Example of SGRS Implementation for Cooperative Transient Stabilization Using FACTS

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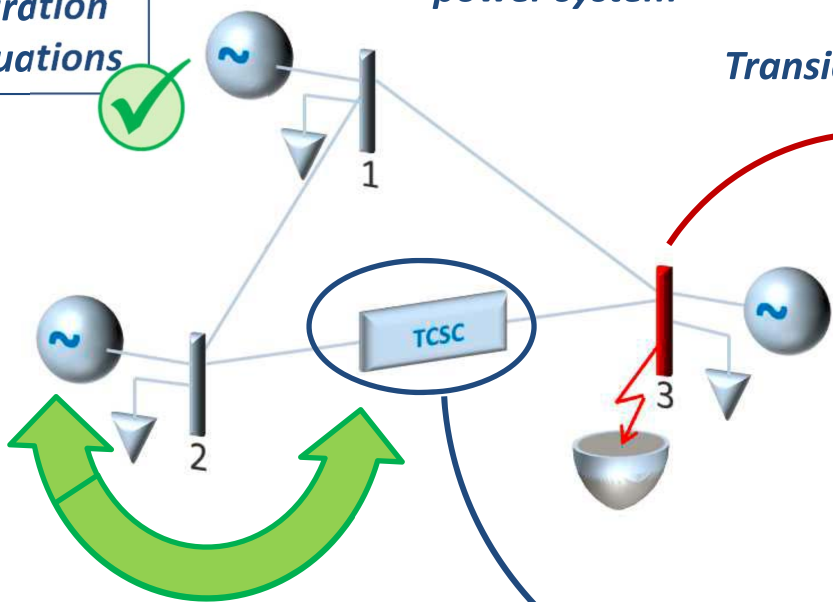
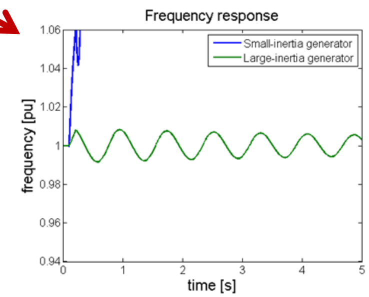
In this talk

Implications for SGRS distributed integration of differential equations

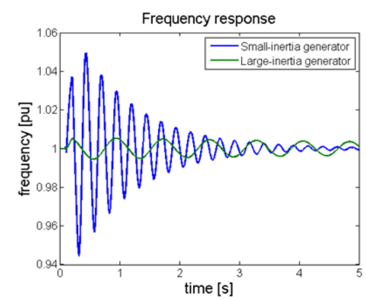
Large scale interconnected power system



Transient stability problem



Unstable



Stable

Interactions are captured using an energy-based model

Cooperative power electronics (FACTS) control

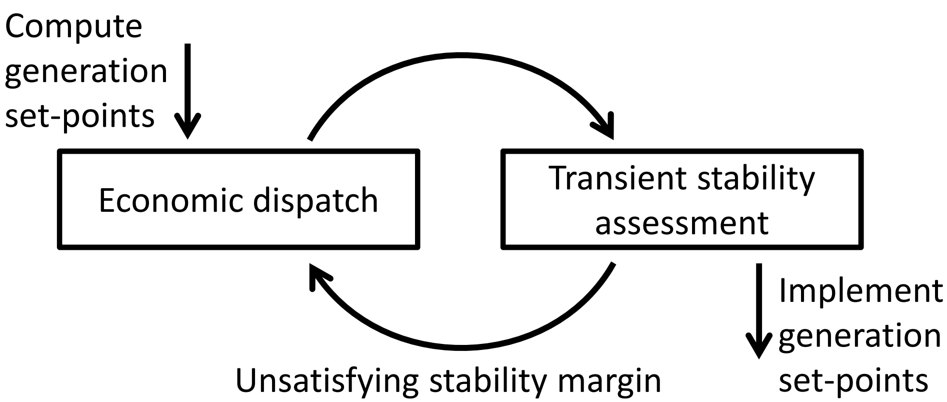
Need for Smarter Control

- **Benefits to system operators:**
- Safer integration of volatile renewables and unanticipated demand behavior
- Improved efficiency and reliability by improving dynamic performance
- Controlled dynamical interactions between devices

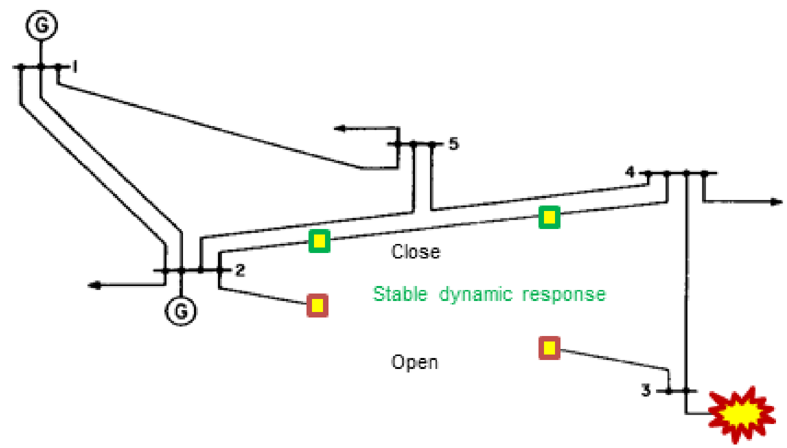
- **Benefits to manufacturers of power electronics:**
- Safe and reliable operation of devices
- Deployment for system-wide stability improvement

Today's Practice for Ensuring Transient Stability

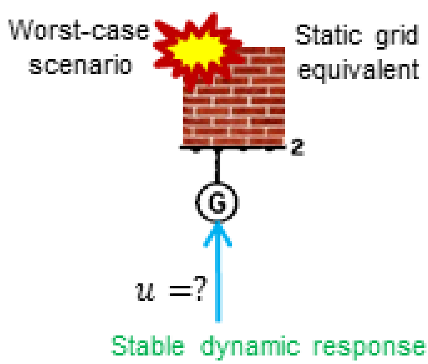
- **Off-line stability assessment**



- **Special protection schemes**



- **Tuning controllers locally**



- **What is missing?**

1. Conservative controller design
2. Interactions are not captured when designing controllers
3. Use of power electronics as controllers in mesh grid topologies

