Control System Stability for Converter-Dominated Grids

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

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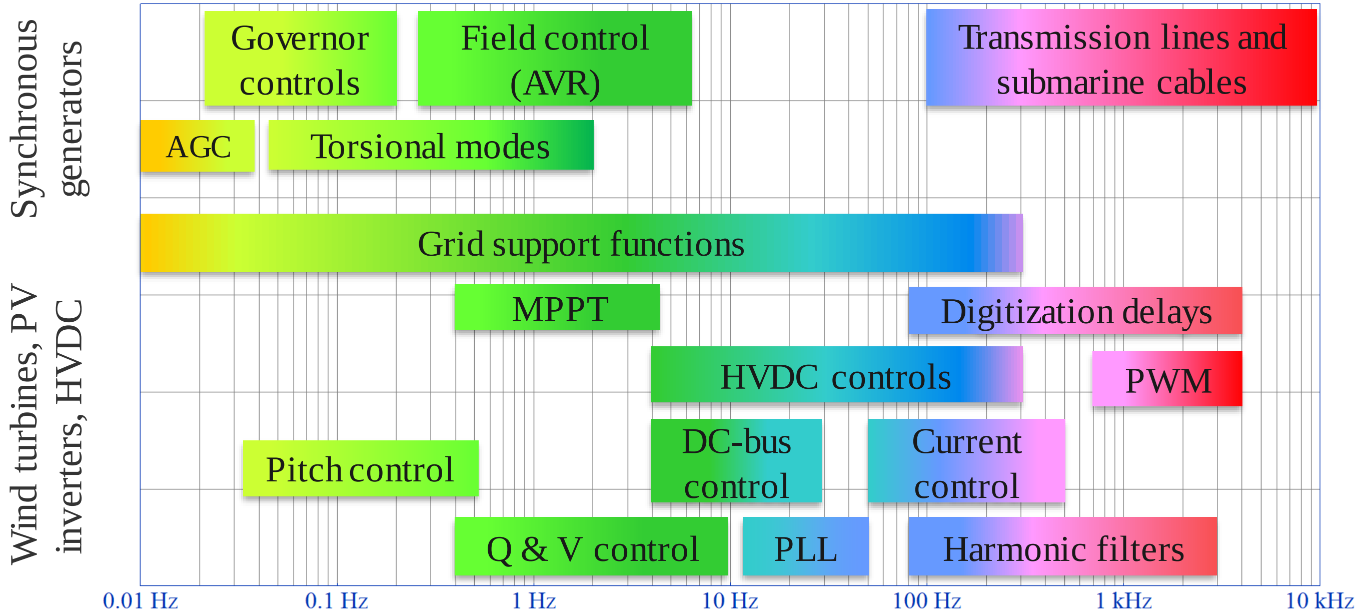
Outline

- 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



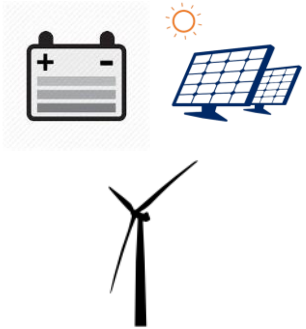
Resonating variables:

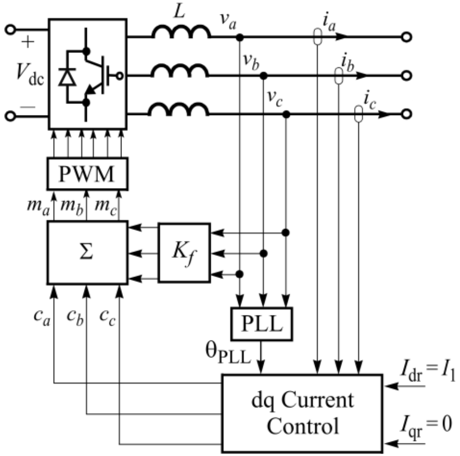
- **Phasor (DC) variables**: *Frequency, voltage magnitude, active and reactive power flow*
- **Phase (AC) variables**: *Phase voltages and currents*

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

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

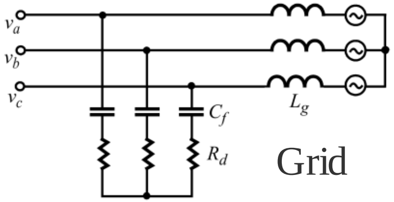
Impedance-Based Stability Analysis





$Z_p(s)$
$Z_n(s)$

$Z_g(s)$

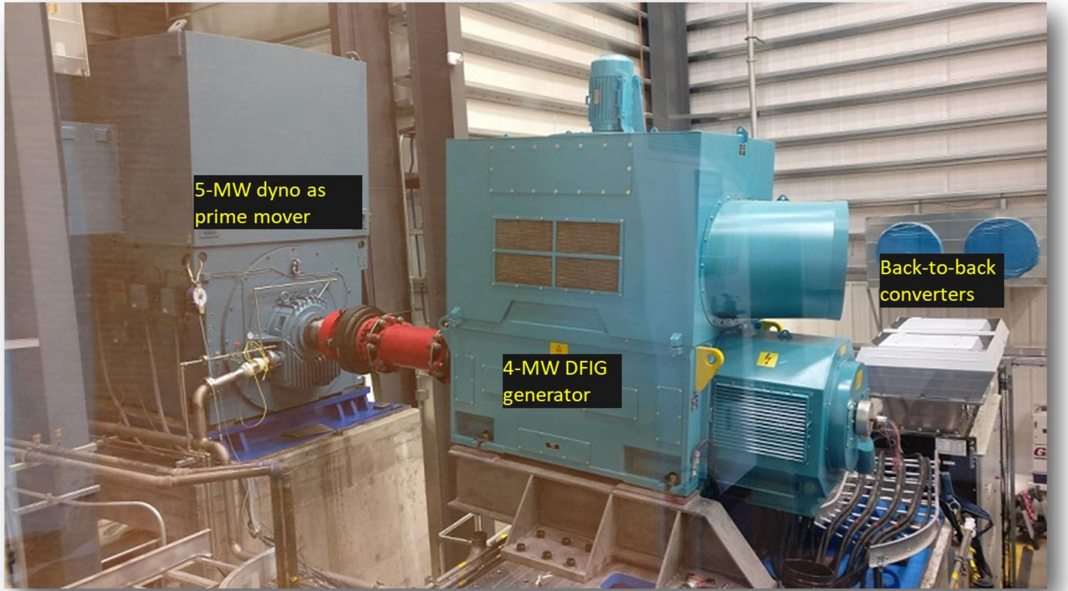


Loop gain:

$$Z_g(s)/Z_p(s), \quad Z_g(s)/Z_n(s)$$

- 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



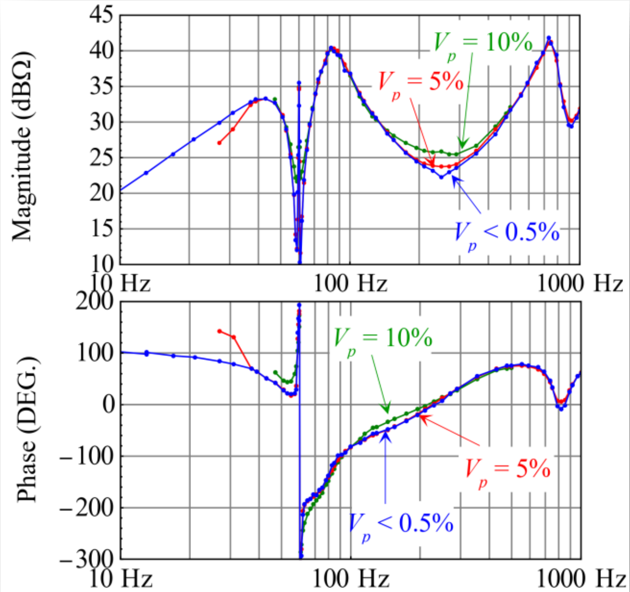


Photo by NREL

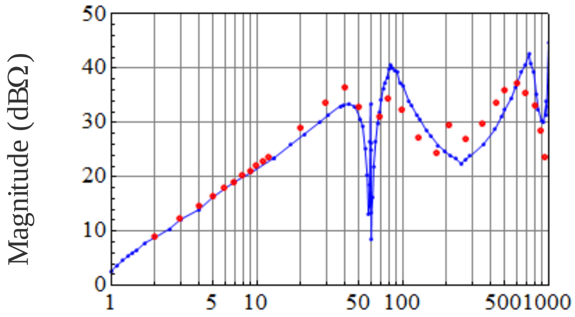
- Automated sequence impedance measurement by a 7-MW grid simulator for different operation conditions

Adoption by Industry

Root-cause finding; grid codes; control design

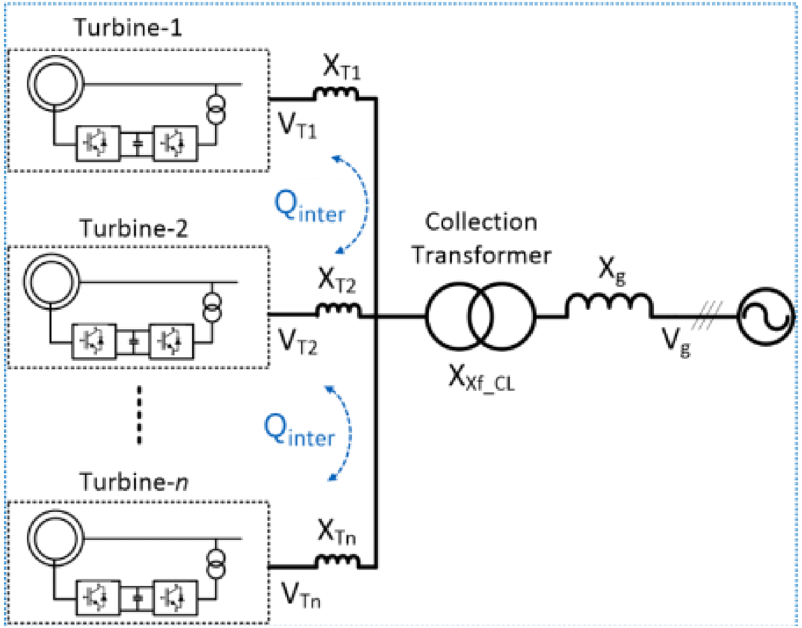
- TenneT (Germany)
  - Wind power plant owner needs to ensure stability and avoid resonance problems.
- ERCOT (United States)
  - Requires new wind projects to conduct SSR studies—impedance scans.
- State Grid (China)
  - CHIL simulation lab of CEPRI
  - Analysis of resonance for new wind power plants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

