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Progressive Hedging for Stochastic Economic Dispatch with AC Power Flow

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Outline

- Operating a Power Grid
- ACOPF formulation
  - IV rectangular
  - PQV rectangular
  - PQV polar
- Stochastic ACOPF with Renewable Energy Resources
- Computational Results
- Conclusions

Operating the electric power grid

- Conceptually simple

$$\sum demand = \sum generation - \sum losses \quad \forall\, t \in T$$

- In practice, this is complicated by
  - Dynamic constraints (ramp rates)
  - Transmission limitations
  - Security (reliability) requirements
  - Market constraints

How do utilities implement this in practice?

Day-Ahead Unit Commitment (SCUC D-8h)

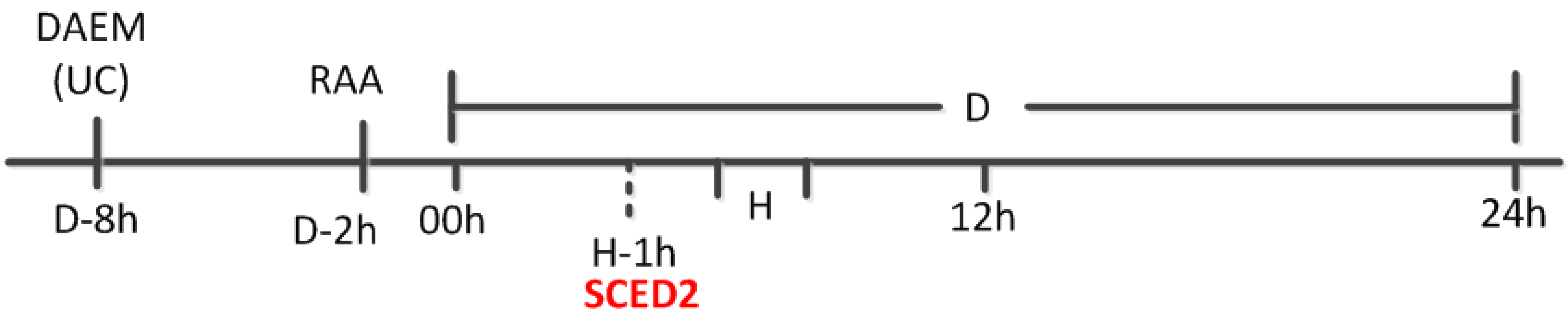
- Day-Ahead Energy Market (DAEM or DAM)
- Clears **demand bids** and **supply offers** at 1600h on the day prior to the operating day
- Produces:
  - Hourly schedules for the next operating day for market participants (i.e., generation and demand)
  - Hourly interchange schedules
  - Hourly day-ahead Locational Marginal Prices (LMPs)
- Some markets optimize reserve requirements simultaneously

Reliability Unit Commitment - RUC (SCUC D-2h)

- Reliability Assessment (Reserve Adequacy Analysis - RAA)
- Minimize additional start-up and no load costs to provide sufficient capacity to satisfy the **forecasted** load plus the operating and replacement reserve requirements
- Clears ISO **forecasted load** at 2200h
- DAM commitments are respected
- Produces:
  - Additional commitments
  - Updated generator dispatch points

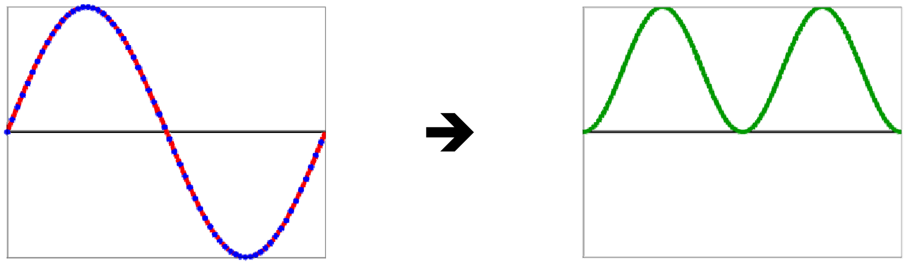
Look-Ahead ED (H-1h)

