Electric Energy Systems Group

Electrical & Computer ENGINEERING

Demonstration of Using Flywheels and FACTS Control for Transient Stabilization and Interactions with Transactive Energy Market

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Outline

- Motivation for fast control

- Transient stabilization using flywheel energy storage systems
  - Competitive control; cancel effect of wind disturbance
  - Demo on the Smart Grid in a Room Simulator (SGRS)
  - Interaction of flywheel control with transactive energy market

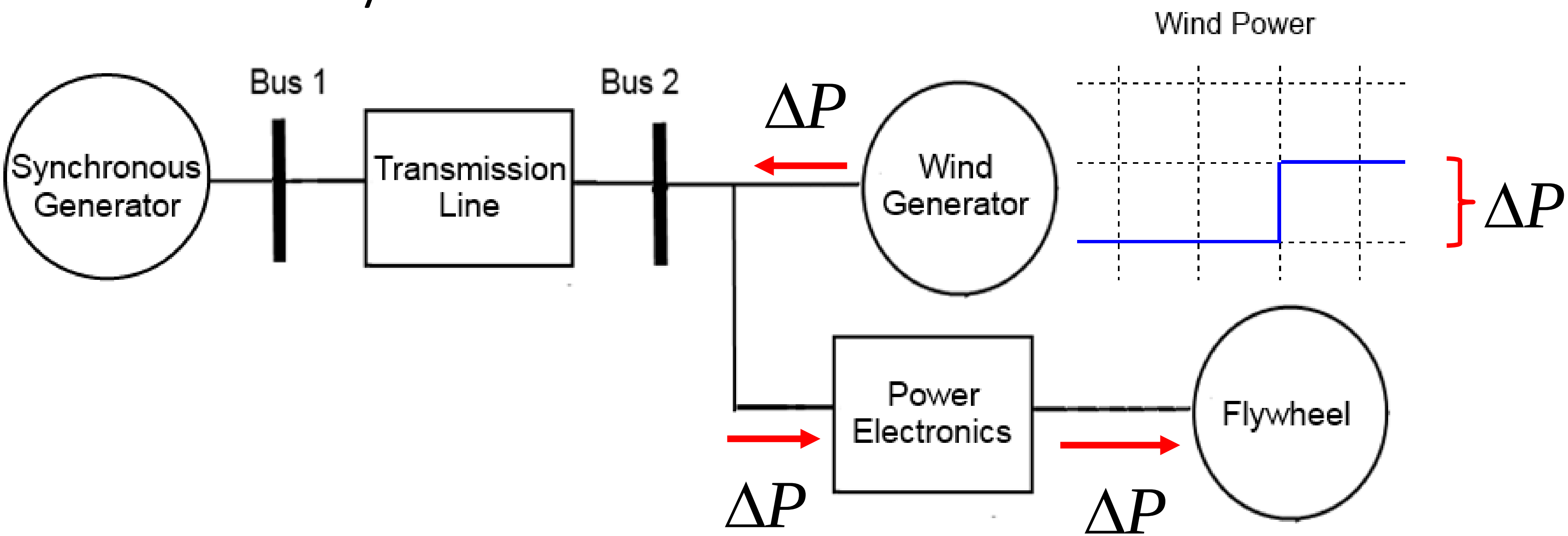
- Transient stabilization using FACTS devices
  - Cooperative control logic based on ectropy
  - Implications for SGRS numerical integration

Motivation for Fast Control

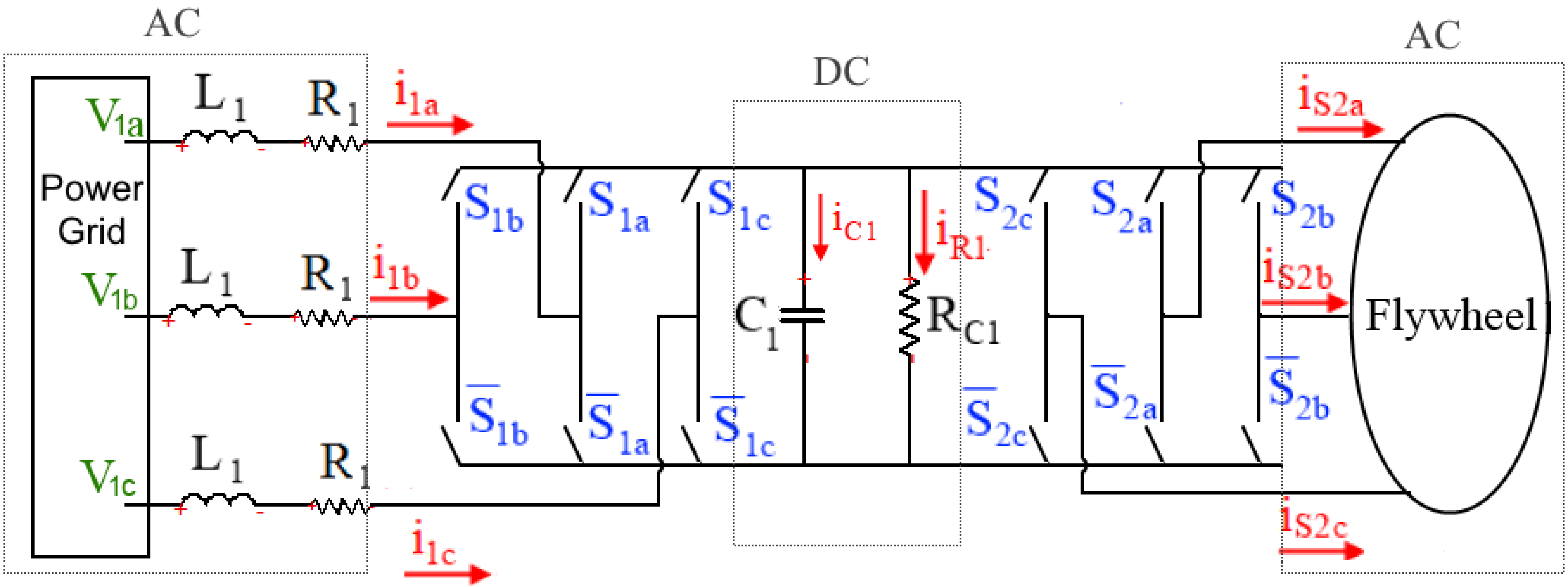
- Transactive energy control is a steady-state scheduling concept
  - Does not guarantee dynamic stability
- Interest in implementing more renewable energy sources into future power grids
- Renewables introduce more uncertainty, intermittency and unpredictability => a challenge for control design
- Large sudden deviations in wind power can cause
  - high deviations in frequency and voltage
  - transient instabilities
- Possible solution: fast energy storage
  - flywheel energy storage systems
  - FACTS devices

Objective

- Use flywheels for transient stabilization of power grids in response to large sudden wind disturbances
- Design nonlinear power electronic control so that the flywheel absorbs the disturbance and the rest of the system is minimally affected



Variable Speed Drives for Flywheels

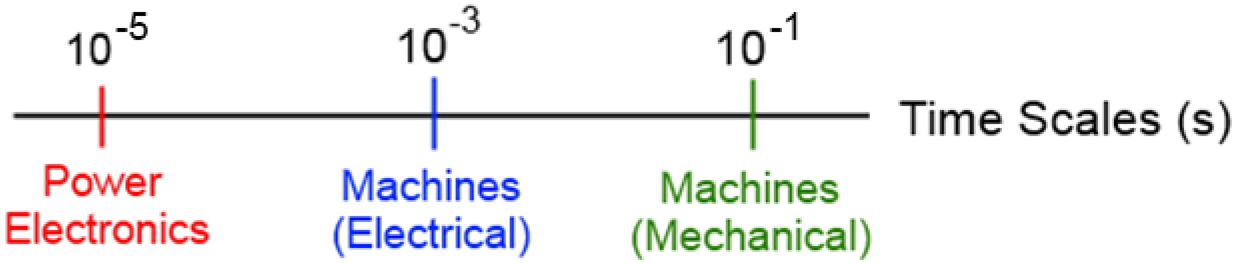


- Use AC/DC/AC converter to regulate the speed of the flywheel (and hence the energy stored) to a different frequency than the grid frequency
- Controllable inputs are the switch positions in the power electronics

