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Electric Energy Systems Group

Electrical & Computer ENGINEERING

Simulation of Power System Dynamics and Transient Stabilization Using Flywheel Energy Storage Systems

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Outline

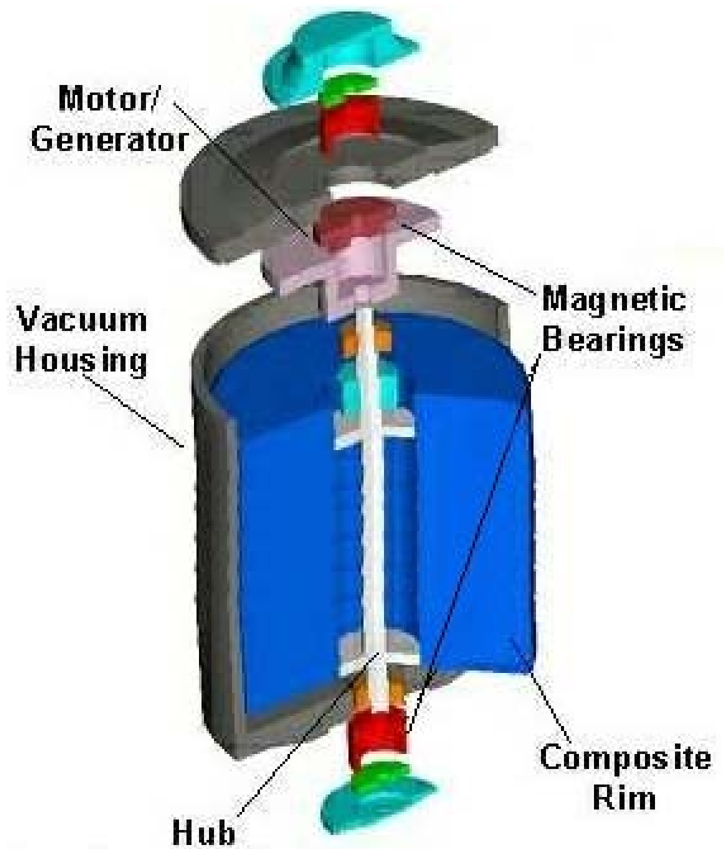
- Introduce and motivate flywheels
- Methods for modeling power system dynamics and designing control using flywheels
  - Model nonlinear power system dynamics using the Lagrangian formulation
  - Variable speed drive controller for flywheels using time-scale separation and nonlinear passivity-based control logic
  - Transient stabilization of interconnected power systems using flywheels
- Smart Grid in a Room Simulator (SGRS)
  - Implementation of simulating power system dynamics in a distributed manner
  - Show demo of flywheel controller

Motivation for Flywheels

- Transactive energy control does not guarantee dynamic stability
  - Instabilities can happen on a fast time-scale
- Interest in implementing more wind power (and other renewable energy sources) into future power grids
- Wind power is difficult to predict and control
- Large sudden deviations in wind power can cause
  - high deviations in frequency and voltage
  - transient instabilities
- One possible solution is to add fast energy storage, such as flywheel energy storage systems

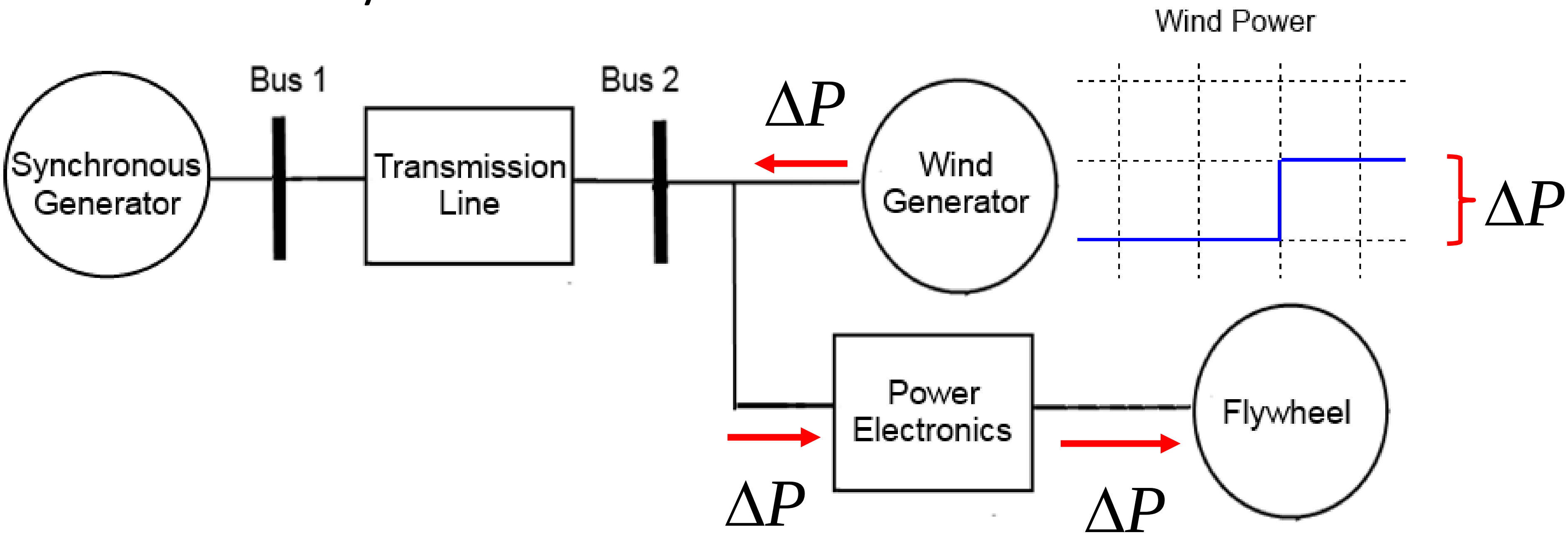
Flywheel Energy Storage System

- Stores mechanical energy by accelerating a rotor to a very high speed
- Not appropriate for large scale applications
  - Low energy capacity
- Many advantages for small-scale transient applications
  - Very efficient
  - Small time constants
  - Not limited to a certain number of charge-discharge cycles



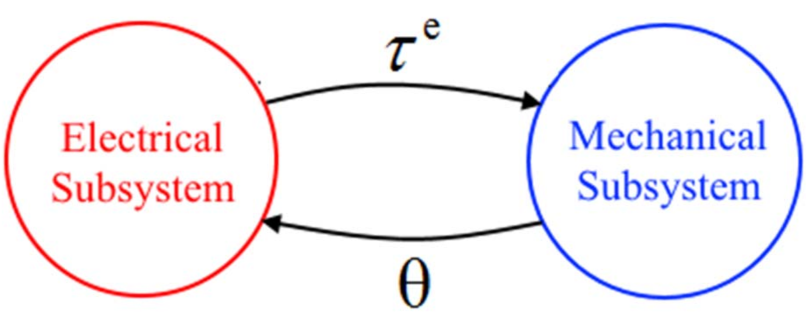
Objective

- 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



Modeling of Power System Dynamics

- To design and test control for flywheels, it is necessary to first derive the dynamic model for the interconnected power system
- Large interconnected power systems contain many coupled electrical and mechanical components
- Conventional modeling of dynamics:
  - Electrical systems: Kirchhoff's voltage and current law equations
  - Mechanical systems: Conservation of force
  - Difficulty is determining the effect of subsystems on each other for mixed energy systems



Source: H. H. Woodson, J. R. Melcher, "Electromechanical Dynamics, Part I: Discrete Systems," New York: Wiley, 1968.

