Inference and control of electric loads given sparse measurements and communications delays

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Benefits and Challenges of the Modern Electric Grid

• Grid sensing and communication systems are becoming more prevalent
  – Cost & privacy concerns
  – Need methods to infer grid/load information from existing measurements

• Renewable energy resources are also becoming more prevalent
  – Most (e.g., wind and solar) are intermittent and uncertain
  – Need new sources of power system reserves
Overview

• **Inference:** Inferring the behavior of distributed energy resources with sparse measurements
  [Ledva, Balzano, & Mathieu *Allerton* 2015]

• **Control:** Controlling distributed electric loads to provide power system services with sparse measurements and input/measurement delays
  [Ledva, Vrettos, Mastellone, Andersson & Mathieu *HICSS* 2015]
  [Ledva & Mathieu *CDC (in review)* 2016]
Disaggregating substation load data

Why do we want to disaggregate resources at the substation?

- Energy efficiency via conservation voltage reduction
- Contingency planning
- Optimal reserve contracting
- Demand response event signaling
- Demand response bidding
- Load coordination feedback

Power consumption of all the loads/generators we care about

Power consumption of all the loads/generators we DON’T care about

Distribution substation

Meter
Disaggregation methods
e.g., [Berges et al. 2009; Kolter et al. 2010; Dong et al. 2013]

- **State estimation**
  - Linear techniques require LTI system models
  - Nonlinear techniques can be computationally demanding

- **Online learning**
  - Optimization formulations
  - Model-free

- **Hybrid approach: Dynamic Mirror Descent** [Hall & Willet 2015]
  - Admits dynamic models of arbitrary forms
  - Optimization-based method to choose a weighted combination of the estimates of a collection of models
Outline: Part 1

- Dynamic Mirror Descent
- Problem setting: Plant data/models
- Algorithm Models
- Results
- Next steps
Dynamic Mirror Descent

- Mirror Descent: online algorithm to estimate a fixed state
- Dynamic Mirror Descent: online algorithm to estimate a dynamic state using a *collection of models* [Hall & Willet 2015]

1. Compute the error between the model predictions and the measured data (i.e., loss function)
2. Update the state in the direction of the negative gradient of the loss function

\[
\tilde{\theta}_t^i = \arg \min_{\theta \in \Theta} \eta_t \left\langle \nabla \ell_t(\hat{\theta}_t^i, y_t), \theta \right\rangle + D \left( \theta \parallel \hat{\theta}_t^i \right)
\]
Dynamic Mirror Descent

3. Use the estimated states to evaluate the models for the next time step

\[ \tilde{\theta}_{t+1}^i = \Phi_t^i(\tilde{\theta}_t^i) \]

4. Compute a weighted version of the estimates

\[ \tilde{\theta}_{t+1} = \sum_{i=1}^{N_{mdl}} w_{t+1}^i \tilde{\theta}_t^i. \]

5. Update the model weights

\[ w_{t+1}^i = \frac{\lambda}{N_{mdl}} + (1 - \lambda) \frac{w_t^i \exp \left( -\eta r \ell_t \left( \tilde{\theta}_t^i, y_t \right) \right)}{\sum_{j=1}^{N_{mdl}} w_t^j \exp \left( -\eta r \ell_t \left( \tilde{\theta}_t^j, y_t \right) \right)} \]
Problem Setting: Plant Data/Models

- Uncontrollable loads: data from Pecan Street Inc. Dataport
- Controllable loads: three-state hybrid models of air conditioners [Sonderegger 1978]
Algorithm Models: Uncontrollable loads

Amplitude [MW]

18
16
14
12

12AM 6AM 12PM 6PM 12AM

Time of Day

$y_t^{uc}$ $\hat{y}_t^{uc,Mon}$ $\hat{y}_t^{uc,Tues}$ $\hat{y}_t^{uc,Wed}$

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Algorithm Models: Controllable loads

- Two-state hybrid models of air conditioners [Mortensen & Haggerty 1988]
  - Temperature and ON/OFF mode
- Sets of Linear Time Invariant (LTI) aggregate system models [Mathieu et al. 2013]
  \[
  x^{i}_{t+1} = A^i x^i_t \\
  \tilde{y}^{c,LTI,i}_t = C^i x^i_t \\
  \quad \quad \quad i \in N^{temps}
  \]
- Sets of Linear Time Varying (LTV) aggregate system models
  \[
  x_{t+1} = A_t x_t \\
  \tilde{y}^{c,LTV}_t = C_t x_t.
  \]
Algorithm Models: Controllable loads

- Two-state hybrid AC models do not work well.
Algorithm Models: Controllable loads