Proposed Approach

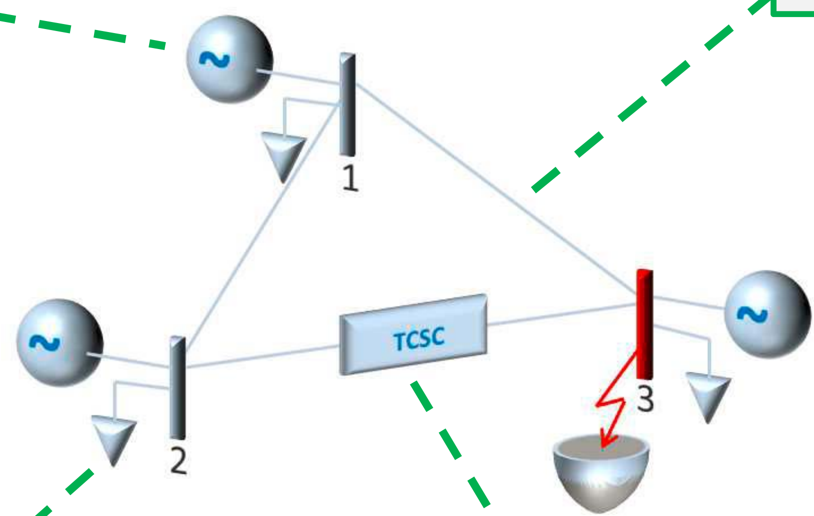
- Use line-flow power electronics as controllers because of
  - Fast thyristor switching (fast response time)
  - Potential to manage flows in the grid
- Energy-based modeling to capture interactions between FACTS and generators
- Tune controllers considering interactions
- Ectropy-based controller to redirect flows of energy in the grid
- SGRS module implementation using interaction-based models

A Comprehensive Power System Model

<u>Generators</u> are modeled using 7th order model:
- Stator current (D,Q)
- Rotor currents (D,Q,F)
- Rotor position angle
- Mechanical frequency

All states are described in the **<u>time-varying phasor domain</u>**

<u>Transmission lines</u> are modeled using a PI model:
- Line current (D,Q)
- Bus voltage (D,Q)

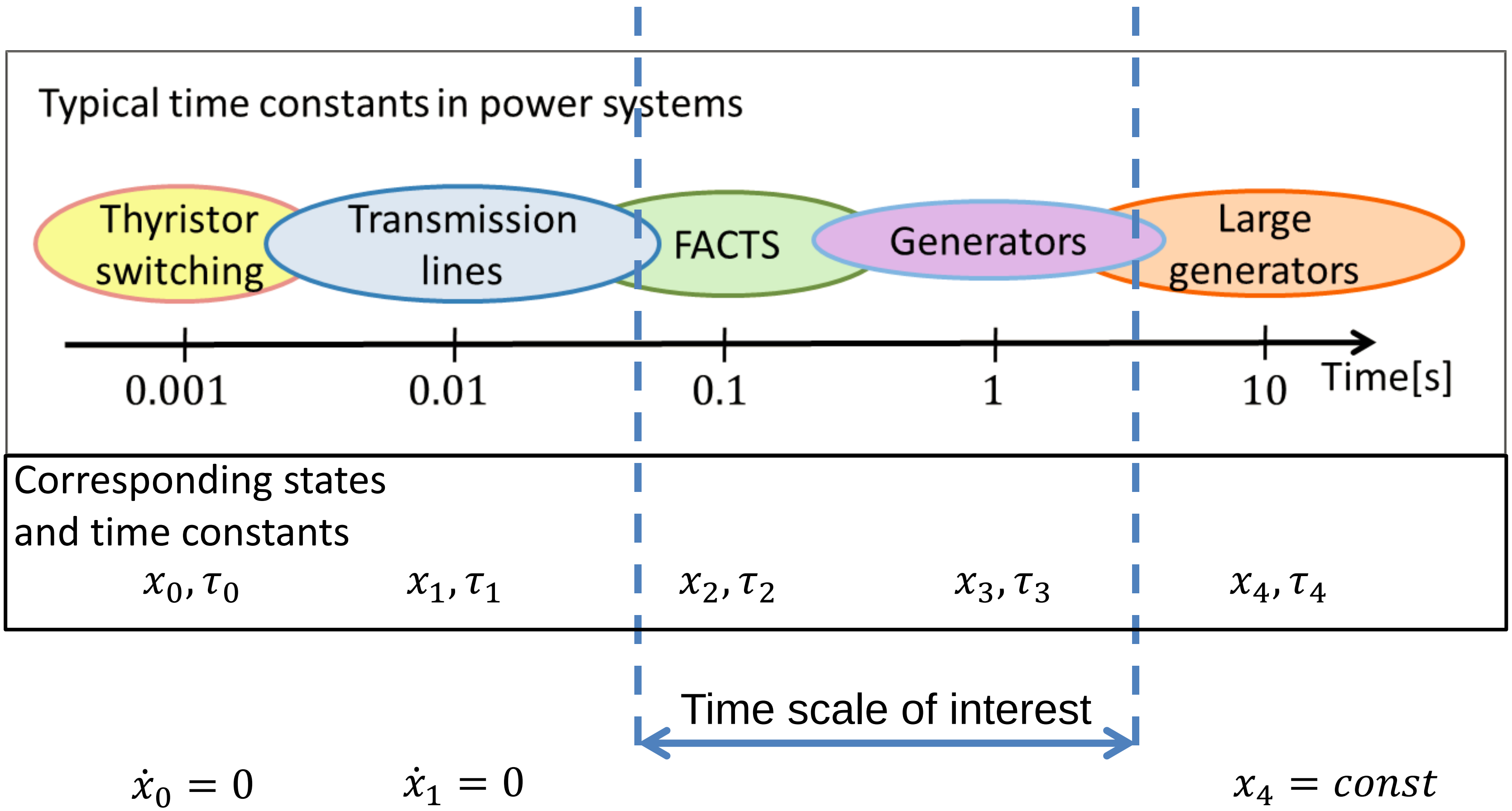


<u>Loads</u> are modeled as constant power loads

<u>TCSC</u> is modeled as an inductor and a capacitor in parallel:
- Inductor current (D,Q)
- Capacitor voltage (D,Q)

