - Reactive power flow is interpreted as instantaneous current.
  - Voltage magnitude is interpreted as instantaneous voltage.



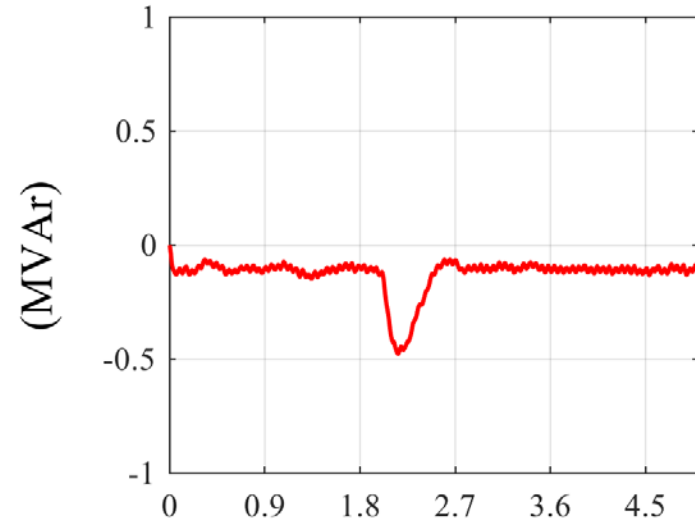
- Analysis results:
  - Inductive grid impedance acts as resistor.
  - Weak inductive grid will damp plant-to-grid reactive power oscillations.
  - Weak inductive grid will not damp turbine-to-turbine reactive power oscillations.

# Effect of Grid Strength on Reactive Power Oscillations

- Very strong grid ( $L_g = 0$ )



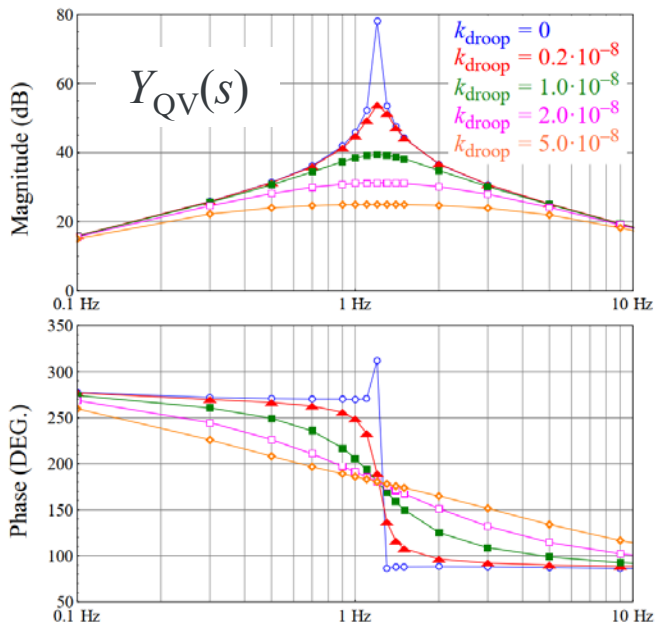
- Not-so-strong grid ( $L_g = 8$  mH)



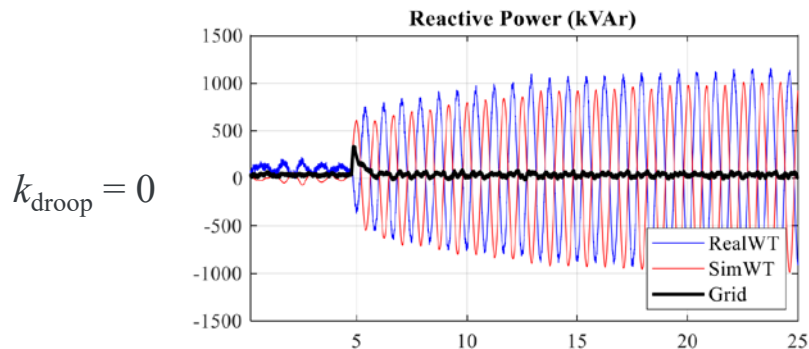
- *Weak grid damps reactive power oscillations from wind power plants.*

