Computational Methods for Distributed Controller Design in the Smart Grid

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Joint work with Matt Wytock

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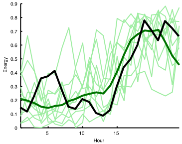
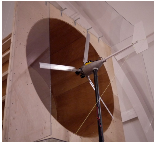
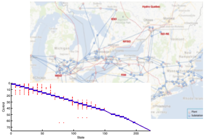
Recent and ongoing projects



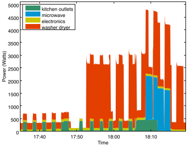
Probabilistic power forecasting



Learning micro wind turbine control

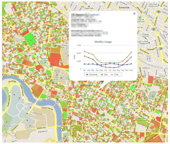


Fast algorithms for decentralized wide area power control



Energy disaggregation

Residential energy data collection



City-level energy modeling and visualization

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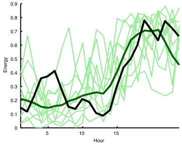

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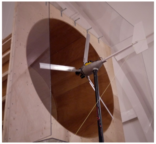

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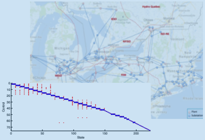

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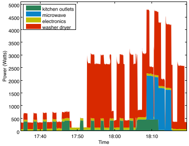

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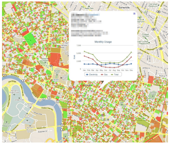

City-level energy modeling and visualization

From big data to big control

Big Data

Many data points
Many features
High data velocity

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Big Control

Big data +
Many decisions
Fast dynamics
Communication limits

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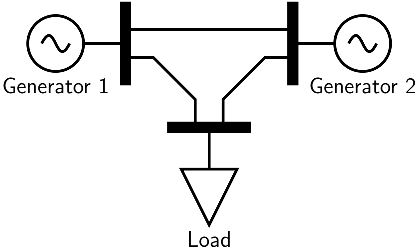
This work: towards bringing CS big data approaches into the computational side of control

Wide area control of power systems



$$x = \begin{bmatrix} \theta_1 \\ \dot{\theta}_1 \\ \theta_2 \\ \dot{\theta}_2 \end{bmatrix}, \quad u = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix}$$

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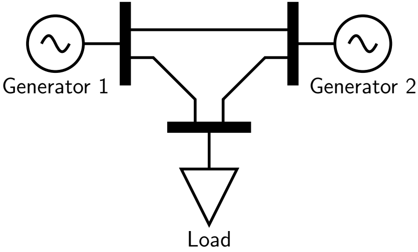


$$x = \begin{bmatrix} \theta_1 \\ \dot{\theta}_1 \\ \theta_2 \\ \dot{\theta}_2 \end{bmatrix}, \quad u = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix}$$

$$K = \begin{bmatrix} {\color{blue}\bullet} & {\color{blue}\bullet} & {\color{red}\bullet} & {\color{red}\bullet} \\ {\color{red}\bullet} & {\color{red}\bullet} & {\color{blue}\bullet} & {\color{blue}\bullet} \end{bmatrix}$$

${\color{blue}\bullet}$ = "local" control

${\color{red}\bullet}$ = "wide area" control

Decentralized control

- Huge area of research dating back to 60s: linear decentralized control known to be suboptimal (Witenhausen, 1962); survey of early work (Sandell Jr. et al., 1978)

- Non-convex for typical control objectives ($\mathcal{H}_2$, $\mathcal{H}_\infty$)

- A great deal of interest in recent years: special systems (e.g., quadratic invariance) where optimal decentralized control *is* sparse (Rotkowitz and Lall, 2006); convexifications using different control objectives (Dvijotham et al., 2013) or restricted Lyapunov functions (Schuler et al., 2013); non-convex optimization and ℓ_1 penalty (Lin et al., 2013)

- *But*, virtually no large-scale algorithms

Problem setup (following Lin et al., 2013)