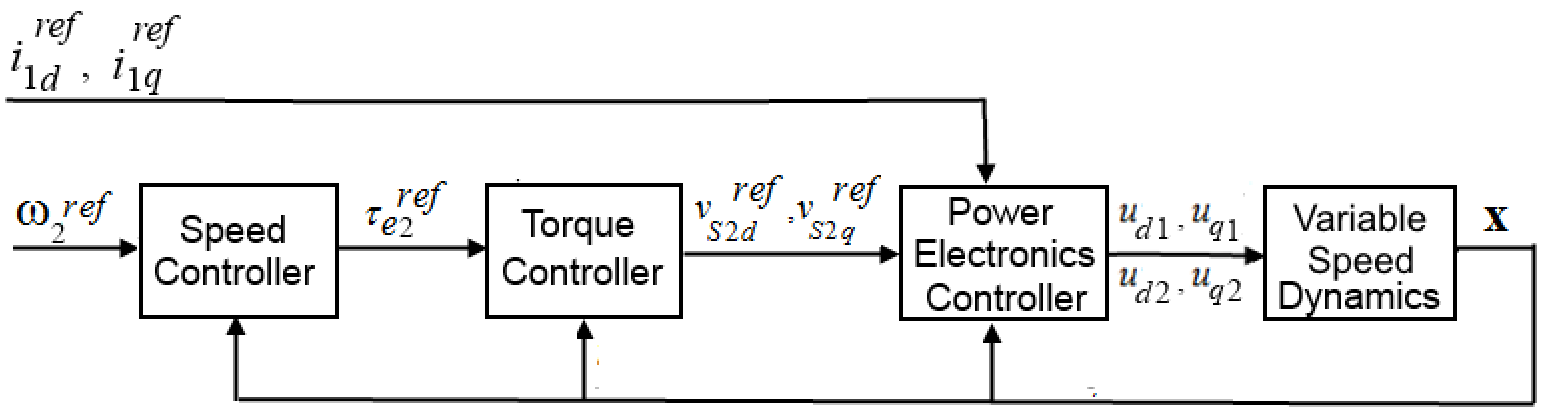
Source: K. D. Bachovchin, M. D. Ilic, "Transient Stabilization of Power Grids Using Passivity-Based Control with Flywheel Energy Storage Systems," *IEEE Power & Energy Society General Meeting*, Denver, USA, July 2015..

Controller Implementation

- Time-scale separation to simplify the control design

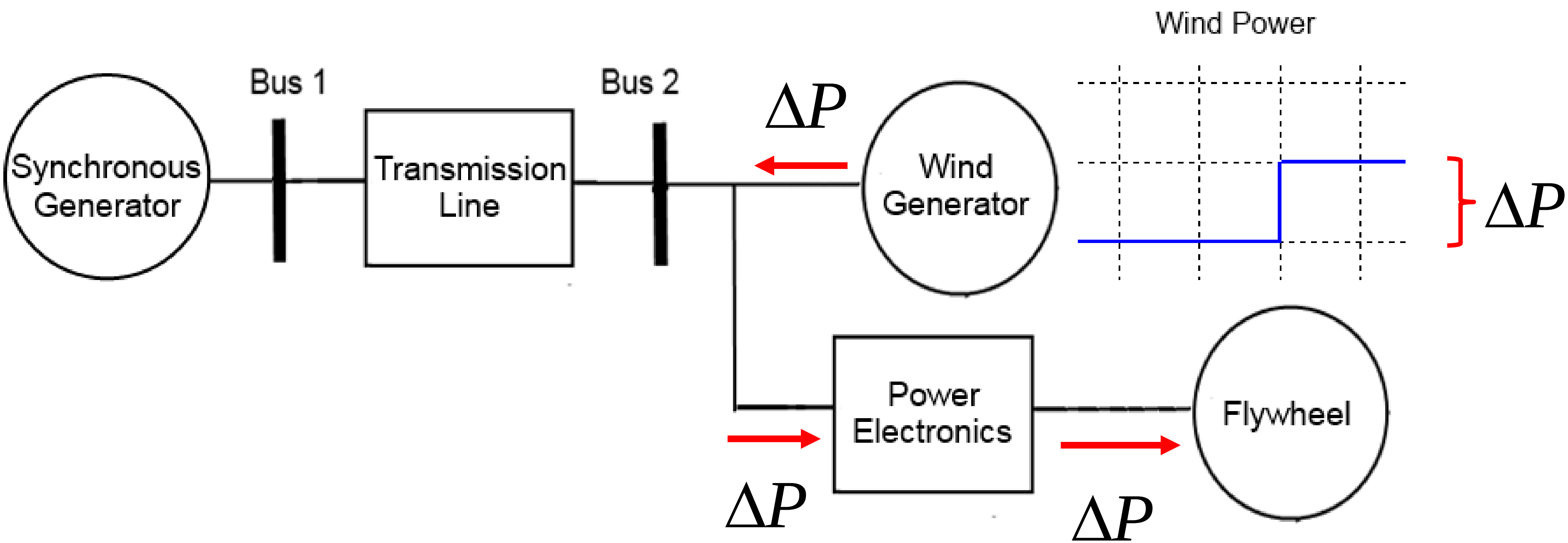


- Regulate both the flywheel speed and the currents into the power electronics using nonlinear passivity-based control



Source: K. D. Bachovchin, M. D. Ilic, "Transient Stabilization of Power Grids Using Passivity-Based Control with Flywheel Energy Storage Systems," *IEEE Power & Energy Society General Meeting*, Denver, USA, July 2015..

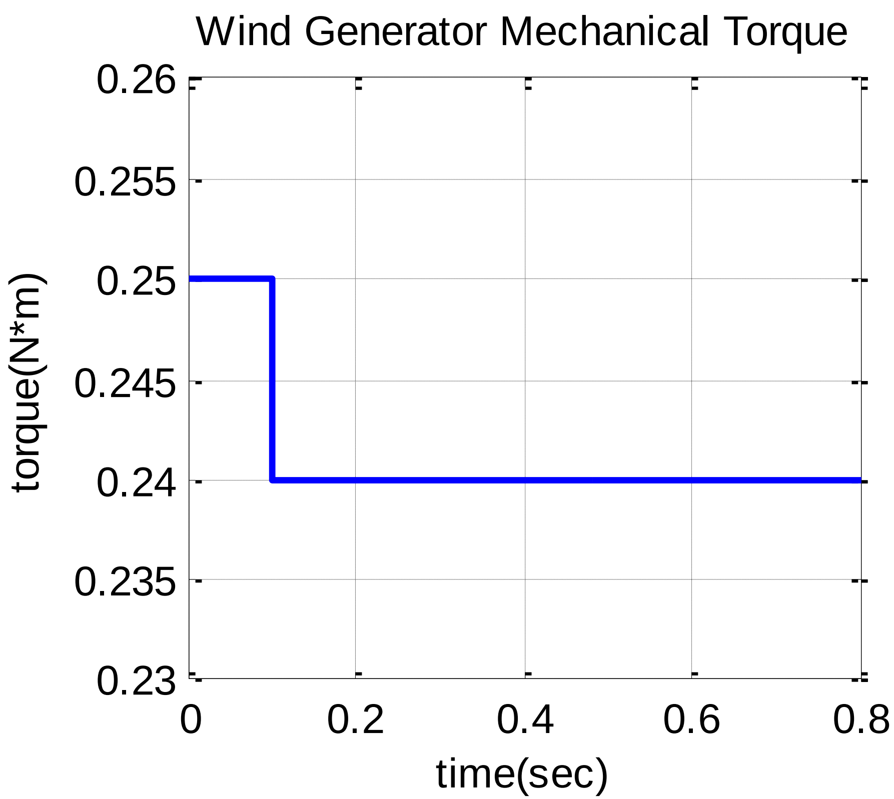
Transient Stabilization Using Flywheels

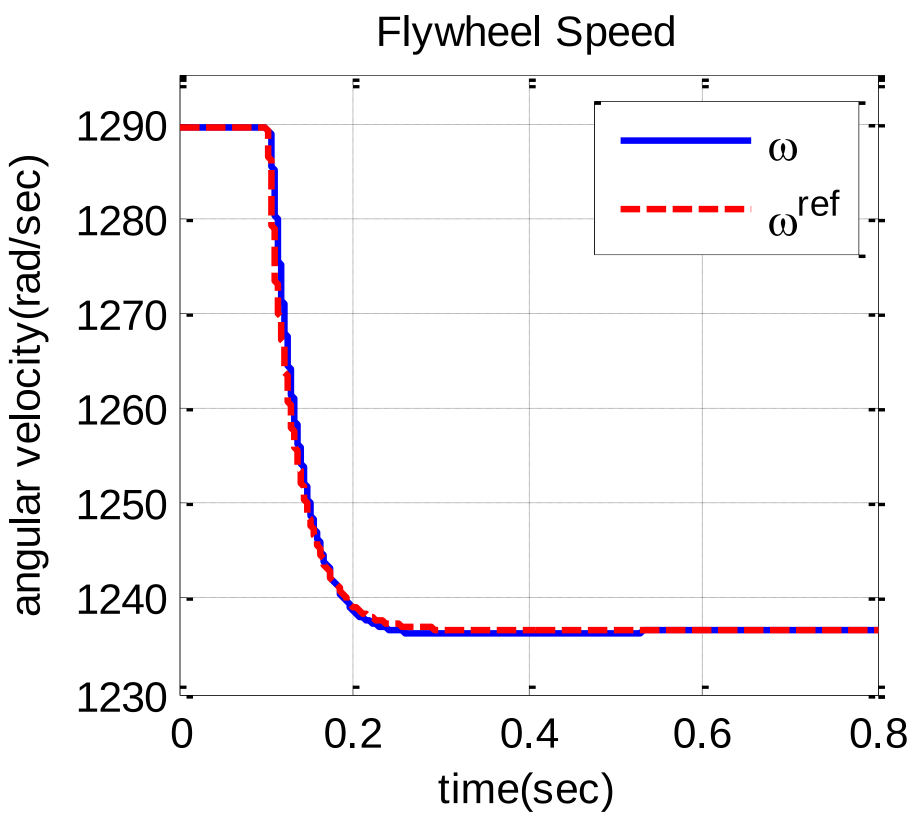


- Want to choose set points so that the wind disturbance power goes to the flywheel and rest of the system is minimally affected