- LTV models work better.
Results:
All combinations of models

Total Load

Controllable Load
Results: Weightings

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Weight [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12AM</td>
<td>0.0</td>
</tr>
<tr>
<td>6AM</td>
<td>0.2</td>
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<tr>
<td>12PM</td>
<td>0.4</td>
</tr>
<tr>
<td>6PM</td>
<td>0.6</td>
</tr>
<tr>
<td>12AM</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Other Models

- $\hat{y}_t^{c,\text{LTV1}}$
- $\hat{y}_t^{c,\text{LTV2}}$
- $\hat{y}_t^{c,\text{LTI,36}}$
- $\hat{y}_t^{c,\text{PA}}$
- Other Models

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Results: Bad Models

- All uncontrollable load models are too low.
## Results: Summary

<table>
<thead>
<tr>
<th>Case</th>
<th>RMS Error (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benchmark:</strong> Use current outdoor temperature to evaluate simple controllable load model</td>
<td>738</td>
</tr>
<tr>
<td><strong>DMD Case 1:</strong> Includes every combination of uncontrollable and controllable models</td>
<td>264</td>
</tr>
<tr>
<td><strong>DMD Case 2:</strong> Case 1 models plus a smoothed version of the actual uncontrollable load</td>
<td>211</td>
</tr>
<tr>
<td><strong>DMD Case 3:</strong> Case 2 models plus more accurate model of the controllable load over time periods where the other models are less accurate</td>
<td>175</td>
</tr>
<tr>
<td><strong>DMD Case 4:</strong> Includes uncontrollable load models that underestimate the uncontrollable load</td>
<td>1392</td>
</tr>
</tbody>
</table>
A. Uncontrollable Demand Model

We detail the various models used within a controllable demand model paired with an uncontrollable demand model. We note their value sets the default combination of models used for predictions. Additional results, which we do not include, trade-off matching the noisy data points with trusting the uncontrollable demand.

The weights are based on each model's historical accuracy with respect to the measurements. The weights are based on each model's historical accuracy. Larger loss values have less influence in the overall estimate. The RMS error in the controllable demand estimate increases with the value $\eta^r$, which penalizes the deviation between the new variable and the prediction. It can be thought of as a term that captures the alignment of the variable.

$$\eta^r = \frac{\lambda N_{mdl} + (1 - \lambda)}{\sum_{j=1}^{N_{mdl}} w_j^i \cdot \text{exp}(-\eta^r \cdot \ell_t(\hat{y}_t^i, y_t))}$$

where (6) incorporates the measurement into the estimate. DMD in this section.

**Results: Varying Algorithm Parameters**

Recall: $w_{t+1}^i = \lambda \sqrt{\frac{N_{mdl}}{N_{mdl}} + (1 - \lambda)}$.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta^r$ [-]</td>
<td>RMS Error [kW]</td>
</tr>
<tr>
<td>0</td>
<td>260</td>
</tr>
<tr>
<td>0.02</td>
<td>280</td>
</tr>
<tr>
<td>0.04</td>
<td>300</td>
</tr>
<tr>
<td>0.06</td>
<td>320</td>
</tr>
<tr>
<td>0.08</td>
<td>340</td>
</tr>
<tr>
<td>0.1</td>
<td>360</td>
</tr>
</tbody>
</table>
Next steps

• Investigate more realistic settings (using more real data)
• Develop better load models
• Improve the algorithm, e.g., alternative weighting functions
• Investigate identifiability
• Incorporate additional measurements (reactive power, voltage) into the approach
Key findings

• Dynamic Mirror Descent (DMD) enables us to solve the substation disaggregation problem leveraging dynamical models of arbitrary form.

• DMD can work well (on simple examples); however, it is easy to find instances where it does not work well.
Overview

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  [Ledva, Vrettos, Mastellone, Andersson & Mathieu *HICSS* 2015]
  [Ledva & Mathieu *CDC (in review)* 2016]
How can loads provide reserves? → your refrigerator is already flexible

How can loads provide reserves?

- your refrigerator is already flexible

- Powered
- Unpowered

- Normal operation
- Non-disruptive load control

Power (kW)

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Thousands of thermostatically controlled loads (TCLs) can track signals and provide reserves.

TCLs: air conditioners, heat pumps, space heaters, electric water heaters, refrigerators

[Mathieu, Koch, and Callaway *IEEE Transactions on Power Systems* 2013]
Simulation results:
1000 ACs tracking 5-minute market signal

Controller gets temperature/state of each load every 2 seconds

Controller infers TCL behavior from power measurements at the substation

➔ The more the controller knows about the loads, the better it can track a signal

[Mathieu, Koch, and Callaway IEEE Transactions on Power Systems 2013]
Data from loads

• Parameters
  – the make/model of the load?
  – its temperature setpoint/dead-band width?
  – some information about the household?