Lagrangian Formulation

- Therefore, for mixed energy systems, often advantageous to derive the dynamics using the Lagrangian formulation from classical mechanics
  - Reformulation of Newtonian mechanics
    - Newtonian mechanics: model in terms of forces
    - Lagrangian mechanics: model in terms of kinetic energy and potential energy of the system
  - Can be applied to other types of systems, such as electric systems, as well as to mixed energy systems

Source: D. Jeltsema, J.M.A. Scherpen, "Multidomain modeling of nonlinear networks and systems," *IEEE Control Systems*, vol.29, no.4, pp.28-59, Aug. 2009

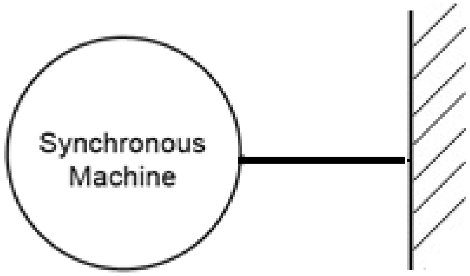
Motivation for the Lagrangian Formulation

- Unified framework for the analyzing systems with multiple types of energy

	Displacement Q_{gen}	Flow F_{gen}	Lagrangian $\mathscr{L}$	Rayleigh dissipation $\mathfrak{R}$	Forcing Function $\mathfrak{F}$
Mechanical (Rotational)	θ	ω	$KE' - PE$	$\mathscr{R}_{\text{mech}} = \sum \frac{1}{2} B\omega^2$	*F*
Electrical	q	i	$W_m' - W_e$	$\mathscr{R}_{elec} = \sum \frac{1}{2} Ri^2$	*V*
Electro-mechanical	θ, q	ω, i	$\mathscr{L} = \mathscr{L}_{elec} + \mathscr{L}_{mech}$	$\mathfrak{R} = \mathfrak{R}_{elec} + \mathfrak{R}_{mech}$	*F,V*

- Passivity-based control
  - Choose closed-loop energy functions
  - Need to derive error dynamics from those closed-loop energy functions in order to derive the control law

Example Using Lagrangian Formulation



Electrical Subsystem:

$$\mathfrak{L}_{elec} = \frac{1}{2}L_R {i_R}^2 + \frac{1}{2}L_S {i_{Sa}}^2 + \frac{1}{2}L_S {i_{Sb}}^2 + \frac{1}{2}L_S {i_{Sc}}^2 - L_{SS} i_{Sa} i_{Sb} - L_{SS} i_{Sa} i_{Sc} - L_{SS} i_{Sb} i_{Sc}$$
$$+ M\cos\theta i_{Sa} i_R + M\cos\left(\theta - 2\pi/3\right) i_{Sb} i_R + M\cos\left(\theta + 2\pi/3\right) i_{Sc} i_R$$

$$\mathfrak{R}_{elec} = \frac{1}{2}R_R {i_R}^2 + \frac{1}{2}R_S {i_{Sa}}^2 + \frac{1}{2}R_S {i_{Sb}}^2 + \frac{1}{2}R_S {i_{Sc}}^2$$

$$\mathfrak{F}_{elec} = \left[v_R \;\; v_{Sa} \;\; v_{Sb} \;\; v_{Sc}\right]$$

Mechanical Subsystem:

$$\mathfrak{L}_{mech} = \frac{1}{2}J\omega^2$$

$$\mathfrak{R}_{mech} = \frac{1}{2}B\omega^2$$

$$\mathfrak{F}_{mech} = \left[\tau^m\right]$$

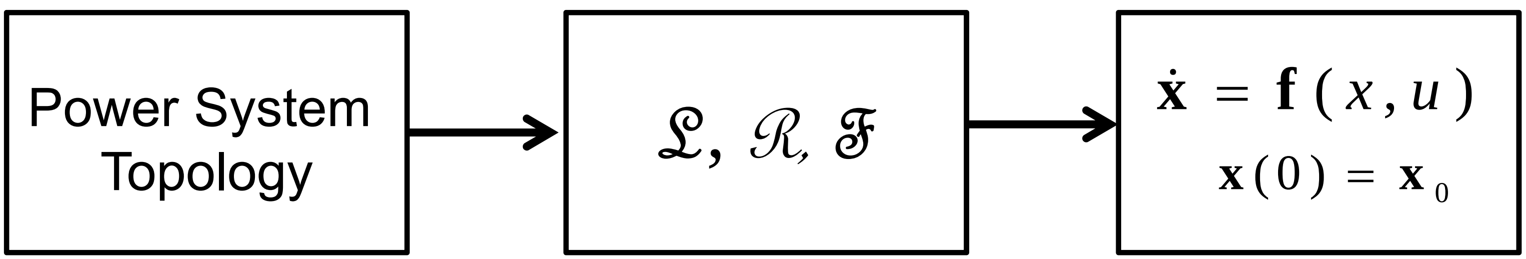
- Compute dynamic equations using the Lagrangian equations:

$$\frac{d}{dt}\left[\frac{\partial \mathfrak{L}}{\partial \mathbf{F}_{gen}(k)}\right] - \frac{\partial \mathfrak{L}}{\partial \mathbf{Q}_{gen}(k)} + \frac{\partial \mathfrak{R}}{\partial \mathbf{F}_{gen}(k)} - \mathfrak{F}(k) = 0$$

Source: R. Ortega, A. Loria, P. Nicklasson, H. Sira-Ramirez, *Passivity-based Control of Euler-Lagrange Systems: Mechanical, Electrical and Electromechanical Applications*, Springer Verlag, New York 1998

