Probabilistic Forecasting for Power System Operations

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June 14, 2017
Washington, DC
Overview

- **Overall Project Objectives**
  - Develop scalable probabilistic forecasting and system simulation tools for real-time operations. Specifically,
    - Forecasts of marginal and joint distributions of LMP, power flow, and reserve;
    - Forecasts of probability mass functions of discrete events such as congestions and contingencies.

- **Why is probabilistic forecasting important?**
  - For operators, probabilistic forecasting is essential to achieve economic efficiency under uncertainty.
  - For market participants, probabilistic forecasting is essential for integrating flexible demand and distributed energy resources.
Outline

- **Major accomplishments and technical contributions**
  - Probabilistic forecasting of power system operation.
  - Multi-area economic dispatch and interchange scheduling
    - Stochastic and robust interchange scheduling
    - Generalized Coordinated Transmission Scheduling (CTS)
- **Deliverables and remaining schedule**
  - Publications and software
  - Industrial collaborations
- **Looking forward**
Probabilistic Forecasting of Real-time Operations

Summary of major contributions

- Functionality: a probabilistic simulation and forecasting tool.
- Scalability: achieving several orders of magnitude reduction in computation costs. (over 0.1% of the computation cost of the state of the art on the 3120 bus 3963 branch Polish network)
- Technical innovation:
  - Parametric programming for real-time operations under uncertainty.
  - Online dictionary learning.

Major publications

Probabilistic Forecasting of Real-time Operations

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Major publications


Probabilistic Forecasting of Real-time Operations

- **Summary of major contributions**
  - **Functionality**: a probabilistic simulation and forecasting tool.
  - **Scalability**: achieving several orders of magnitude reduction in computation costs. (over 0.1% of the computation cost of the state of the art on the 3120 bus 3963 branch Polish network.)
  - **Technical innovation**:
    - Parametric programming for real-time operations under uncertainty.
    - Online dictionary learning.

- **Major publications**
Geometry of Multiparametric LP/QP

\[
\begin{align*}
\min_x & \quad z(x) \\
\text{subject to} & \quad Ax \leq b + E\theta
\end{align*}
\]

Theorem (critical region generation)
Given parameter \( \theta_0 \) and the solution of a nondegenerate MPLP \( x^*(\theta_0) \), the critical region \( \Theta_0 \) that contains \( \theta_0 \) is given by the matrix-vector pair \( (W, w) \):

\[
\Theta_0 = \left\{ \theta \in \Theta | W\theta < w \right\}, \quad W := \bar{A}\bar{A}^{-1}\bar{E} - \bar{E}, \quad w := \bar{b} - \bar{A}\bar{A}^{-1}\bar{b}.
\]

The solution \( x^*(\theta) \) for any \( \theta \in \Theta_0 \) is defined by \( (F, f) \)

\[
x^*(\theta) = F\theta + f, \quad F := \bar{A}\bar{A}^{-1}\bar{E}, \quad f := \bar{A}^{-1}\bar{b}
\]

Here \( \bar{A}, \bar{E} \) and \( \bar{b} \) are, respectively, the submatrices of corresponding to the active constraints, and \( \bar{A}, \bar{E} \) and \( \bar{b} \) similarly defined for the inactive constraints.
Weatherman’s forecast
Summary of major contributions

- Optimal multi-area interchange scheduling that
  - addresses operation uncertainty in stochastic and robust settings.
  - provides synchronous and asynchronous interchange involving two or more areas.
  - eliminates economic loss from unintended loop flows and guarantees revenue adequacy.

Selected publications

NE: 402 gen, 260 loads. NY: 582 gen units, 1026 load.

Tie-line capacity between ISONE and NYISO is 1800MW (12% of ISONE's consumption in 2009).

In 2009, 1.6 TWh NYISO to ISONE, 1.9 TWh in reverse.
Essential features of interchange scheduling

- ISOs can trade power only through market participants.
  - Market participants submit (virtual) bids to buy and offers to sell electricity at specific “proxy buses.”

- A two-stage process
  - ISOs clear bids/offers and set interchange quantity ahead of time.
  - ISOs optimize local dispatch in real time. Trades are settled based on real-time LMP.

- Decentralized scheduling with limited exchange and minimum iterations.

- The state-of-the-art: Coordinated Transaction Scheduling (CTS).
  - Currently being implemented for MISO-PJM, NYISO-ISONE.
  - Estimated cost saving: 9M~26M/year. So far only small portion has been realized
  - Sources of inefficiency: inaccurate forecast, uncertainty, and market illiquidity.
Coordinated Transaction Scheduling

- Each ISO has a simplified model of the neighboring area with a proxy bus.
- Market participants submit offers/bids for external transactions at proxy buses.