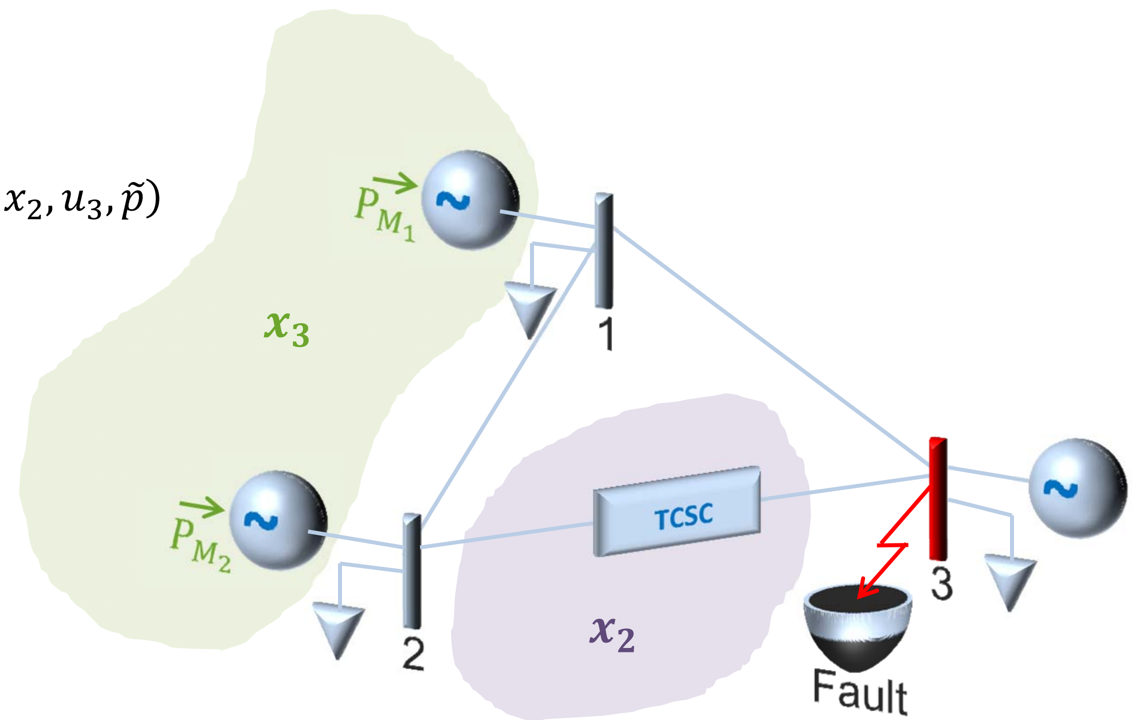
Extracting Time Scale of Interest

- Singular perturbation is used to simplify the power system model



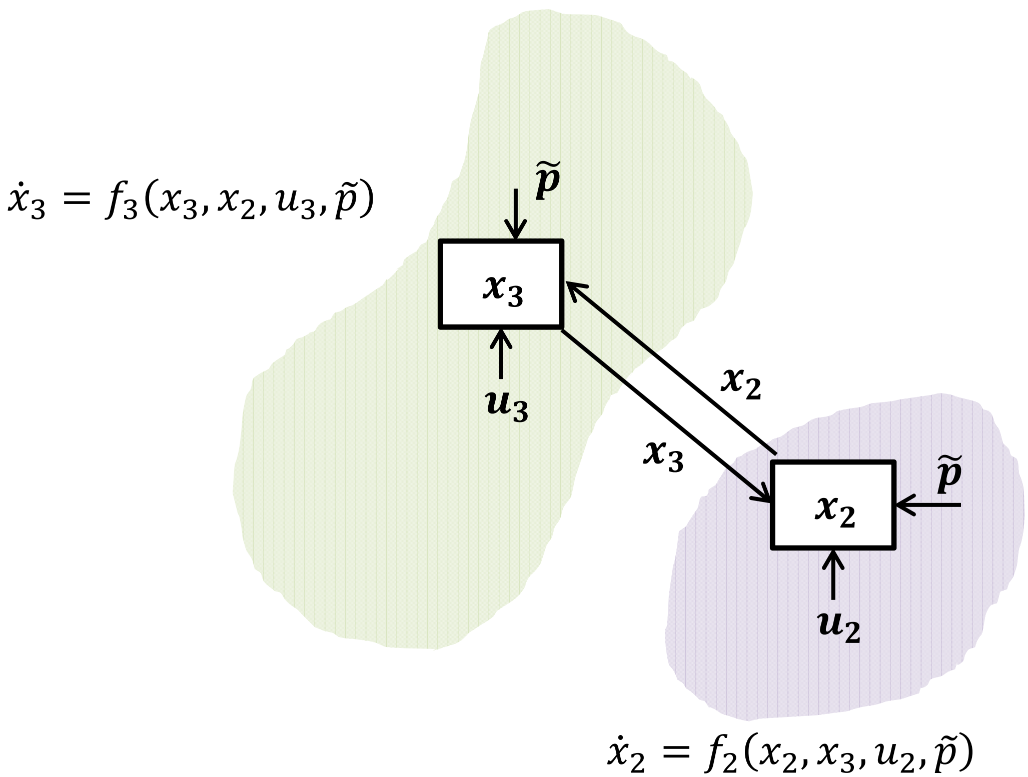
Reduced Order Model for Transient Stability

$\dot{x}_3 = f_3(x_3, x_2, u_3, \tilde{p})$



$\dot{x}_2 = f_2(x_2, x_3, u_2, \tilde{p})$

Reduced Order Model for Transient Stability Modular Form



A practical concern:

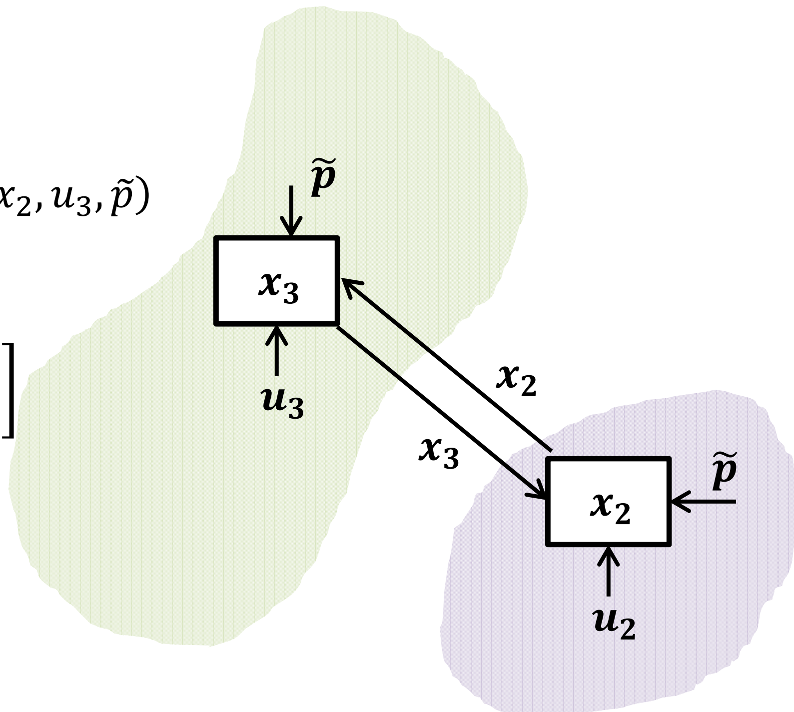
Control signals u_2, u_3 are, in general, functions of all system states x_2, x_3