Simulation Results: Flywheel

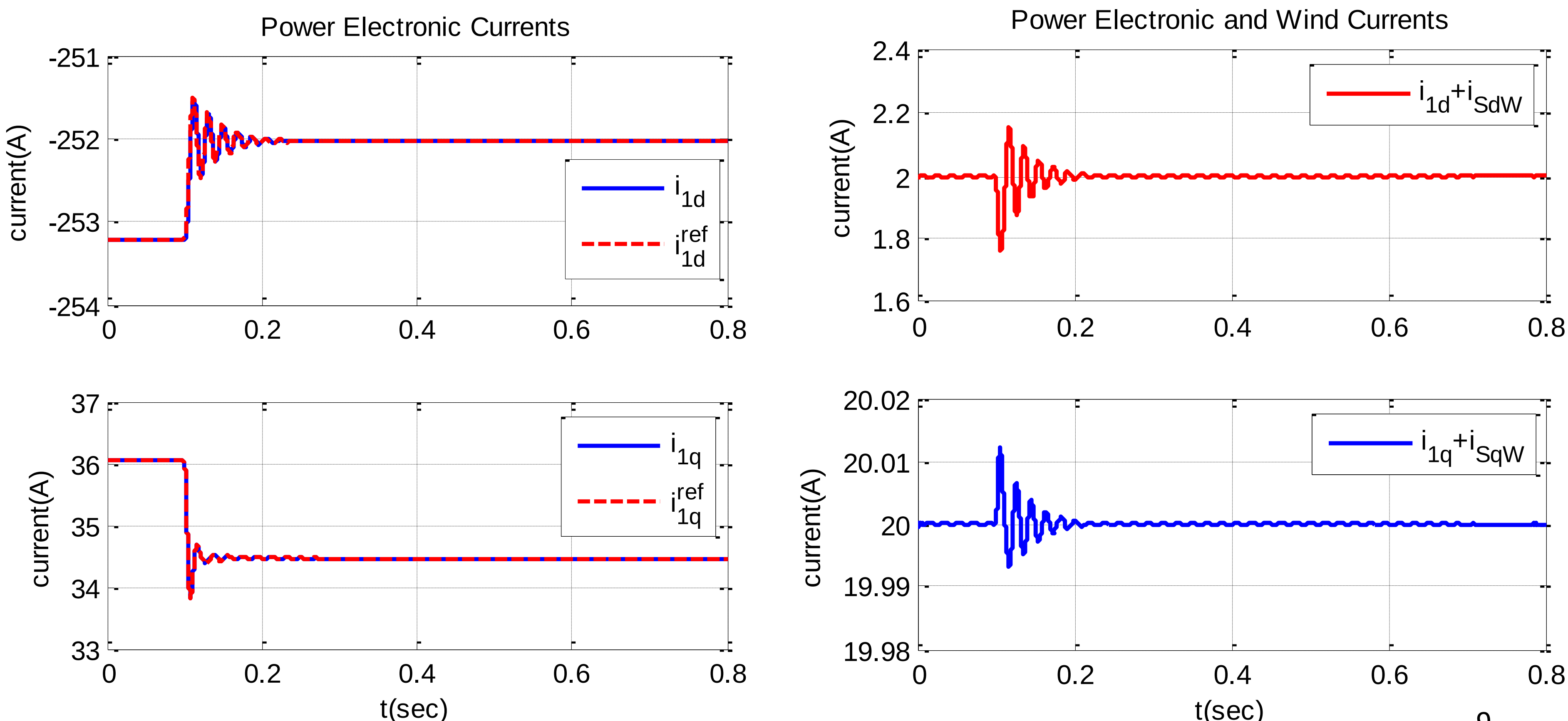
- Since the power output of the wind generator decreases during the disturbance, the flywheel set point decreases





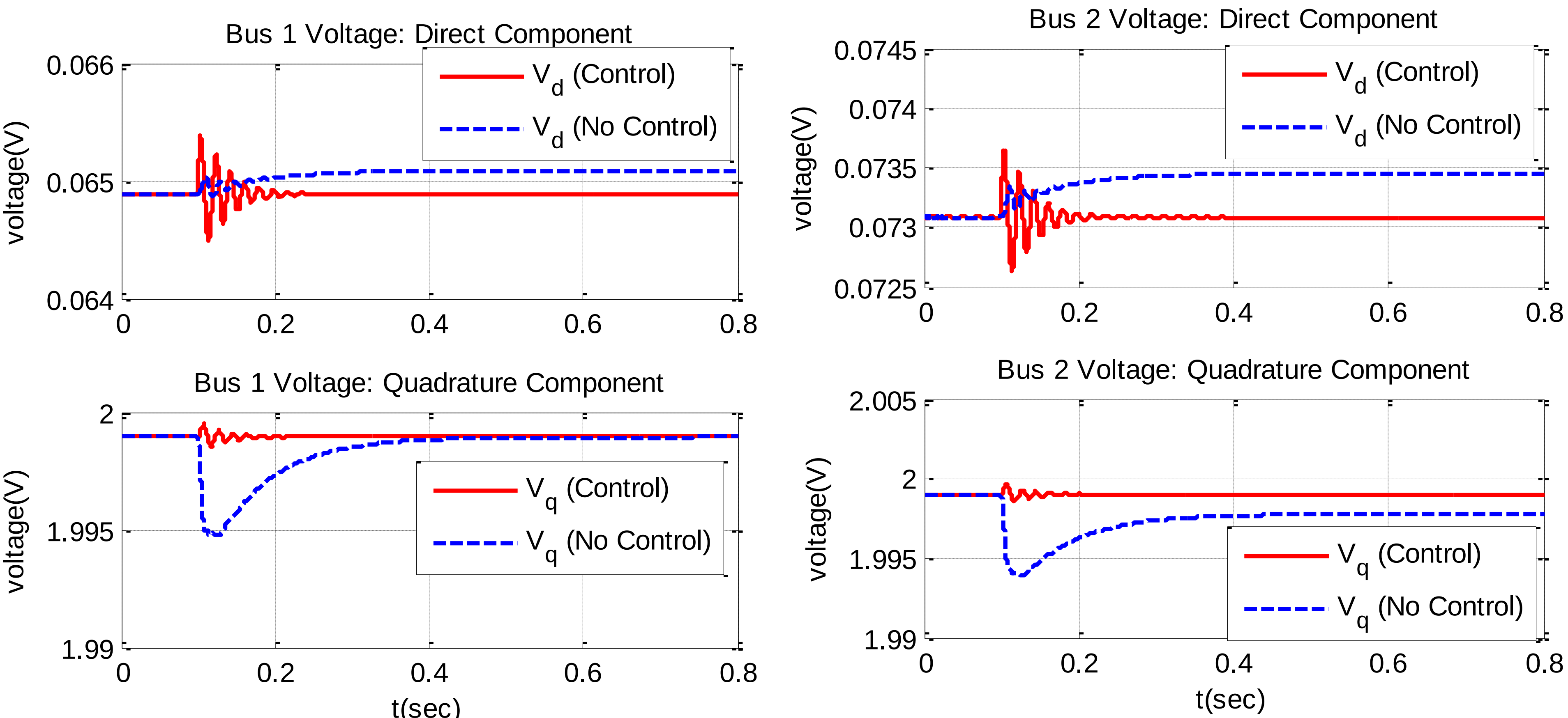
Simulation Results: Power Electronics

- The set points for the power electronic currents are chosen so that the total current out of Bus 2 remains constant during the disturbance