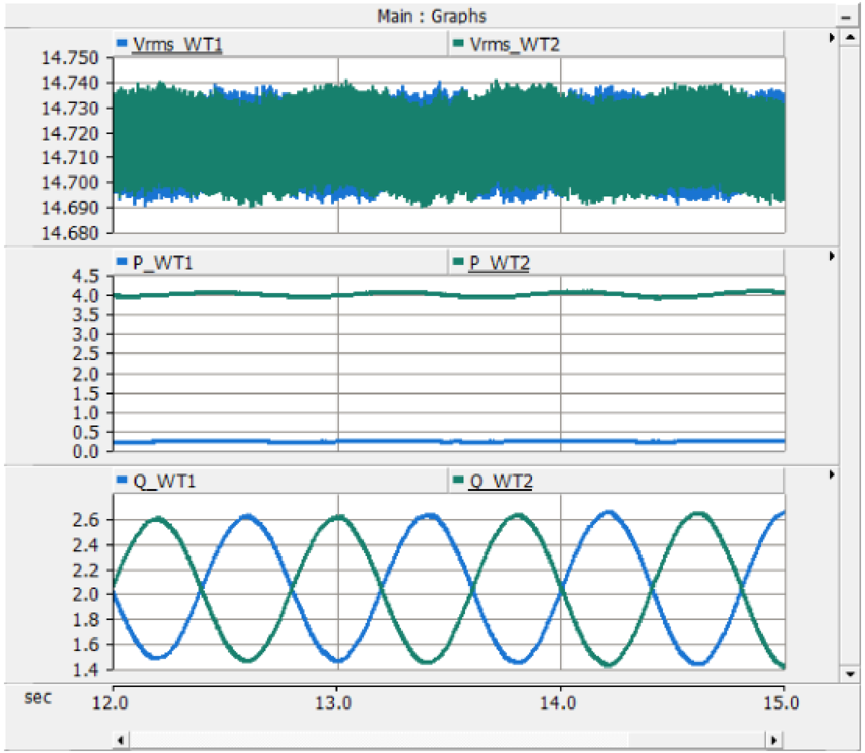
- Model validation



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

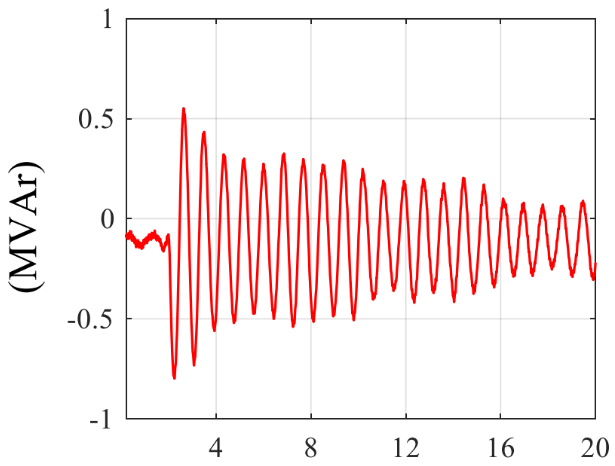
Reactive Power Oscillations Between Turbines





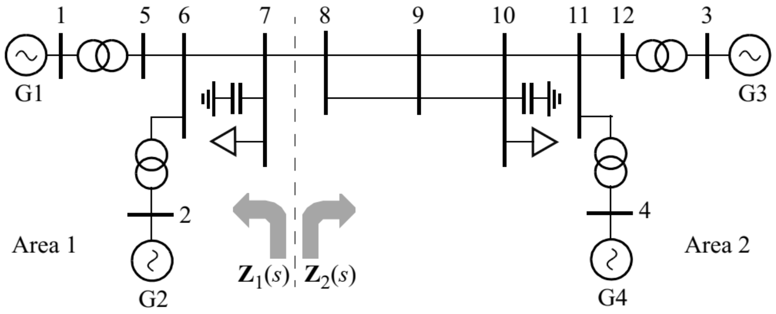
Reactive Power Oscillations in Wind

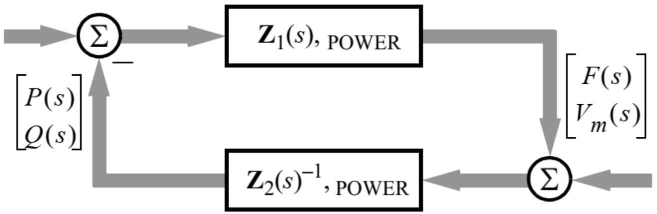
- 4-MW wind turbine at NREL:
  - Turbine reactive power output had 1.2-Hz oscillations following a small (1%) step change in voltage.