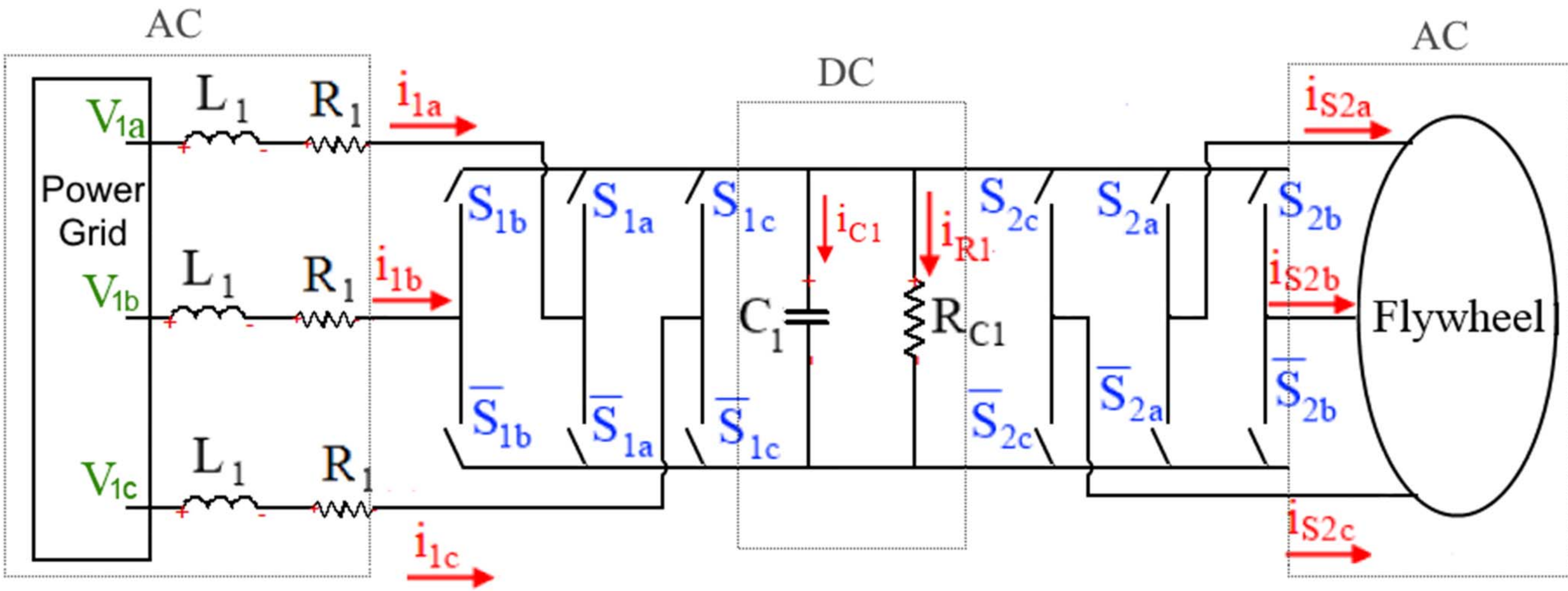
Automated Modeling of Power System Dynamics

- Implemented an automated procedure for symbolically deriving the dynamic equations using the Lagrangian formulation
  - User specifies the power system topology
  - Code symbolically solves for the energies of the system
  - Code computes dynamic equations by evaluating the Lagrangian equations and re-expresses in standard state space form



Source: K. D. Bachovchin, M. D. Ilić, "Automated Modeling of Power System Dynamics Using the Lagrangian Formulation," *International Transactions on Electrical Energy Systems* [to appear, 2014]

Variable Speed Drives for Flywheels

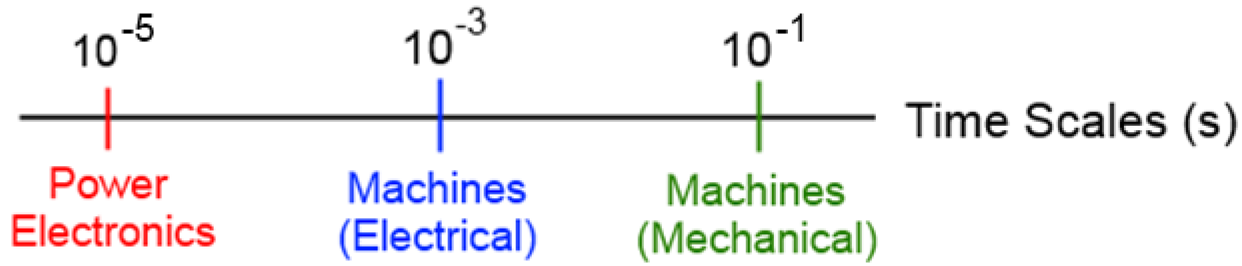


- Use AC/DC/AC converter to regulate the speed of the flywheel (and hence the energy stored) to a different frequency than the grid frequency
- Controllable inputs are the duty ratios of the switch positions in the power electronics

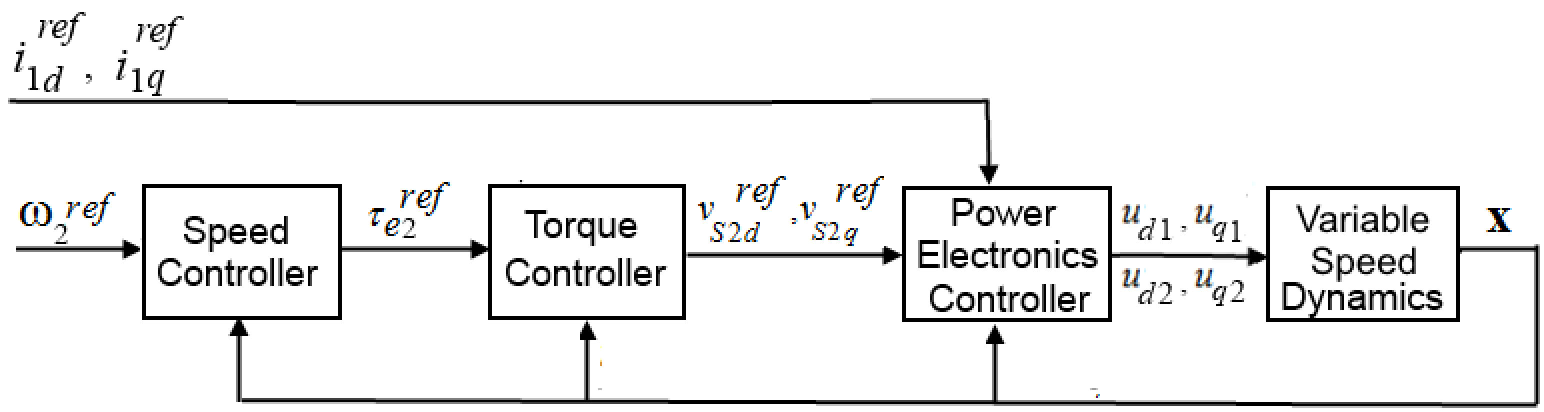
Source: K. D. Bachovchin, M. D. Ilic, "Transient Stabilization of Power Grids Using Passivity-Based Control with Flywheel Energy Storage Systems," *IEEE Power & Energy Society General Meeting*, Denver, USA, July 2015..