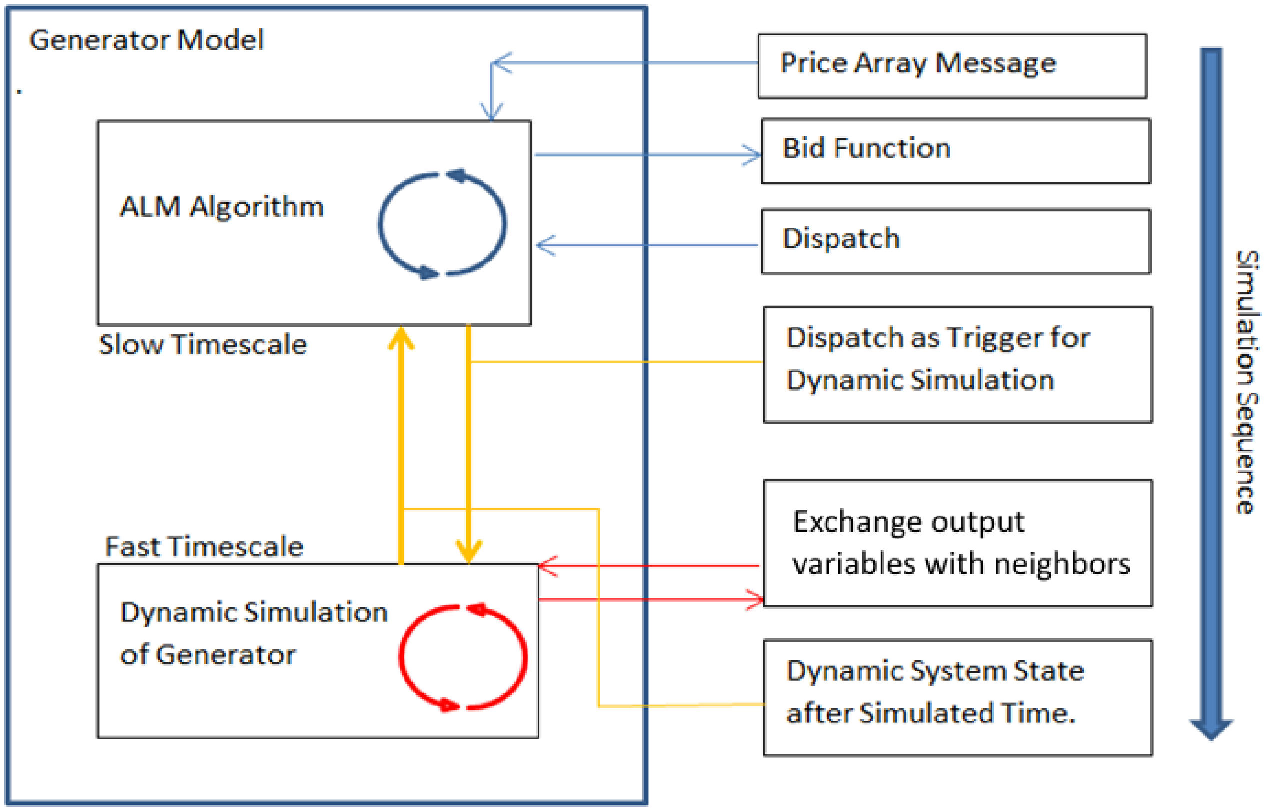
Simulation Results: Rest of System

- With the control, the effect on the rest of the system is very minimal and lasts only a short time



Linking Multi Time-Scale Simulations

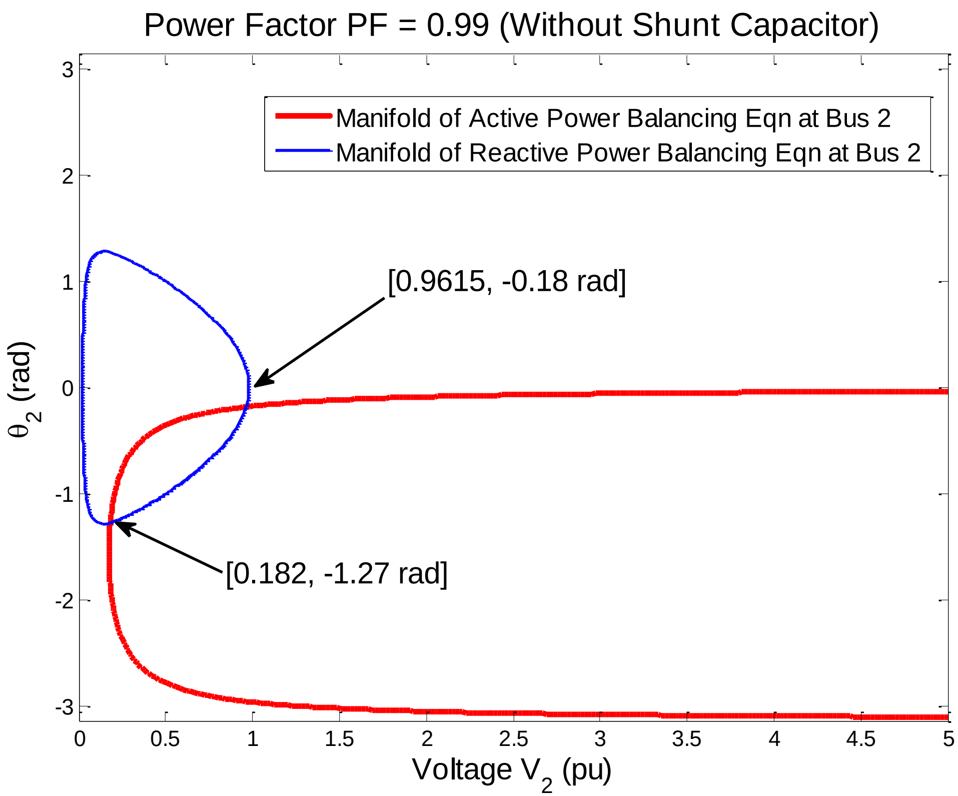
- Communication for multi time-scale simulation with ALM and fast dynamics for generators

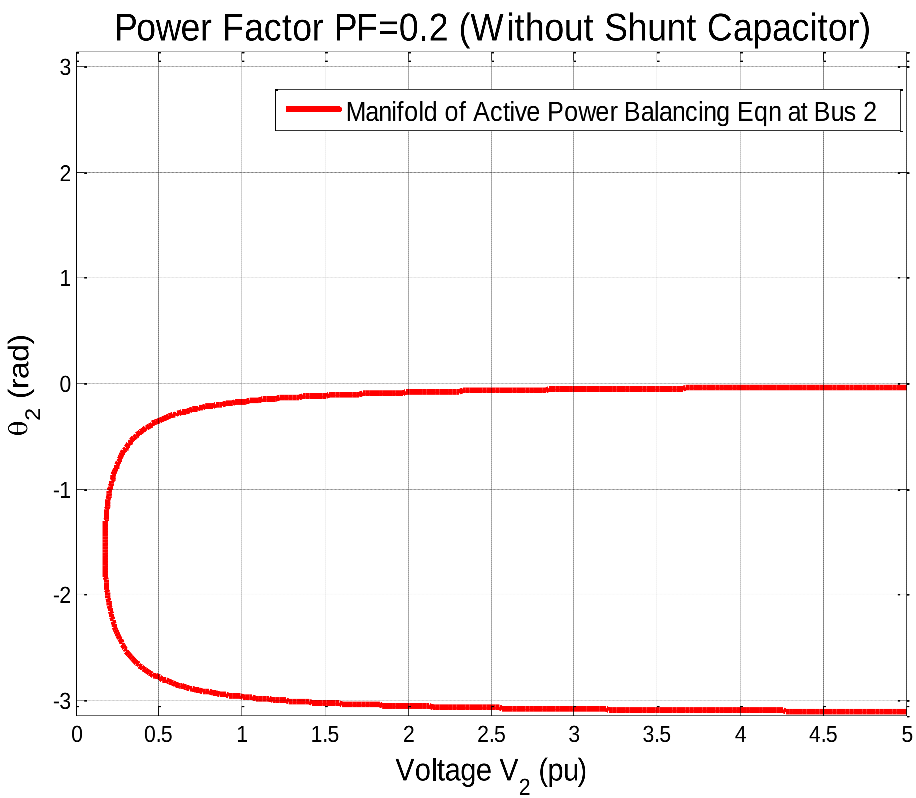


Source: M. R. Wagner, K. D. Bachovchin, M. D. Ilić, "Computer Architecture and Multi Time-Scale Implementations for Smart Grid in a Room Simulator," EESG Working Paper No. R-WP-1-2014, March 2015.

