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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)

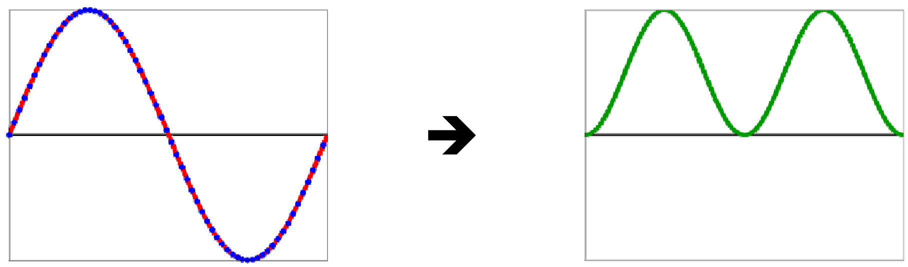
- Reliability Assessment (Reserve Adequacy Analysis - RAA)
- Minimize additional start-up and no load costs to provide sufficient capacity to satisfy the **forecasted** load plus the operating and replacement reserve requirements
- Clears ISO **forecasted load** at 2200h
- DAM commitments are respected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

Look-Ahead Economic Dispatch (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

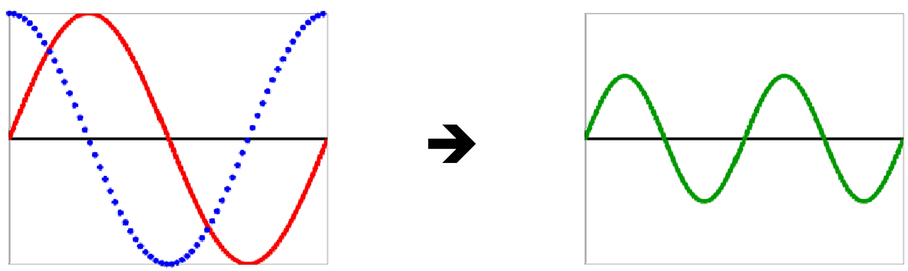
Power flow in an electric grid

- (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
  - Explicitly capture network topology
  - Minimize total generation costs
- 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
    - $V \cdot \sin(\omega + \theta) = v^r \cdot \sin(\omega) + v^j \cdot \sin(\omega + \pi/2)$.
    - 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)

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

ACOPF-IV (rectangular)

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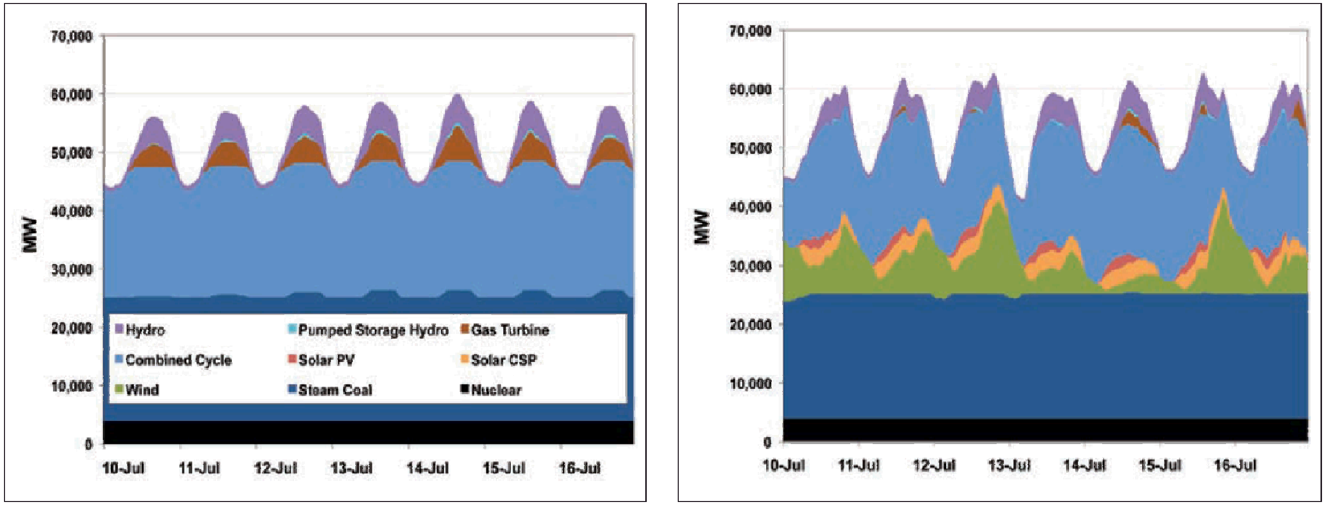
$$
\begin{aligned}
\min \quad & c(P + jQ) \\
s.t. \quad & I = YV \\
& P = V^r \cdot I^r + V^j \cdot I^j + P^d \\
& Q = V^j \cdot I^r - V^r \cdot I^j + Q^d \\
& P^{\min} \le P \le P^{\max} \\
& Q^{\min} \le Q \le Q^{\max} \\
& (i_{nmk})^2 \le (i_k^{\max})^2 \\
& (V^{\max})^2 \le V^r \cdot V^r + V^j \cdot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