- Continuous time linear dynamical system

$$\dot{x}(t) = Ax(t) + Bu(t) + W^{1/2}\epsilon(t)$$

- LQR/$\mathcal{H}_2$ objective for state feedback controller $u(t) = Kx(t)$

$$J(K) = \lim_{T\to\infty} \frac{1}{T} \int_0^T \big(x(t)^T Q x(t) + u(t) R u(t)\big)\, dt$$

$$= \begin{cases} \operatorname{tr} PW & A + BK \text{ stable} \\ \infty & \text{otherwise} \end{cases}$$

$$(A+BK)^T P + P(A+BK) + Q + K^T R K = 0$$

- Optimization objective with ℓ_1 term

$$\underset{K}{\text{minimize}}\, J(K) + \lambda \|K\|_1$$

(a difficult optimization problem)

Computational challenges

- Taking inspiration from sparse big-data methods: Newton Coordinate Descent approaches (e.g. Hsieh et al., 2011, Tseng and Yun, 2009)

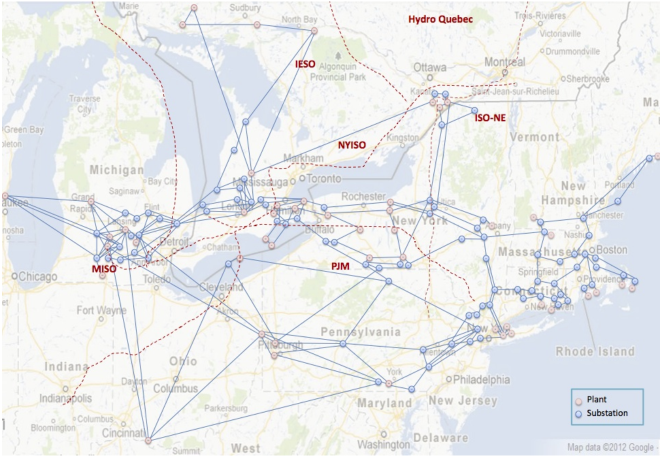
- Iteratively form quadratic approximation and minimize over search direction Δ

$$\mathrm{tr}(\nabla_K J(K))^T \Delta + \mathrm{vec}(\Delta)^T (\nabla_K^2 J(K)) \, \mathrm{vec}(\Delta) + \lambda \|K + \Delta\|_1$$

  where this step can exploit recent advances in fast ℓ_1 optimization

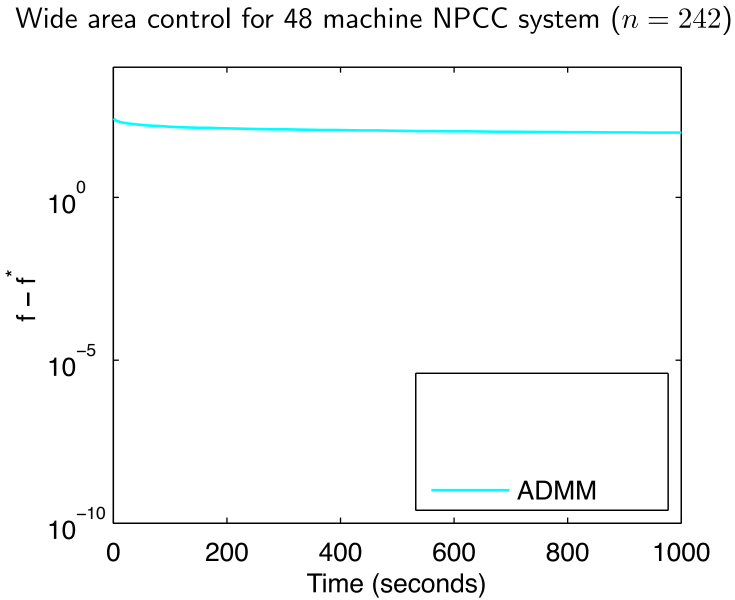
- But, Hessian products in particular are computationally intensive; majority of the work focuses on bringing this from $O(n^3) \rightarrow O(n)$