Importance of Reactive Power

- Typically the market only specifies the active power set point
- However the reactive power is critically important to the equilibria and stability of the system

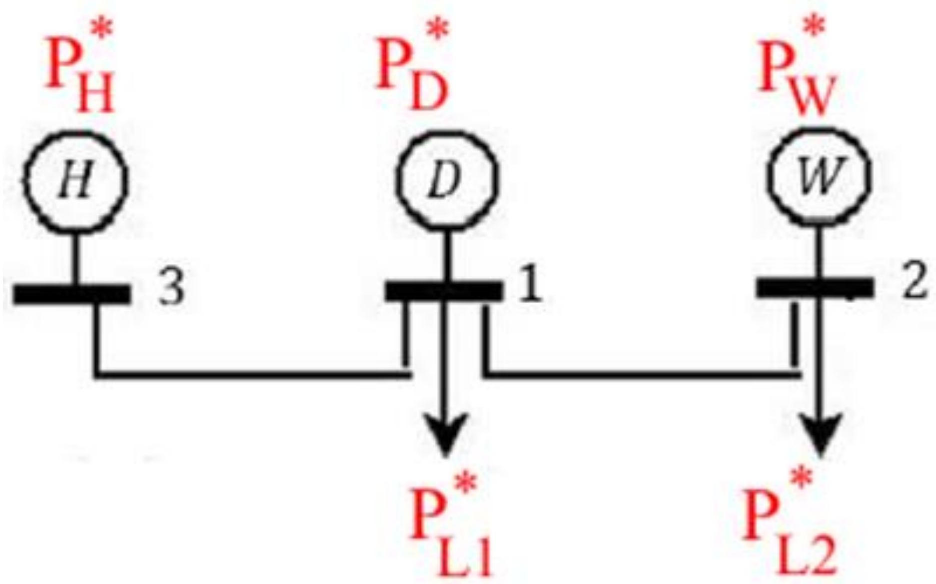




Source: X. Miao, K. D. Bachovchin, M. D. Ilić, "Effect of Load Type and Unmodeled Dynamics in Load on the Equilibria and Stability of Electric Power System," EESG Working Paper No. R-WP-1-2014, March 2015.

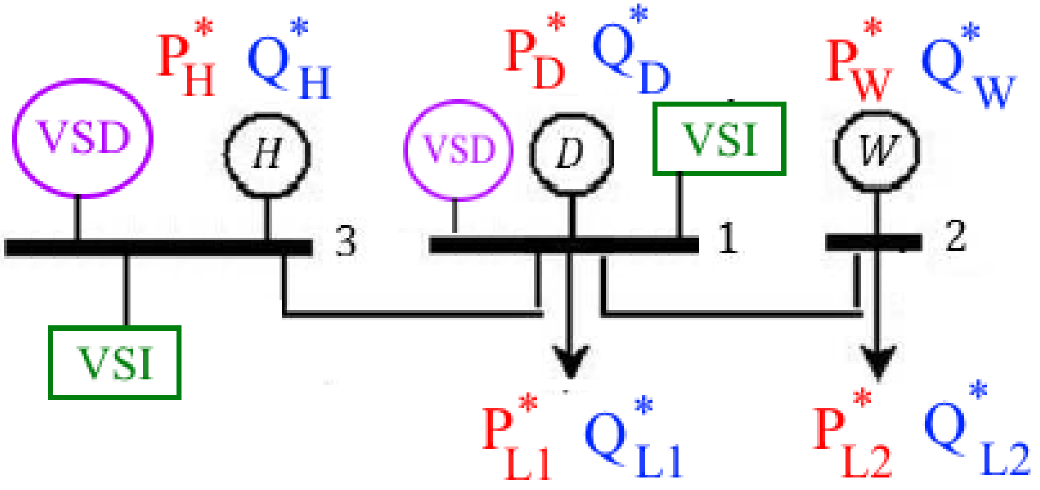
Flores Island – Market

- Based on prices, market computes active power set points P* from each component



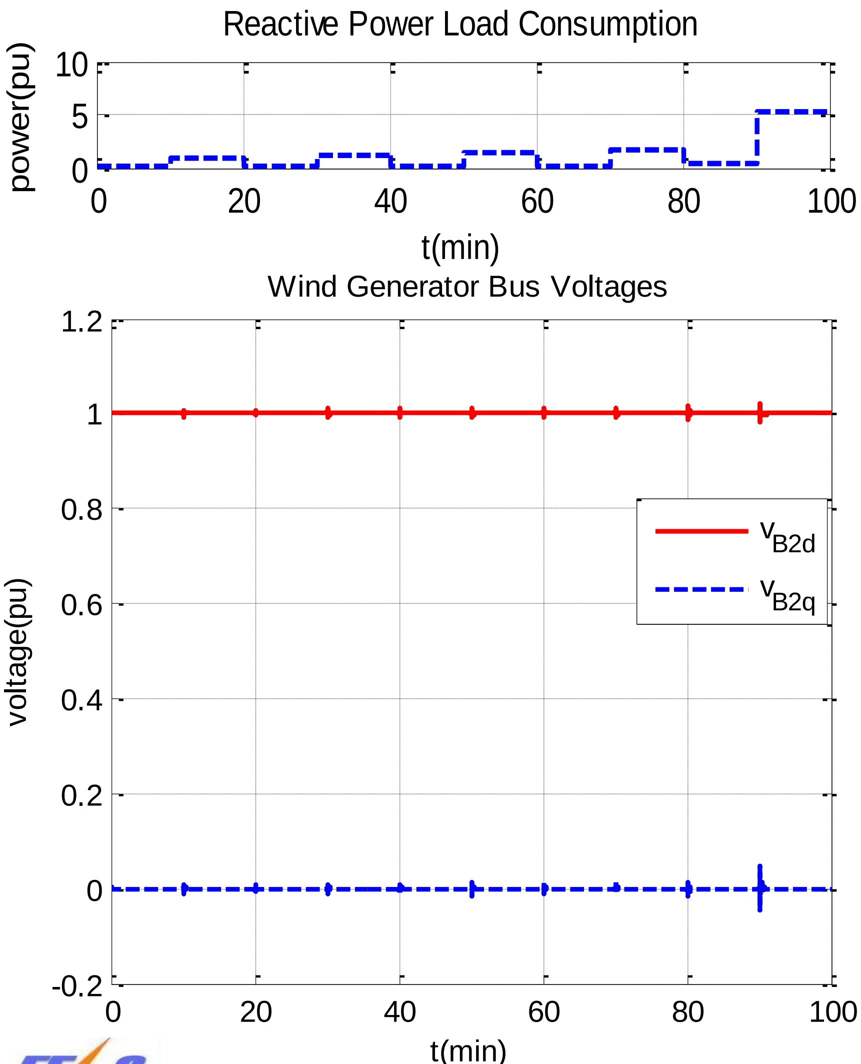
Flores Island – Dynamics

- Since currently the market does not specify reactive power set points Q*, data for Q* is randomly created
- Place a voltage source inverter and the variable speed drive on the hydro and diesel generator buses
- Control the sum of the power out of the hydro and diesel generators to match the active and reactive power set points

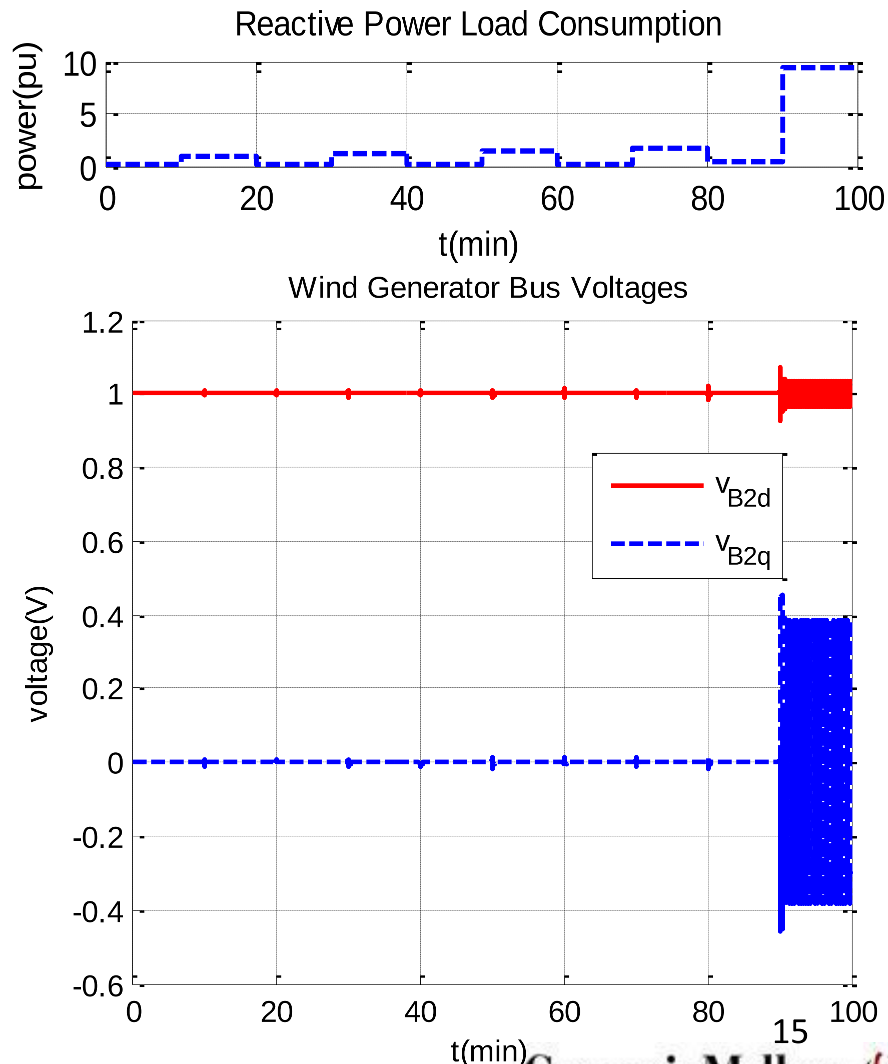


Simulation Results – Combining Dynamics and ALM

Stable Case:



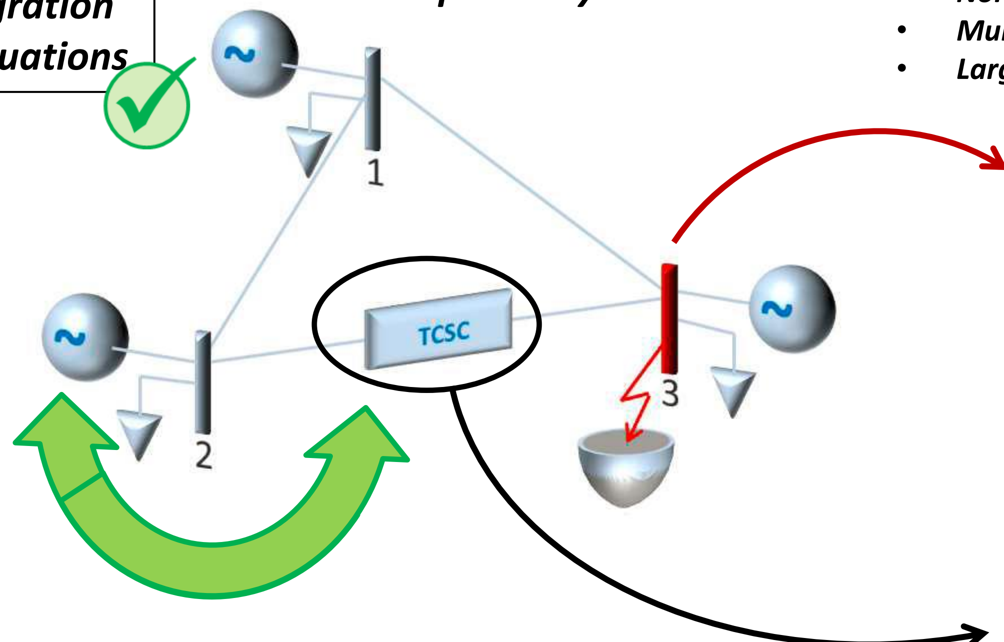
Unstable Case:



Transient Stabilization of Interactions Using FACTS

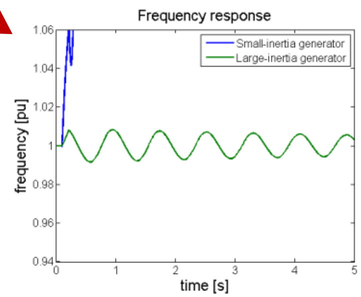
Implications for SGRS distributed integration of differential equations

Large scale interconnected power system

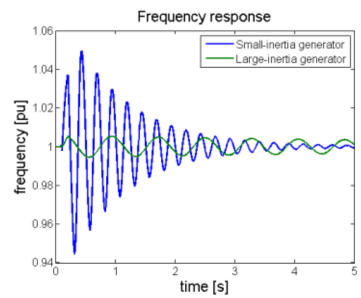


Transient stability problem

- *Nonlinear dynamics*
- *Multiple time scales*
- *Large regions*



Unstable



Stable

Interactions are captured using an energy-based model

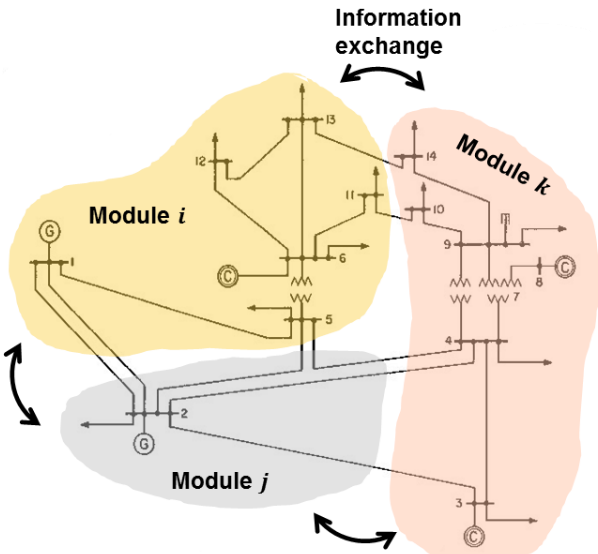
- *Accumulated energy as a measure of stability*
- *Managing energy to ensure stability*

<u>Cooperative</u> power electronics (FACTS) control

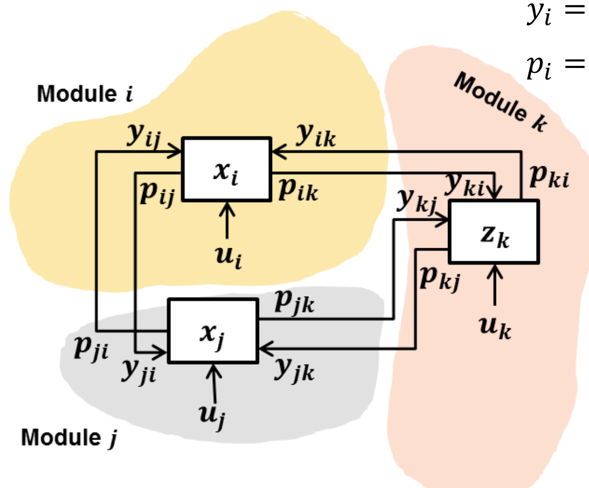
- *Fast thyristor switching*
- *Flow control*

Common Modeling Approach for FACTS Control

- **Create a simplified power system model**
  - Control logic is case dependent
  - Loaded as test case for transients simulator
- **Create a structure preserving system model by combining dynamic models of individual components**
  - Coupling achieved through states on ports of components y_i, p_i
  - Competitive control design



Component-based approach to modeling

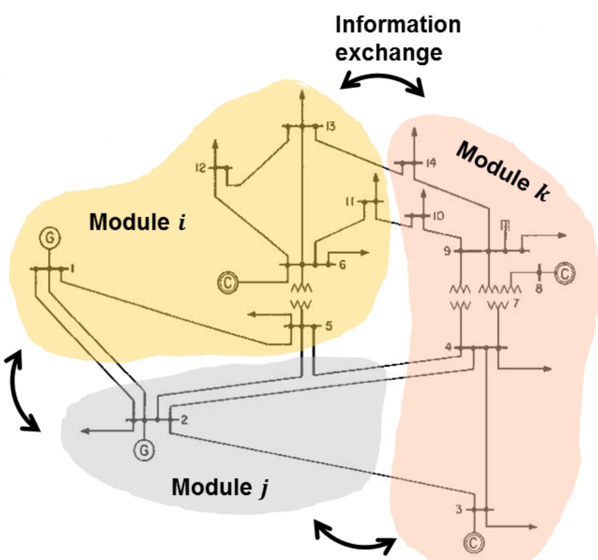


Module description

$$\dot{x}_i = f_i(x_i, y_i, u_i, d_i)$$
$$y_i = [y_{ij}(x_j) \quad y_{ik}(x_k)]$$
$$p_i = [p_{ij}(x_i) \quad p_{ik}(x_i)]$$

Proposed Modeling Approach

- **Represent components of power systems using a two-level model which separates their internal dynamics from the dynamics of their interactions**
  - Internal dynamics are described using internal dynamic states $\bar{x}$
  - Interaction dynamics are described using interaction variables z

