Toward standards for dynamics in future electric energy systems—

The basis for plug-and-play industry paradigm

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Outline

- Overview of current NERC standards and evolving standards for wind and solar plants
- Issues with current standards
- Our proposal :
  - Plug-and-play (TCP/IP) like protocols/standards
  - Introduction of intelligent Balancing Authority (iBAs)
- Examples of iBAs
- Theoretical foundations for new standards (TCP/IP like)
- Proof-of-concept examples of controller designs which meet such protocols

NERC standards Transmission Planning Standards

- System simulations and associated assessments are needed periodically to ensure that reliable systems are developed that meet specified performance (http://www.nerc.com)

Category	Contingencies	System Stable and both Thermal and Voltage Limits within Applicable Rating	Loss of Demand
A	No contingency	Yes	No
B	Event resulting in the loss of a single element.	Yes	No
C	Event(s) resulting in the loss of two or more (multiple) elements.	Yes	Planned/ Controlled
D	Extreme event resulting in two or more (multiple) elements removed or Cascading out of service.	Evaluate for risks and Consequences. - May involve substantial loss of customer Demand and generation in a widespread area or areas. - Portions or all of the interconnected systems may or may not achieve a new, stable operating point. -Evaluation of these events may require joint studies with neighboring systems.	

Evolving standards for Wind and Solar Generation Technologies

- voltage/var control/regulation
- voltage ride-through
- power curtailment and ramping
- primary frequency regulation
- inertial response

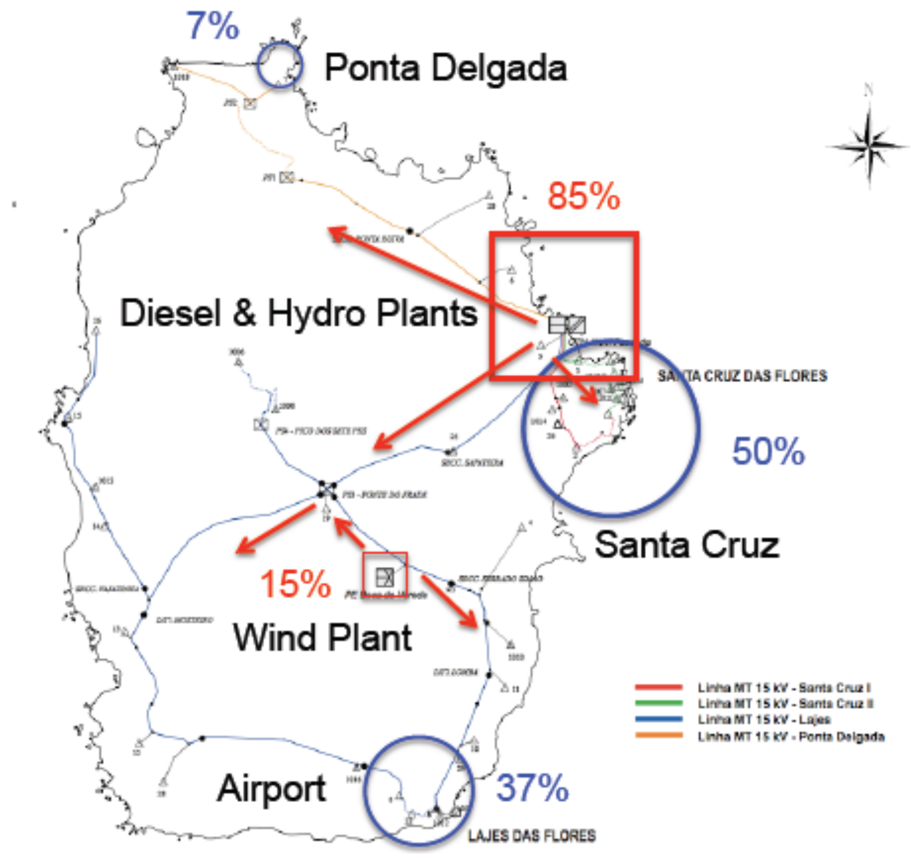
http://www.nerc.com/files/2012_IVGTF_Task_1-3.pdf

NERC 2012 Special Assessment: Interconnection Requirements for Variable Generation September 2012

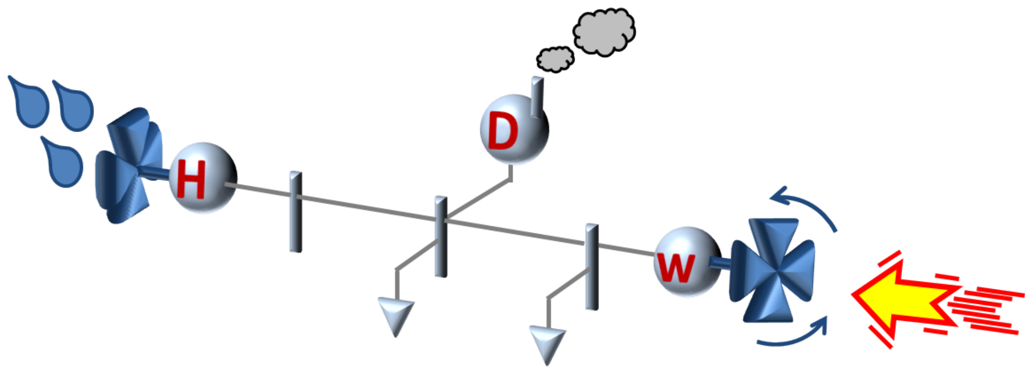
Need for a new paradigm

- Today’s industry approach– the worst case approach, inefficient and does not rely on on-line automation and regulation other than energy feed-forward economic dispatch
- Emphasis on large-scale time-domain system simulations for transient stability, voltage, collapse, power flow feasibility, etc
- Primary control is constant gain tuned assuming no dynamic interactions with the rest of the system
- Existing and emerging system-level unacceptable interactions; no incentives for ``smarts” of modules

From old to new paradigm—Flores Island Power System, Portugal [11]



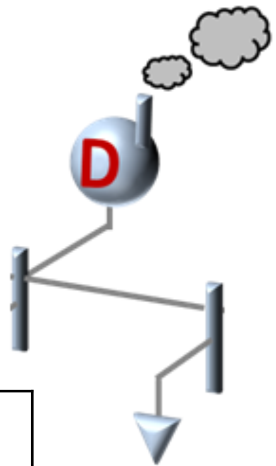
Controllable components—today's operations (very little dynamic control, sensing)



H – Hydro
D – Diesel
W – Wind

*Sketch by Milos Cvetkovic

Two Bus Equivalent of the Flores Island Power System



State	Equilibrium
$e'_q[pu]$	0.9797
$\delta[rad]$	0.0173
$\omega[pu]$	1
$v_r[pu]$	0.8527
$e_{fd}[pu]$	0.7482
$v_f[pu]$	0
$P_m[pu]$	0.01
$a[pu]$	0

Generator	Diesel
$x_d[pu]$	8.15
$x_q[pu]$	8.15
$x'_d[pu]$	0.5917
$x'_q[pu]$	0.5917
$T'_{q0}[s]$	2.35
$T'_{d0}[s]$	2.35
$J[s]$	2.26
$D[pu]$	0.005

Transmission line	From Diesel to Load bus
$R[pu]$	0.3071
$L[pu]$	0.1695

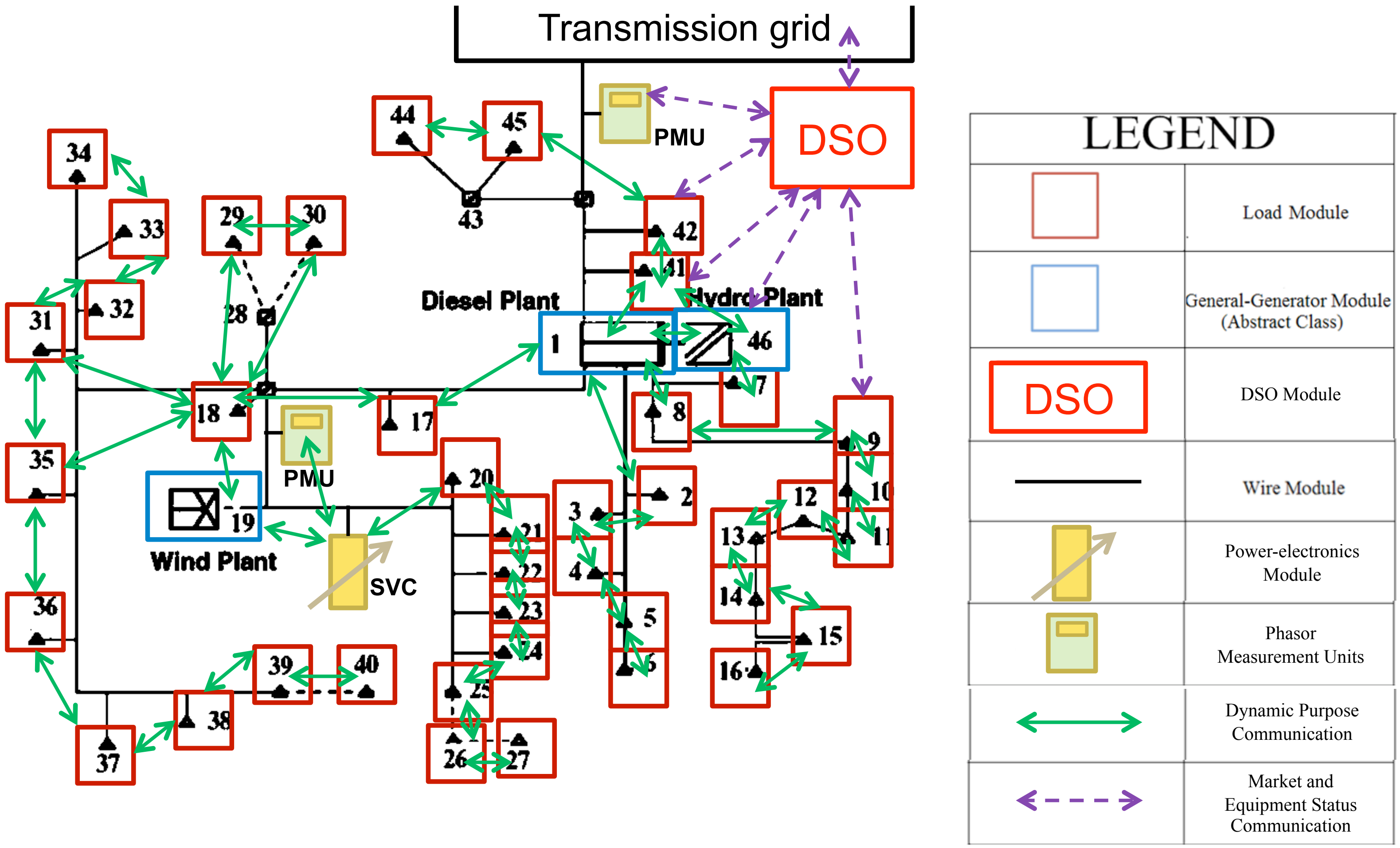
Base values
$S_b = 10MVA$
$V_b = 15KV$

AVR	Diesel
$K_A[pu]$	400
$T_A[s]$	0.02
$K_E[pu]$	1.3
$T_E[s]$	1
$S_E[pu]$	0.1667
$K_F[pu]$	0.03
$T_F[s]$	1

Governor	Diesel
$k_t[pu]$	40
$T_g[s]$	0.6
$r[pu]$	1/0.03
$T_t[s]$	0.2

Base values $S_b = 10MVA, V_b = 0.4KV$

Information exchange in the case of Flores---new (lots of dynamic control and sensing)



Possible dynamical problems seen by particular dynamic components

	Dynamical problems							
		Small signal instab.	Transient instab.	SSR	SSCI	Freq. instab.	Volt. Instab.	Power flow imbalance
Types of Component	Synchronous generators	?	?	?	?	?	?	?
	Wind generators	?	?	?	?	?	?	?
	Solar plants	?	?	?	?	?	?	?
	FACTS	?	?	?	?	?	?	?
	Storage	?	?	?	?	?	?	?