Controller Implementation

- Time-scale separation to simplify the control design



- Regulate both the flywheel speed and the currents into the power electronics using 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..

Nonlinear Passivity-Based Control

- Nonlinear control method
- Exploits the intrinsic energy properties of the system dynamics
- Robust due to the avoidance of exact cancellation of nonlinearities
- Relies on Lyapunov stability argument
  - For a dynamic system $\dot{\mathbf{x}} = \mathbf{f}(x)$, if there exists a Lyapunov function $V(x)$ such that
    - $V(x)$ is positive definite
      - $V(0) = 0$ and $V(x) > 0 \; \forall \; x \neq 0$
    - $\dot{V}(x)$ is negative definite
      - $\dot{V}(0) = 0$ and $\dot{V}(x) < 0 \; \forall \; x \neq 0$

  then $\mathbf{x} = 0$ is an asymptotically stable equilibrium

Source: R. Ortega, A. Loria, P. Nicklasson, H. Sira-Ramirez, *Passivity-based Control of Euler-Lagrange Systems: Mechanical, Electrical and Electromechanical Applications*, Springer Verlag, New York 1998

Automated Passivity-Based Control Law Derivation

State space model: $\dot{\mathbf{x}} = \mathbf{f}(x, u)$

Closed-loop energy functions: $\tilde{W}_m{}'(\tilde{\mathbf{x}}),\ \tilde{W}_e(\tilde{\mathbf{x}})$

where $\tilde{\mathbf{x}} = \mathbf{x} - \mathbf{x}^D$

Closed-loop dissipation function: $\tilde{\mathcal{R}}(\tilde{\mathbf{x}})$

Set point equations: $\mathbf{f}_r(x^D) = \mathbf{r}^*$

Lyapunov function:

$$V(\tilde{\mathbf{x}}) = \tilde{W}_m{}'(\tilde{\mathbf{x}}) + \tilde{W}_e(\tilde{\mathbf{x}})$$

$$\frac{dV(\tilde{\mathbf{x}})}{dt} = \frac{dV(\tilde{\mathbf{x}})}{d\tilde{\mathbf{x}}}\frac{d\tilde{\mathbf{x}}}{dt}$$

If
- $V(\tilde{\mathbf{x}})$ is positive definite
- $\frac{dV(\tilde{\mathbf{x}})}{dt}$ is negative definite

Then $\tilde{\mathbf{x}} \to 0,\ \mathbf{x} \to \mathbf{x}^D$

can derive control law in an automated manner

Passivity-Based Control Law:

$$\mathbf{u} = \mathbf{g}_1(x, x^{Dn}, r^*)$$

$$\dot{\mathbf{x}}^{Dn} = \mathbf{g}_2(x, x^{Dn}, r^*)$$

Non-directly controlled desired state variable dynamics must be stable for control to be physically realizable.

Source: K. D. Bachovchin, M. D. Ilić, "Automated Passivity-Based Control Law Derivation for Electrical Euler-Lagrange Systems and Demonstration on Three-Phase AC/DC/AC Converter," EESG Working Paper No. R-WP-5-2014, August 2014.

Power Electronics Passivity-Based Control

Dynamic Model:
(Power electronic time-scale)

$$\dot{\mathbf{x}}_{pe} = \mathbf{f}_{pe}\left(x_{pe}, u_{pe}\right)$$

$$\mathbf{x}_{pe} = \left[i_{1d} \;\; i_{1q} \;\; q_{C1}\right]^T$$

$$\mathbf{u}_{pe} = \left[u_{1d} \;\; u_{1q}\right]^T$$

Closed-loop energy functions:

$$\tilde{W}_m{}' = \frac{1}{2} L_1 \left(\tilde{i}_{1d}{}^2 + \tilde{i}_{1q}{}^2\right)$$

$$\tilde{W}_e = \frac{1}{2} \frac{\tilde{q}_{C1}{}^2}{C}$$

Closed-loop dissipation function:

$$\tilde{\mathcal{R}} = \frac{1}{2} R_1 \left(\tilde{i}_{1d}{}^2 + \tilde{i}_{1q}{}^2\right) + \frac{1}{2} R_{C1} \tilde{i}_{R1}{}^2$$

Set Point Equations:

$$i_{1d}{}^D = i_{1d}{}^*$$

$$i_{1q}{}^D = i_{1q}{}^*$$

Lyapunov function:

$$V = \tilde{W}_m{}' + \tilde{W}_e = \frac{1}{2} L_1 \left(\tilde{i}_{1d}{}^2 + \tilde{i}_{1q}{}^2\right) + \frac{1}{2} \frac{\tilde{q}_{C1}{}^2}{C_1}$$

Positive definite function

$$\dot{V} = \frac{dV}{d\tilde{\mathbf{x}}} \frac{d\tilde{\mathbf{x}}}{dt} = -R_1 \left(\tilde{i}_{1d}{}^2 + \tilde{i}_{1q}{}^2\right) - \frac{\tilde{q}_{C1}{}^2}{C_1{}^2 R_{C1}}$$

Negative definite function

Source: K. D. Bachovchin, M. D. Ilić, "Automated Passivity-Based Control Law Derivation for Electrical Euler-Lagrange Systems and Demonstration on Three-Phase AC/DC/AC Converter," EESG Working Paper No. R-WP-5-2014, August 2014.

Passivity-Based Control for Power Electronics Controller

Automated Control Law:

$$u_{1d} = \frac{2\left(C_1 V_{1d} - C_1 R_1 i_{1d}{}^{ref} + C_1 L_1 i_{1q}{}^{ref} \omega_1\right)}{q_{C1}{}^{D}} \qquad u_{1q} = \frac{2\left(C_1 V_{1q} - C_1 R_1 i_{1q}{}^{ref} - C_1 L_1 i_{1d}{}^{ref} \omega_1\right)}{q_{C1}{}^{D}}$$