- 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

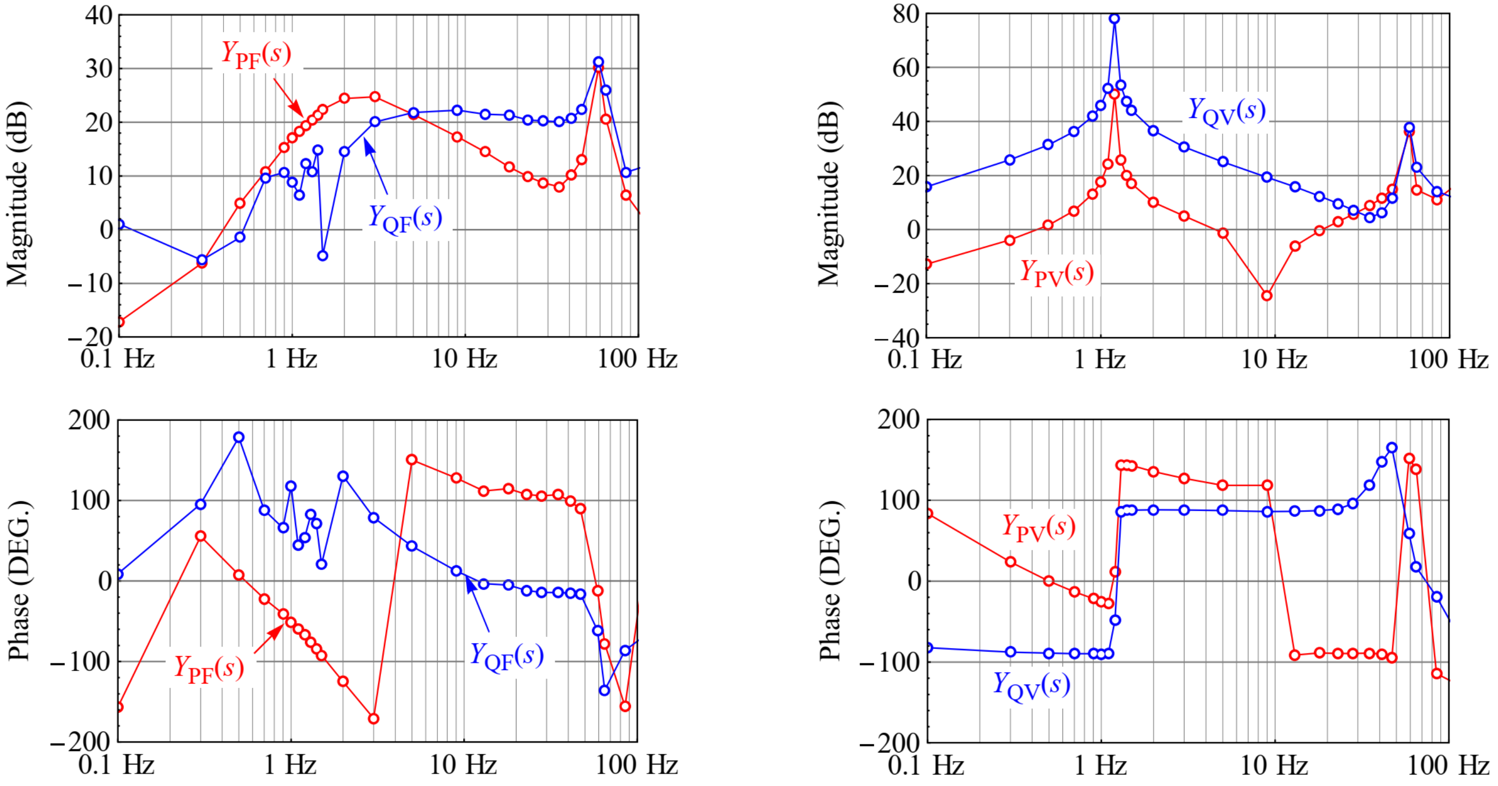




- Definition of power domain impedance:

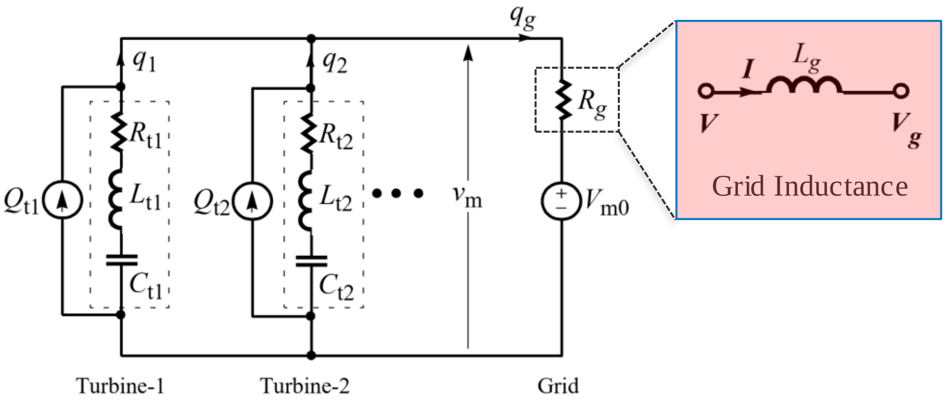
$$\begin{bmatrix} F(s) \\ V_m(s) \end{bmatrix} = \begin{bmatrix} Z_{\mathrm{FP}}(s) & Z_{\mathrm{FQ}}(s) \\ Z_{\mathrm{VP}}(s) & Z_{\mathrm{VQ}}(s) \end{bmatrix} \begin{bmatrix} P(s) \\ Q(s) \end{bmatrix} \qquad \begin{bmatrix} P(s) \\ Q(s) \end{bmatrix} = \begin{bmatrix} Y_{\mathrm{PF}}(s) & Y_{\mathrm{PV}}(s)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

Power Domain Admittance of 4-MW Turbine



Analysis of Reactive Power Dynamics

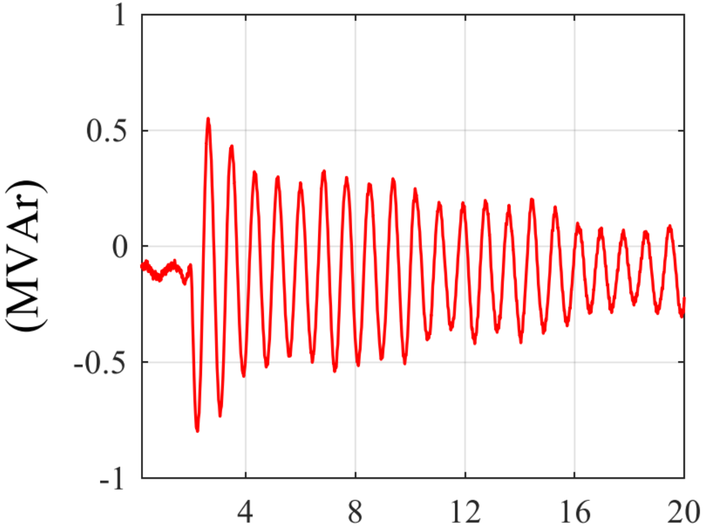
- Equivalent circuit:
  - Reactive power flow is interpreted as instantaneous current.
  - Voltage magnitude is interpreted as instantaneous voltage.



