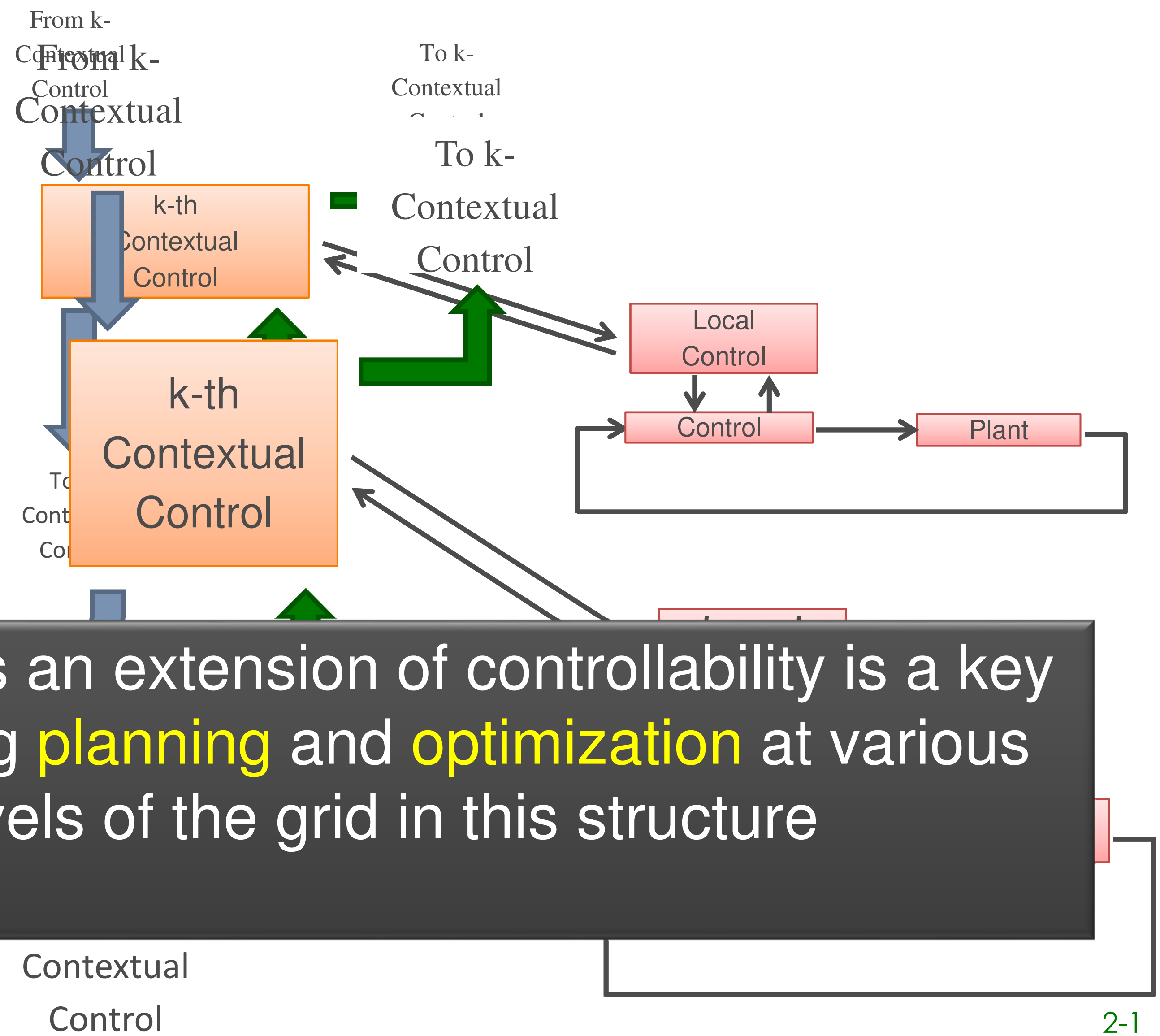
Introduction

Two-tier control structure



Flatness as an extension of controllability is a key to enabling planning and optimization at various levels of the grid in this structure

Flat Systems

- First introduced by Fliess using the formalism of differential algebra.
- The nonlinear structure of the system is well characterized (flat means defect free)
- Designing control algorithms for the systems in two levels of planning, trajectory generation, and following the desired trajectories.