Introducing Interaction Variables

$$\dot{x}_3 = f_3(x_3, x_2, u_3, \tilde{p})$$

$$z_3 = E_3(x_3)$$

$$x_3 \rightarrow \begin{bmatrix} \bar{x}_3 \\ z_3 \end{bmatrix}$$



Solution:
Accumulated energies z_2, z_3 as states of the model (interaction variables)

$$\dot{x}_2 = f_2(x_2, x_3, u_2, \tilde{p})$$

$$z_2 = E_2(x_2)$$

$$x_3 \rightarrow \begin{bmatrix} \bar{x}_3 \\ z_3 \end{bmatrix}$$

Accumulated energy interaction variable

From physical state space to energy state space

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

A Two-level Model Using Interaction Variables

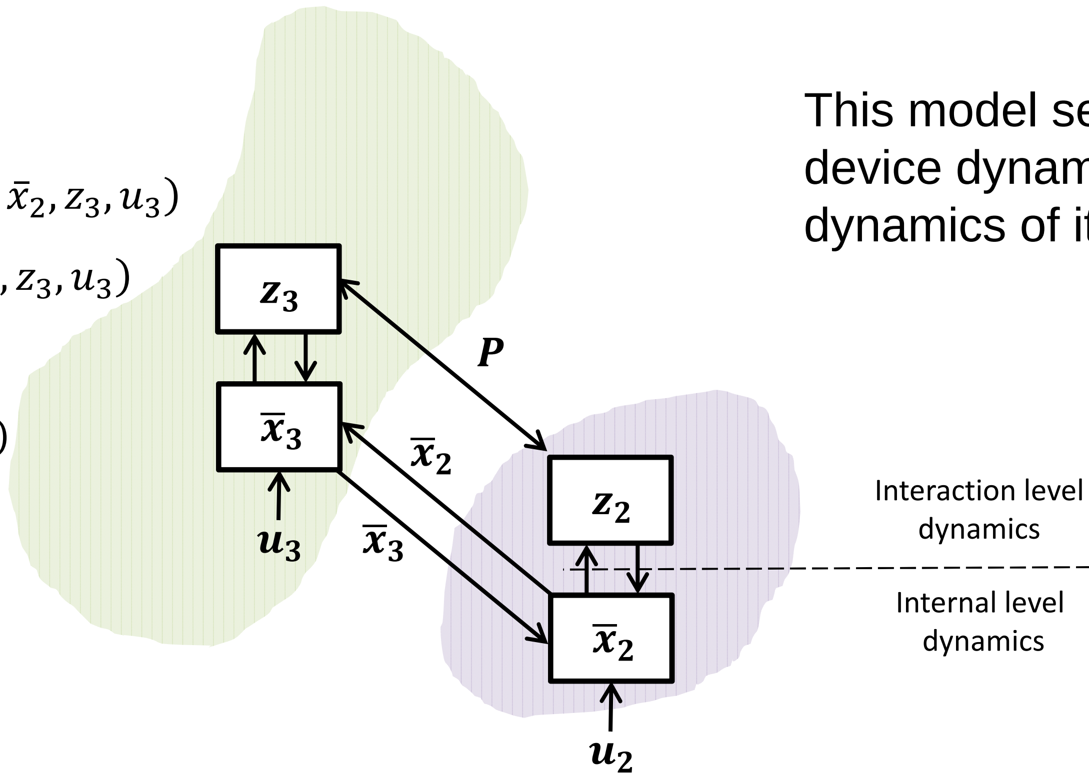
This model separates internal device dynamics from dynamics of its interactions

$$\dot{\bar{x}}_3 = \bar{f}_3(\bar{x}_3, \bar{x}_2, z_3, u_3)$$

$$\dot{z}_3 = g_3(\bar{x}_3, \bar{x}_2, z_3, u_3)$$

$$\downarrow$$

$$\dot{z}_3 = g_3(\bar{x}_3, P, u_3)$$



$$\dot{\bar{x}}_2 = \bar{f}_2(\bar{x}_2, \bar{x}_3, z_2, u_2)$$

$$\dot{z}_2 = g_2(\bar{x}_2, \bar{x}_3, z_2, u_2) \quad \rightarrow \quad \dot{z}_2 = g_2(\bar{x}_2, P, u_2)$$

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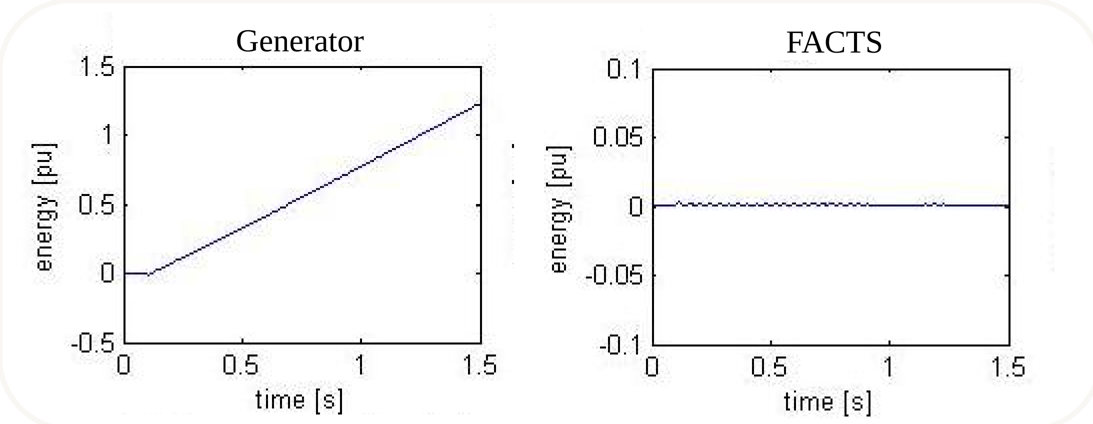
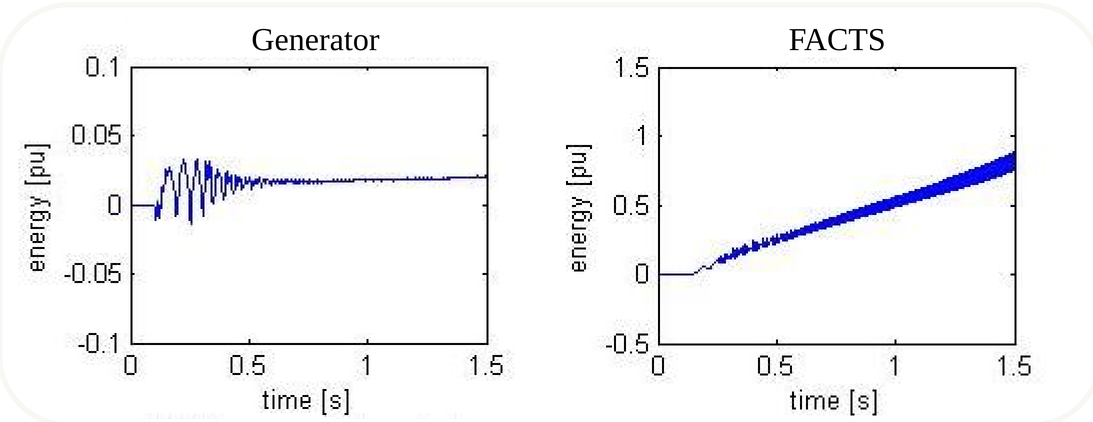
Proposed Cooperative Controller