- SCED with ability to bring online fast start resources
- It's intended to meet intra-hour power fluctuations
- Update load and variable generation forecasts
- It produces:
  - Generator setpoints
  - Schedule of fast start units



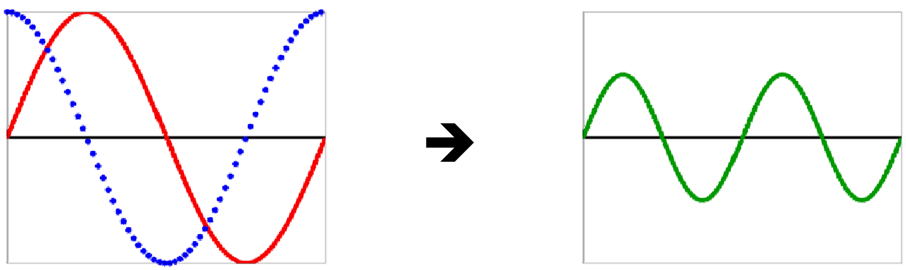
Power flow in an electric grid

- (Real) Power (P) is the integrated product of voltage (V) and current (I)
  - For AC circuits with only resistive loads



$P = V^{RMS} * I^{RMS}$

  - Reactive loads (inductors & capacitors) shift the I-V phase; worst case:



$P = 0$

- Apparent Power (S) is $V^{RMS} * I^{RMS}$
  - Governs generation costs and transmission constraints
  - $(S^2 - P^2)^{1/2}$ is the Reactive Power (Q)

Solving Economic Dispatch

- In practice, operators linearize the underlying system
  - Basis of Stochastic UC presented in previous talk
- DCOPF
  - “Small angle” assumption for voltage angle
  - Omit reactive power
  - $P_{1,2} = B (\theta_2 - \theta_1)$
- Yields suboptimal (and frequently infeasible) solutions
  - Actual system voltage angles can exceed 30 degrees

Formulating the ACOPF

- ACOPF: Determine P, Q, V, I for every line, generator in grid
- Multiplicity of formulations
  - Choice of basis (for network constraints) significant:
    - PQV polar: P, Q, V, θ
    - PQV rectangular: P, Q, v^r, v^j
    - IV rectangular: P, Q, i^r, i^j, v^r, v^j
  - Rectangular basis
    - $V \cdot \sin(w + \theta) = v^r \cdot \sin(w) + v^j \cdot \sin(w + \pi/2)$.
    - V, I in the complex plane

ACOPF-PQV (polar)

$$
\begin{aligned}
\min \quad & c(P^2 + Q^2) \\
s.t. \quad & P_n = \sum_{mk} V_n V_m (G_{nmk} \cos\theta_{nm} + B_{nmk} \sin\theta_{nm}) + P_n^d \\
& Q_n = \sum_{mk} V_n V_m (G_{nmk} \sin\theta_{nm} - B_{nmk} \cos\theta_{nm}) + Q_n^d \\
& P^{\min} \le P \le P^{\max} \\
& Q^{\min} \le Q \le Q^{\max} \\
& V^{\min} \le V \le V^{\max} \\
& \theta_{nm}^{\min} \le \theta_n - \theta_m \le \theta_{nm}^{\max}
\end{aligned}
$$

ACOPF-PQV (rectangular)

$$
\begin{aligned}
\min \quad & c(P + jQ) \\
s.t. \quad & P + jQ = V \bullet Y^{*} V^{*} + P^{d} + jQ^{d} \\
& P^{\min} \le P \le P^{\max} \\
& Q^{\min} \le Q \le Q^{\max} \\
& p_{nmk}^{2} + q_{nmk}^{2} \le (s_{k}^{\max})^{2} \\
& (V^{\max})^{2} \le V^{r} \bullet V^{r} + V^{j} \bullet V^{j} \le (V^{\max})^{2} \\
& \theta_{nm}^{\min} \le \arctan\left(\frac{v_{n}^{j}}{v_{n}^{r}}\right) - \arctan\left(\frac{v_{m}^{j}}{v_{m}^{r}}\right) \le \theta_{nm}^{\max}
\end{aligned}
$$