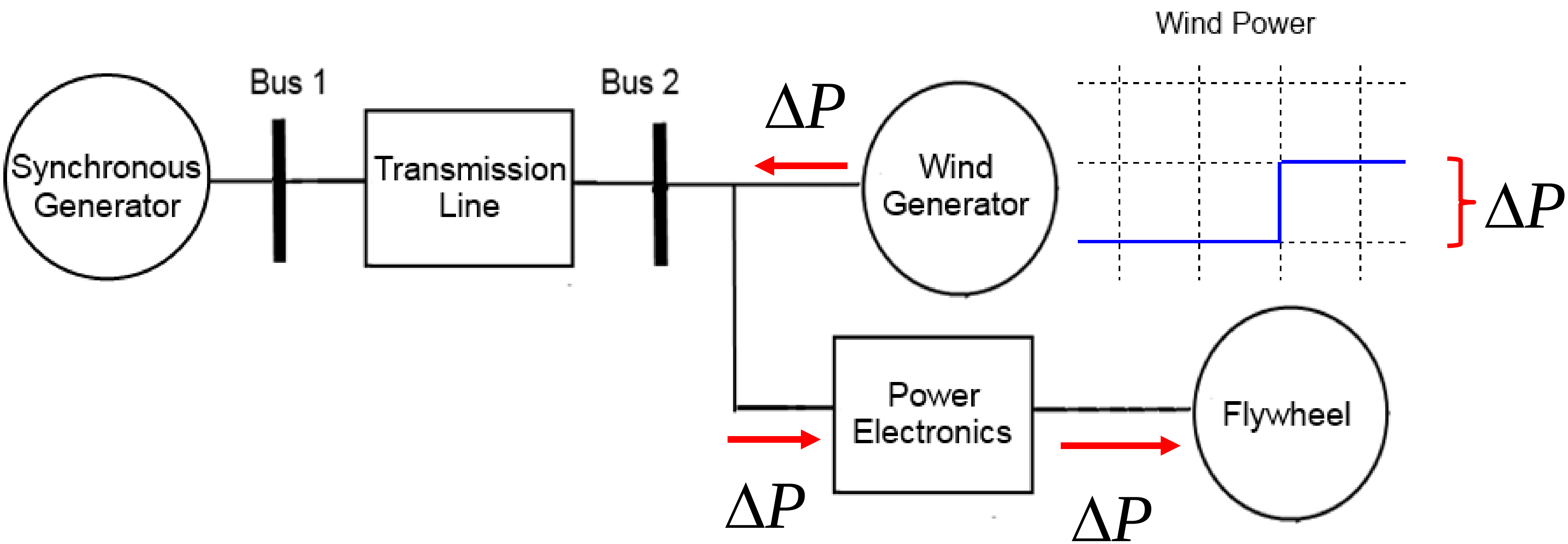
$$\frac{dq_{C1}{}^{D}}{dt} = \frac{C_1\left(V_{1d} i_{1d}{}^{ref} + V_{1q} i_{1q}{}^{ref} - R_1\left(i_{1d}{}^{ref}\right)^2 - R_1\left(i_{1q}{}^{ref}\right)^2 - v_{S2d}{}^{ref} i_{2d} - v_{S2q}{}^{ref} i_{2q}\right)}{q_C{}^{D}} - \frac{q_C{}^{D}}{CR_C}$$

- A stable equilibrium for $q_{C1}{}^{D}$ only exists when

$$\underbrace{V_{1d} i_{1d}{}^{ref} + V_{1q} i_{1q}{}^{ref} - R_1\left(i_{1d}{}^{ref}\right)^2 - R_1\left(i_{1q}{}^{ref}\right)^2}_{\text{power input to power electronics}} \geq \underbrace{v_{S2d}{}^{ref} i_{2d} + v_{S2q}{}^{ref} i_{2q}}_{\text{power output of power electronics}}$$

Source: K. D. Bachovchin, M. D. Ilić, "Automated Passivity-Based Control Law Derivation for Electrical Euler-Lagrange Systems and Demonstration on Three-Phase AC/DC/AC Converter," EESG Working Paper No. R-WP-5-2014, August 2014.