- Redistribute energy of disturbance



Accumulated (stored) energy in an uncontrolled system



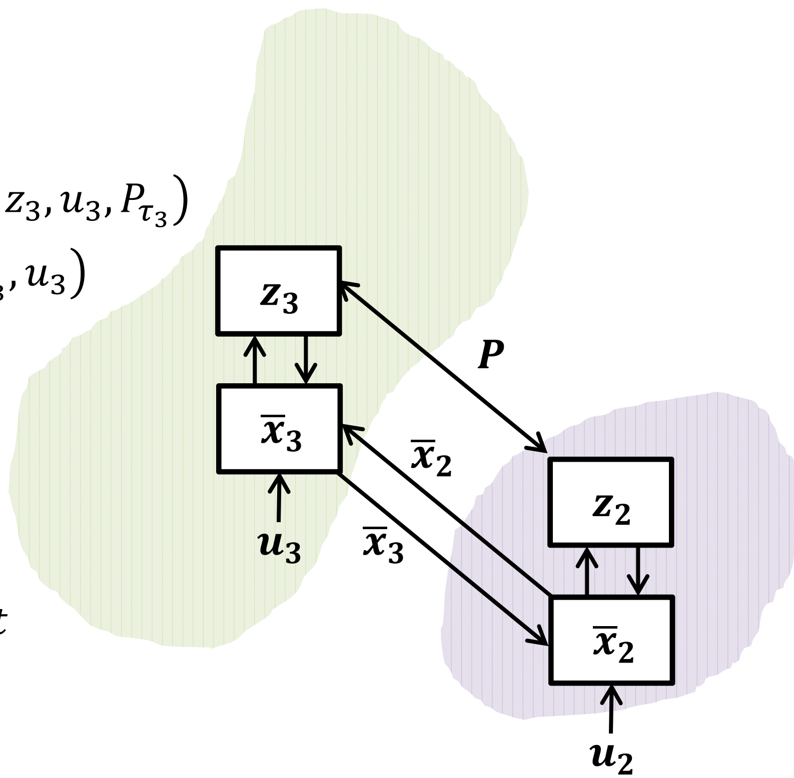
Accumulated (stored) energy in a system controlled by power electronics

Cooperative control is expressed in terms of higher (interaction) 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.

Control Objective at the Slower Time Scale

$$\dot{\bar{x}}_3 = \bar{f}_3(\bar{x}_3, z_3, u_3, P_{\tau_3})$$
$$\dot{z}_3 = g_3(\bar{x}_3, P_{\tau_3}, u_3)$$



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

Power exchanged at the slower time scale

$$\dot{\bar{x}}_2 = \bar{f}_2(\bar{x}_2, \bar{x}_3, z_2, u_2) = 0$$
$$\dot{z}_2 = g_2(\bar{x}_2, P, u_2) = 0$$

Assume instantaneous dynamics of power electronics

Stabilize interaction variable of the generators module using ectropy

$$\varepsilon = \frac{1}{2}(z_3 - z_3^*)^2$$
$$\dot{\varepsilon} = (z_3 - z_3^*)g_3(\bar{x}_3, P_{\tau_3}, u_3)$$

$$P_{\tau_3} = P$$
$$\downarrow$$
$$g_3(\bar{x}_3, P, u_3) = -K_z(z_3 - z_3^*)$$
$$\dot{\varepsilon} < 0$$

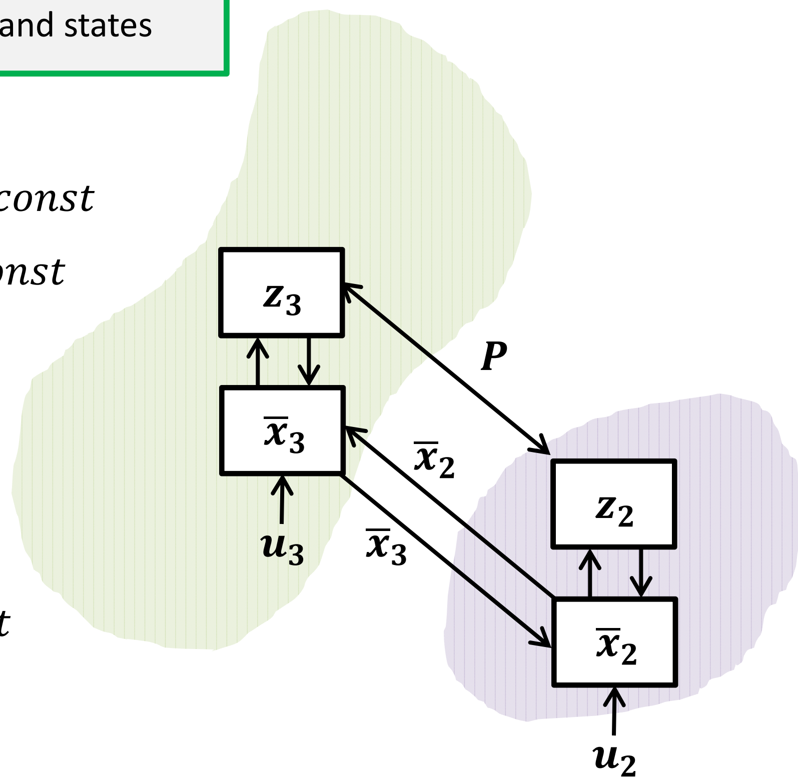
M. Cvetkovic, M. Ilic, "*Cooperative Line-flow Power Electronics Control for Transient Stabilization*", IEEE Conference on Decision and Control, December 2014.

Control Logic at the Faster Time Scale

Assume slow generator interaction and states

$\bar{x}_3 = const$

$z_3 = const$



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

Power exchanged at the faster time scale

$$\dot{\bar{x}}_2 = \bar{f}_2(\bar{x}_2, z_2, u_2, P_{\tau_2})$$
$$\dot{z}_2 = g_2(\bar{x}_2, P_{\tau_2}, u_2)$$

Track the power reference obtained from the ectropy stabilization problem

$$\nu = \frac{1}{2}(P_{\tau_2} - P_{\tau_3})^2$$

$$\dot{\varepsilon} = (P_{\tau_2} - P_{\tau_3})\frac{dg_2(\bar{x}_2, P_{\tau_2}, u_2)}{dt}$$

$$u_2 = u$$
$$\downarrow$$
$$\frac{dg_2(\bar{x}_2, P_{\tau_2}, u)}{dt} = -K_P(P_{\tau_2} - P_{\tau_3})$$
$$\dot{\nu} < 0$$

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

Numerical Implementation for SGRS

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

$$\dot{\bar{x}}_3 = \bar{f}_3(\bar{x}_3, z_3, u_3, P_{\tau_3})$$
$$\dot{z}_3 = g_3(\bar{x}_3, P_{\tau_3}, u_3)$$

$$\dot{\bar{x}}_2 = \bar{f}_2(\bar{x}_2, z_2, u_2, P_{\tau_2})$$
$$\dot{z}_2 = g_2(\bar{x}_2, P_{\tau_2}, u_2)$$