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Flat Systems

- Definition

The nonlinear system

$$\dot{x} = f(x, u)$$

is said (differentially) flat if and only if there exists $y = (y_1, \dots, y_n)$ such that:

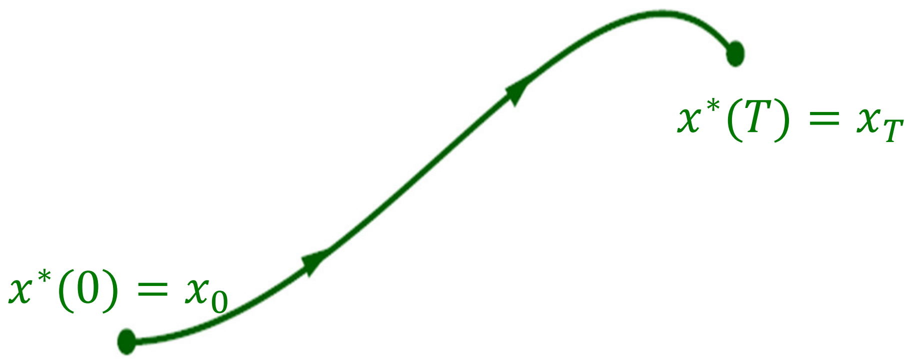
- y and successive derivatives $\dot{y}, \ddot{y}, \dots$,are independent
- $y = h(x, u, \dot{u}, \dots, u^{(\gamma)})$
- Conversely, x and u are given by:

$$x = \varphi\left(y, \dot{y}, \dots, y^{(\alpha-1)}\right)$$
$$u = \psi(y, \dot{y}, \dots, y^{(\alpha)})$$

The vector y is called the flat output

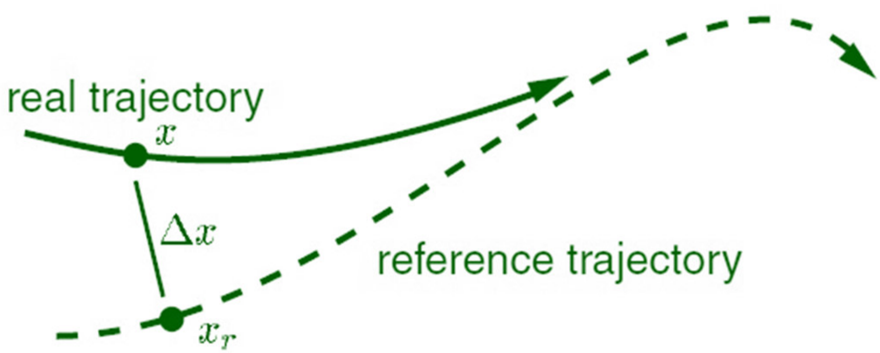
Flat Systems

- Trajectory Generation



find $t \rightarrow x^*(t), u^*(t)$
s.t.
$\dot{x}^*(t) = f(x^*(t), u^*(t))$
$x^*(0) = x_0,\ x^*(T) = x_T$

- Trajectory Tracking



find a feedback law
such that
the system tracks the
reference trajectory
following a perturbation

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Flatness Based AGC

- In this example:
  - Flatness-based approach is applied to automatic generation control(AGC) of multi-area systems with wind generation units
  - In two level control structure, secondary control action represents local control and the contextual control determines the reference trajectory to be tracked by the local control

Flatness Based AGC

AGC equations in original space in area *i*

$$\dot{\delta}_i = \omega_i - \omega_s$$

$$\dot{\omega}_i = \frac{1}{2H}\left[P_{mi} - D(\omega_i - \omega_s) - \frac{E_i V_i}{x'_{di}} sin(\delta_i - \theta_i)\right]$$

$$\dot{P}_{gvi} = \frac{1}{\tau_{gi}}\left(P_i^{ref} - \frac{\omega_i - \omega_s}{R\omega_s} - P_{gvi}\right)$$

$$\dot{P}_{mi} = \frac{1}{\tau_{Ti}}\left(P_{gvi} - P_{mi}\right)$$

Deriving AGC equations in flat space

$$\dot{\delta}_i = \omega_i - \omega_s$$

$$\begin{cases} \delta_1^{(4)} = v_1 \\ \vdots \\ \delta_n^{(4)} = v_n \end{cases} \Rightarrow$$