# Reactive Power Droop for Damping

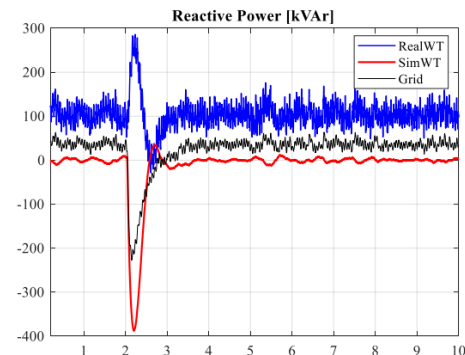
- Transfer function from voltage magnitude to reactive power output



- Turbine-to-turbine oscillations

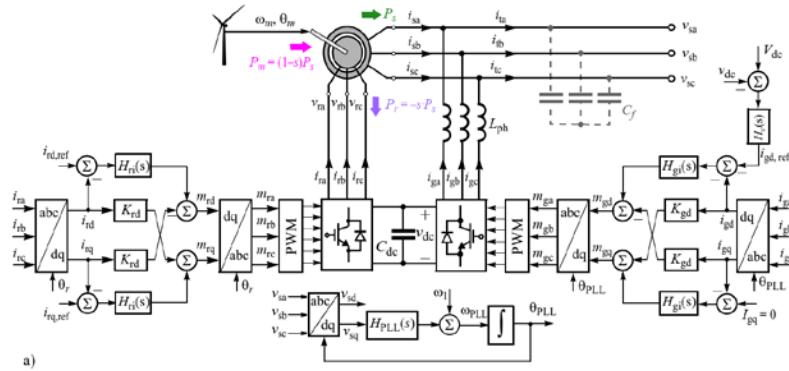


$k_{\text{droop}} = 1 \times 10^{-8}$

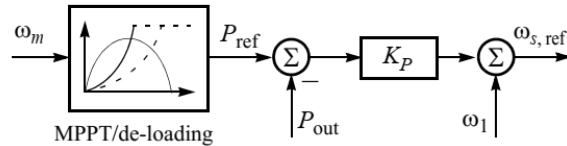