Power system wide area control

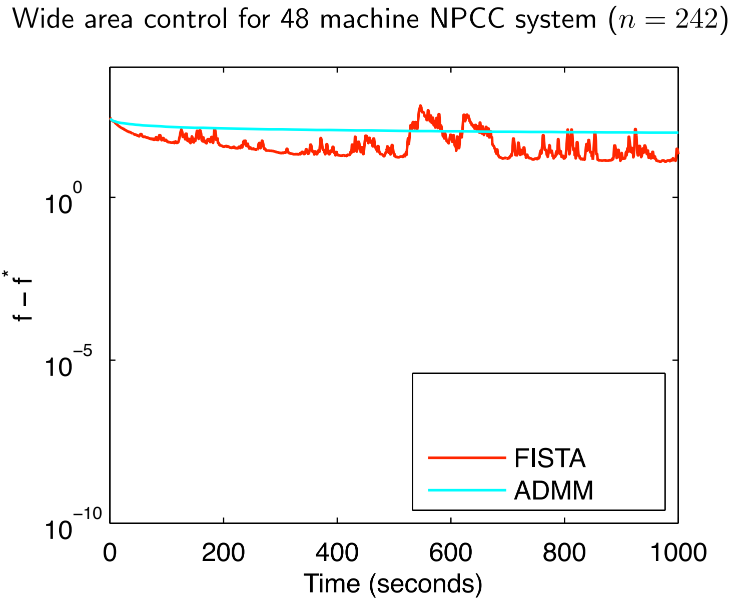


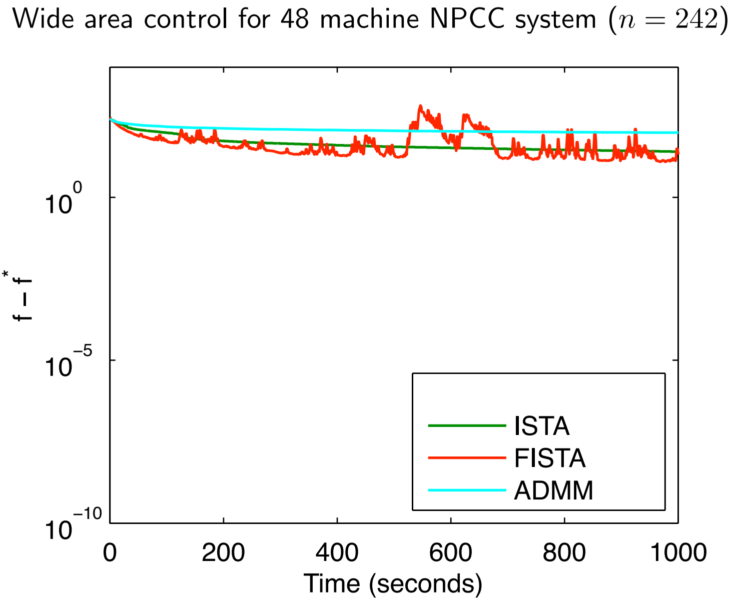
NPCC 48 machine, 140 bus system (Chow et al, 1995)

24 machines equipped with exciters and turbine governors, $n = 242$



Wide area control for 48 machine NPCC system ($n = 242$)
10^{0}
10^{-5}
10^{-10}
f − f*
0
200
400
600
800
1000
Time (seconds)
ADMM


Wide area control for 48 machine NPCC system ($n = 242$)
f – f*
10^0
10^−5
10^−10
0
200
400
600
800
1000
Time (seconds)
FISTA
ADMM


