Carnegie Mellon

Electric Energy Systems Group

Electrical & Computer ENGINEERING

Modeling for plug-and-play control in strongly coupled nonlinear networks

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Intro

- Many real-world network systems (electric power grids, coupled robotic systems, biological systems) are becoming more strongly coupled than in the past; coupling is both temporal and spatial
- A basic question: Can coupling can be used for systematic design of cooperative control?
- Can't apply SSP modeling for near-optimal composite control design (temporal simplifications)
- Cant apply NSSP modeling for spatial simplifications
- Relevant because of implications on complexity and performance of control/communication designs
- Potential of controllers in the nodal components of the network, as well as potential of fast switched control of its branch components

Problem description

❖ Three controllers (governor, Exciter and FACTS)

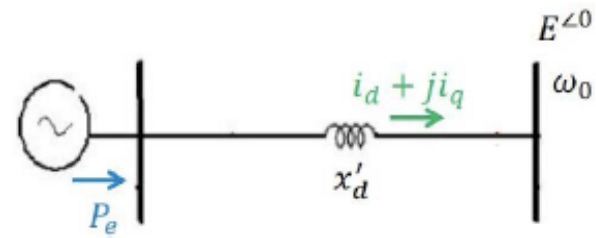

Fig.1 Electric power network

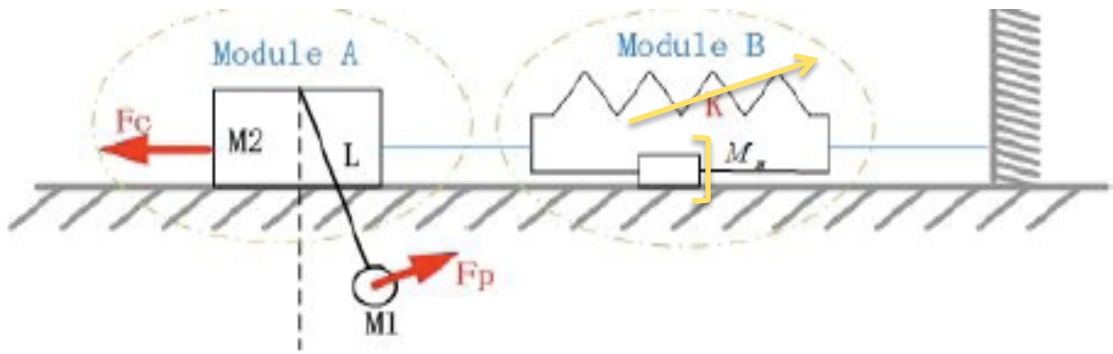

Fig. 2 Mechanical analogy of the electric power network

❖Three controllers (Fp, Fc, and controllable inerter)

Modeling questions for plug-and-play control design

- Control problem—strong coupling of modules A and B; MIMO design so that
- 1) pendulum is synchronized; 2) states and control within the pre-specified limits

Mechanical system modeling options

The standard state space model is

$$\dot{X}_A = f(X_A, X_B, u_A) \qquad X_A = [\theta \quad \omega \quad x_2 \quad v_2]^T \qquad U = [u_A \quad u_B]^T \qquad u_A = [F_P \quad F_C]^T$$

$$\dot{X}_B = f(X_B, X_A, u_B) \qquad X_B = [x_B \quad v_B]^T \qquad u_B = [K]$$

❖Acceleration as the coupling (interaction) variable of modules A and B

$$\dot{X}_{pendulum} = f\left(X_{pendulum}, \dot{v}_2, u_p\right) \quad \text{where } u_p \text{ is } F_P$$

$$\dot{X}_{M2} = f\left(X_{M2}, \dot{\omega}, \dot{v}_B, u_M\right) \quad \text{where } u_M \text{ is } F_C$$

Stored energy and rate of change of stored energy coupling (interaction) variable—new state space

$$Z_A = \frac{1}{2}J\omega^2 + \frac{1}{2}m_2 v^2{}_2 + m_1 g l(\cos\theta - 1) \quad \text{where } J = m_1 l^2 \qquad P_A = J\omega\dot{\omega} + m_2 \dot{v}_2 v_2 - m_1 g l \sin\theta$$

$$Z_B = \frac{1}{2}m_B v_B{}^2 + \frac{1}{2}k(x_B - x_0)^2 \quad \text{where } x_0 \text{ is inital length of spring}$$

$$P_B = m_B v_B \dot{v}_B + k(x_B - x_0)x_B$$

The new state space takes on the form

$$X_A{}^{new} = \left[\bar{\bar{X}}_A \quad Z_A \quad P_A\right]^T \; \bar{\bar{X}}_A = [\theta \quad \omega]^T \qquad X_B{}^{new} = [Z_B \quad P_B]$$

Internal dynamics module A

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

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

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

Zoom-out layer in terms of Interaction variables

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

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

Comparison of modular models

- Acceleration as an interaction variable works w/o assumptions if actuator dynamics are neglected; otherwise, projection of centrifugal force effect on M2 needs to be ignored; conjecture—if dynamics of actuator accounted for only stabilization around stable pendulum position possible; also acceleration must be communicated, hard to do
- When stored energy and rate of stored energy used as coupling (interaction) variables –no approximations needed; can stabilize around inverted pendulum (Furuta, Astrom)
- only local power measurement needed, completely decentralized
- It is possible to specify interactions over several time horizons —important for complex networks

Open problem

- Extend nonlinear control design to multi-layered strongly coupled complex networks.
- Provable performance precludes solutions in which position changes in an unbounded way
- New problem, when assumptions are not made (acceleration ideal input)
- Motivation--- functional specifications for interconnected smart grids with lots of fast power electronics switching; micro-grids; systems with wind power plants and delivery power electronically controlled to increase dellivery