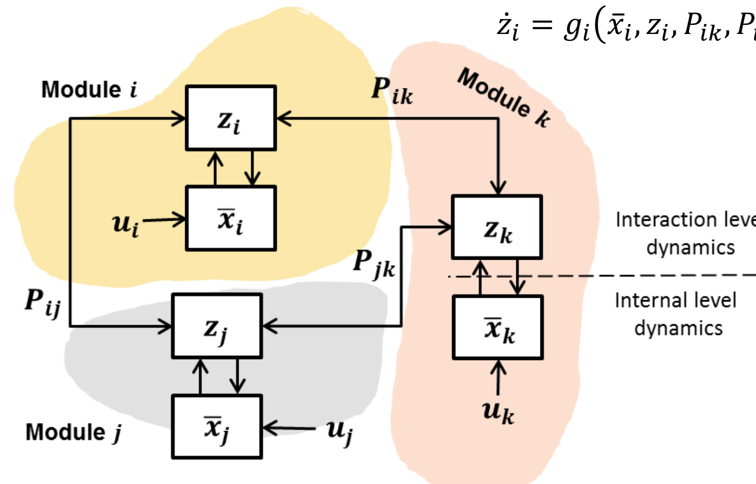


Interaction variable-based modeling

<u>Two-level module description</u>

$$\dot{\bar{x}}_i = \bar{f}_i(\bar{x}_i, z_i, P_{ik}, P_{ij}, u_i, d_i)$$

$$\dot{z}_i = g_i(\bar{x}_i, z_i, P_{ik}, P_{ij}, u_i, d_i)$$

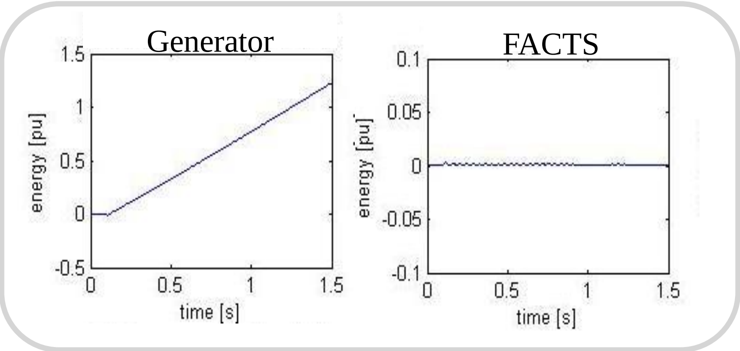


M. Cvetkovic, M. Ilic, "*A Two-level Approach to Tuning FACTS for Transient Stabilization*", IEEE PES General Meeting, July 2014.

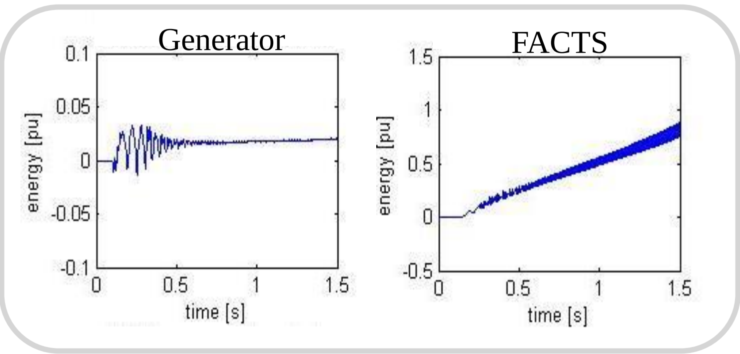
Interaction variable z is the accumulated energy inside a module.

Proposed Cooperative Controller

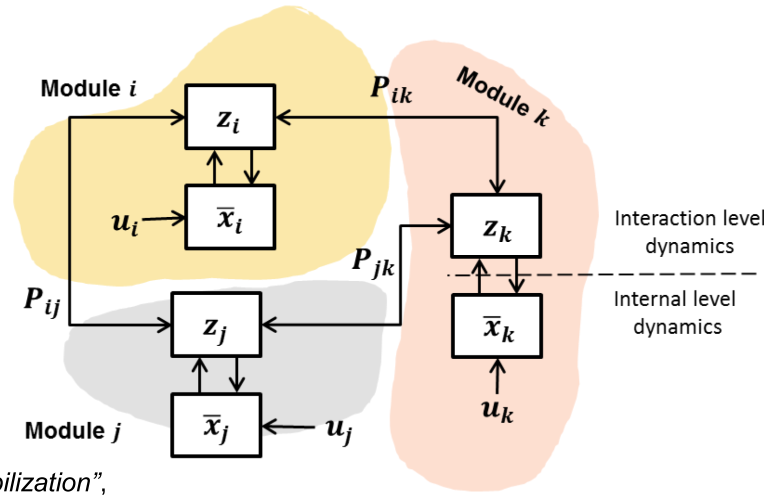
Accumulated (stored) energy
in an uncontrolled system



Accumulated (stored) energy in a system
controlled by power electronics



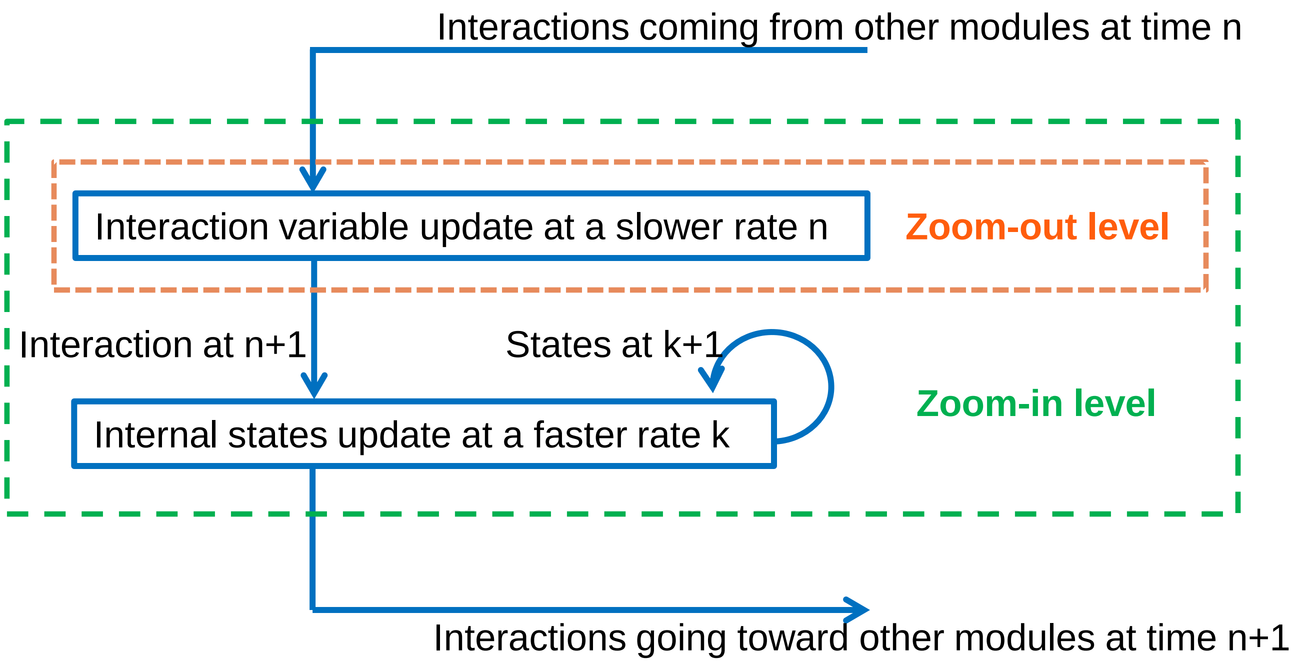
- **Redistribute energy of disturbance**
- **Cooperative control is expressed in terms of higher (interaction) level dynamics**
- **Enabled by using time scale separation between interaction and internal level dynamics**



M. Cvetkovic, M. Ilic, "*Ectropy-based Nonlinear Control of FACTS for Transient Stabilization*",
IEEE Transactions on Power Systems, Vol. 29, No. 6, November 2014, pp. 3012-3020.

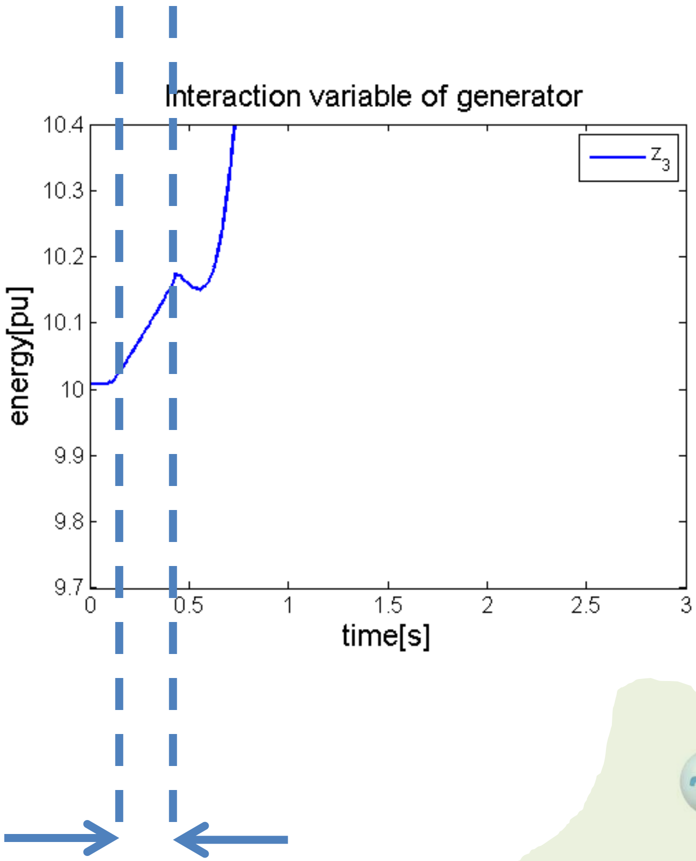
SGRS Hierarchical Distributed Simulation of Dynamics