Table 1.

Our proposal: TCP/IP like standards

- Given **specified disturbances and range of operating conditions within a known system**:

    - specified with e.g voltage, power
    - similar to LVRT curves for wind turbines
    - with specified duration

- **All components** (synchronous gens, wind gens) **should guarantee** that they would not create any of the problems in Table 1. (Clear objectives goals for components, assigned responsibility for system reliability)

- Two key **questions**: Q1-- Why does it matter?

  Q2)--- Can this be technically done?

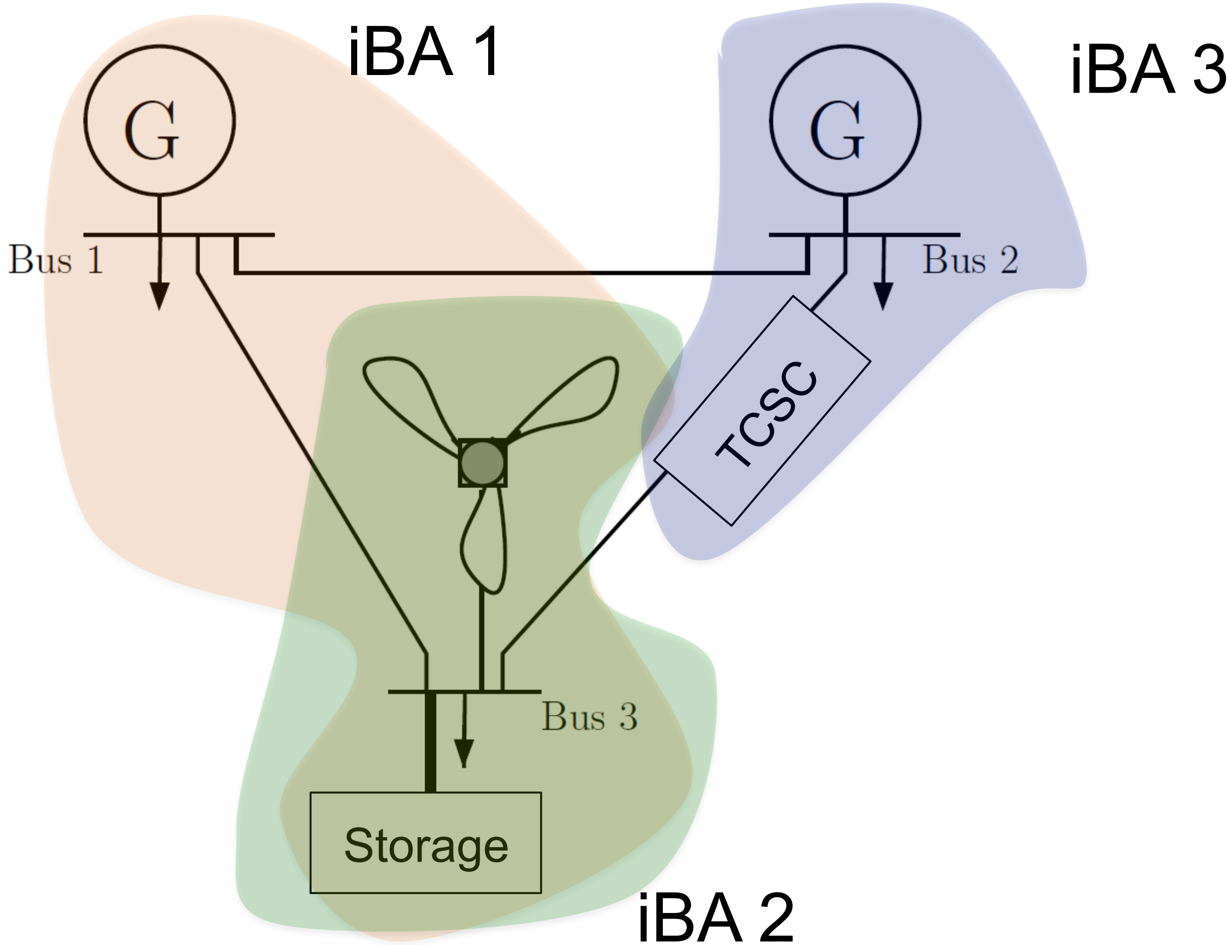
  Not one way to achieve these!

Not one way to meet the standards -iBAs

- **iBAs (intelligent Balancing Authorities)**
  - **Single component** or **group of components** which meet the desired objectives: Given **specified disturbances** their components do not cause any of the dynamical problems in Table 1.
  - **Dynamic notion** of Control Areas—intelligent Balancing Authorities (iBAs)
- iBAs **would utilize advanced control design** methods to meet the protocol; could be either decentralized or wide area control (cooperative control to save on number of controllers and energy used within the iBA)
  - Huge potential for **exploiting efficiently new technologies** like **storage** and **FACTS** and at the same time have guaranteed system performance

S.Baros, M.Ilic intelligent Balancing Authorities (iBAs) for Transient Stabilization of Large Power Systems IEEE PES General Meeting 2014

A1: Examples of iBAs—it matters for ensuring both reliable and efficient operations [13]

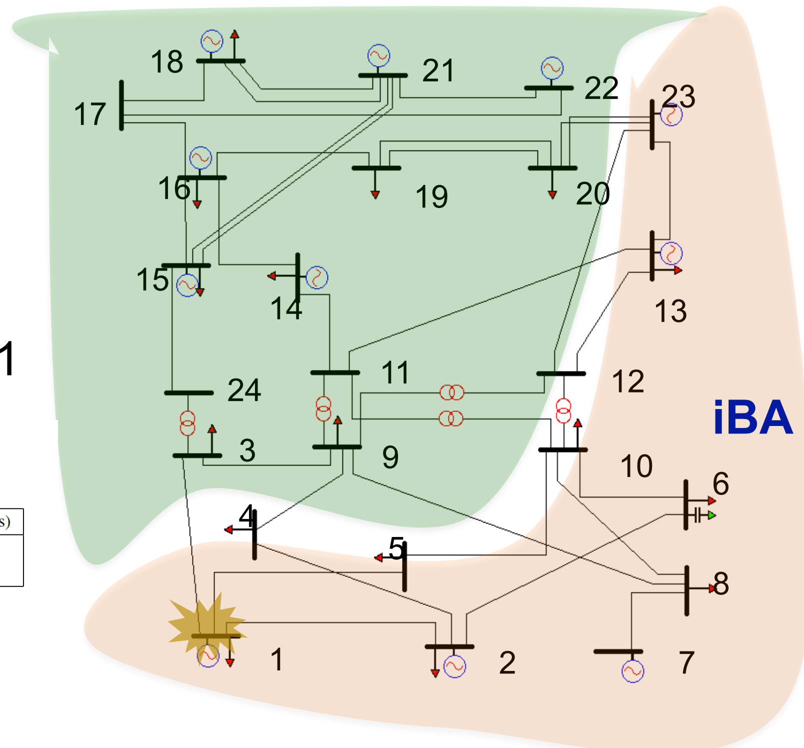


Possible to create iBAs for meeting transient stability distributed standard

Given disturbance
Tripping of generator 1

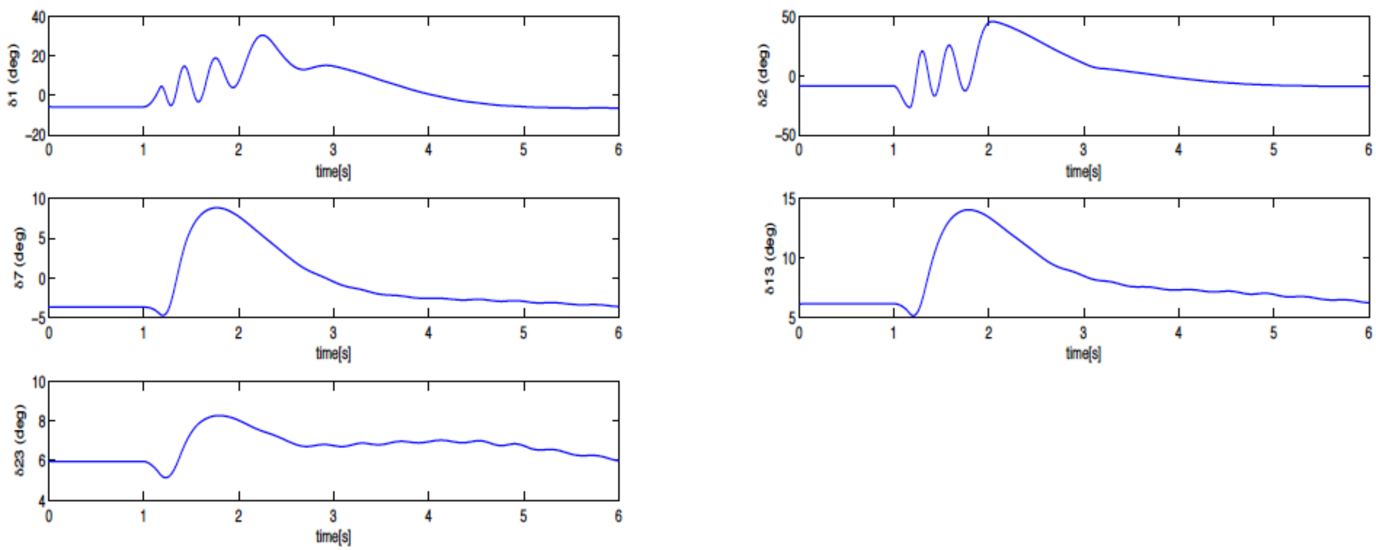
TABLE I
CONTINGENCY CONSIDERED ON THE IEEE RTS 24 BUS SYSTEM

CONTINGENCY (CATEGORY B)	DURATION (secs)
Tripping of generator 1 after 3-phase fault on its terminal bus	0.17



S.Baros, M.Ilic intelligent Balancing Authorities (iBAs) for Transient Stabilization of Large Power Systems IEEE PES General Meeting 2014

Rotor angle response of iBA generators



(b) Transient stabilization of critical generators i=1,2,7,13,23 with iBA-based control in low-load scenario

Q2: Can we have a unifying theoretically sound approach to TCP/IP like standards for smart grids? [12]