Stochastic ACOPF Motivation

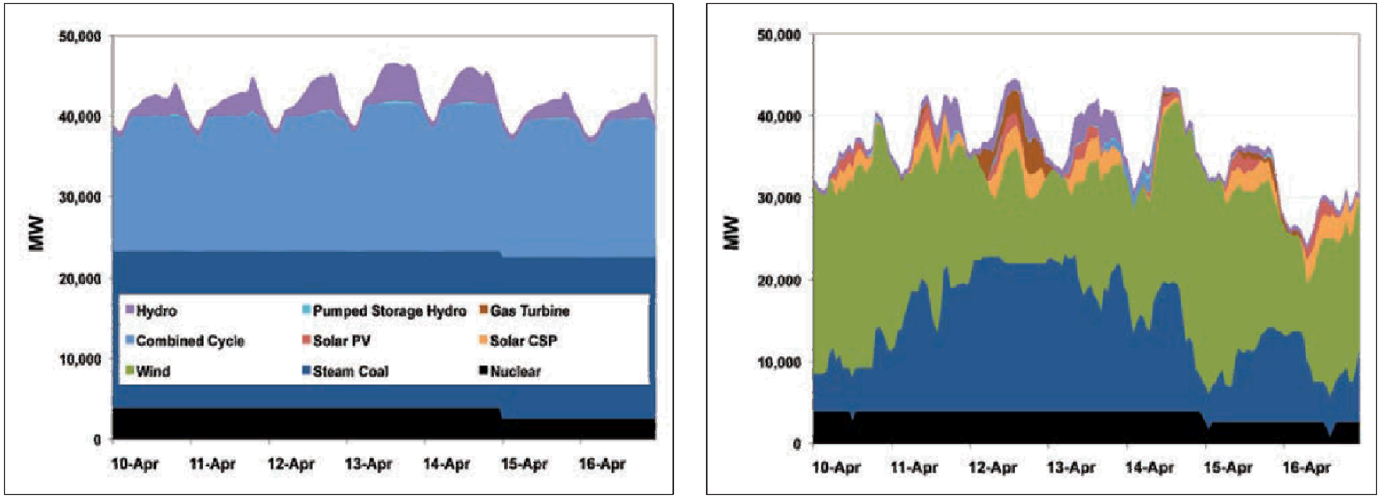
- Increased penetration of renewable (nondispatchable) energy impacts fossil-fuel plants, in particular unit cycling.
  - Sudden availability / loss of renewable generation must be absorbed by dispatchable generation
  - Curtailing renewables frequently disallowed by contract / regulation



0% and 30% renewable penetration for an "easy week" in July.
Reproduced from NREL 2010 *Western Wind and Solar Integration Study*

Stochastic ACOPF Motivation

- Units that are designed for base-load operation are being employed to help absorb renewable plants variability
  - Results in 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?