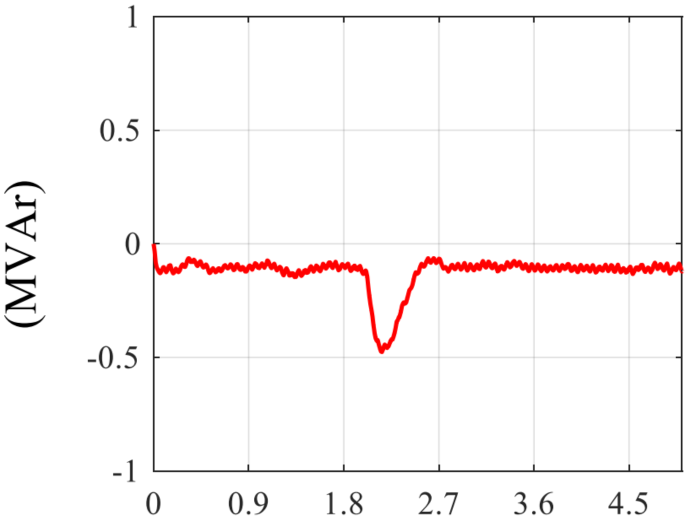
- Analysis results:
  - Inductive grid impedance acts as resistor.
  - Weak inductive grid will damp plant-to-grid reactive power oscillations.
  - Weak inductive grid will not damp turbine-to-turbine reactive power oscillations.

Effect of Grid Strength

- Very strong grid ($L_g = 0$)



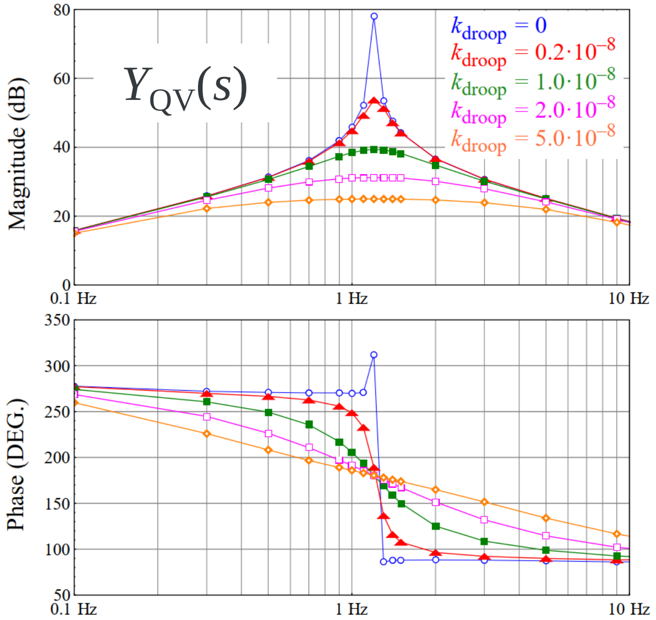
- Not-so-strong grid (L_g = 8 mH)



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

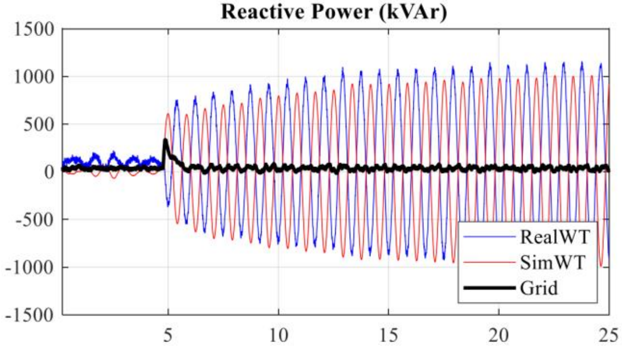
Reactive Power Droop for Damping

- Transfer function from voltage magnitude to reactive power output

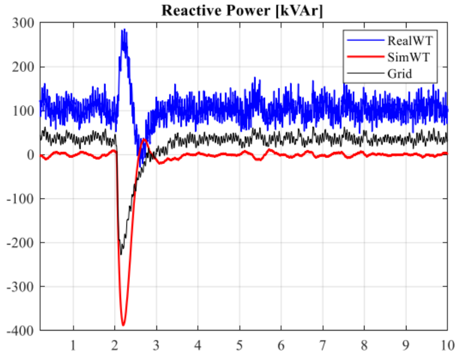


- Turbine-to-turbine oscillations

$k_{droop} = 0$

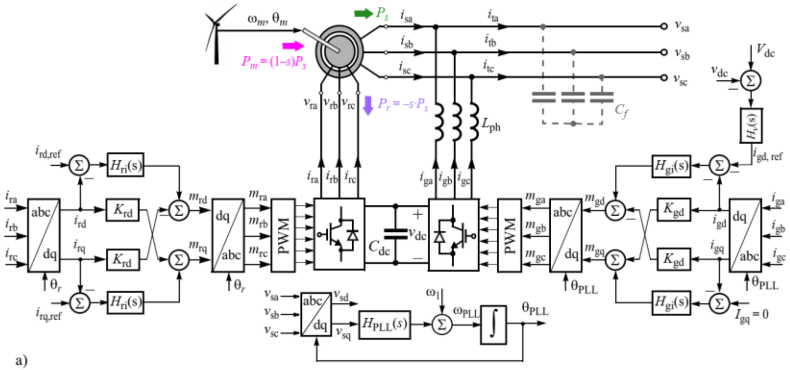


$k_{droop} = 1 \times 10^{-8}$



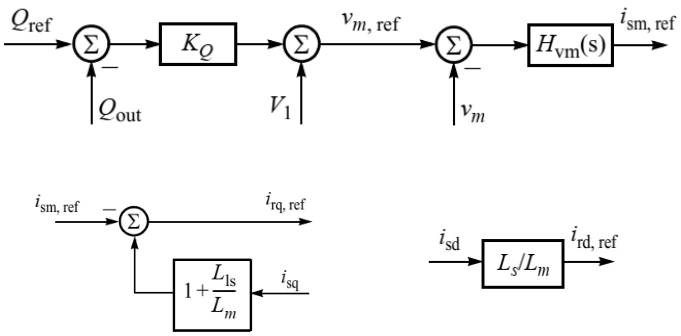
Grid-Forming Control of Type III Wind Turbines