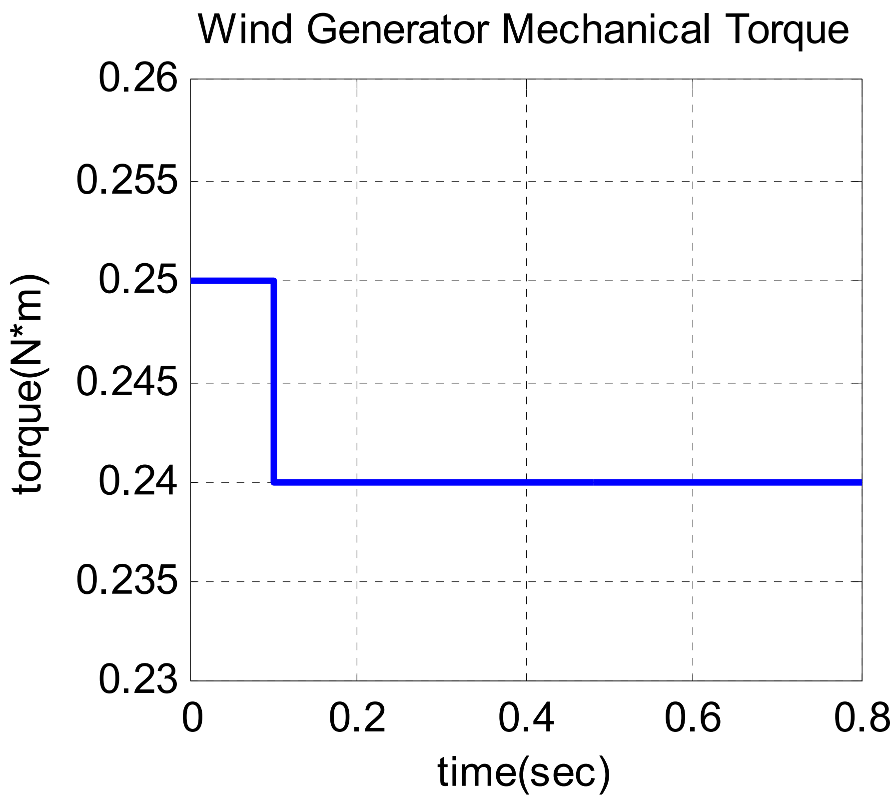
Transient Stabilization Using Flywheels

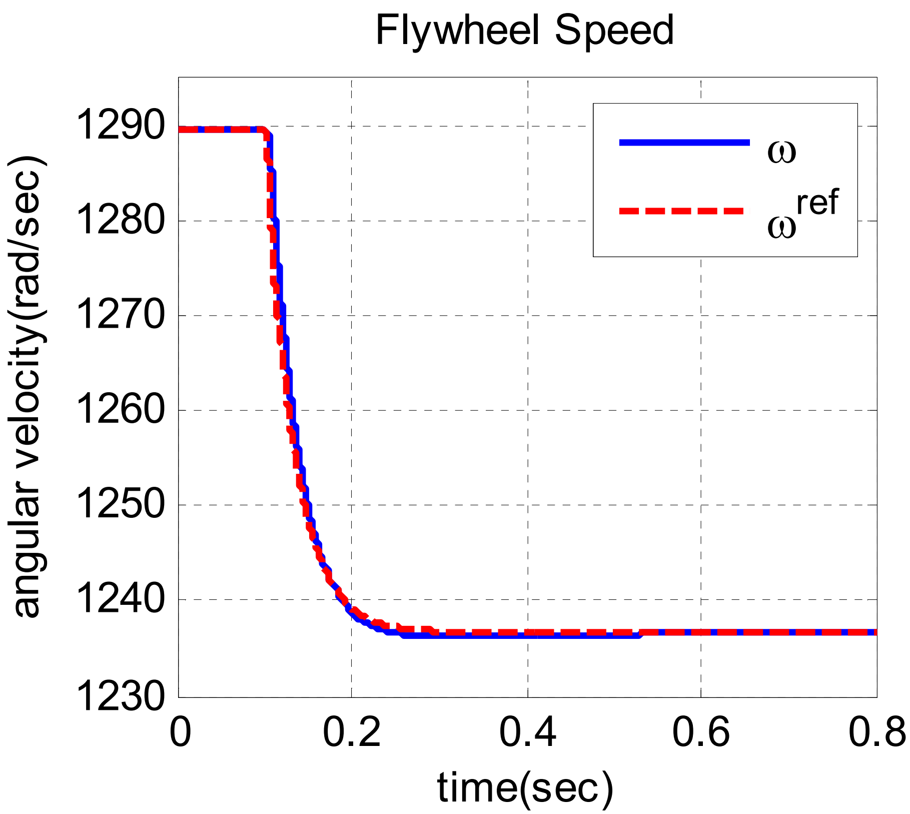


- Want to choose set points so that the wind disturbance power goes to the flywheel and rest of the system is minimally affected

Simulation Results: Flywheel

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





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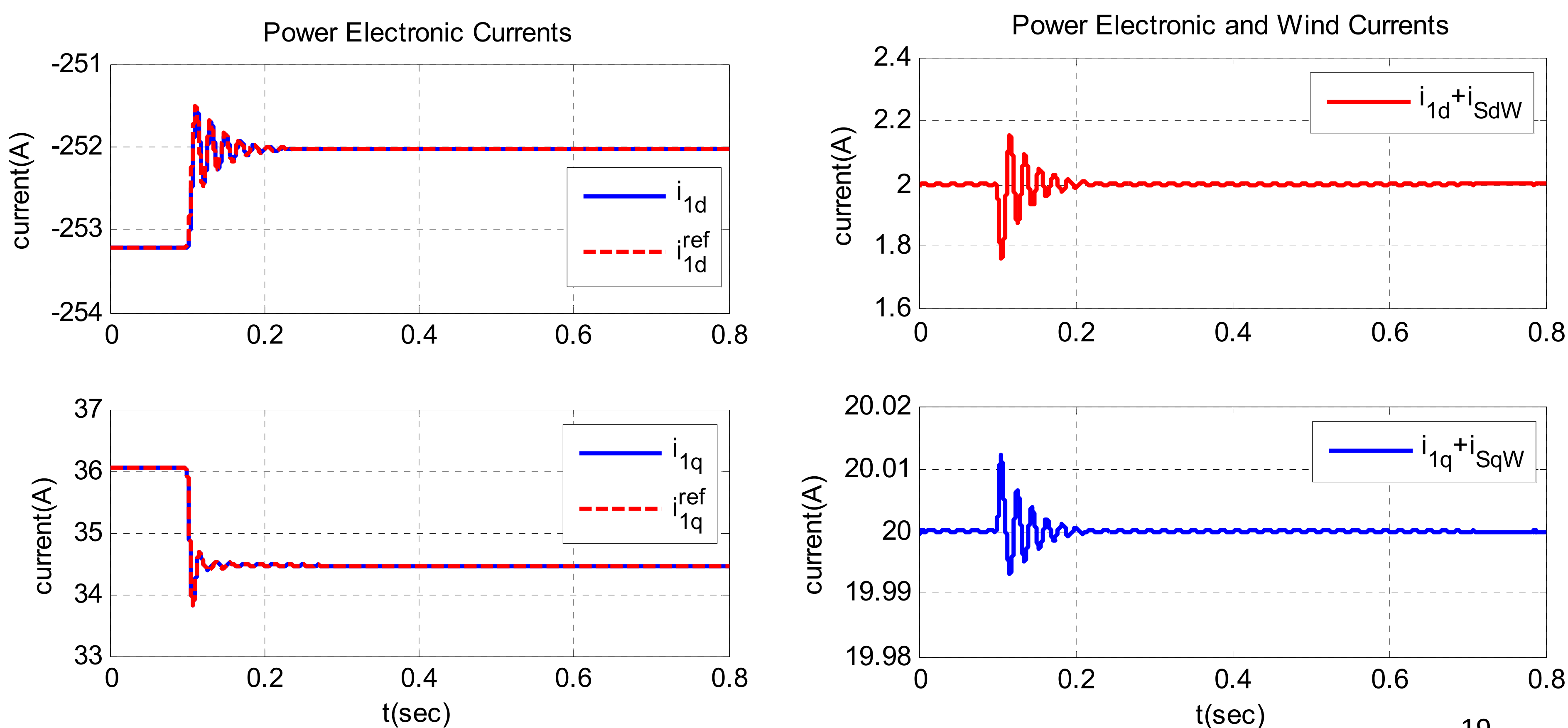
Simulation Results: Power Electronics