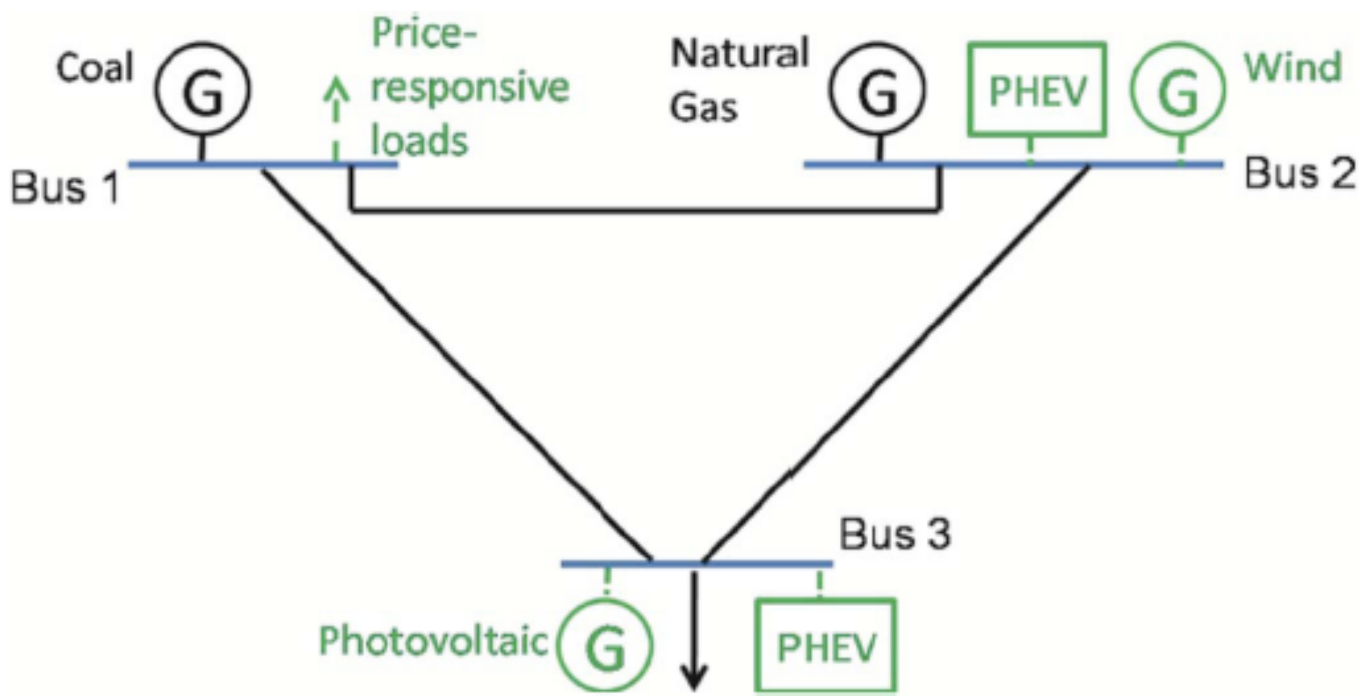


Fig. 5. Small example of the future electric energy system.

Basic functionalities

- Simple transparent TCP/IP like functionalities
- Transparency based on a unifying modular modeling of network system dynamics
- Provable performance-difficult
- Proposal—use interaction variables to specify family of standards sufficient to avoid operating problems
  - Measure of how well modules balance themselves in steady state
  - Measure of rate of exchange of stored energy between a module and the rest of the system over different time horizons

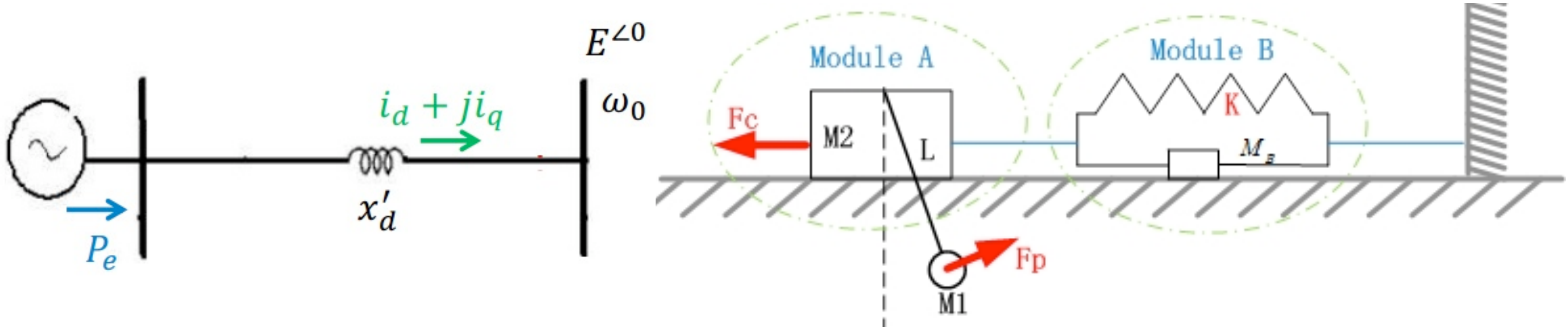
Unifying modeling and control approach—
use of multi-scale interaction variables

- Standards/protocols --- specifications of module interactions for plug-and-play operations; architectures define how are sets of protocols organized
- Cyber design for managing multi-layered interactions
- New physics-based modeling and control as the basis for interaction variables-based protocols
- Illustrations of possible standards-based enhancements (transient stabilization using power electronics switching; storage control in micro-grids)

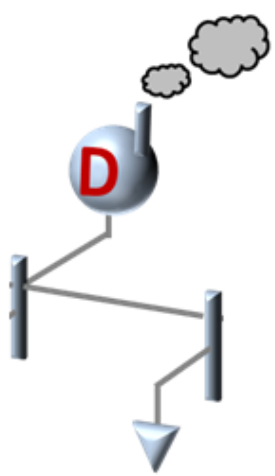
New physics-based modeling and control using interaction variables [12]

- Mechanical system representation of electric power grids
- Physics-based state transformation for multi-layered dynamics
- Defining interaction variables over different time horizons (to capture bounds on change in stored energy over T and on the rate of change of stored energy)
- Multi-layered specifications for interaction variable-based standards

Two-module power system in Flores



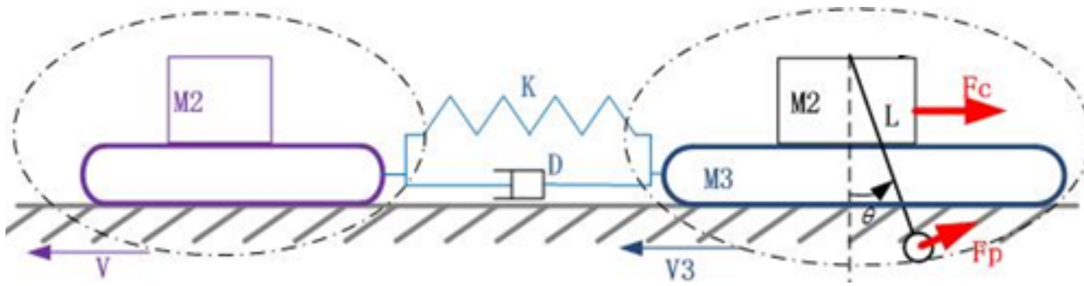
❖Module A—power plant with its governor and excitation control
❖Module B—transmission line controlled by FACTS



Interconnected power system and its mechanical representation

Induction Machine-

Conventional generator



- Each mechanical sub-system is analogous to a generator within interconnected power system (with Xia Miao)
- Spring and damper between pendulum-mass systems the same as transmission line in interconnected power system;
- Only conveyor components of mechanical systems are connected and placed on the same reference (ground);
- If speed of each pendulum-mass systems are not same, interactions will happen.

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Analogy Table

- Component level

Mechanical Quantity	Power System Analogue
Force, F_p	Mechanical Power Input, P_m
Velocity, V	Current, I
Force, F_C	Exciter input, E_{fd}
Force between M_2 & M_3, F_{32}	Back EMF

- System level

Mechanical Quantity	Power System Analogue
Velocity, V_3	Terminal Voltage, V
Interaction Force, F_s	Current, I

Very intriguing questions

- Can this system synchronize around inverted pendulum position? Is this acceptable? What should be a standard/protocol for plug-and-play?
- Which controller works? Why?
- Answers depend on the actual operating conditions (close to the stable or unstable equilibrium); on control laws applied to Fp and/or Fc; if the equilibrium is not known (stabilization) energy-based controller will work, while constant gain controller will not. It will also depend on the load model used. The control effort and quality of response vary .
- Not all ``smarts" are the same in smart grids!

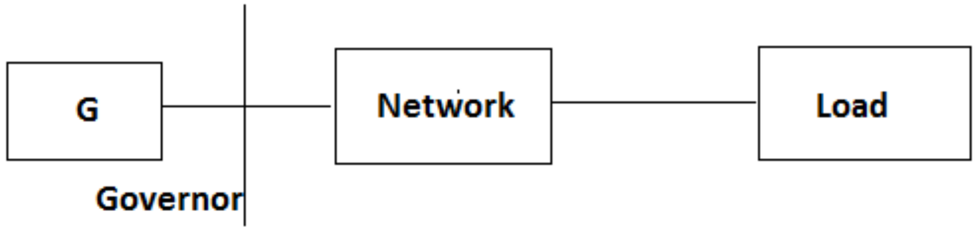
Three different architectures of interest

- Bulk power system can be represented as an infinite bus (ideal voltage source)

- Flores Island (micro-grid)– diesel power plant has dynamics—hydro and wind negative constant power load

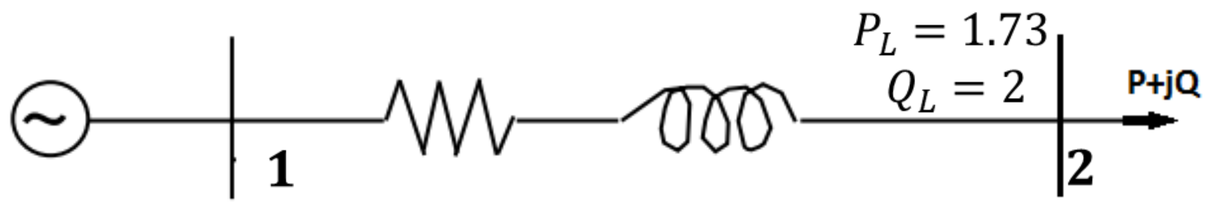
- Flores Island (micro-grid)-diesel power plant dynamics and the load is constant impedance

Governor of AC Generator



- Governor is the main synchronizing controller.
- In mechanical representation, Fp responds to the deviations of speed from synchronous speed.
- Does not synchronize around inverted pendulum position.
- It does synchronize when Fp also responds to x3-xB (phase lock loop).