\[
\begin{align*}
\min_{q, q_1, q_2} & \quad C_1(q_1) + C_2(q_2) + C_{\text{bid}}(q) \\
\text{subject to} & \quad \text{power balance constraints for Area 1 and 2} \\
& \quad \text{transmission constraints for Area 1 and 2} \\
& \quad \text{generator constraints for Area 1 and 2} \\
& \quad \text{interface capacity constraint}
\end{align*}
\]
Stochastic Coordinated Transmission Scheduling (SCTS)

\[(P_1) \min_{q \leq Q} \sum_{i=1}^{2} \mathbb{E}_{d_i} [C_i(g_i^*(q, d_i))]\]

\[(P_2) \min_{g_i \in S_i} C_i(g_i)\]

subject to

\[\mathbf{1}^T(d_i - g_i) \pm q = 0, \quad (\lambda_i)\]

\[S_i(d_i - g_i) \pm T_i q \leq F_i, \quad (\mu_i)\]

\[\pi_i(q, d_i) \triangleq \lambda_i(q, d_i) + (T_i)^T \mu_i(q, d_i)\]

Theorem 1

The optimal interchange is given by the solution \(q^*\) of

\[\pi_1(q) = \pi_2(q)\]

if \(q^* < Q\) and \(Q\) otherwise.
Stochastic Coordinated Transmission Scheduling (SCTS)

\[(P_1) \min_{q \leq Q} \sum_{i=1}^{2} E_{d_i} [C_i(g_i^*(q, d_i))]\]

\[(P_2) \min_{g_i \in S_i} C_i(g_i)\]

subject to

\[1^T(d_i - g_i) \pm q = 0, \quad (\lambda_i)\]

\[S_i(d_i - g_i) \pm T_i q \leq F_i, \quad (\mu_i)\]

\[\pi_i(q, d_i) \triangleq \lambda_i(q, d_i) + (T_i)^T \mu_i(q, d_i)\]

**Theorem 2**

*Interface-by-Interface Scheduling (IBIS)*

Algorithm generates a sequence \(\{q^{(k)}\}_{k=0}^{\infty}\) that converges to the global optimal solution.
Generalized CTS

- **Key shortcomings of CTS**
  - Inaccurate proxy bus approximations.
  - Loop flow causing security violation and loss.
  - Lack of revenue adequacy guarantee.
  - Difficult to deal with multiple interfaces (> 2 areas).

- **Features of generalized CTS**
  - Preserve the CTS market structure and objective
  - Bids define physical tie-line flows (thus eliminate loop flow).
  - Allow asynchronous/asynchronous scheduling of multiple areas.
  - Guarantees revenue adequacy.

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Key idea 1: Preserving the CTS structure

- Bid-based look-ahead schedule.
  - Allow bids submitted to arbitrary $M \times N$ physical buses.
- Bids cleared by minimizing total generation and market costs
- Bids settled by real-time prices (locational).

<table>
<thead>
<tr>
<th>Bid ID</th>
<th>Source</th>
<th>Sink</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B11</td>
<td>B21</td>
<td>[0,50]</td>
</tr>
<tr>
<td>2</td>
<td>B12</td>
<td>B22</td>
<td>[0,10]</td>
</tr>
<tr>
<td>3</td>
<td>B21</td>
<td>B12</td>
<td>[0,100]</td>
</tr>
<tr>
<td>4</td>
<td>B22</td>
<td>B13</td>
<td>[0,60]</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Key idea 2: bids defined tie-line flows

- DC power flow

\[
\begin{bmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{bmatrix}
\begin{bmatrix}
\theta_1 \\
\bar{\theta}_1
\end{bmatrix}
= 
\begin{bmatrix}
g_1 - d_1 \\
g_2 - d_2
\end{bmatrix}
\]

- Tie-line power flow: KCL on the boundary

\[
\begin{bmatrix}
\tilde{Y}_{11} & \tilde{Y}_{12} \\
Y_{21} & \tilde{Y}_{22}
\end{bmatrix}
\begin{bmatrix}
\bar{\theta}_1 \\
\bar{\theta}_2
\end{bmatrix}
= 
\begin{bmatrix}
-Y_{11}Y_{11}^{-1}(g_1 - d_1) \\
-Y_{12}Y_{22}^{-1}(g_2 - d_2)
\end{bmatrix}
\]
Key idea 2: Interface bids define tie-line flows

- Tie-line power flows w/o interface bids

\[
\begin{bmatrix}
\tilde{Y}_{11} & Y_{12} \\
Y_{21} & \tilde{Y}_{22}
\end{bmatrix}
\begin{bmatrix}
\tilde{\theta}_1 \\
\tilde{\theta}_2
\end{bmatrix} =
\begin{bmatrix}
-Y_{11}Y_{11}^{-1}(g_1 - d_1) \\
-Y_{12}Y_{22}^{-1}(g_2 - d_2)
\end{bmatrix}
\]

- Equivalent network with bids

\[
\begin{bmatrix}
\tilde{Y}_{11} & Y_{12} \\
Y_{21} & \tilde{Y}_{22}
\end{bmatrix}
\begin{bmatrix}
\theta_1 \\
\theta_2
\end{bmatrix} =
\begin{bmatrix}
M_1 \\
M_2
\end{bmatrix} s
\]