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



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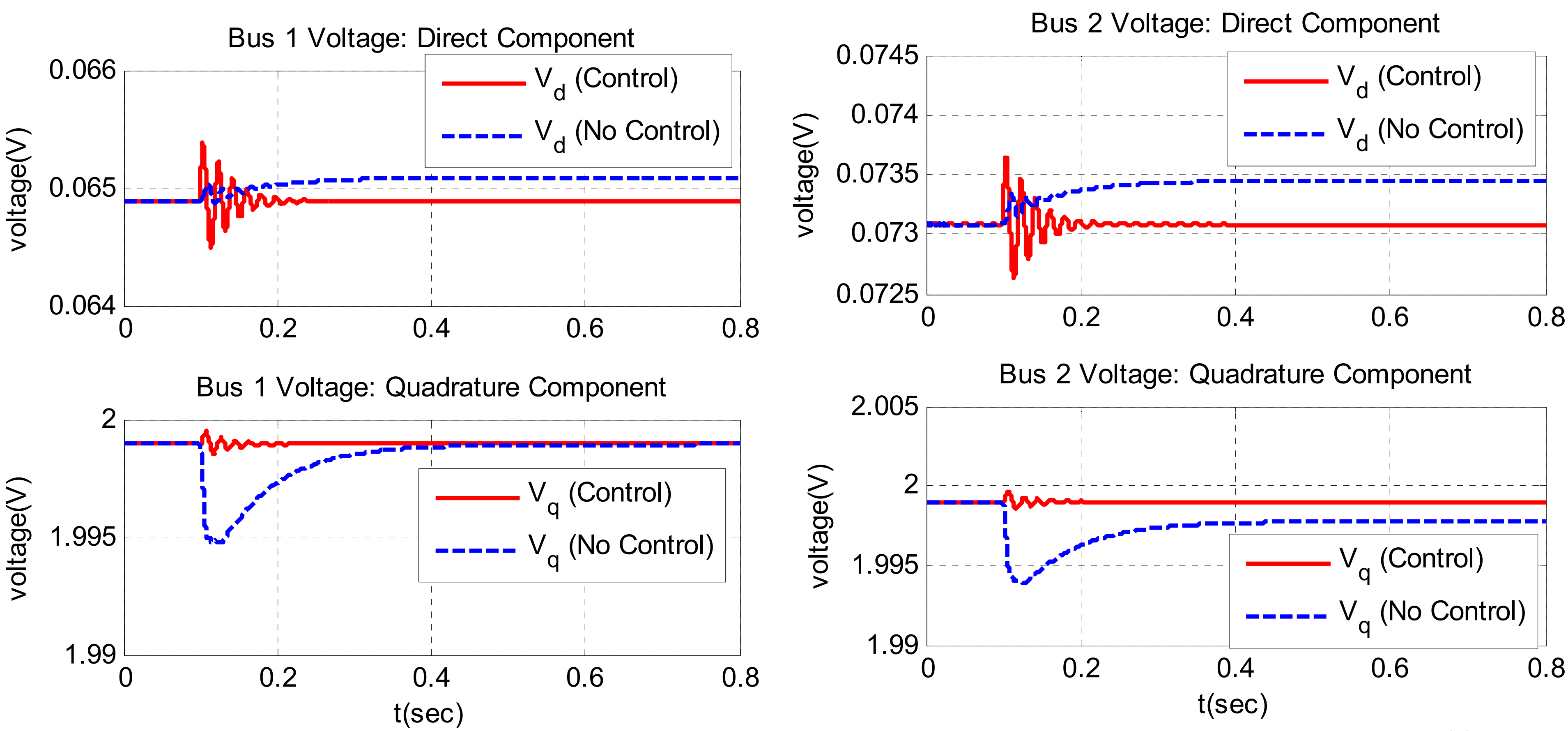
Simulation Results: Rest of System

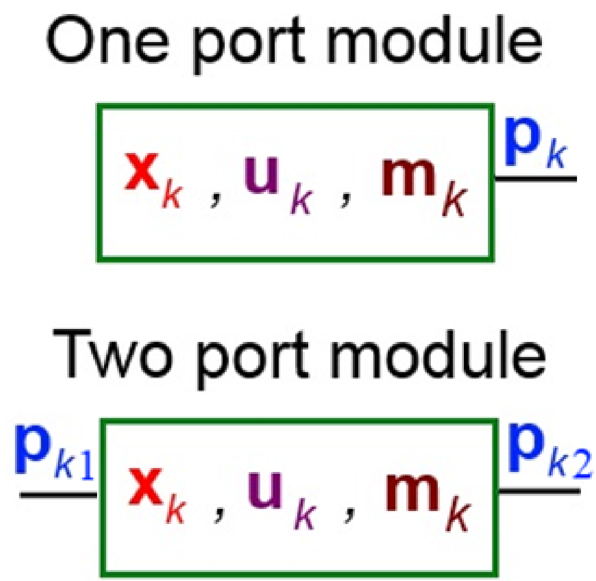
- With the control, the effect on the rest of the system is very minimal and lasts only a short time



SGRS: Modular Modeling of Open-Loop Dynamics

- For the Smart Grid in a Room Simulator, a modular object-oriented approach is used for modeling power system dynamics
  - lends itself to distributed computing
  - scalable for large systems
- Open-loop dynamics of each object depend on
  - State variables $\mathbf{x}_k$
  - Controllable inputs $\mathbf{u}_k$
  - Exogenous inputs $\mathbf{m}_k$
  - Port inputs $\mathbf{p}_k$

$$\dot{\mathbf{x}}_k = \mathbf{f}_k\left(x_k, p_k, u_k, m_k\right)$$



Source: K. D. Bachovchin, M. D. Ilić, "Automated and Distributed Modular Modeling of Large-Scale Power System Dynamics," EESG Working Paper No. R-WP-8-2014, October 2014

SGRS: Modular Modeling of Closed-Loop Dynamics

- Controllable inputs depend on
  - State variables $\mathbf{x}_k$
  - Outputs of connecting modules $\mathbf{y}_{ck1}$
  - Internal set points $\mathbf{y}_k^{ref}$

$$\mathbf{u}_k = \mathbf{g}_k\left(x_k, y_{ck1}, y_k^{ref}\right)$$

- Internal set points depend on
  - Outputs of connecting modules $\mathbf{y}_{ck2}$
  - Set points from market $\boldsymbol{r}^{ref}$

$$\mathbf{y}_k^{ref} = \mathbf{h}_k\left(y_{ck2}, r^{ref}\right)$$

$$\downarrow$$

$$\mathbf{u}_k = \mathbf{G}_k\left(x_k, y_{ck}, r^{ref}\right)$$

$$\mathbf{y}_{ck} = \left[\mathbf{y}_{ck1} \;\; \mathbf{y}_{ck2}\right]^T$$

Variable Speed Drive Controller:

$$\mathbf{u}_k = \left[u_{1d} \;\; u_{1q} \;\; u_{2d} \;\; u_{2q}\right]^T$$

$$\mathbf{x}_k = \left[i_{1d} \;\; i_{1q} \;\; q_{C1} \;\; i_{S2d} \;\; i_{S2q} \;\; i_{R2} \;\; \omega \;\; \theta\right]^T$$

$$\mathbf{y}_{ck1} = \left[v_d \;\; v_q\right]^T$$

$$\mathbf{y}_k^{ref} = \left[\omega_2^{ref} \;\; i_{1d}^{ref} \;\; i_{1q}^{ref}\right]^T$$