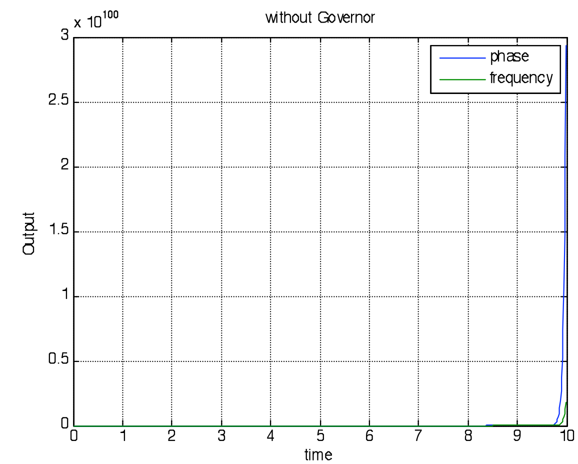
Constant power load model



Microgrid

- ***Unstable Equilibrium Set***

$$\begin{cases} V_2^{(2)} = 2.7419 \\ \theta_2^{(2)} = -149.348 \end{cases}$$



***Unstable** equilibrium*

- ***System Matrix***

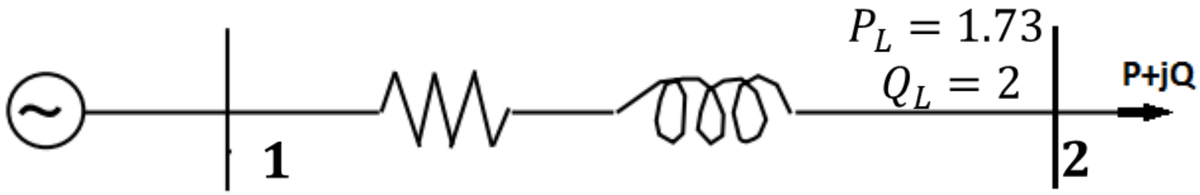
$$A_{open} = \begin{bmatrix} 0 & 377 \\ 1.398 & -0.0221 \end{bmatrix} \qquad \begin{cases} \lambda_1 = 22.9569 \\ \lambda_2 = -22.9569 \end{cases}$$

- ***Participation Factor***

$$P = \begin{bmatrix} 0.5 & 0.4998 \\ 0.4998 & 0.5 \end{bmatrix}$$

- θ and ω contribute same to the unstable eigenvalue which means governor should take care of θ as well as ω (PI control)

Synchronized system to constant power load



- ***Governor Design***

$$Governor: K_d(\omega - \omega^*) + K_i(\theta - \theta^*)$$

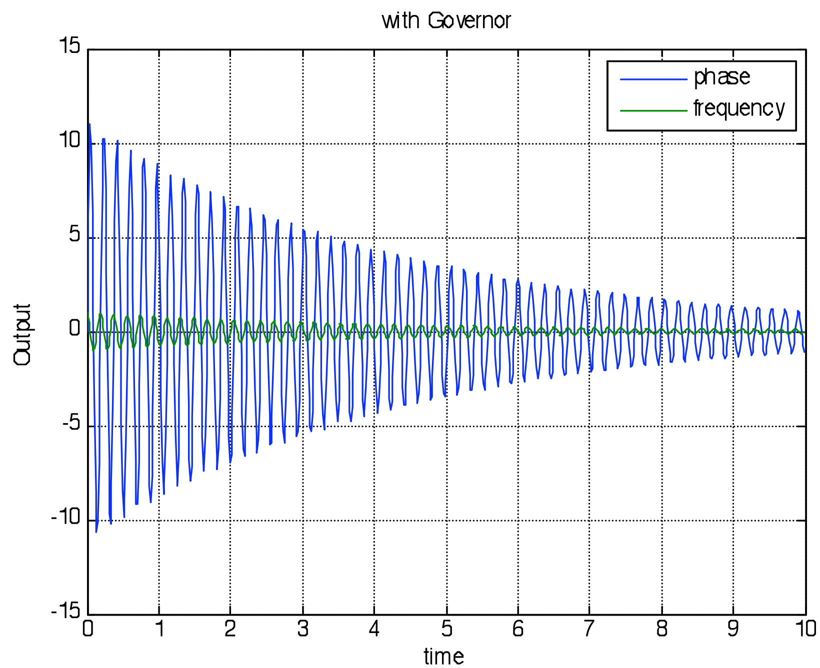
- ***System Matrix***

$$A_{closed} = \begin{bmatrix} 0 & 377 \\ -3.03 & -0.46 \end{bmatrix}$$

$$\begin{cases} \lambda_1 = -0.23 + 33.779i \\ \lambda_2 = -0.23 - 33.779i \end{cases}$$

- ***System response***

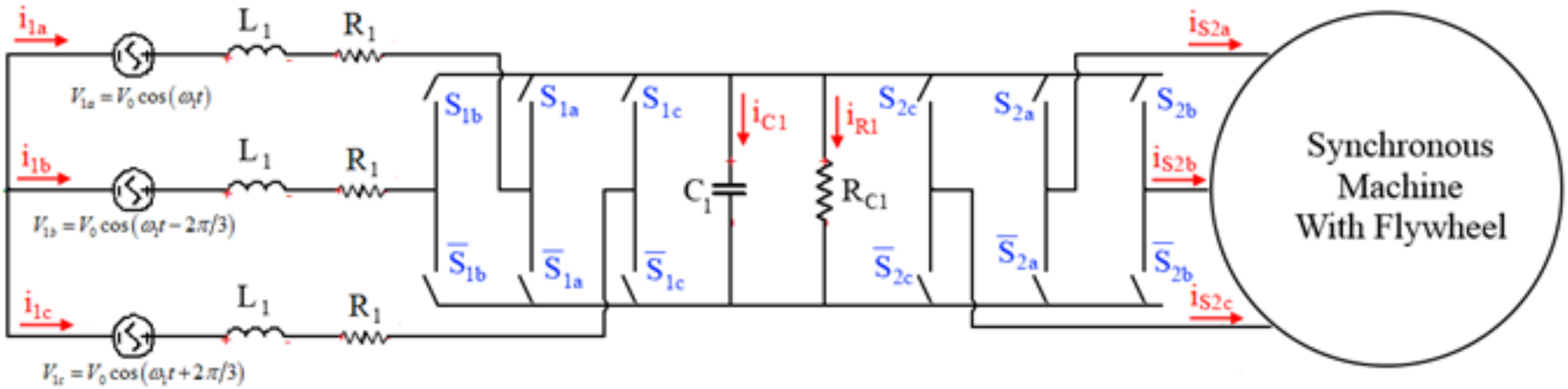
Stable



Second control –fast Fc

- Exciter in power plant
- Fc responds to acceleration of rotating pendulum
- Mechanical analogy—control acceleration of the pendulum pivot
- Internal interactions non-unique—can control with Fp, Fc or a combination (competitive at the module A level)
- Module B could also control stiffness of the spring ***FACTS is controllable inerter** to help stabilize module A (cooperative control)

Gets complicated fast—
Variable Speed Drives for Flywheels

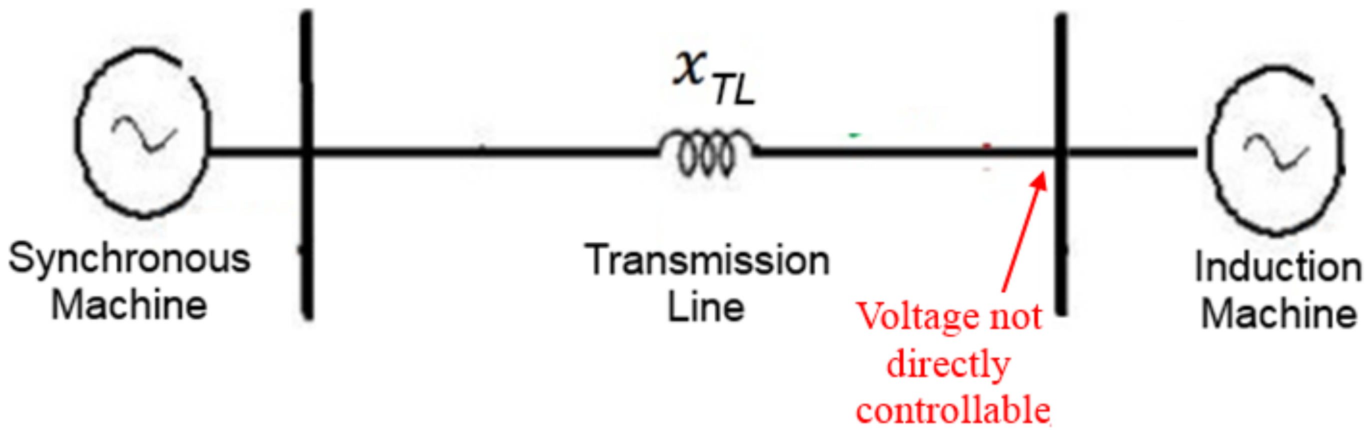


- Stator voltages of synchronous machine with flywheel are NOT assumed to be directly controllable
- The only controllable inputs are the switch positions of the power electronics
- Use AC/DC/AC converter to regulate the speed of the flywheel to a different frequency than the grid frequency

Source: K. D. Bachovchin, M. D. Ilić, "Passivity-Based Control Using Three Time-Scale Separations of Variable Speed Drives for Flywheel Energy Storage Systems," EESG Working Paper No. R-WP-6-2014, October 2014.

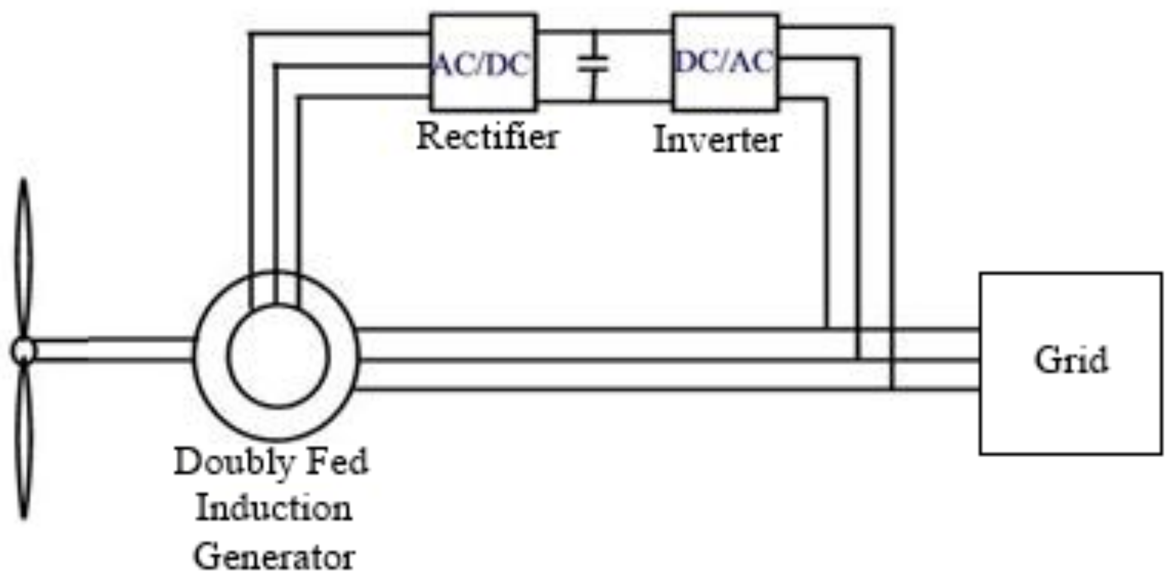
Standalone vs. Interconnected Variable Speed Drives

- For standalone variable speed drives, the voltage of the stator windings is directly controllable
- For interconnected systems, the voltage of the stator windings is not directly controllable and depends on the dynamics of the rest of the system
  - Need power electronics (AC/DC/AC converter) in order to control the stator voltages