- Vector current control

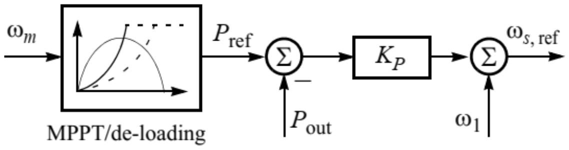


a)

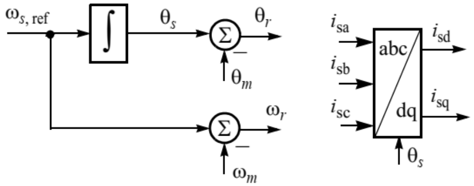
- Voltage control



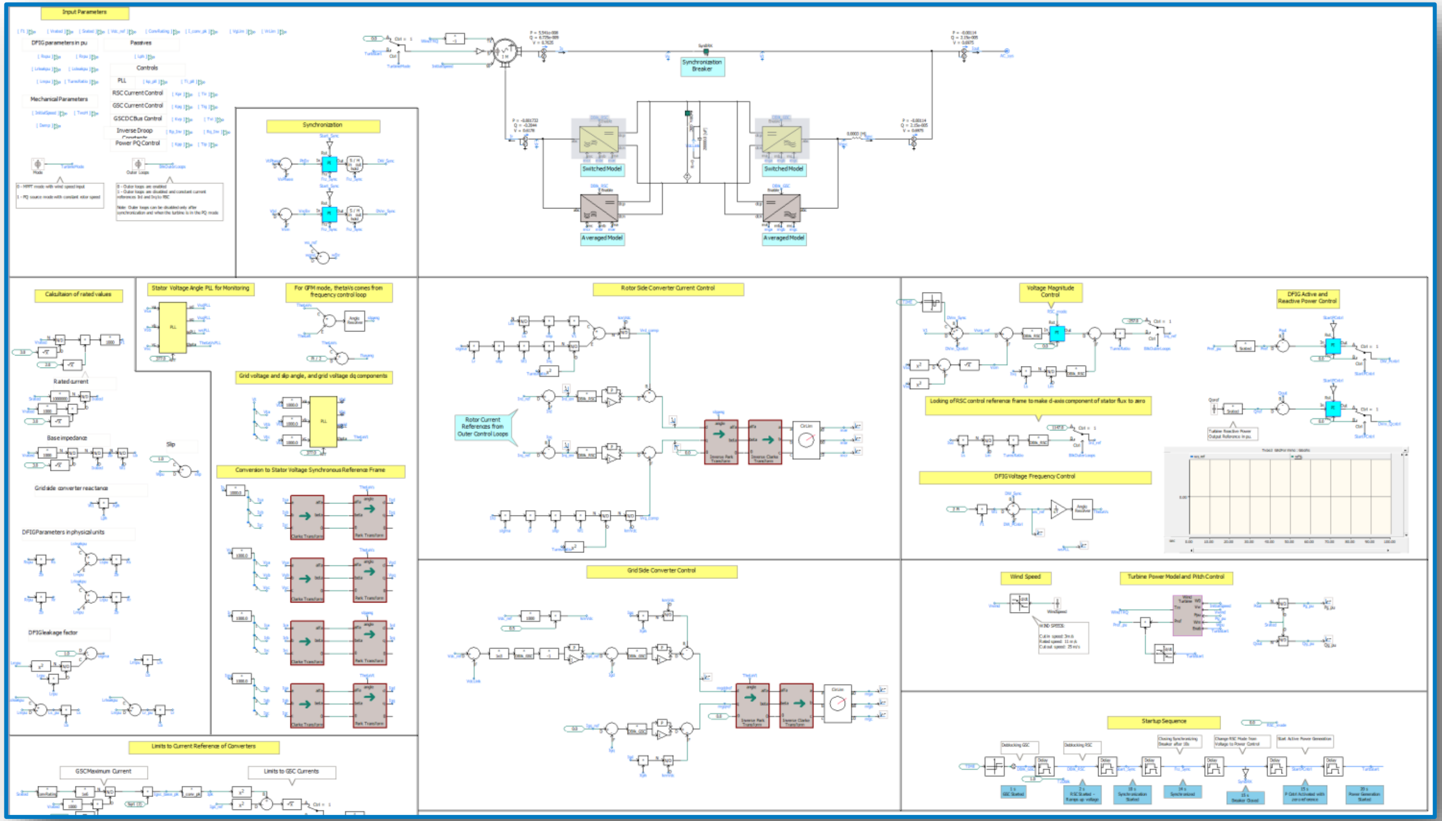
- MPPT/active power control