# Grid-Forming Control of Type III Wind Turbines

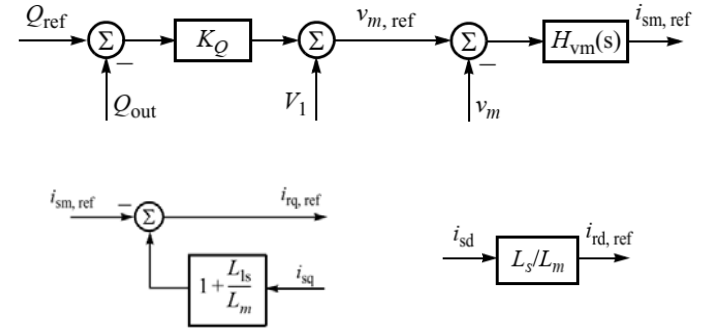
- Vector current control



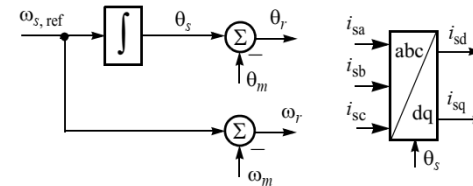
- MPPT/active power control



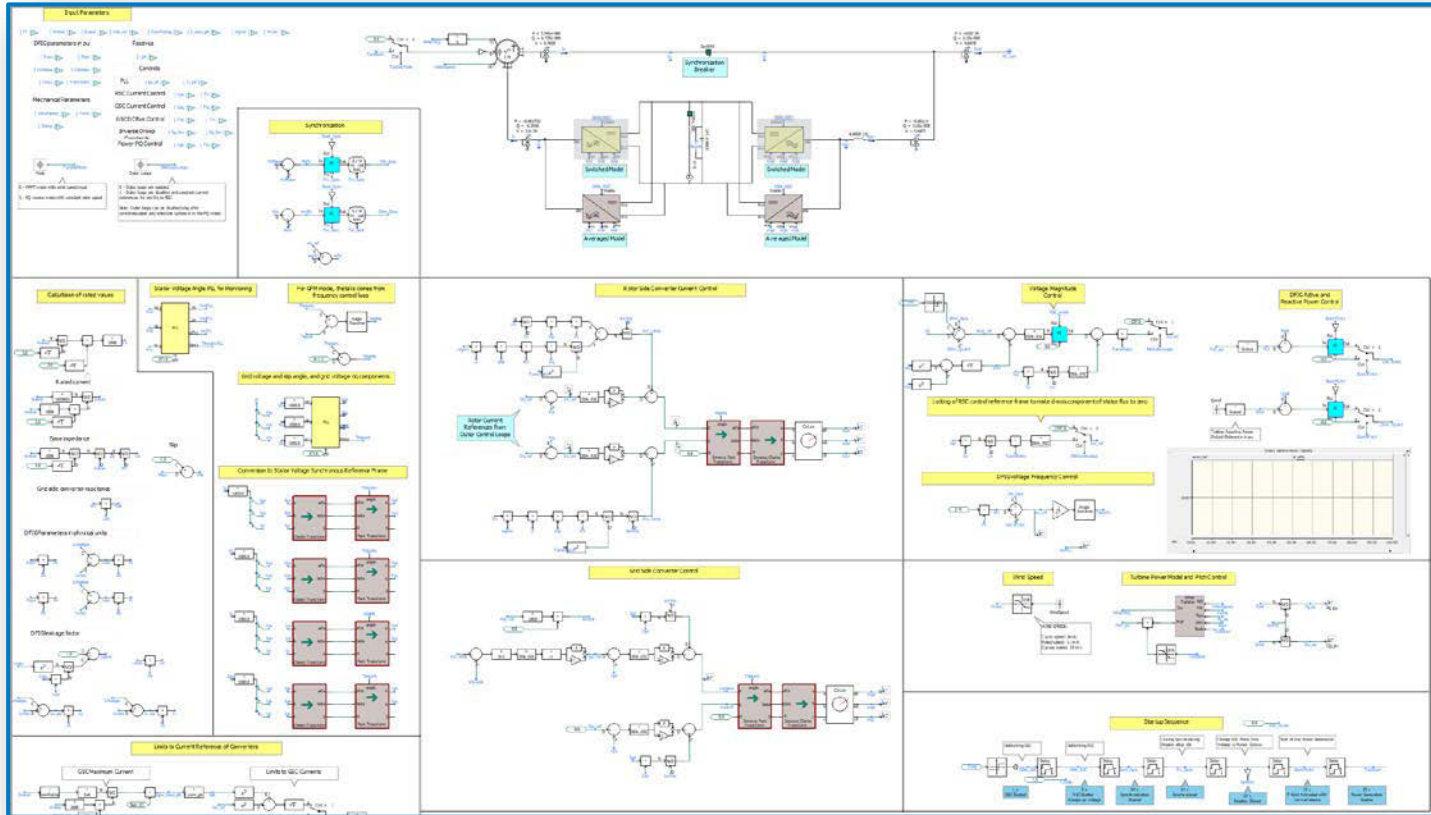
- Voltage control



- Frequency control