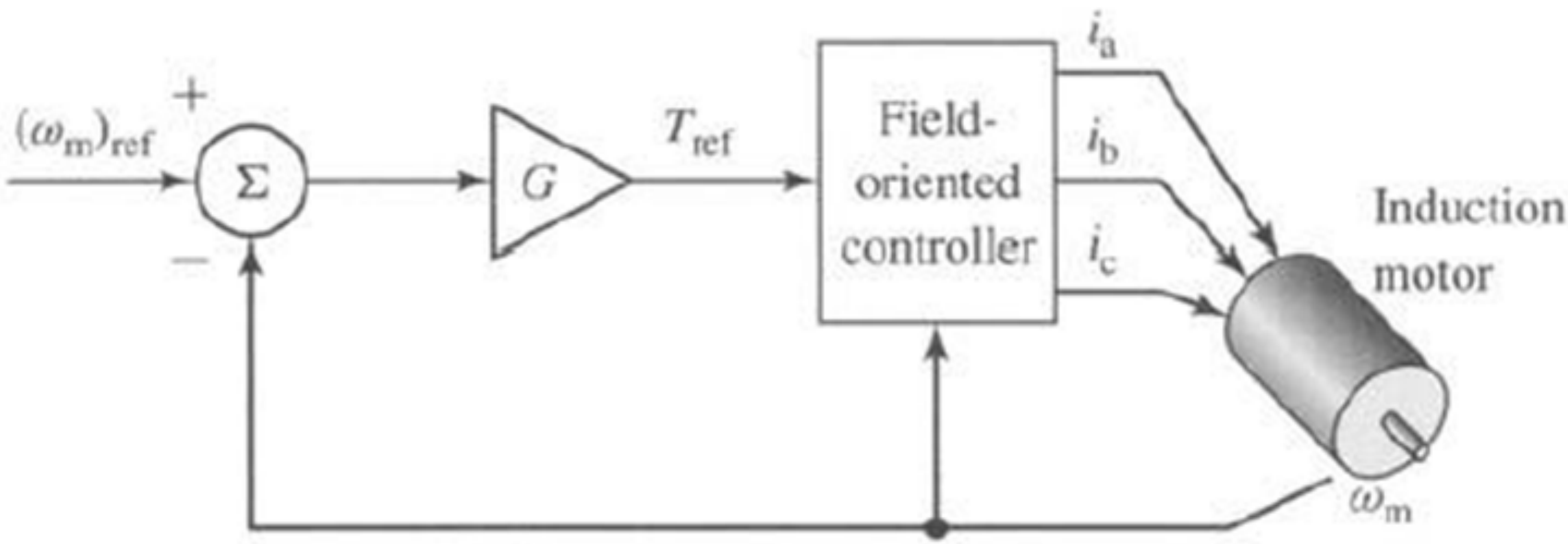


Doubly-fed induction machines (DFIG)—wind power plant

- AC/DC/AC converter interfacing between the stator windings and the rotor windings of the DFIM
- The rotor voltage is controlled through switches in the AC/DC/AC converters



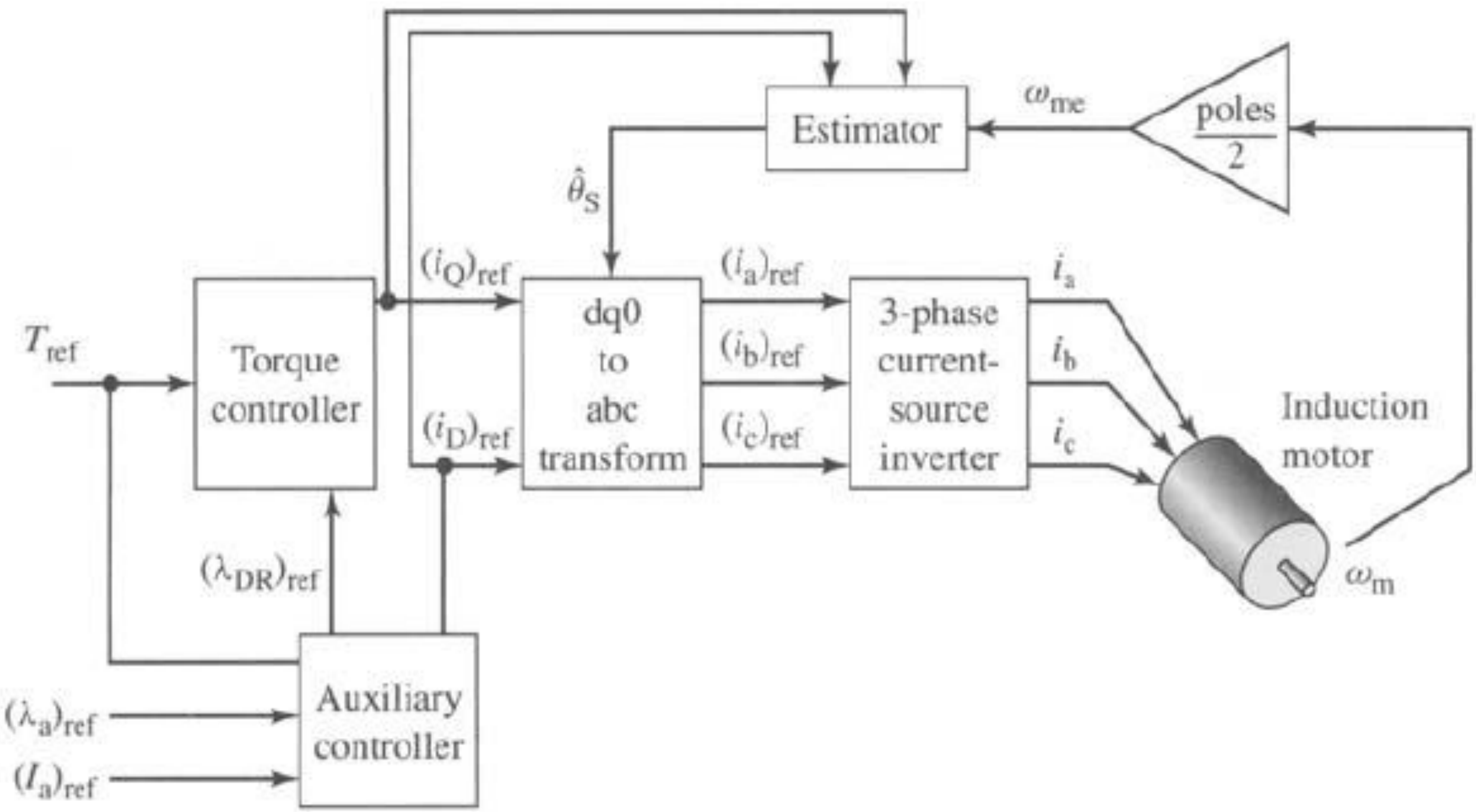
Field Oriented Control for Variable Speed Drives



- Outer (proportional) controller regulates the speed of the induction machine
- Inner (field oriented) controller regulates the torque to the set point given by outer controller

Source: A. Fitzgerald, C. Kingsley Jr., and S. Umans, *Electric Machinery*. Piscataway, NJ: McGraw-Hill, 2003.

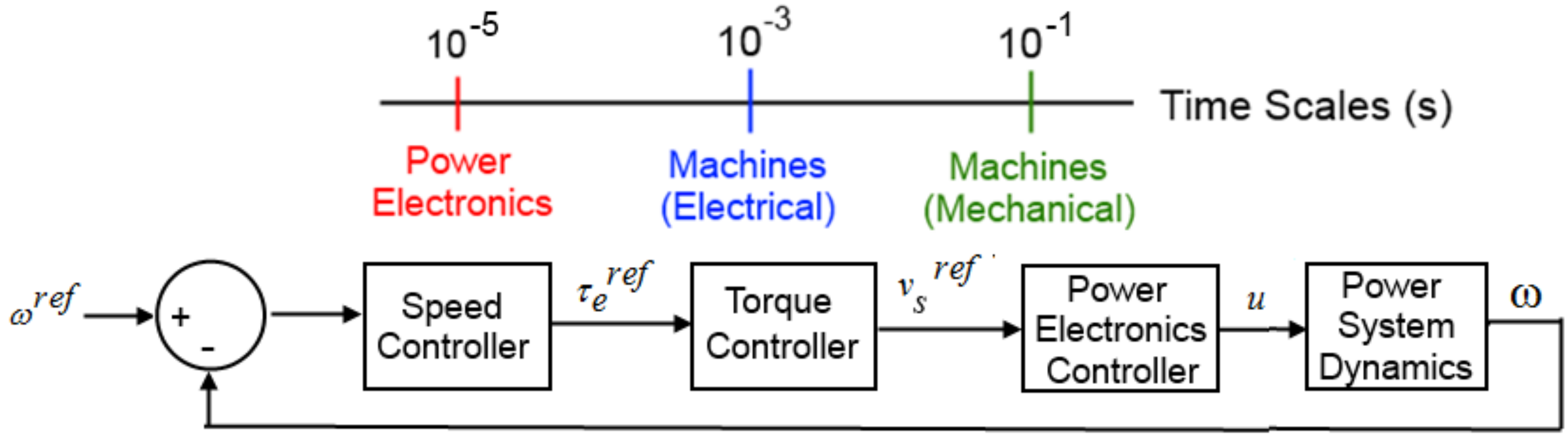
Field Oriented Controller Block Diagram



Source: A. Fitzgerald, C. Kingsley Jr., and S. Umans, *Electric Machinery*. Piscataway, NJ: McGraw-Hill, 2003.

Controller Implementation--detailed

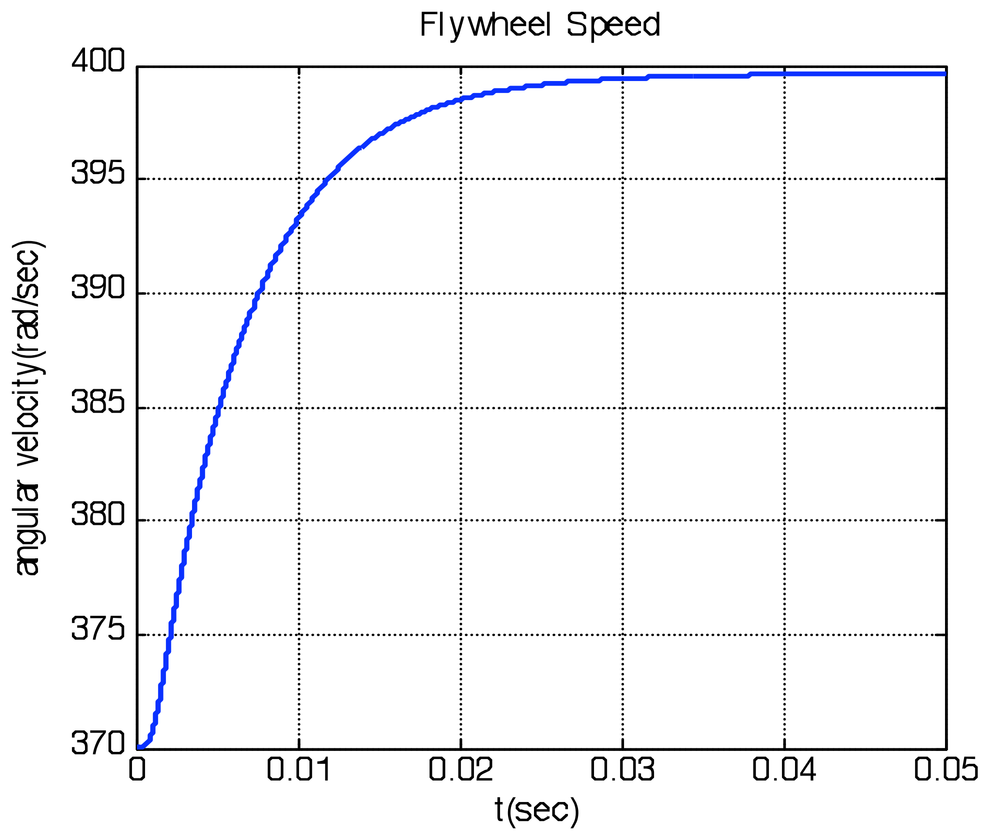
❖ Can use time-scale separation to simplify the control design