ACOPF-IV (rectangular)

$$
\begin{aligned}
\min \quad & c(P + jQ) \\
s.t. \quad & P = V^r \bullet I^r + V^j \bullet I^j + P^d \\
& Q = V^j \bullet I^r - V^r \bullet I^j + Q^d \\
& P^{\min} \leq P \leq P^{\max} \\
& Q^{\min} \leq Q \leq Q^{\max} \\
& (i_{nmk})^2 \leq (i_k^{\max})^2 \\
& (V^{\max})^2 \leq V^r \bullet V^r + V^j \bullet V^j \leq (V^{\max})^2 \\
& \theta_{nm}^{\min} \leq \arctan\left(\frac{v_n^j}{v_n^r}\right) - \arctan\left(\frac{v_m^j}{v_m^r}\right) \leq \theta_{nm}^{\max}
\end{aligned}
$$

Stochastic ACOPF Motivation

- Increased penetration of renewable energy impacts fossil-fuel plants, in particular unit cycling.
- Units that are designed for base-load operation are being employed to help absorb renewable plants variability
- Consequences are increased O&M costs and higher forced outage rates
- How to dispatch generation to minimize the cycling of slow generators while taking into account the stochastic nature of wind and solar plants?

Stochastic ACOPF Formulation

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- Objective

$$\min \sum_{s \in S} p_s \cdot C(P)$$

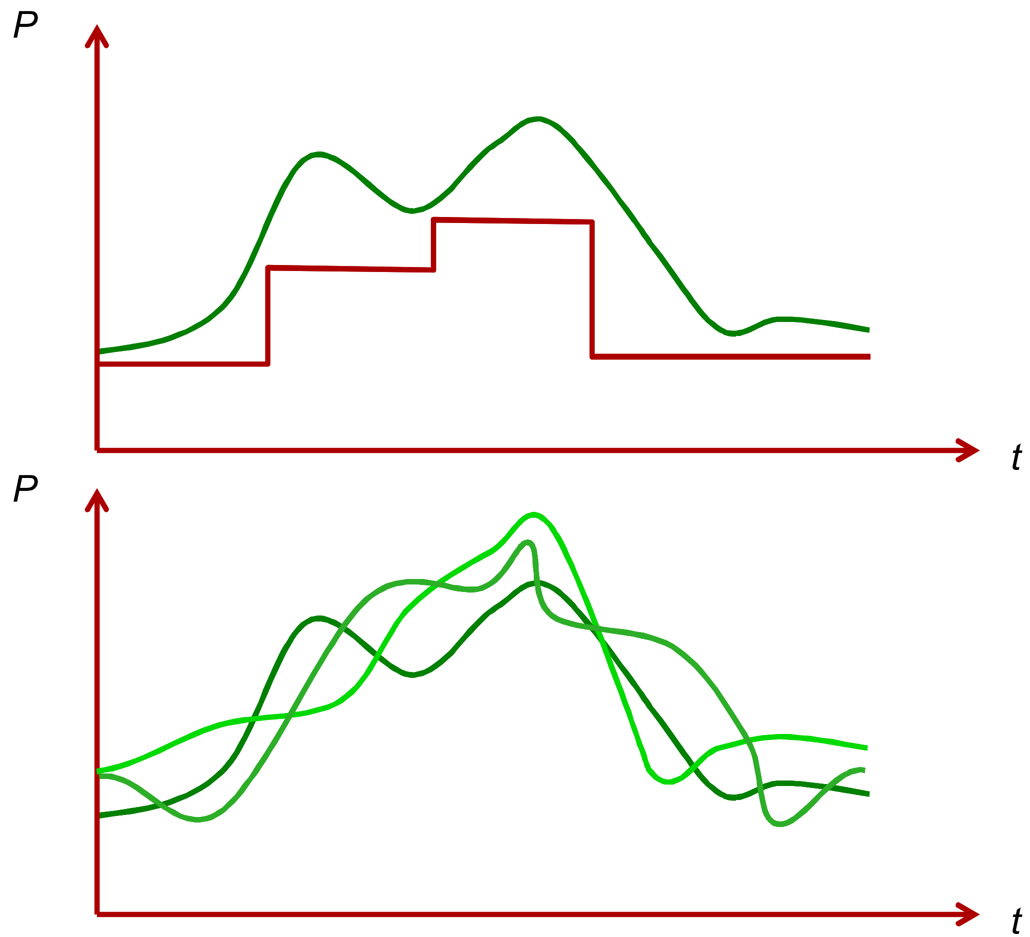
- where

$$C(P) = a + bP + cP^2 + kP_\Delta^2$$

$$P_\Delta(t) = P(t) - P(t-1) \qquad \forall t \in T$$

- First-stage variables are the generator set points at the first time step $P_{ed} = P(1)$
- Second-stage variables are the ramping of the units throughout time P_Δ s.t. $P(t) = P_{ed} + \sum_{i=0}^{t} P_\Delta(i)$
- Base load units have high *k* values
- Peakers have zero *k* value

Stochastic ACOPF Illustration



Adding Renewables to ACOPF

- Renewable plants are a significant source of stochasticity
- They do use no "fuel" to provide power = No changes to objective function