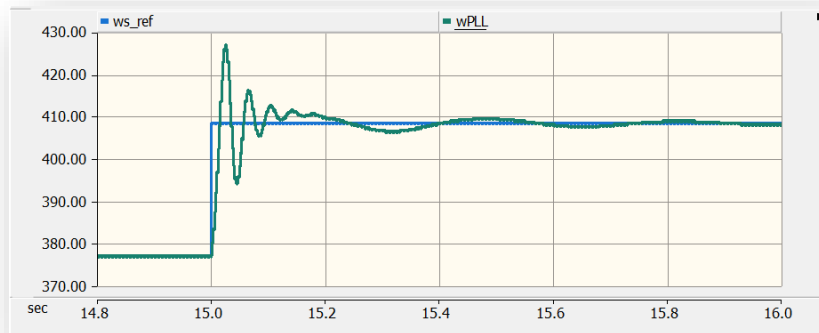


# PSCAD Model



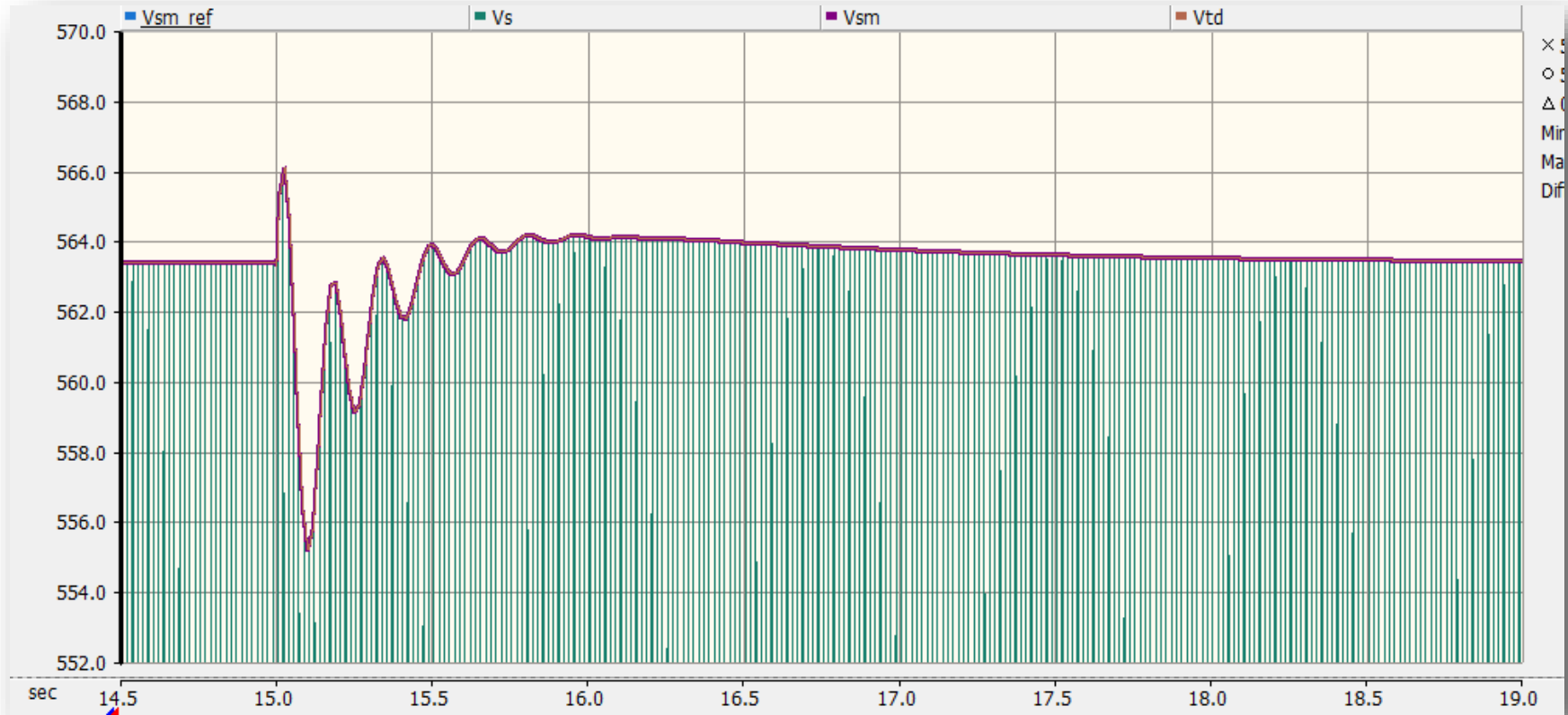
# Voltage and Frequency Control Performance

- Frequency reference increased by 5 Hz:
  - Islanded operation.
- Voltage magnitude reference increased by 10%:
  - Islanded operation.