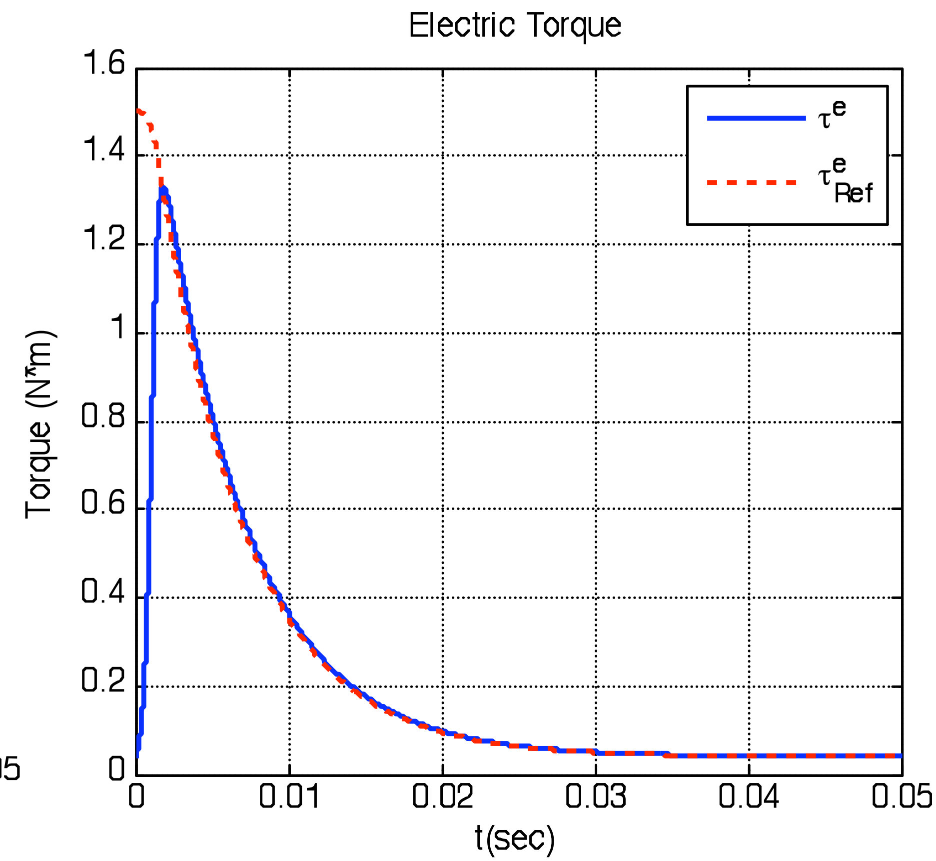


- Speed controller uses dynamic model at the mechanical machine (slowest) time-scale
- Torque controller uses dynamic model at the electrical machine time-scale
- Power electronics controller uses dynamic model at the power electronics (fastest) time-scale

Source: K. D. Bachovchin, M. D. Ilić, "Passivity-Based Control Using Three Time-Scale Separations of Variable Speed Drives for Flywheel Energy Storage Systems," EESG Working Paper No. R-WP-6-2014, October 2014.

Control design—can be done





- Can control speed of the flywheel to set point $\omega_2 = 400\ rad/sec$
- The actual electric torque converges very quickly to the reference electric torque

Source: K. D. Bachovchin, M. D. Ilić, "Passivity-Based Control Using Three Time-Scale Separations of Variable Speed Drives for Flywheel Energy Storage Systems," EESG Working Paper No. R-WP-6-2014, October 2014.

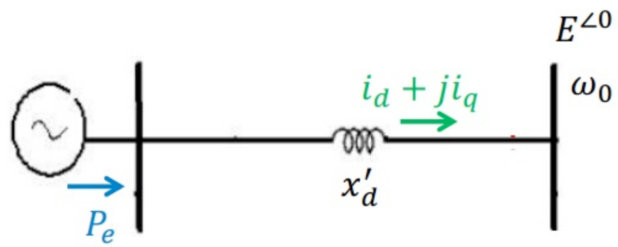
Must simplify!

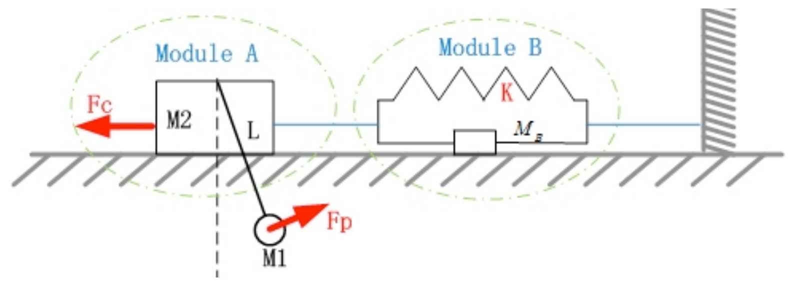
- Utilities are having hard time adding all these new components and their smarts for simulating system-wide dynamics
- Is there a ``smarter" way to model and define modular functionalities so that the interconnected system meets system-level performance (Table 1)?
- 80% of each solution is modeling (Petar Kokotovic, Chalenges in Control Theory, Santa Clara, circa 1982)

From acceleration to stored energy

- Basis for Furuta stabilization of pendulum around the inverted equilibrium; actuator dynamics neglected, acceleration control Fc. No Fp. Requires lots of effort
- A better approach: Energy approach Astrom, Furuta
- For power systems this would mean: Avoiding blackout by changing the logic of Fc when close to voltage ``collapse”

Dynamics of interconnected system in new state space





- Standard state space of interconnected system

$$\dot{\bar{\bar{X}}}_A = f_A\left(\bar{\bar{X}}_A, Z_A, P_A, u_A\right)$$

$$\dot{Z}_A = f_{ZA}\left(\bar{\bar{X}}_A, Z_A, P_B\right)$$

Dynamics of Interaction variables

$$\dot{P}_A = f_{PA}\left(\bar{\bar{X}}_A, P_A, \dot{P}_B\right)$$

$$\dot{Z}_B = f_{ZB}\left(Z_B, P_A, u_B\right)$$

$$\dot{P}_B = f_{PB}\left(P_B, \dot{P}_A\right)$$

Interaction variable-based two-layer model

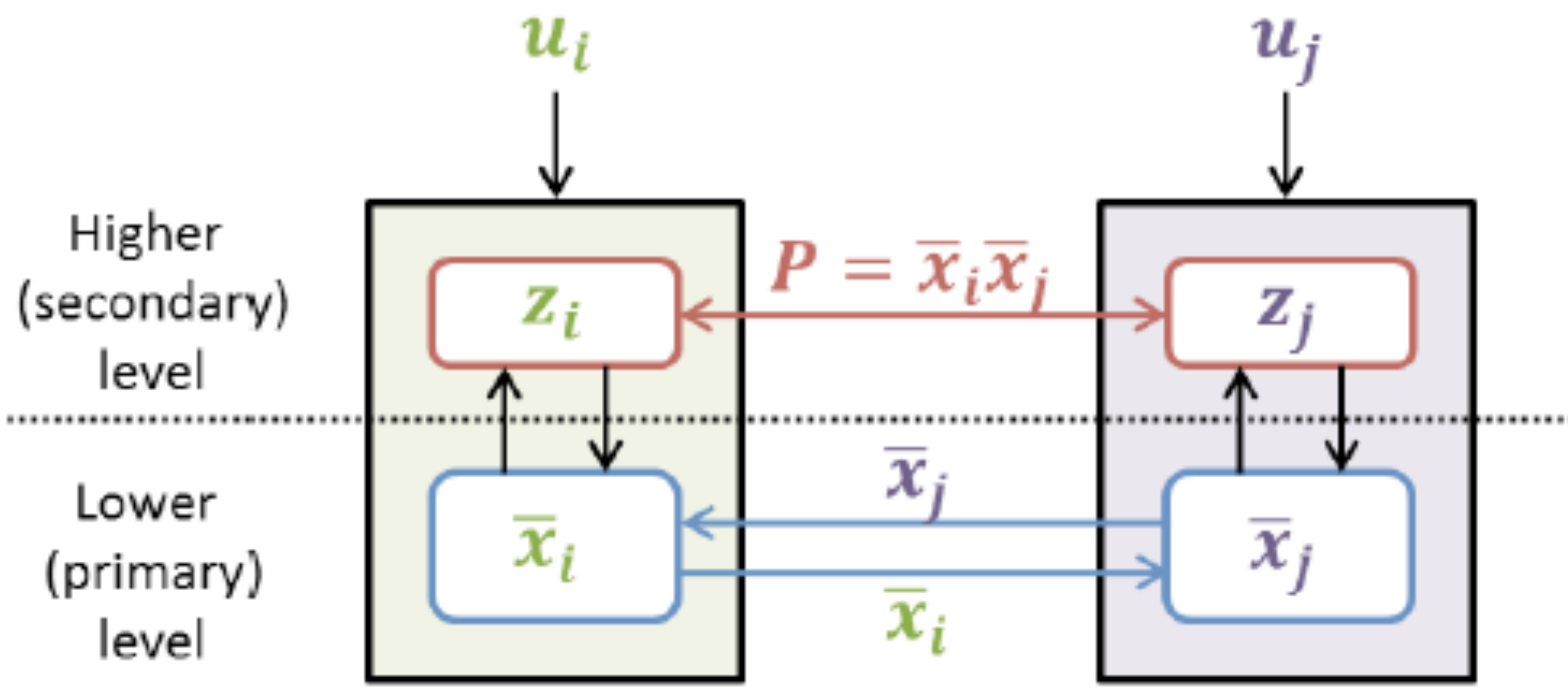
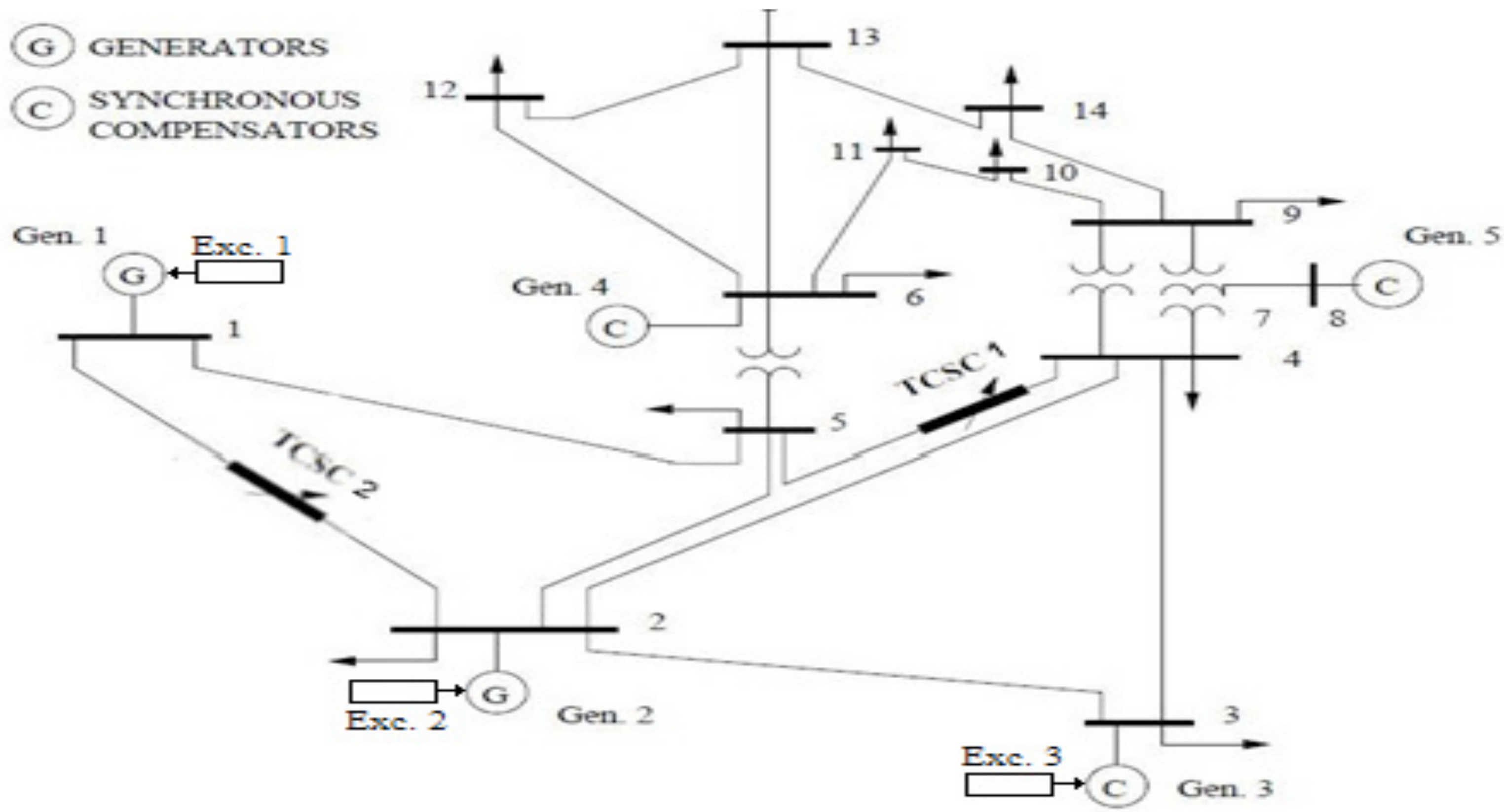