$$\mathbf{y}_{ck2} = \left[i_{Wd} \;\; i_{Wq}\right]^T$$

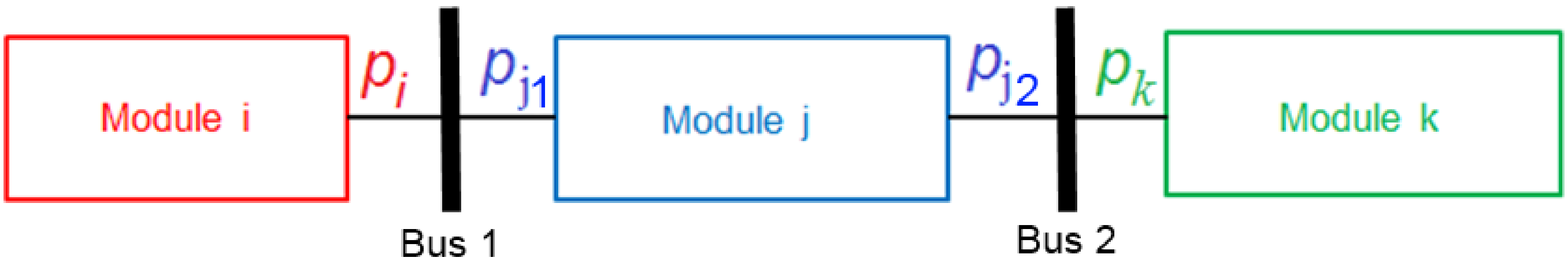
$$\mathbf{r}^{ref} = \left[i_{Totd}^{ref} \;\; i_{Totq}^{ref}\right]^T$$

Explicit Equations

$$\begin{cases} i_{1d}^{ref} = i_{Totd}^{ref} - \sum i_{Wd} \\ i_{1q}^{ref} = i_{Totq}^{ref} - \sum i_{Wq} \end{cases}$$

SGRS: Modeling of Interconnected Power System

- Dynamics of the interconnected power system can be symbolically solved for in a distributed manner



$$\dot{\mathbf{x}}_i = \mathbf{f}_i(x_i, p_i, u_i, m_i) \qquad \dot{\mathbf{x}}_j = \mathbf{f}_j(x_j, p_{j1}, p_{j2}, u_j, m_j) \qquad \dot{\mathbf{x}}_k = \mathbf{f}_k(x_k, p_k, u_k, m_k)$$

Bus 1 solves for

$$p_i = g_1(y_j),\ p_{j1} = g_2(y_i)$$

Bus 2 solves for

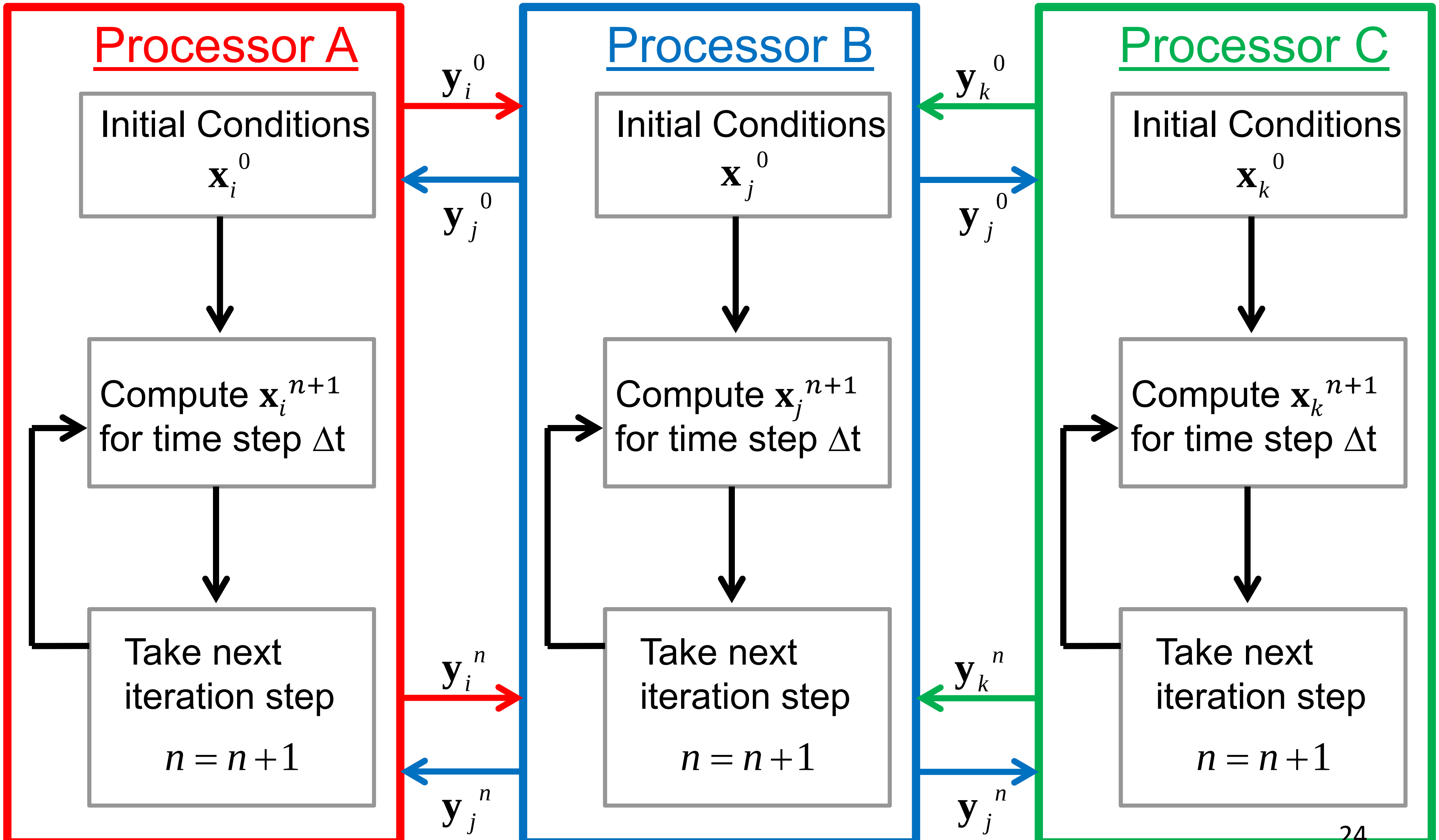
$$p_k = h_1(y_j),\ p_{j2} = h_2(y_k)$$

- Dynamics of each module depend only on its own state variables and the outputs of connecting modules

$$\dot{\mathbf{x}}_k = \mathbf{F}_k(x_k, y_{ck}, u_k, m_k)$$

Source: K. D. Bachovchin, M. D. Ilić, "Automated and Distributed Modular Modeling of Large-Scale Power System Dynamics," EESG Working Paper No. R-WP-8-2014, October 2014

SGRS: Communication Structure for Distributed Simulation of Dynamics and Control



Conclusions

- Designed a novel variable speed drive for flywheels using three time-scale separations and passivity-based control logic
- Demonstrated the effectiveness of this controller in the SGRS for transiently stabilizing an interconnected power system against a wind generator disturbance

Future Work

- Larger power systems with multiple wind generator disturbances and multiple flywheels
- More general flywheel control logic for systems where the source of the disturbance is not known