Injection at \( \tilde{\theta}_1 \) from area 1

Injection @ bus m in Area 1

Withdraw @ bus n in Area 2
Key idea 3: market clearing & settlement

- **Clearing of interface bids**

  \[
  \begin{align*}
  \min_{\{g_i, s, \theta, \theta_i\}} c(g_i, s) &= \sum_{i=1}^{2} c_i(g_i) + \Delta \pi^T s \\
  \text{subject to } &H_i \theta_i + H_i \tilde{\theta}_i \leq f_i, i = 1, 2 \\
  &H_1 \tilde{\theta}_1 + H_2 \tilde{\theta}_2 \leq \bar{f} \\
  &\tilde{g}_i \leq g_i \leq \hat{g}_i, i = 1, 2 \\
  &0 \leq s \leq s_{\max}
  \end{align*}
  \]

  \[
  \begin{bmatrix}
  Y_{11} & Y_{12} \\
  Y_{21} & Y_{22}
  \end{bmatrix}
  \begin{bmatrix}
  \theta_1 \\
  \theta_2
  \end{bmatrix}
  =
  \begin{bmatrix}
  g_1 - d_1 \\
  0
  \end{bmatrix}
  
  \begin{bmatrix}
  \tilde{\theta}_1 \\
  \tilde{\theta}_2
  \end{bmatrix}
  \begin{bmatrix}
  M_1 s^* \\
  M_2 s^*
  \end{bmatrix}
  
  \text{Tie-line flow constraint}

- **Settlement of interface bids**

  \[
  \begin{align*}
  \min_{\{\theta_1, \theta_1, \tilde{\theta}\}} c^R(g_1), \\
  \text{subject to } &H_1 \theta_1 + H_1 \tilde{\theta}_1 \leq f_1 \\
  &\tilde{g}_1 \leq g_1 \leq \hat{g}_1, i = 1, 2 \\
  &\rho_1
  \end{align*}
  \]

  \[
  \begin{bmatrix}
  Y_{11} & Y_{12} & Y_{1I} & Y_{12} \\
  Y_{21} & Y_{22} & Y_{2I} & Y_{22}
  \end{bmatrix}
  \begin{bmatrix}
  \theta_1 \\
  \theta_2 \\
  \tilde{\theta}_1 \\
  \tilde{\theta}_2
  \end{bmatrix}
  =
  \begin{bmatrix}
  g_1 - d_1^R \\
  0
  \end{bmatrix}
  \]

  \[
  \begin{bmatrix}
  \tilde{Y}_{1I} & \tilde{Y}_{12} \\
  \tilde{Y}_{2I} & \tilde{Y}_{22}
  \end{bmatrix}
  \begin{bmatrix}
  \tilde{\theta}_1 \\
  \tilde{\theta}_2
  \end{bmatrix}
  =
  \begin{bmatrix}
  M_1 s^* \\
  M_2 s^*
  \end{bmatrix}
  \]

  \text{Tie-line flow constraint}

Theorem (revenue adequacy) The net revenue for each area is equal to the congestion rent.

Example 1: single tie line

14-bus system

30-bus system

\[ x = 0.15, \bar{h} = 100 \, \text{MW} \]

JED = CTS = GCTS
Example 2: two tielines

- Default cost coefficients, no internal congestion
- Bids: price 0.1/ max quantity 100MW

- Loop flow in CTS:
  - Area 1, 16.17MW;
  - Area 2, 15.43MW.

<table>
<thead>
<tr>
<th></th>
<th>JED</th>
<th>CTS</th>
<th>G-CTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Inter.</td>
<td>93.4</td>
<td>80.3</td>
<td>93.3</td>
</tr>
<tr>
<td>Total cost</td>
<td>3880.6</td>
<td>4115.6</td>
<td>3890.0</td>
</tr>
</tbody>
</table>
Bids at proxy buses @ 0.5/MW-h, 100MW.

Internal flow constraints.

Pairwise scheduling of CTS

CTS has 6 flow constraint violations.

Loop flow (CTS): 4.58%/29.98%/6.52%
Multi-area interchange via robust optimization

Deliverables and remaining schedule

- **Publications**
  - IEEE Transactions on Power Systems (TPS): 3 appeared, 3 under review, 1 to be submitted by the end of August.
  - 9 conference papers (PESGM, ACC, HICSS). 1 best paper award, 1 best paper nomination.
  - Probabilistic forecasting simulation tools.

- **Remaining schedule:**
  - Industrial collaborations: PJM (6/29), NYISO (6/23), ISONE (?), PNNL (8/?)
  - Simulation studies on impacts of loop flows
  - Publications: Journal & PESGM submissions
Looking ahead

- **Machine learning approach to operation forecasting**
  - From market operation to system operation: incorporating probabilistic AC power flow.
  - PROFS: PRobabilistic Online Forecasting and Simulations

- **Stochastic and robust multi-area operation**
  - Understanding impacts of stochastic loop flow on cost, reliability, and market design
  - Extensions to micro-grid operations
Publications: archival journal

Publications: conferences