AGC in a *n*-area power system is decoupled into *n* subsystems in canonical form

Flatness-based AGC: Trajectory Generation

- Economic dispatch is performed to find the desired operating points in contextual control
- To follow load changes and wind variations the operating point is updated every 5 minutes
- Trajectory generation

$$\delta_i(t_0) \coloneqq \sum_j A_{ij}\lambda_j(0) \qquad \delta_i(5) \coloneqq \sum_j A_{ij}\lambda_j(5)$$

$$\vdots \qquad\qquad \vdots$$

$$\delta_i^{(3)}(t_0) \coloneqq \sum_j A_{ij}\lambda_j^{(\alpha_i - 1)}(0) \qquad \delta_i^{(3)}(5) \coloneqq \sum_j A_{ij}\lambda_j^{(\alpha_i - 1)}(5)$$

- The trajectory is calculated for each generator independently

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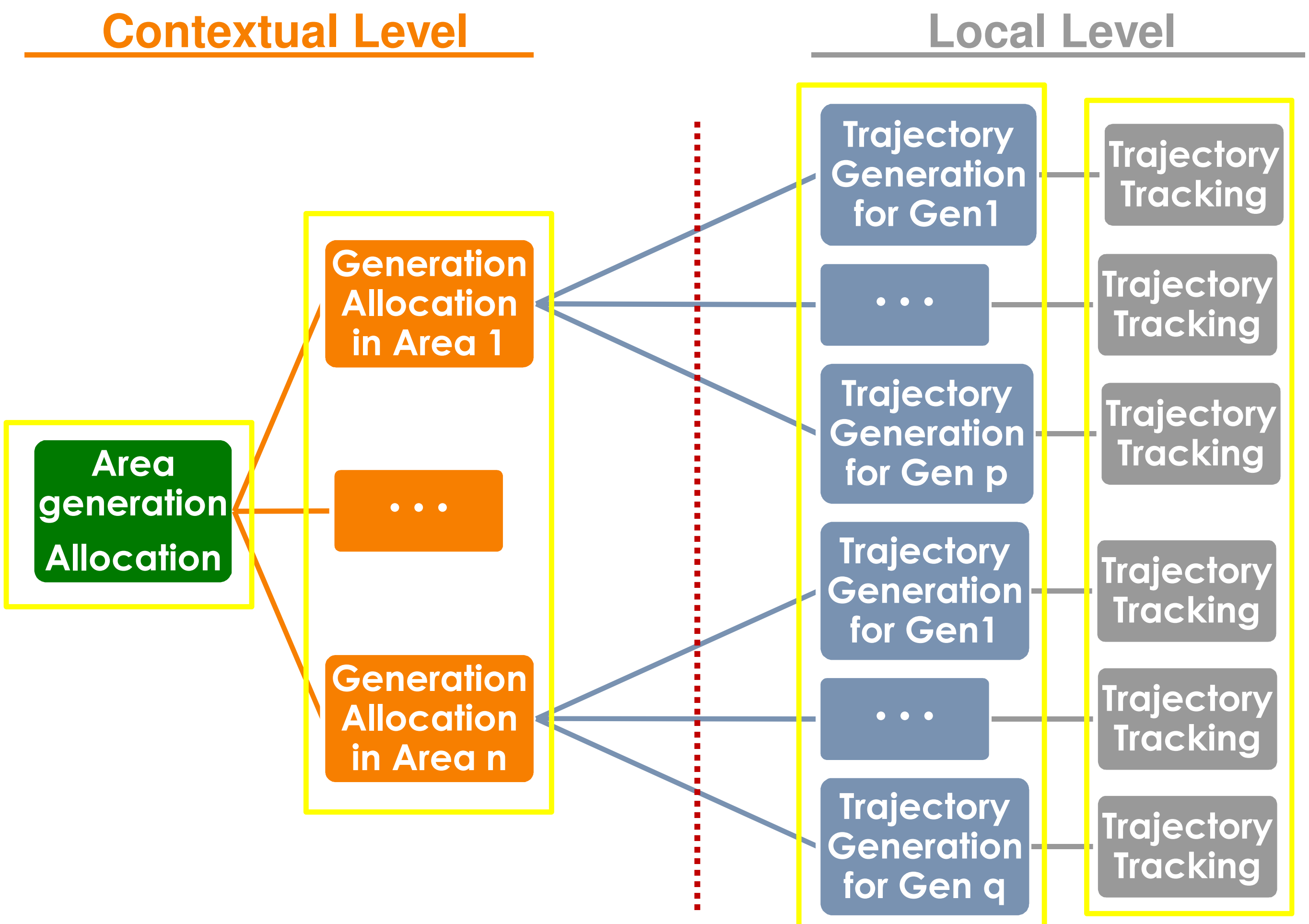
Flatness-based AGC Structure