• Real-time data
  – Measurements of the on/off state and/or internal temperature?
  – Household smart meter data?
  – Power measurements from the distribution network?

• Recorded data
  – high resolution power measurements of each load?

→ Modeling

→ Feedback control

High quality, infrequent

Low quality, frequent

→ Auditing
Communication and control scenario

Load aggregator

Infrequent state measurements

Frequent aggregate power (output) measurements

substation

broadcast

Delay

Delay

Delay

[Ledva, Vrettos, Mastellone, Andersson, & Mathieu HICSS 2015]
Delays cause unsynchronized arrivals of inputs at the loads and measurements at the controller.
The challenge

• Design an estimator and controller to enable loads to track a signal *despite delays*

• Assuming...
  – Control inputs & measurements are time-stamped
  – Delay statistics are known
  – State measurements are taken frequently; measurement *histories* are transmitted infrequently
  – Aggregate power measurements are very noisy (though the noise is normally distributed, zero-mean, and the standard deviation is known)
Two-state TCL model

Each TCL $i$ is modeled with a stochastic hybrid difference equation:

Temperature of the space

$$\theta_i(k+1) = a_i \theta_i(k) + (1-a_i)(\theta_{a,i} - m_i(k)\theta_{g,i}) + \epsilon_i(k)$$

On/off state

$$m_i(k+1) = \begin{cases} 
0, & \theta_i(k+1) < \theta_{set,i} - \delta_i/2 \\
1, & \theta_i(k+1) > \theta_{set,i} + \delta_i/2 \\
m_i(k), & \text{otherwise}
\end{cases}$$

where $a$, $\theta_g$, $\theta_a$, $\epsilon$, $\theta_{set}$, $\delta$, $\theta_{a,i}$, $\theta_{g,i}$, and $\theta_{set,i}$ are thermal parameter, temperature gain, ambient temperature, noise, set point, dead-band width, and set point of the $i$th TCL, respectively.

Aggregate System Model

\[ x(k + 1) = Ax(k) + Bu(k) + B_\omega \omega(k) \]
\[ y(k) = C x(k) + \nu(k) \]

Similar models in the literature:
- Lu & Chassin 2004/2005
- Bashash & Fathy 2011/2013
- Kundu & Hiskens 2011
- Zhang et al. 2013

[Mathieu, Koch, and Callaway IEEE Transactions on Power Systems 2013]
Estimator Designs

• Based on Kalman Filtering
  – Estimator 1: Parallel filter estimator
    • One Kalman Filter per load
    • Each time a measurement arrives, filter it
    • Synthesize aggregate estimate from individual estimates
  – Estimator 2: Single Kalman Filter Using Aggregate State Predictions
    • Use state measurement histories to estimate *individual* load parameters (two-state model)
    • Use individual load models to predict current state
    • Use predictions in Kalman Filter
Controller Design

• Based on Model Predictive Control
  – Use knowledge of delay distributions and past control inputs

First control sequence: \( u_1, u_2, u_3, \ldots, u_n \)

Second control sequence: \( u_2, u_3, \ldots, u_{n+1} \)

Third control sequence: \( u_3, u_4, \ldots, u_{n+1} \)

Input estimate: \( \hat{u}_k = U_k P \)
Control Formulation

\[
\begin{aligned}
\min_{u, \delta} & \sum_{k=t}^{t+N_{mpc} - 1} \left[ c_{y} (y_{k}^{err})^2 + c_{\delta} (\delta_{k}^- + \delta_{k}^+ \right) + \\
\text{s.t.} & \quad x_{k+1} = Ax_k + Bu_k, \\
& \quad \hat{u}_k = U_k P, \\
& \quad y_{k}^{err} = y_{k}^{P, ref} - CP x_k, \\
& \quad u_{k|\Delta}^i \leq x_k^i, \\
& \quad -u_{k|\Delta}^i \leq x_k^{N^x+1-i}, \\
& \quad 0 - \delta_{k}^- \leq x_k \leq 1 + \delta_{k}^+, \\
& \quad 0 \leq \delta_{k}^-, \delta_{k}^+. 
\end{aligned}
\]
Case Studies

- PJM Regulation Signals, Reg-A & Reg-D
- Average input delay of 20 seconds
- (Delayed) state histories arrive every 15 minutes
Results

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Demand Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Estimator 1</td>
</tr>
<tr>
<td>0.25</td>
<td>Estimator 2</td>
</tr>
<tr>
<td>0.5</td>
<td>Reference Signal</td>
</tr>
<tr>
<td>0.75</td>
<td>Reg-A</td>
</tr>
<tr>
<td>1</td>
<td>Reg-D</td>
</tr>
</tbody>
</table>

The graph shows the demand change over time for Estimator 1, Estimator 2, and the reference signal. The graphs are labeled with Reg-A and Reg-D, indicating different regulatory scenarios.
Results: Model Mismatch

<table>
<thead>
<tr>
<th>Demand Change (%)</th>
<th>0</th>
<th>20</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (hr)</td>
<td>0</td>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>Estimator 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimator 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference Signal</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reg-A

Reg-D

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Control Results: Reg-A

Two-State Plant

Three-State Plant

RMSE (%)

PJM Score (-)

Average Delay (sec.)