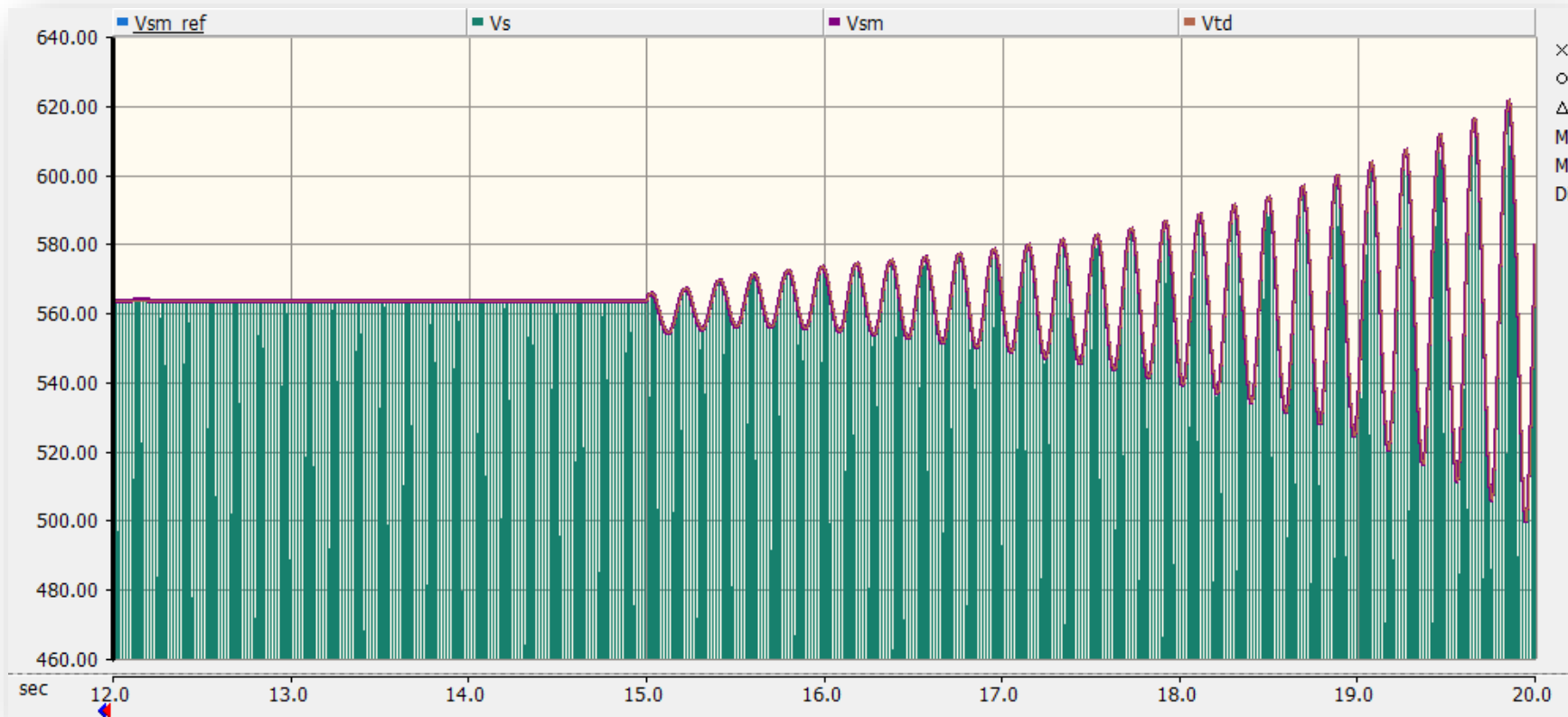




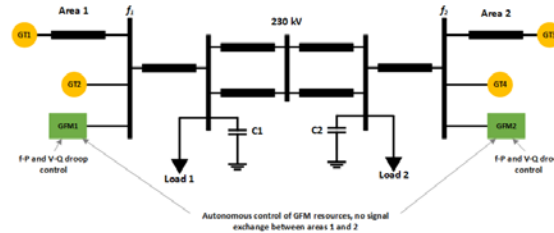
# Operation with Weak Grid



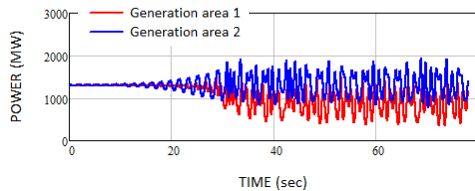
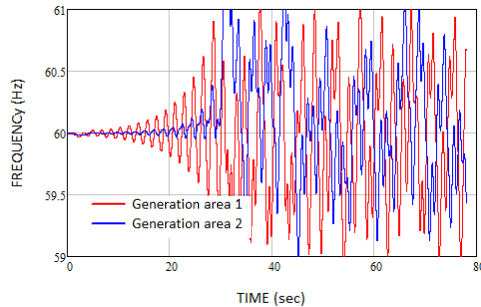
# Operation with Strong Grid



# Damping of Inter-Area Modes by GFM Inverters



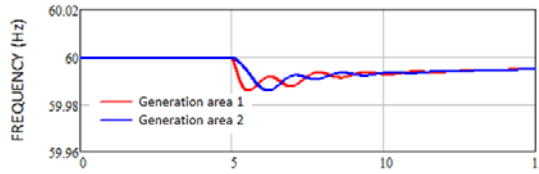
Without GFM inverters



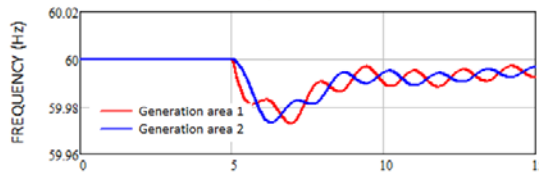
With GFM inverters

Frequency in areas 1 and 2

Droop = 2 mHz/MW

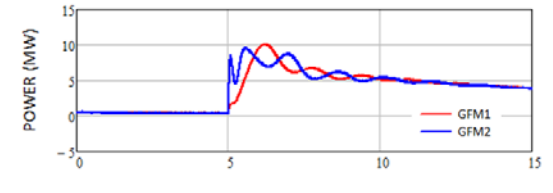


Droop = 8 mHz/MW

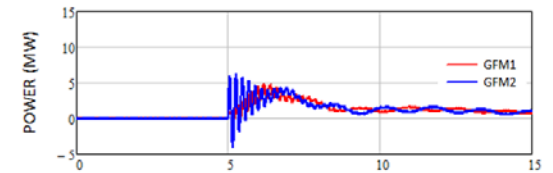


Response of GFM resources 1 and 2

Droop = 2 mHz/MW



Droop = 8mHz/MW



# Summary

- Impedance methods are effective for understanding stability impacts of inverter-based resources
- Vendor-supplied high-fidelity EMTP models of inverter-based resources are required for stability analysis of modern power systems.
  - Focusing on only one control function, e.g., phase-locked loop, in modeling might not be enough.
  - Weak grids are not always “bad” from the stability standpoint.
- Grid-forming resources are helpful for fundamental voltage and frequency stability.
  - But they might worsen existing or introduce new dynamic stability problems.

# Thank you!

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