- Frequency control

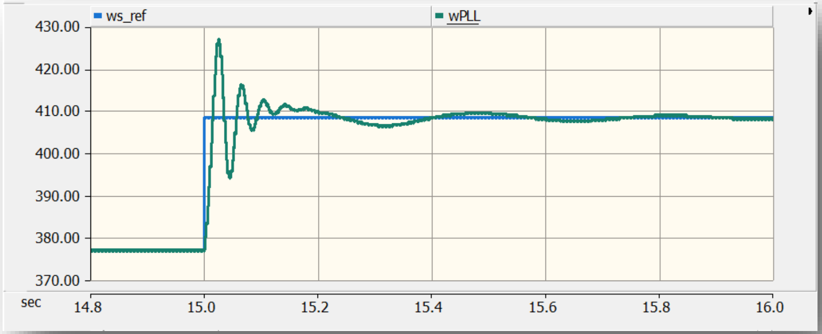


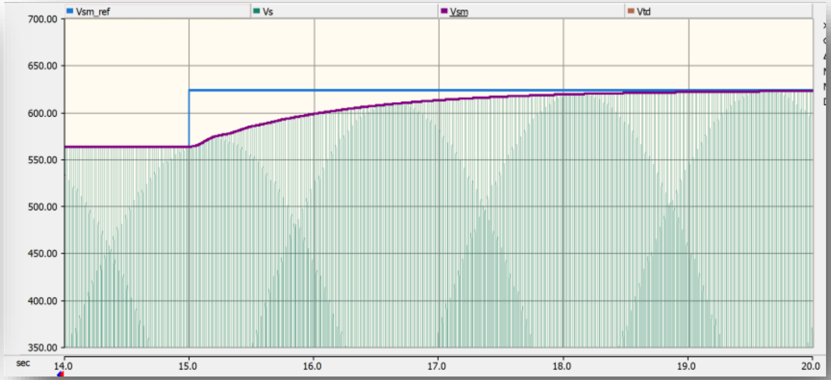
PSCAD Model



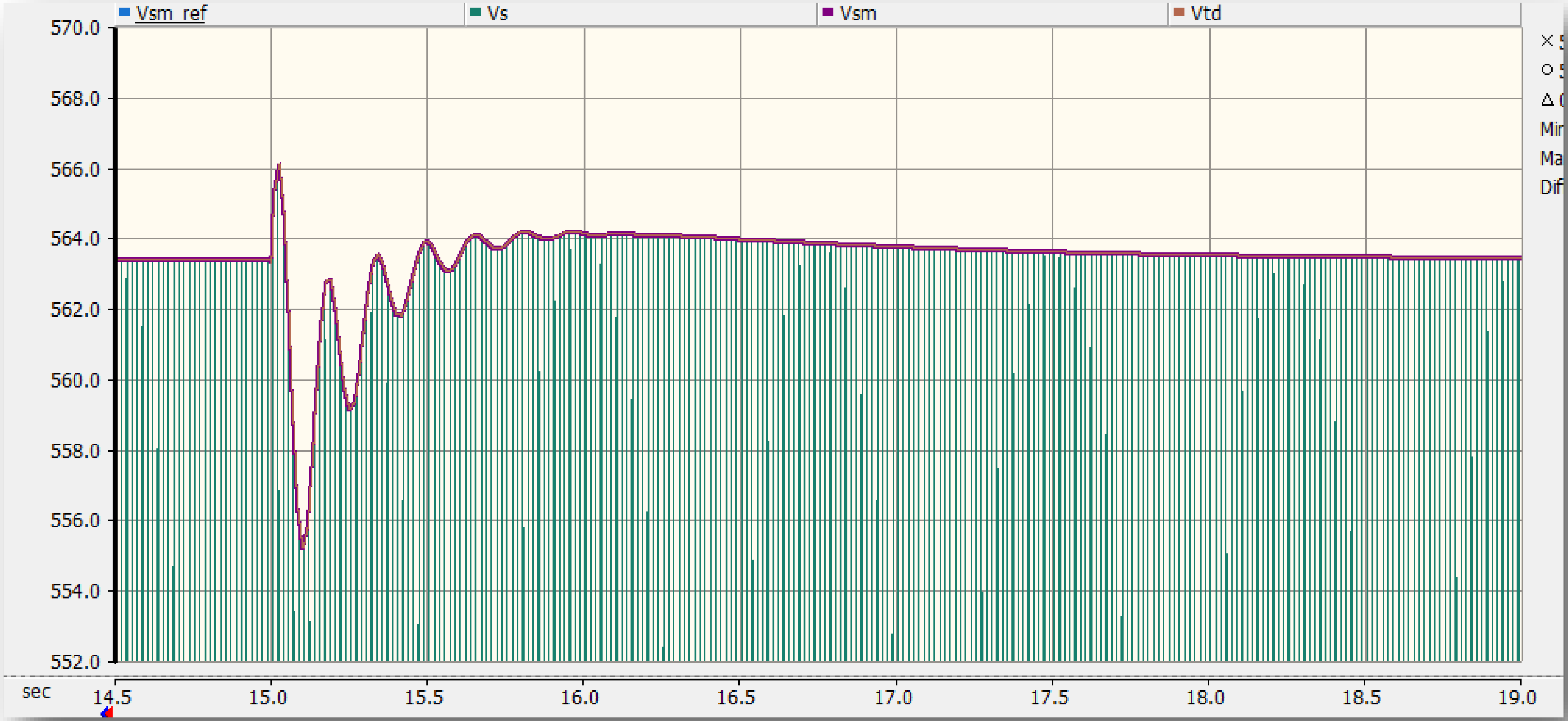
Voltage and Frequency Control Performance