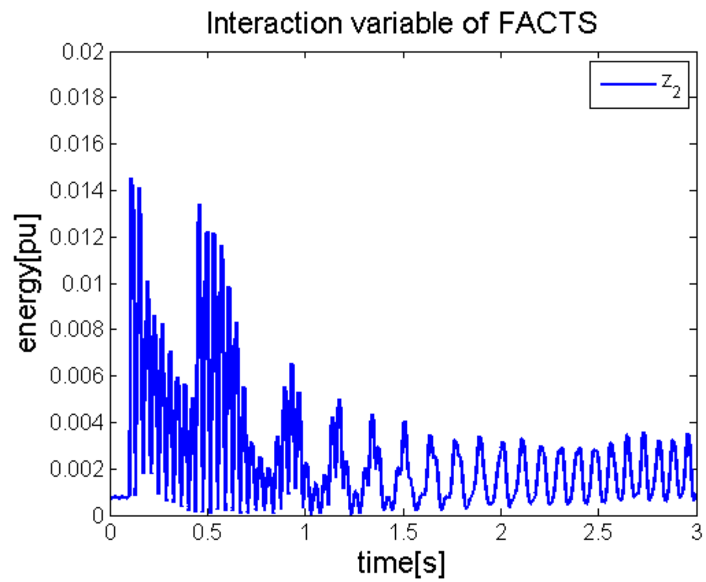
- **Aggregation od dynamics using interaction variables separates the rate of exchange of information and the rate of internal state computations**



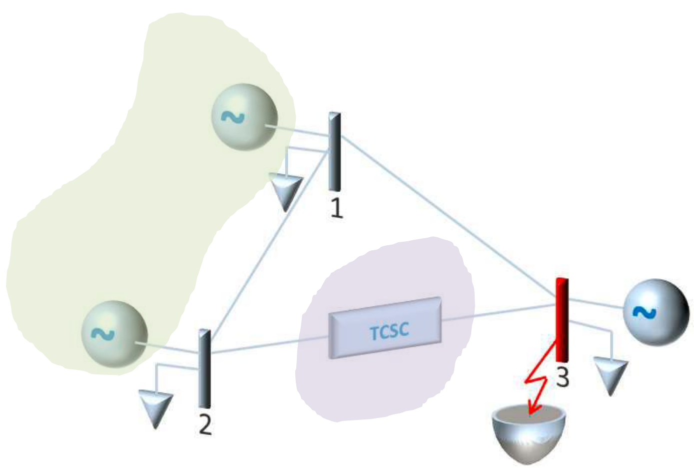
M. Cvetkovic, M. Ilic, "Dynamic Simulation of Power System Transients in Energy State Space", *in preparation.*

Response of Uncontrolled System



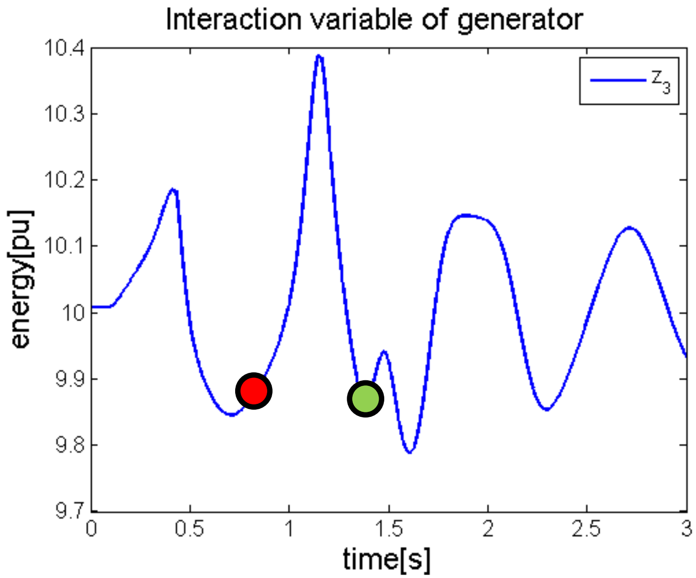


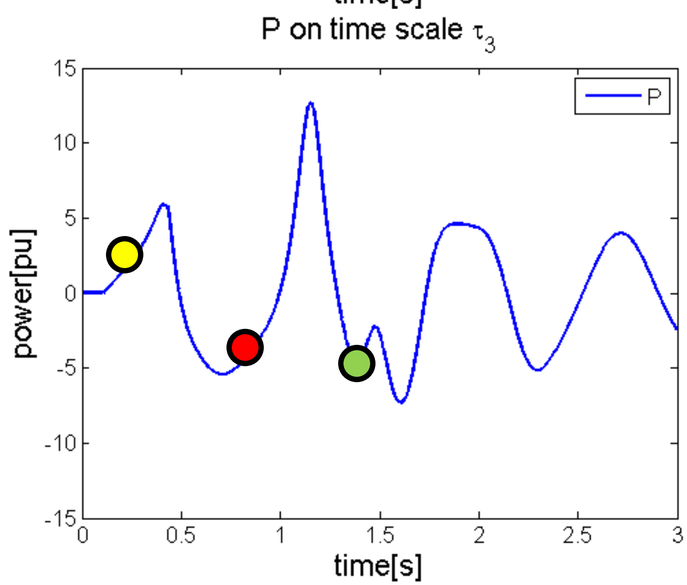
Short circuit at bus 3
in duration of 0.35 sec



M. Cvetkovic, M. Ilic, "*Cooperative Line-flow Power Electronics Control for Transient Stabilization*", IEEE Conference on Decision and Control, December 2014.

Controlled System Response



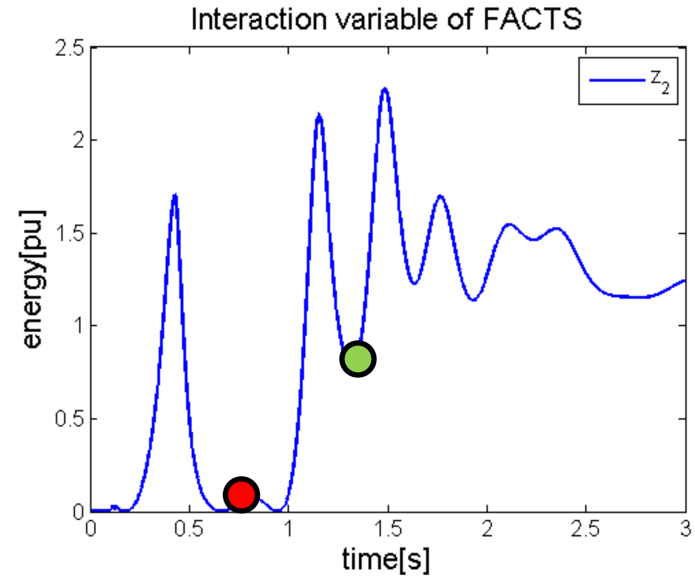


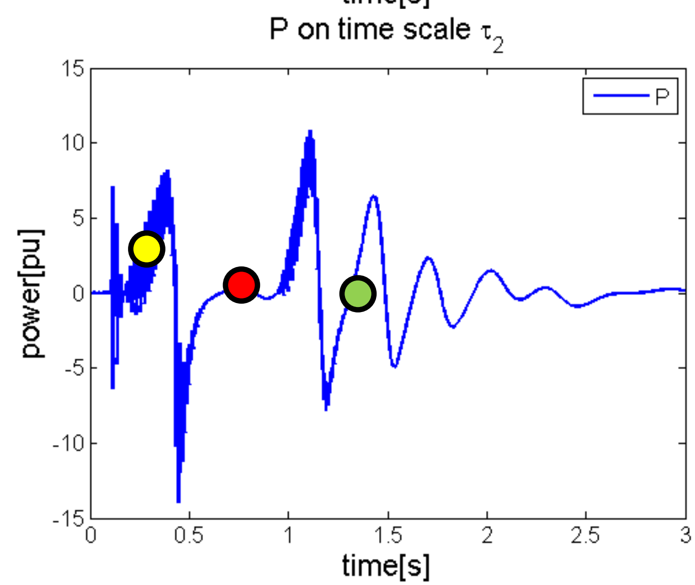
$$P_{\tau_3} = \frac{1}{\tau_3} \int_{\tau_2} P_{\tau_2} dt$$

$z_2 = 0$

FACTS energy has reached zero

States converge to a different equilibrium





M. Cvetkovic, M. Ilic, "*Cooperative Line-flow Power Electronics Control for Transient Stabilization*", IEEE Conference on Decision and Control, December 2014.

Questions?