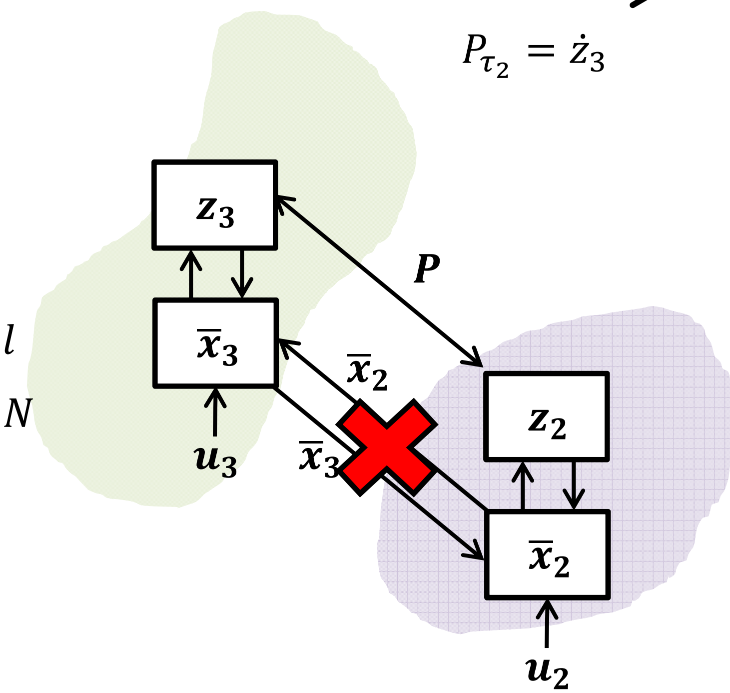
$$P_{\tau_2} = \dot{z}_3$$

$\bar{x}_3$ fast compared to z_3

$\bar{x}_3$ evolves at rate τ_l, step l

z_3 evolves at rate τ_3, step N

$$N > l$$



$\bar{x}_2$ at the same rate as z_2

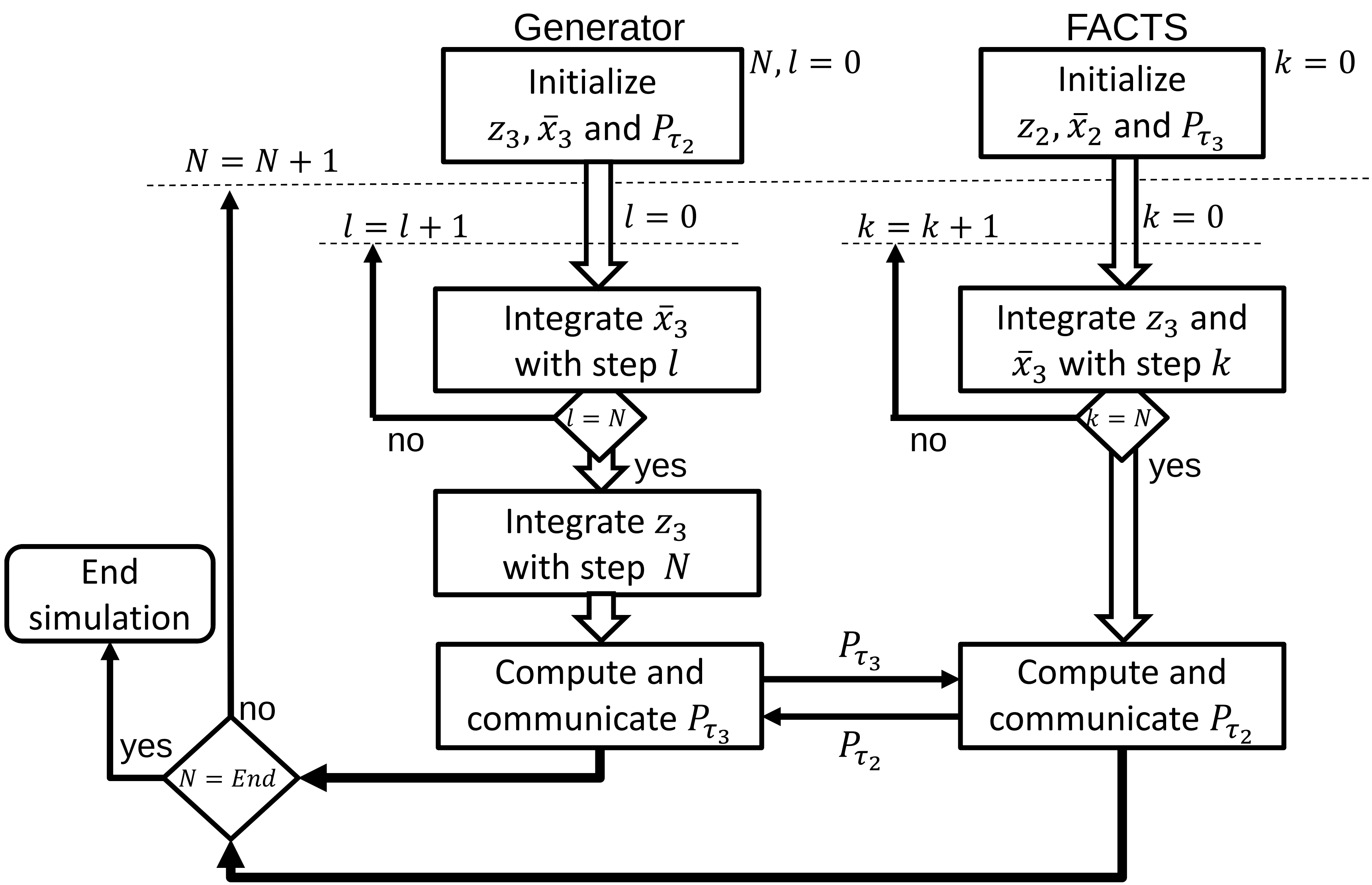
$\bar{x}_3, z_3$ evolve at rate τ_2, step k