Estimator 1

Estimator 2
Control Results: Reg-D

**Two-State Plant**

- **RMSE (%)**
  - Estimator 1: 2.0 ± 0.1
  - Estimator 2: 2.2 ± 0.2

- **PJM Score (-)**
  - Estimator 1: 0.5 ± 0.05
  - Estimator 2: 0.55 ± 0.05

**Three-State Plant**

- **RMSE (%)**
  - Estimator 1: 1.5 ± 0.05
  - Estimator 2: 1.75 ± 0.1

- **PJM Score (-)**
  - Estimator 1: 0.6 ± 0.05
  - Estimator 2: 0.65 ± 0.05

Average Delay (sec.):
- 0, 10, 20
Controller Reformulation

Original Model
\[ x_{k+1} = A x_k + B u_k \]
\[ y_k = C x_k. \]

Modal Model
\[
\begin{bmatrix}
1 \\
\tilde{x}_{k+1}
\end{bmatrix}
= 
\begin{bmatrix}
1 & 0 \\
0 & \tilde{A}
\end{bmatrix}
\begin{bmatrix}
1 \\
\tilde{x}_k
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
\tilde{B}
\end{bmatrix} u_k
\]
\[ y_k = \begin{bmatrix}
yss \\
\tilde{C}
\end{bmatrix}
\begin{bmatrix}
1 \\
\tilde{x}_k
\end{bmatrix} \]

Reduced-Order Model
\[ \tilde{x}_{k+1} = \tilde{A} \tilde{x}_k + \tilde{B} u_k \]
\[ \tilde{y}_k = \tilde{C} \tilde{x}_k. \]
Controller Reformulation

The linear controller uses constant gains generated from an output-regulating Linear Quadratic Regulator (LQR) with reference feedforward.

**Linear Controller**

\[ u^\text{seq}_t = -K^x_\infty x_t - K^w_\infty w_t + K^y_\infty y^\text{des}_t \]

**LQR Formulation**

\[ \min_u \sum_{k=t}^{\infty} \begin{bmatrix} \tilde{x}_k \\ w_k \end{bmatrix}^T \begin{bmatrix} \tilde{C}^T & q^y \tilde{C} \\ 0 & q^w \end{bmatrix} \begin{bmatrix} \tilde{x}_k \\ w_k \end{bmatrix} + (u^\text{seq}_k)^T R u^\text{seq}_k \]

s.t. \[ \begin{bmatrix} \tilde{x}_{k+1} \\ w_{k+1} \end{bmatrix} = \begin{bmatrix} \tilde{A} & 0 \\ \tilde{C} & 0 \end{bmatrix} \begin{bmatrix} \tilde{x}_k \\ w_k \end{bmatrix} + \begin{bmatrix} \tilde{B} \\ 0 \end{bmatrix} u^\text{seq}_k \]

**Feedforward Gain**

\[ K^y_\infty = \left( \tilde{C} \{ zI - \tilde{A} + \tilde{B} K^x_\infty \}^{-1} \tilde{B} \right)^{-\dagger} \]
Case Studies

• PJM Regulation Signals, Reg-A & Reg-D
• Average input delay of 20 seconds
• Full state feedback, no measurement delay
• Three-state models used for the plant
Future work will also explore the inclusion of an integrator in measurement transmission, e.g., [14].

Future work will design the linear feedback controller that mitigates the effect of input delays, and we compared it to a previously developed MPC controller while attempting to track real frequency regulation signals. Both methods counteract tracking in the scenarios considered even though it does not.
Results Summary

Reg-A Reference

Reg-D Reference

<table>
<thead>
<tr>
<th>Delay Scenario</th>
<th>MPC</th>
<th>LIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LIN is 100 times faster than MPC
Key takeaways

• Communication network limitations necessitate controller/estimator designs that cope with delays, bandwidth limitations, etc.

• Delays make loads less capable of providing fast services, but we can mitigate these impacts through delay-aware control and estimation.
Conclusions

- Need methods to infer electric load behavior from existing measurements
  - Dynamic mirror descent applied to distribution substation measurements

- Need new sources of power system reserves
  - Coordination of distributed electric loads using delay-aware control/estimation

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