0% and 30% renewable penetration for an "challenging week" in April.
Reproduced from NREL 2010 *Western Wind and Solar Integration Study*

Adding Renewables to ACOPF

- Renewable plants are a significant source of uncertainty
- They do not use "fuel" to provide power
  - No structural changes to objective function (zero cost coefficients)
- Renewables are modeled as "must-take" resources
  - negative real power loads

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

- 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

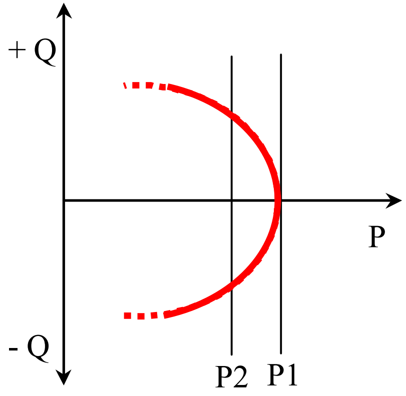
Adding Renewables to ACOPF

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

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

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

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



Stochastic ACOPF Formulation

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- Objective

$$\begin{aligned} \min \quad & \sum_{t \in T} \sum_{g \in G} C_{gt} \\ s.t. \quad & C_{gt} = a + b \max(P_g, P(t)) + c \max(P_g, P(t))^2 + k(P_{gt}^{\Delta})^2 \\ & P(t) = P_g + \sum_{\tau=0}^{\tau=t} P_{g\tau}^{\Delta} \end{aligned}$$

- Add explicit ramping costs (*k*)
- First-stage: generator set points (P_g) at the first time step
- Second-stage: ramping of the units through time
  - Base load units have high *k* values
  - Peakers have low *k* value

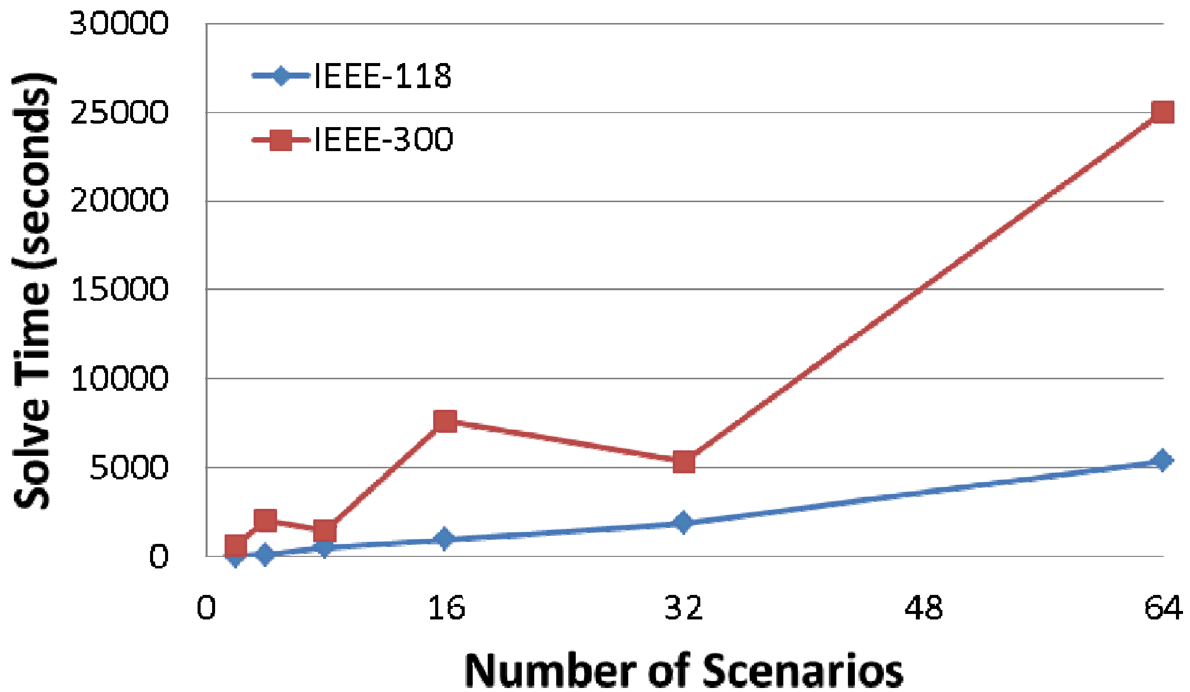
Case Studies

- IEEE Test cases
  - 118-bus system
    - 118 buses
    - 186 lines
    - 54 generators
  - 300-bus system
    - 300 buses
    - 411 lines
    - 69 generators
- 4 period model