$$N > k$$

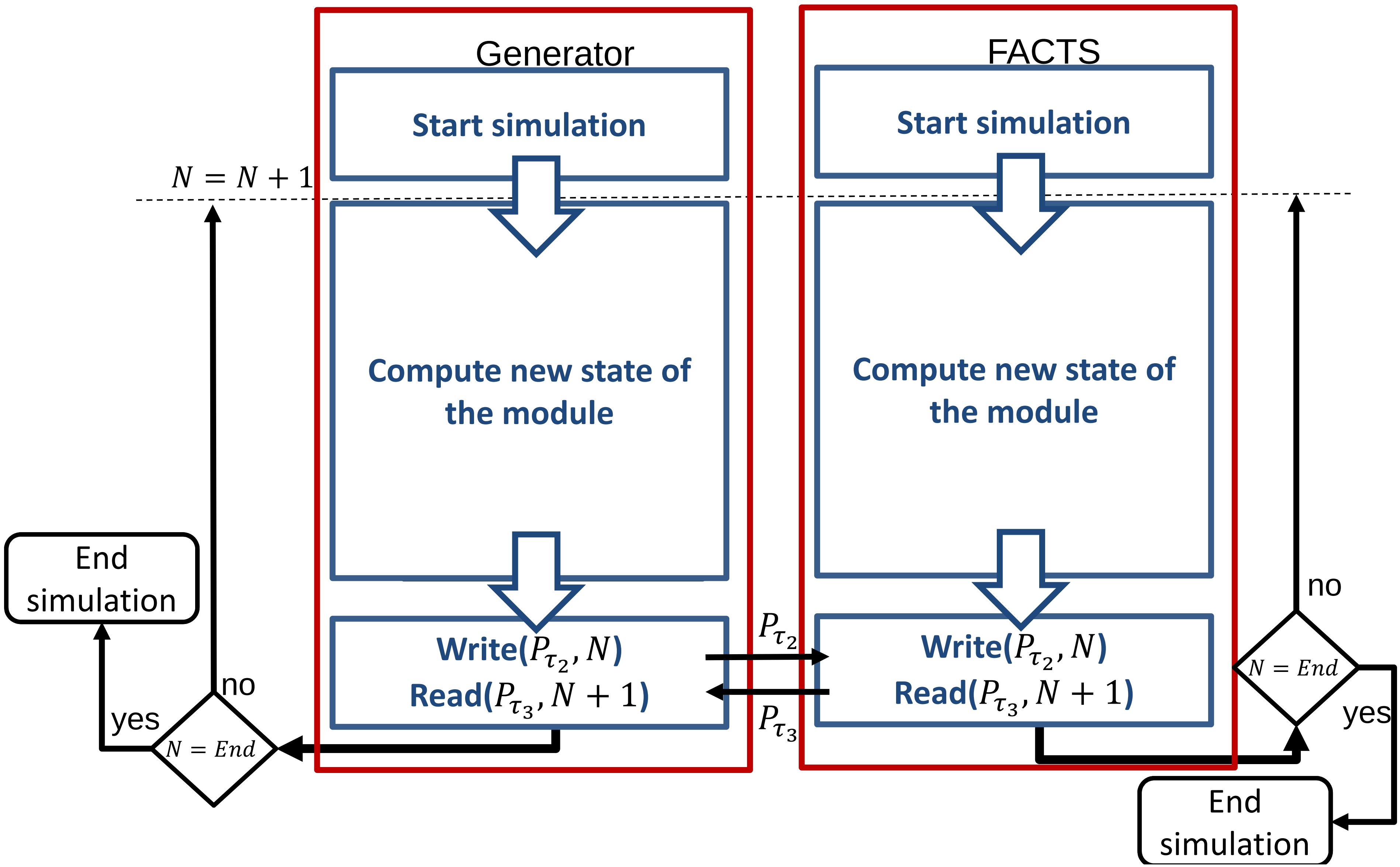
$$\bar{x}_3[l+1] = \bar{x}_3[l] + \tau_l \bar{f}_3(\bar{x}_3[l], z_3[l], u_3[l], P_{\tau_3}[l])$$
$$z_3[N+1] = z_3[N] + \tau_3 g_3(\bar{x}_3[l], P_{\tau_3}[N], u_3[l])$$
$$P_{\tau_2}[k] = \frac{z_3[N] - z_3[N-1]}{N}$$

$$\bar{x}_2[k+1] = \bar{x}_2[k] + \tau_2 \bar{f}_2(\bar{x}_2[k], z_2[k], u_2[k], P_{\tau_2}[k])$$
$$\dot{z}_2[k+1] = z_2[k] + \tau_2 g_2(\bar{x}_2[k], P_{\tau_2}[k], u_2[k])$$
$$P_{\tau_3}[N] = \frac{1}{N/k}\sum_{i=1}^{N/k} P_{\tau_2}[N-1+i]$$