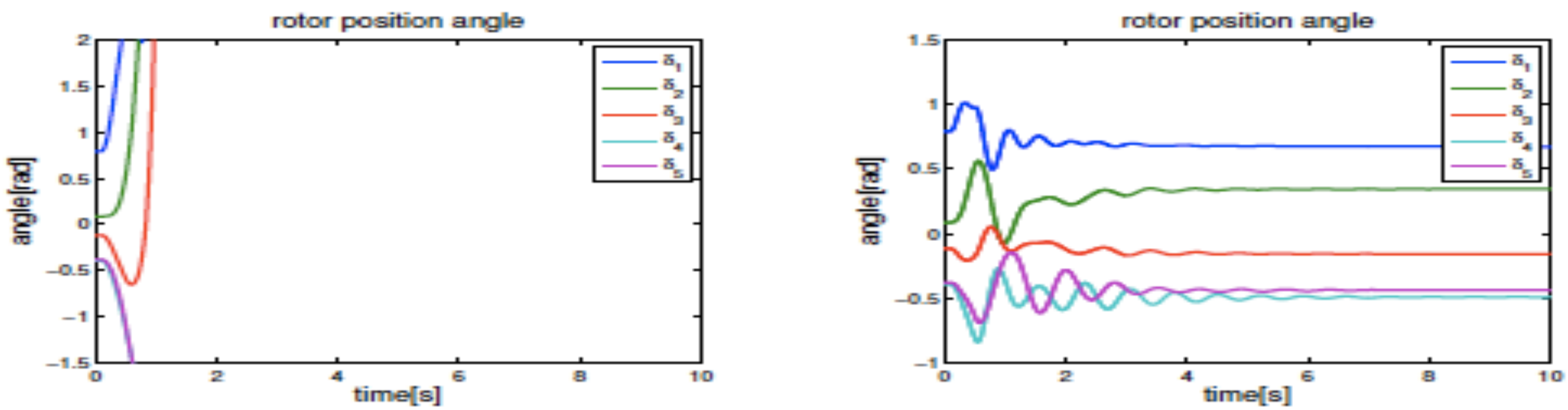
Fig. 1. An example of a system comprised of two modules i and j.

Nonlinear cooperative control of FACTS in the new state space to synchronize generator 2



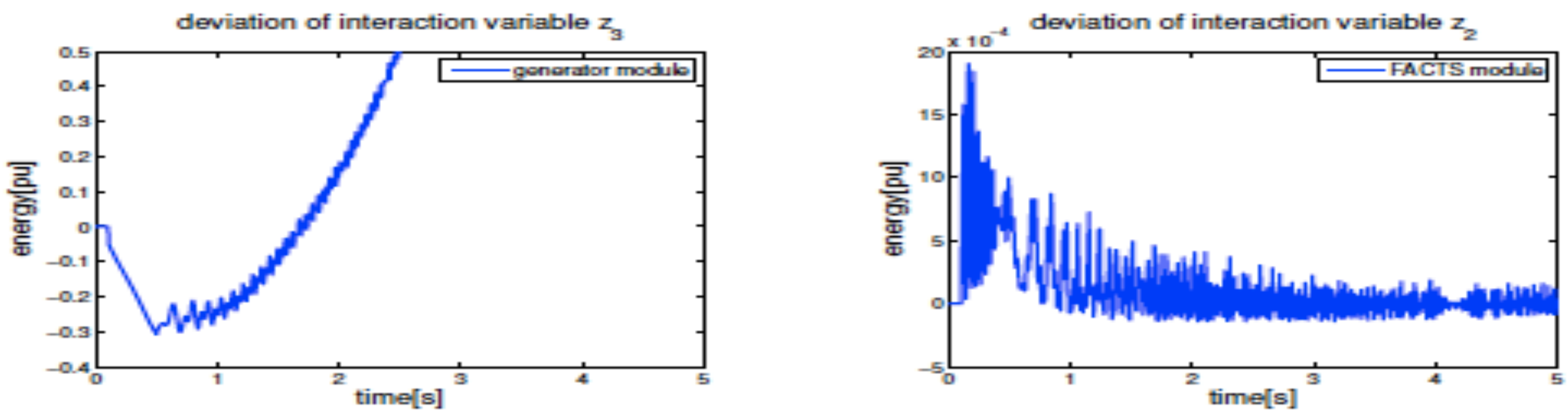
3. IEEE 14 bus system with two TCSC and five excitation controllers.

With Milos Cvetkovic



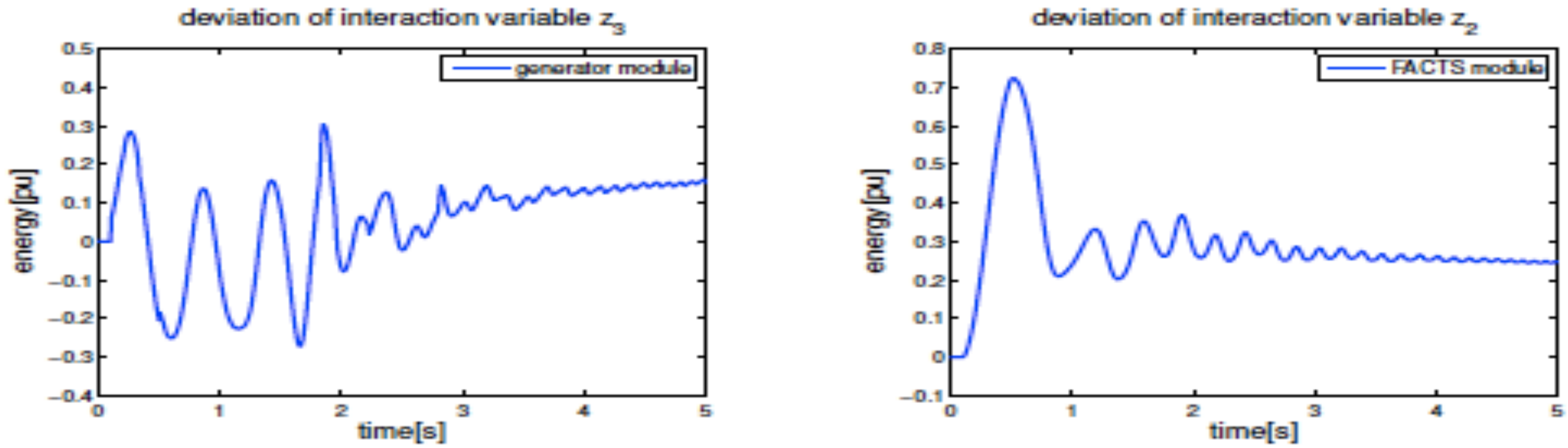
(a) Uncontrolled system (b) With cooperative controllers

Fig. 4. Generator rotor angle response with and without the controller.



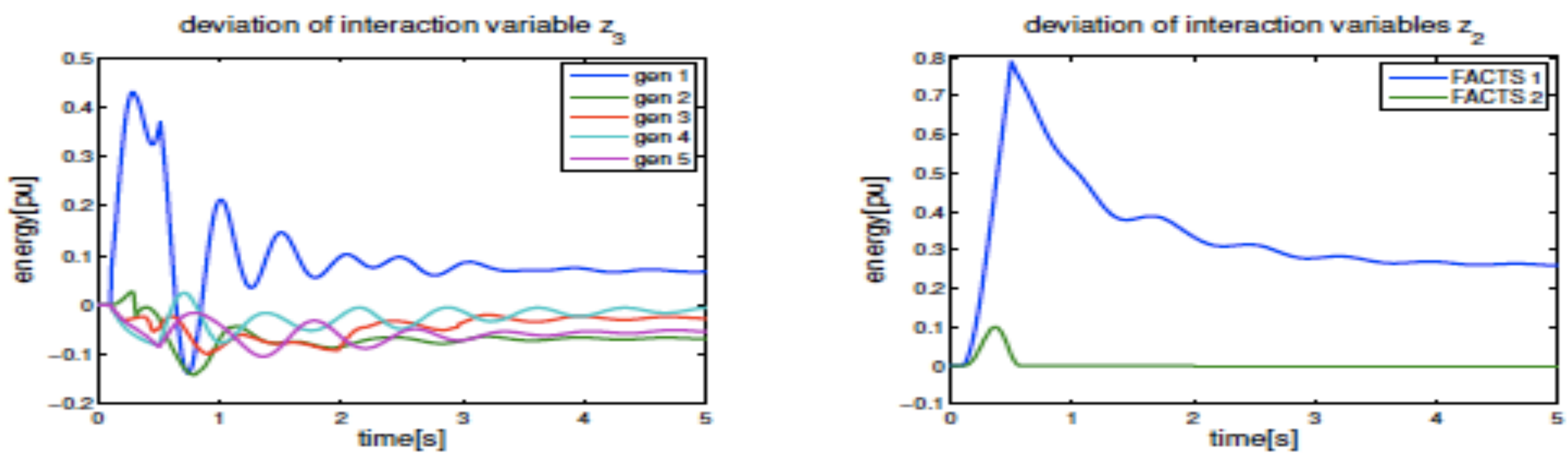
(a) Generator modules (b) FACTS modules

Fig. 5. Interaction variables without any controllers in *Case 1*.



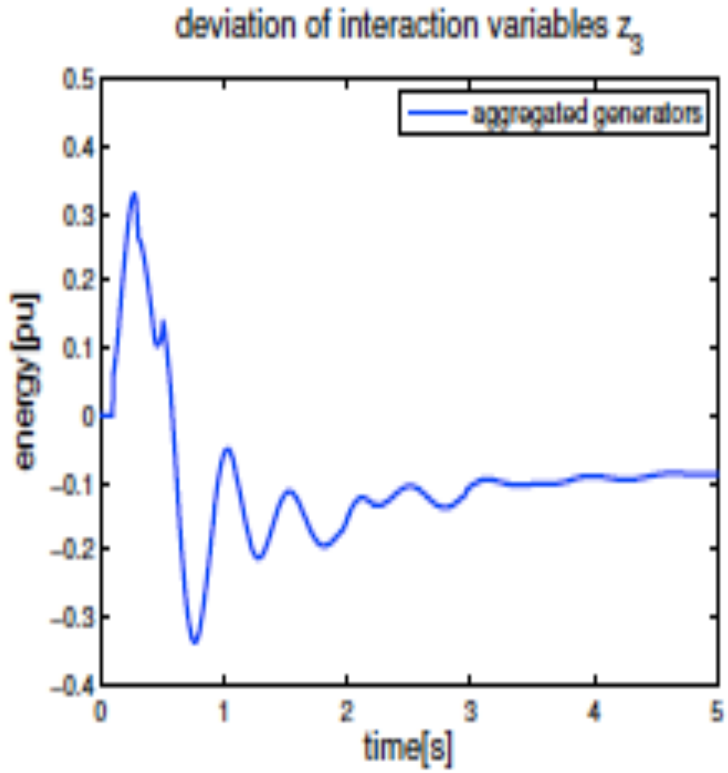
(a) Generator modules (b) FACTS modules

Fig. 6. Interaction variables in the controlled system in *Case 1*.