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

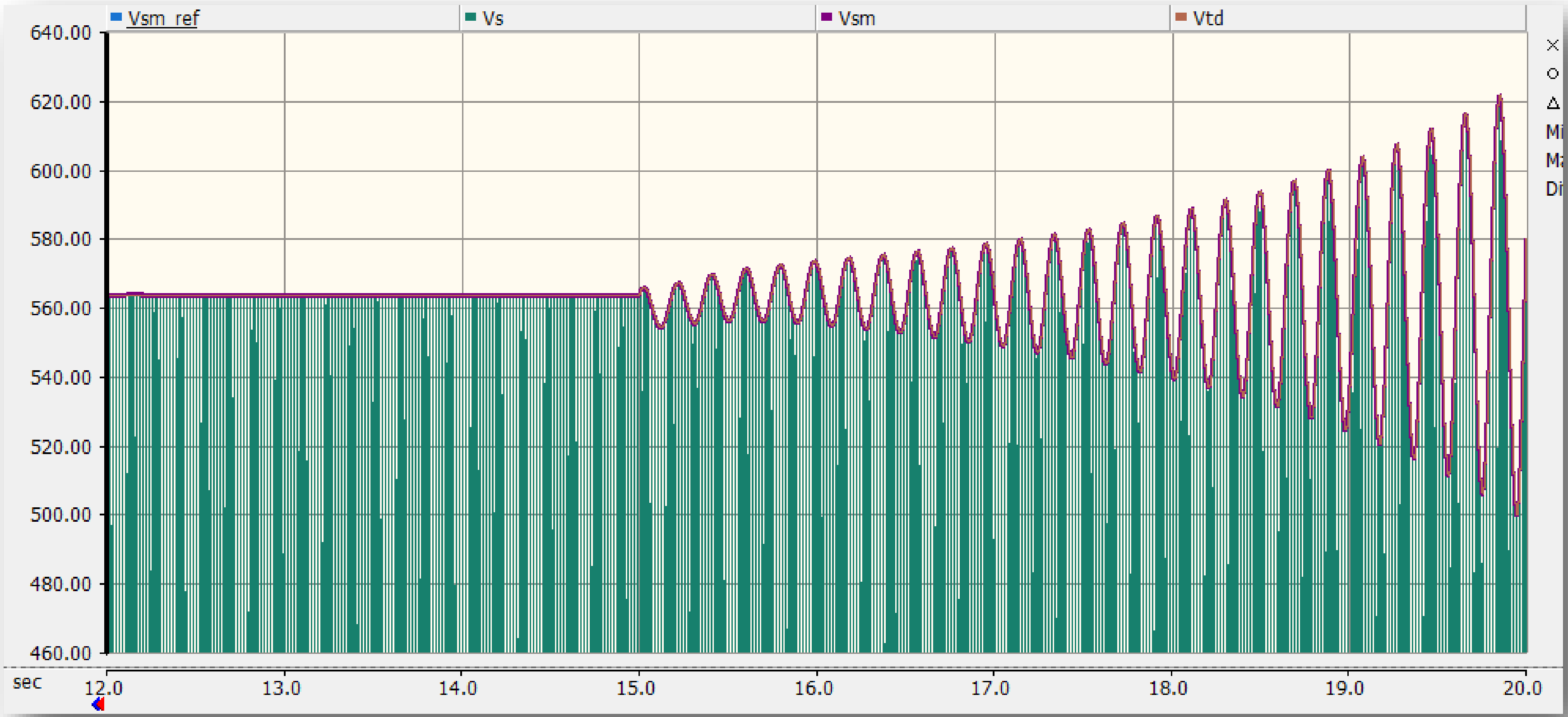




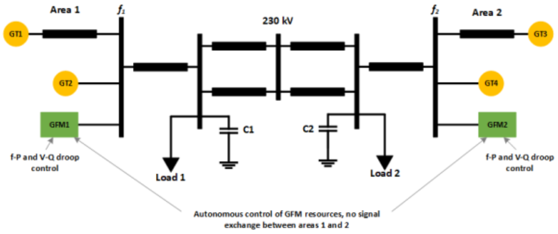
Operation with Weak Grid



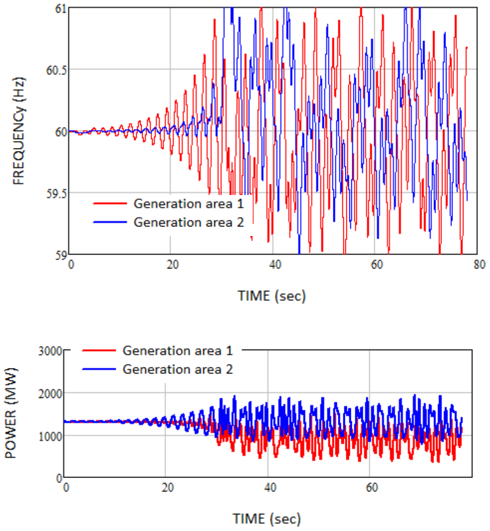
Operation with Strong Grid



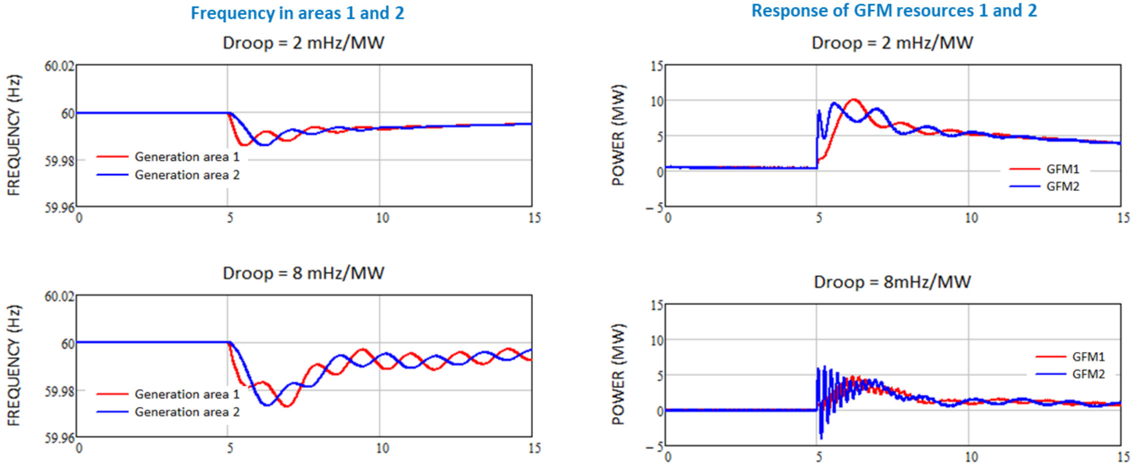
Damping of Inter-Area Modes by GFM Inverters



Without GFM inverters



With GFM inverters



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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Shahil.Shah@nrel.gov

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