- Renewables are modeled as "must-take" resources: negative real power loads

$$\sum_{g \in G_n} P + \sum_{w \in W_n} P_w + \sum_{l \in L_n} P_l - \sum_{m \in M_n} P_m - \sum_{d \in D_n} P_d = 0 \qquad \forall n \in N, t \in T$$

- where
  - G_n are the generators at node n
  - W_n are the renewable generators at node n
  - L_n are the lines connected into node n
  - M_n are the lines out of node n

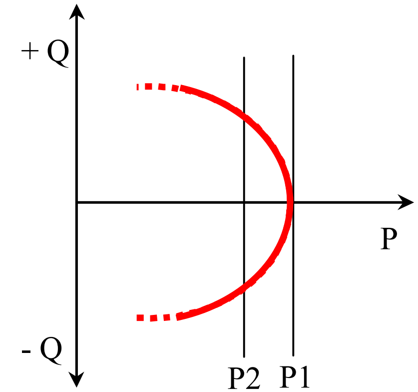
Adding Renewables to ACOPF

- Modern renewable power plants can control their reactive power output, thus Q_w is a variable

$$\sum_{g\in G_n} Q_g + \sum_{w\in W_n} Q_w + \sum_{l\in L_n} Q_l - \sum_{m\in M_n} Q_m - \sum_{d\in D_n} Q_d = 0 \quad \forall n\in N, t\in T$$

- Additionally, reactive power limits are given by their power electronics interface rating (MVA)

$$P_w^2 + Q_w^2 \le MVA_{rating}^2 \quad \forall w\in W, t\in T$$



Test Case Results

- Benefit Analysis for one representative day
  - Stochastic ED
    - Total fixed cost: $341,808.28
    - Total expected production cost: $188,434.03
    - Total expected load shed: 12.75 MWh
  - Deterministic ED
    - Total fixed cost: $286,944.62
    - Total expected production cost: $270,058.91
    - Total expected load shedding: 418.84 MWh
  - Total expected savings: $26,761.22

Computational Results

- Test instance
  - IEEE 118, 300
  - Stochastic wind, 100 scenarios
- Extensive form
  - IPOPT, after 1 day of CPU on a 16-core workstation
    - No feasible solution found
- PH, 20 iterations, serial
  - ~14 hours, 2.5% optimality gap
- PH, 20 iterations, parallel (100 nodes)
- ~15 minutes, 2.5% optimality gap
- PH, 20 iterations, parallel with bundling (2 scenarios/bundle)
  - ~15 minutes, 1.5% optimality gap

QUESTIONS