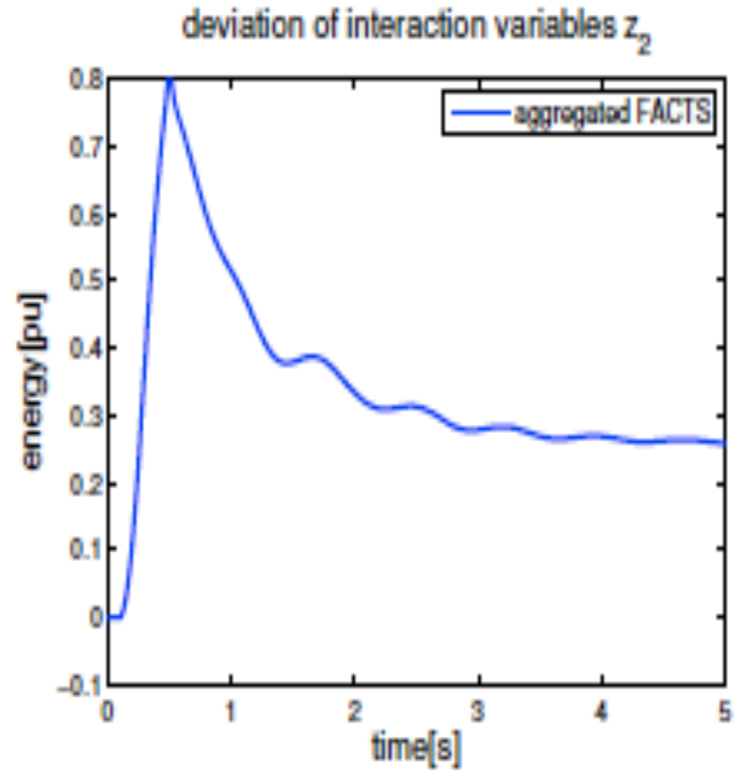


(a) Generator modules (b) FACTS modules

Fig. 7. Interaction variables of the controlled system in *Case 2*.



(a) Generator modules



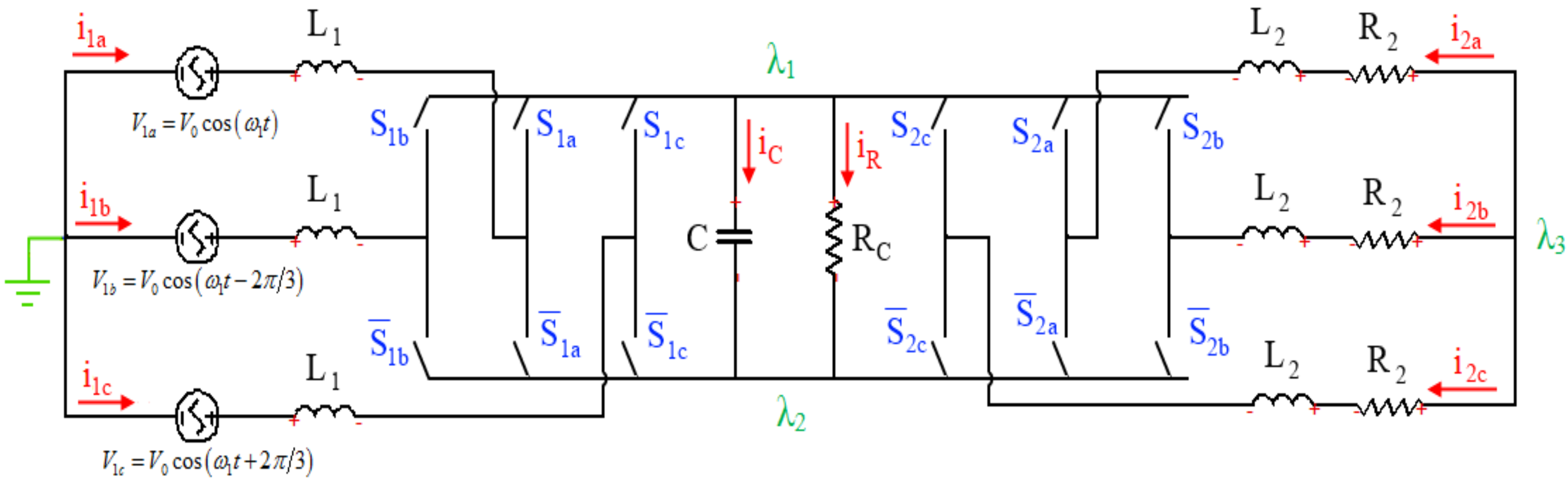
(b) FACTS modules

Fig. 8. Aggregated interaction variables in *Case* 2.

Interaction variables in new state space

- ❖ System dynamics separable into multi-layer system: internal layer and interaction layer;
- ❖ Rate of change of stored energy zero when module disconnected
- ❖ Natural evolution of control area specifications (ACE) – linearized, steady-state notion; can cooperate for AGC
- ❖ Essential for iBA-level transient stabilization, power flow feasibility, SSCI, SSR standards (non-existent today)
- ❖ Using this modeling framework, different control strategy can be used and designed: competitive or cooperative control
- ❖ Note on synchronization—in the new state space entirely decentralized controller

Passivity-based AC/DC/AC Converter control



- Choose to directly regulate the direct and quadrature components of the load and source currents
- Desired capacitor charge has dynamics

$$\frac{dq_C{}^D}{dt} = -\frac{\left(q_C{}^D\right)^2 - C^2 R_C\left(V_{1d} i_{1d}{}^* + V_{1q} i_{1q}{}^*\right) + C^2 R_C R_2\left(i_{2d}{}^{*2} + i_{2q}{}^{*2}\right) + C^2 R_C R_1\left(i_{1d}{}^{*2} + i_{1q}{}^{*2} - i_{1d} i_{1d}{}^* - i_{1q} i_{1q}{}^*\right)}{C R_C q_C{}^D}$$

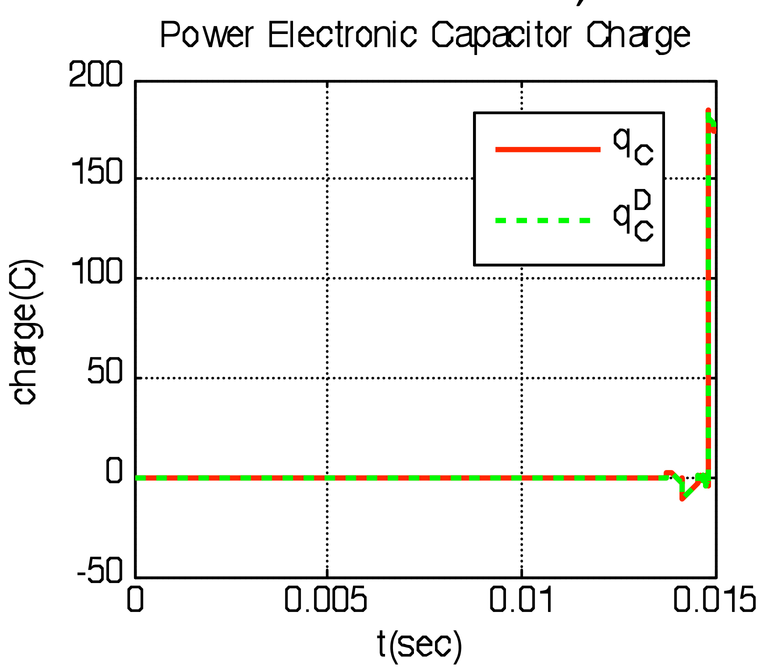
Source: K. D. Bachovchin, M. D. Ilić, "Automated Passivity-Based Control Law Derivation for Electrical Euler-Lagrange Systems and Demonstration on Three-Phase AC/DC/AC Converter," EESG Working Paper No. R-WP-5-2014, August 2014.

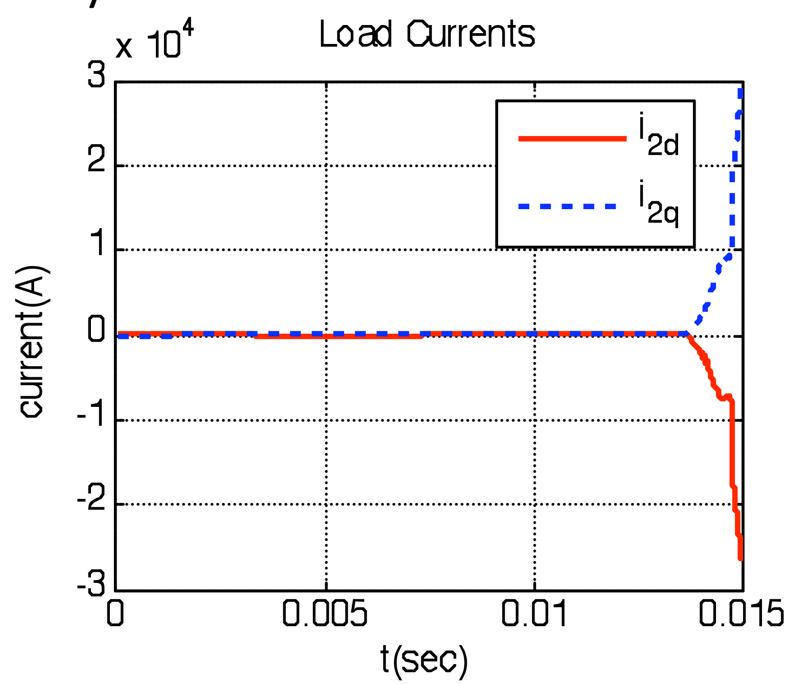
Existence of stable equilibrium

- A stable equilibrium for $q_C^{\,D}$ only exists when

$$\underbrace{V_{1d}i_{1d}^{\ *} + V_{1q}i_{1q}^{\ *}}_{\text{power input by source}} \geq \underbrace{R_2 i_{2d}^{\ *2} + R_2 i_{2q}^{\ *2}}_{\text{power dissipated by load}}$$

- If this condition is violated, then the passivity-based controller will be unstable





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.

Interaction variables between complex modules

- Need to understand both module-level dynamics and inter-modular dynamics
- Cooperative control between modules w/o detailed knowledge of internal dynamics is possible according to functional performance quantifiable in terms for interaction variables requirements for several time horizons.
- Competitive control of individual modules without much information exchange with the rest of the system also possible?
- Potential for unstable interactions --sub--synchronous control instabilities (instabilities created by power electronics controllers on wind power plants and FACTS controllers in Texas power grid) managed by protocols avoiding problems in Table 1.

Conclusions

- Our proposal: Interaction variable-based
- Standards/protocols for interactive iBAs can set the basis for plug-and-play in smart grids—bounds on stored energy change and on rate of change of stored energy for T of interest
- Standards need to define transparent protocols for all dynamic components
  - Complexity of smart grids can be managed this way
  - At the same time system performance is guaranteed
- With current NERC standards system performance cannot be mapped into responsibilities of different components

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