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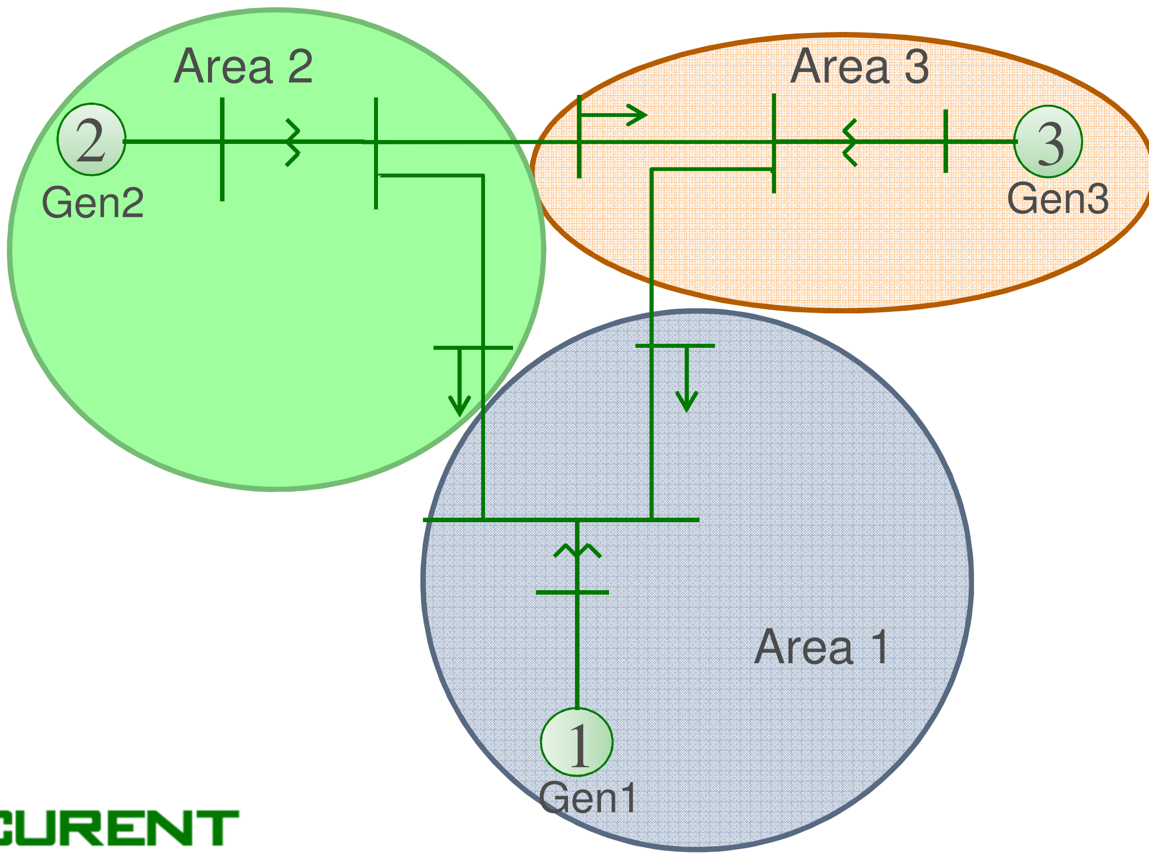
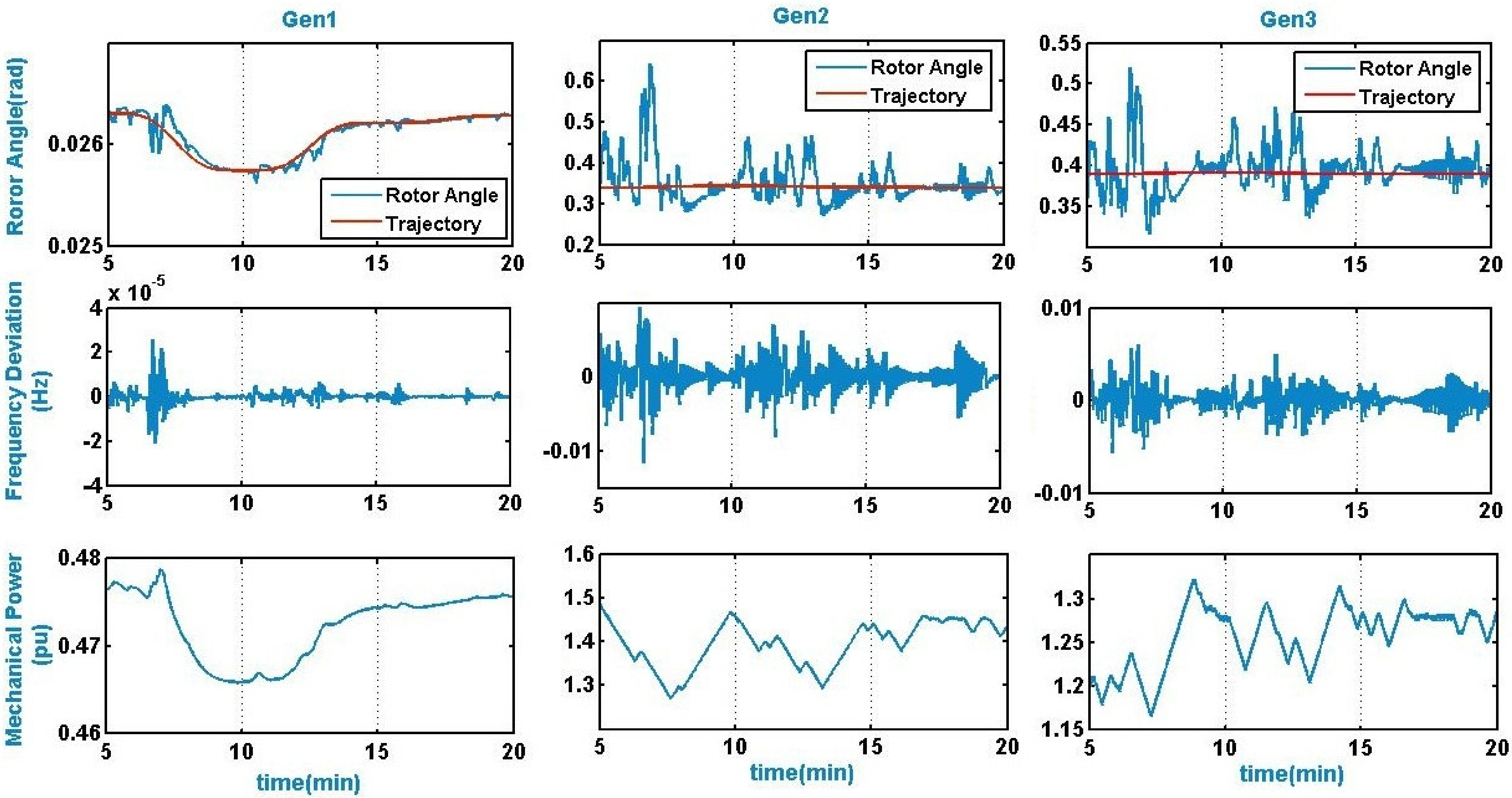
Simulation

- The approach is implemented on a 3-machine, 9-bus system (Ref: P. Sauer and A. Pai, Power System Dynamics and Stability)



CPS1: NERC Control Performance Standard

Simulation Results: Adding Wind Units



Conclusion

- Key to flat output is phase measurement
- Two level control consisting of trajectory generation and trajectory tracking substitutes for conventional AGC
- Decoupling into *n* linear controllable sub-systems in canonical form
- Local linear controllers for each sub-system
- The proposed approach can be applied to every controller in the power system

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Discussion