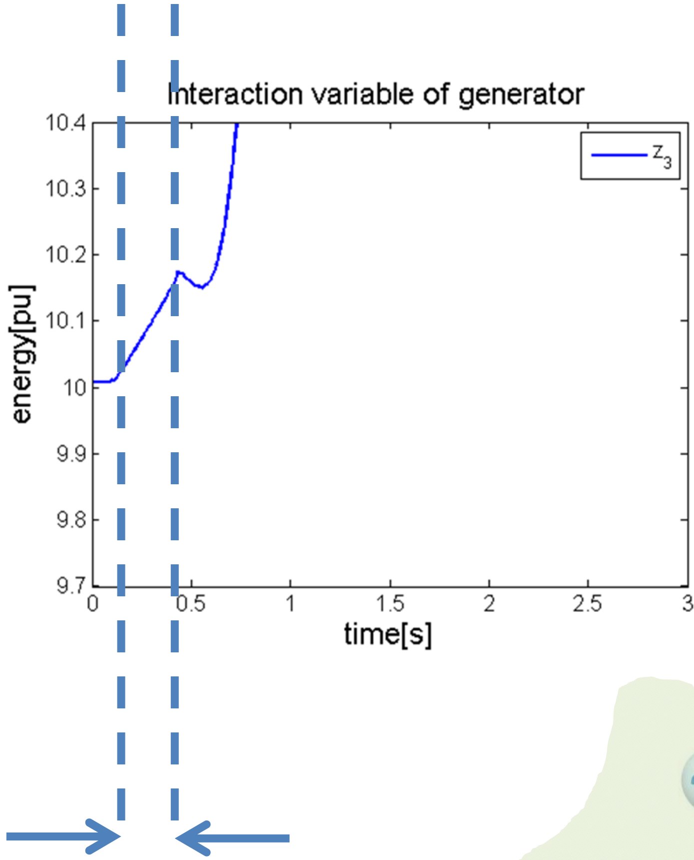
Numerical Integration Flow Chart

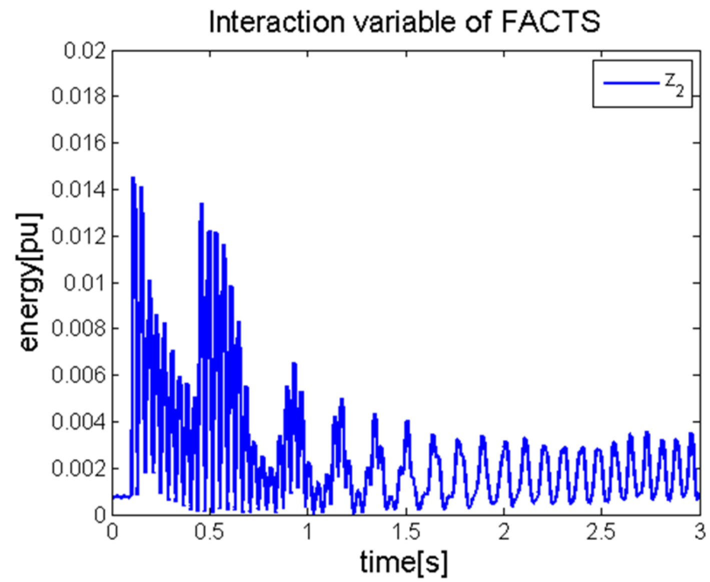


SGRS Implementation

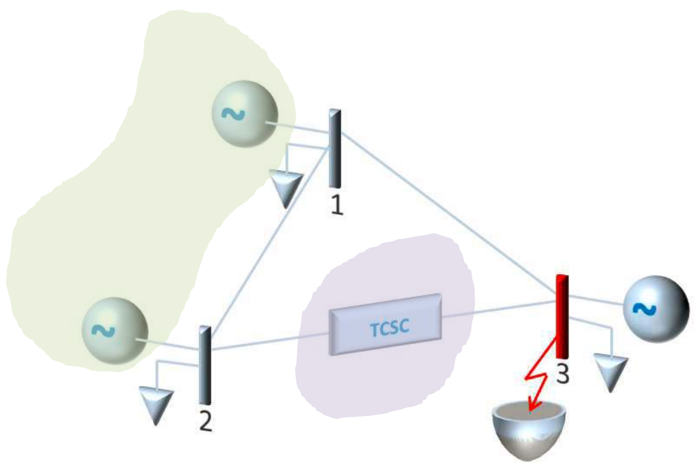


Response of Uncontrolled System

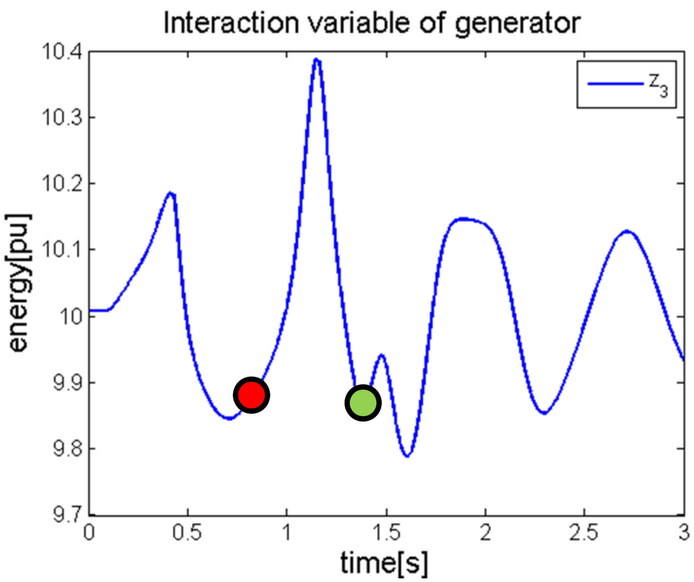


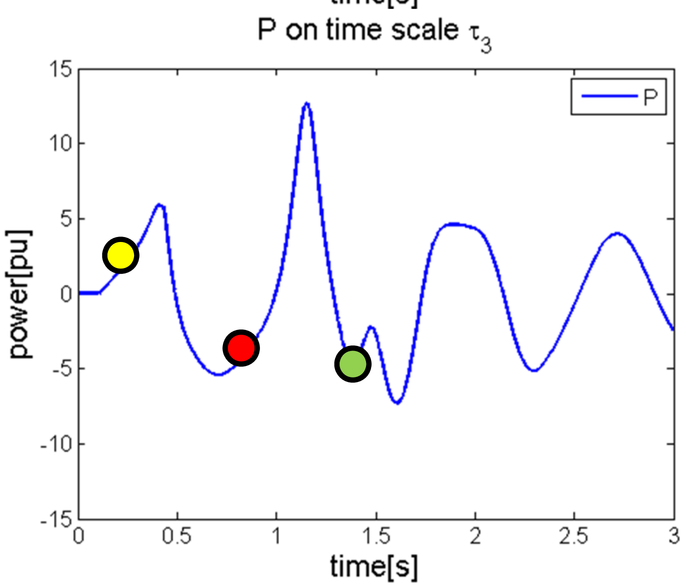


Short circuit at bus 3
in duration of 0.35 sec



Controlled System Response



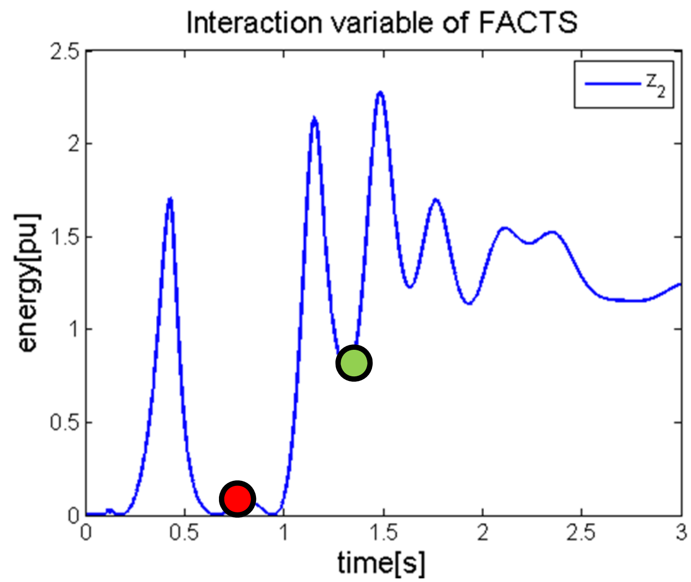


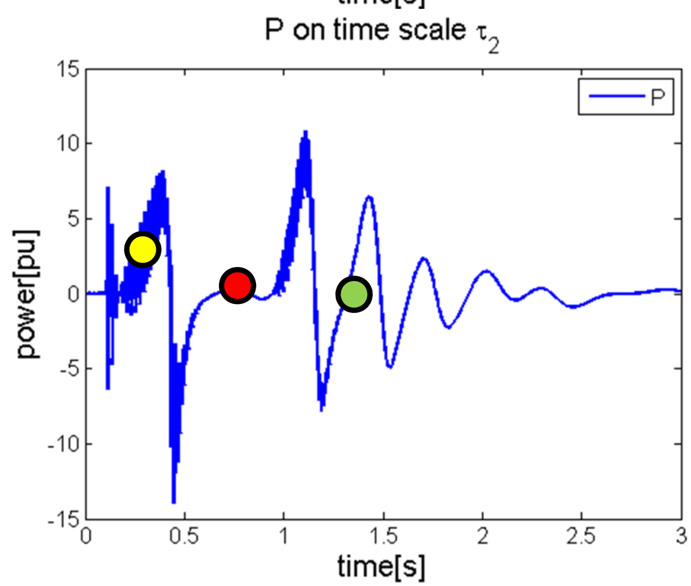
$$P_{\tau_3} = \frac{1}{\tau_3} \int_{\tau_2} P_{\tau_2} dt$$

$z_2 = 0$

FACTS energy has reached zero

States converge to a different equilibrium





Conclusions

- A two-level approach to power system modeling lends itself to:
  - Cooperative control design for power electronics
  - Time scale separation for reduced communication rate

- **Open questions:**
  - Sensitivity to time scale overlap
  - Shortest communication rate between any two modules constrains the simulation
  - Selection of modules for control purposes