Wide area control for 48 machine NPCC system ($n = 242$)
f − f*
10^{0}
10^{-5}
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0
200
400
600
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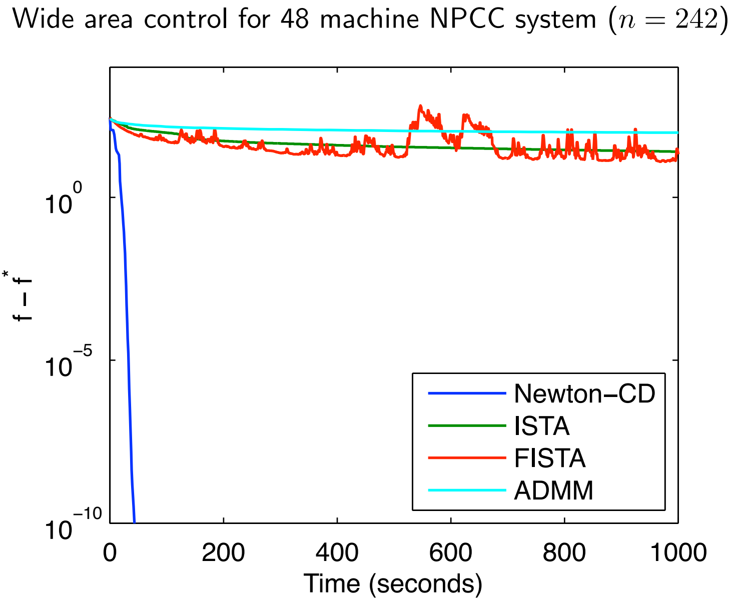
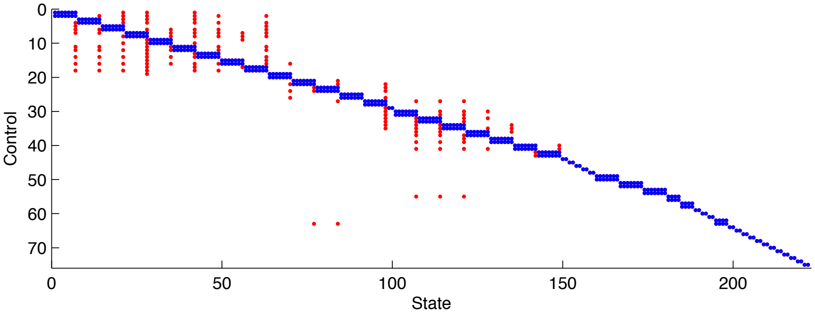
1000
Time (seconds)
ISTA
FISTA
ADMM



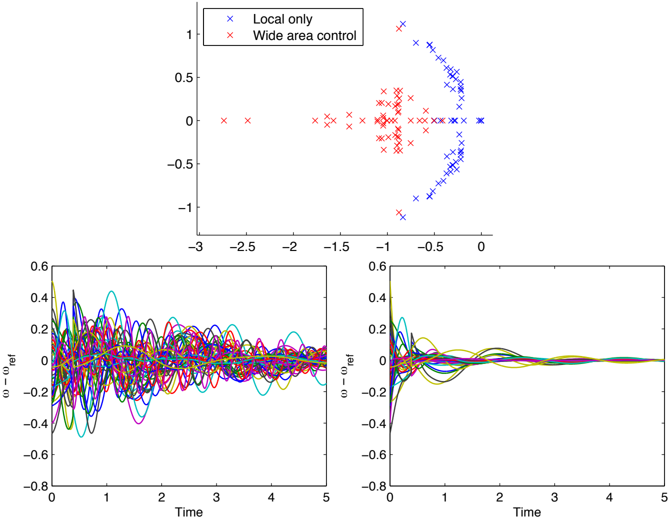
Wide area control for 48 machine NPCC system ($n = 242$)
$f - f^*$
10^0
10^{-5}
10^{-10}
0
200
400
600
800
1000
Time (seconds)
Newton−CD
ISTA
FISTA
ADMM

NPCC 48 machine system



Plot of controller sparsity

NPCC 48 machine system



Eigenvalues and regulation of intial / wide area control systems

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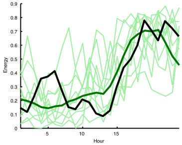

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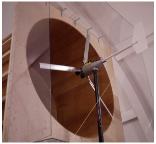

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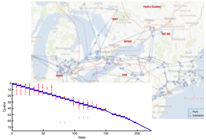

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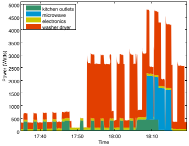

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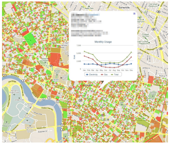

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