- Implementation
  - PQV (rectangular)
  - Pyomo / PySP
  - Ipopt 3.10.1 w/ MA27
  - 4x Intel Xeon E5-4650 (32 cores @ 2.70GHz)
  - 512 GB RAM

Extensive form not tractable

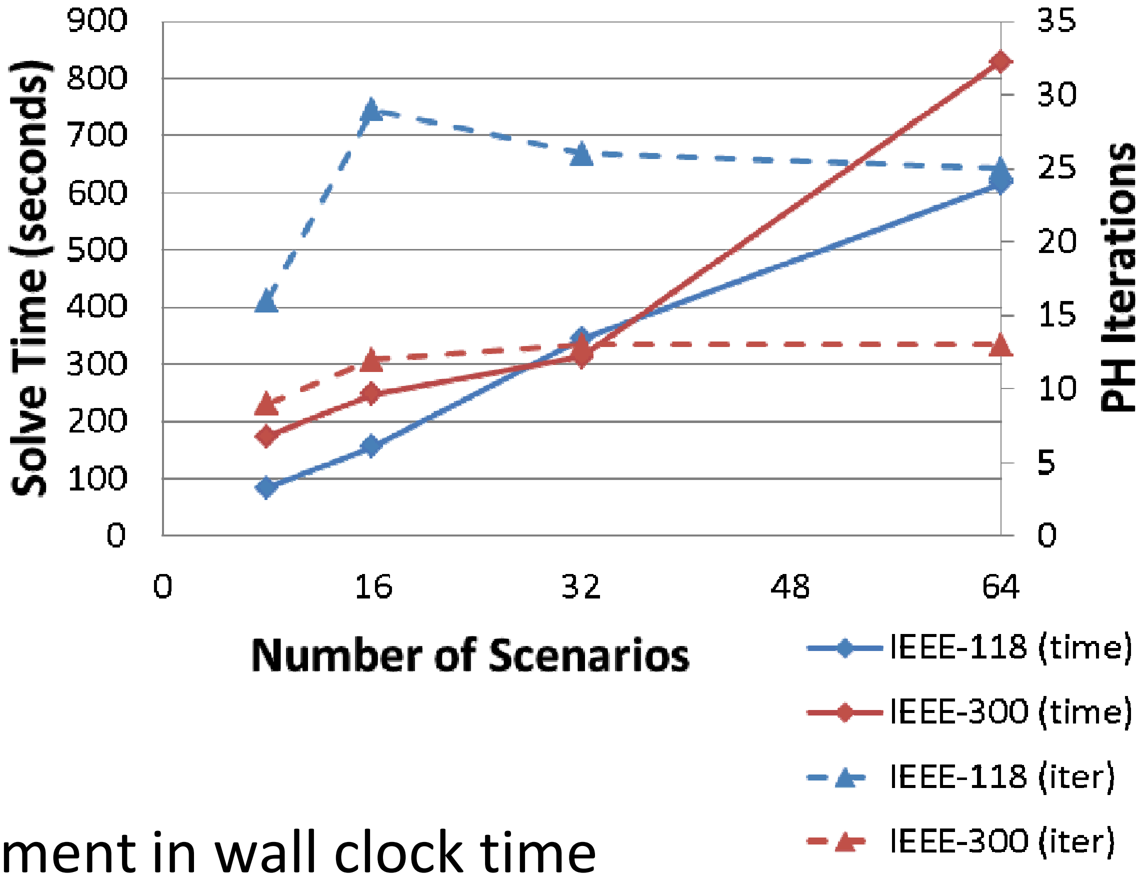
- Target:
  - <<300 seconds



- Disclaimer: Significant tuning opportunities remain
  - Warm-starting / initialization
  - Model presolve (not currently available in Pyomo)

Progressive Hedging

- Parallel solution
  - MPI on single machine
  - Weak scaling

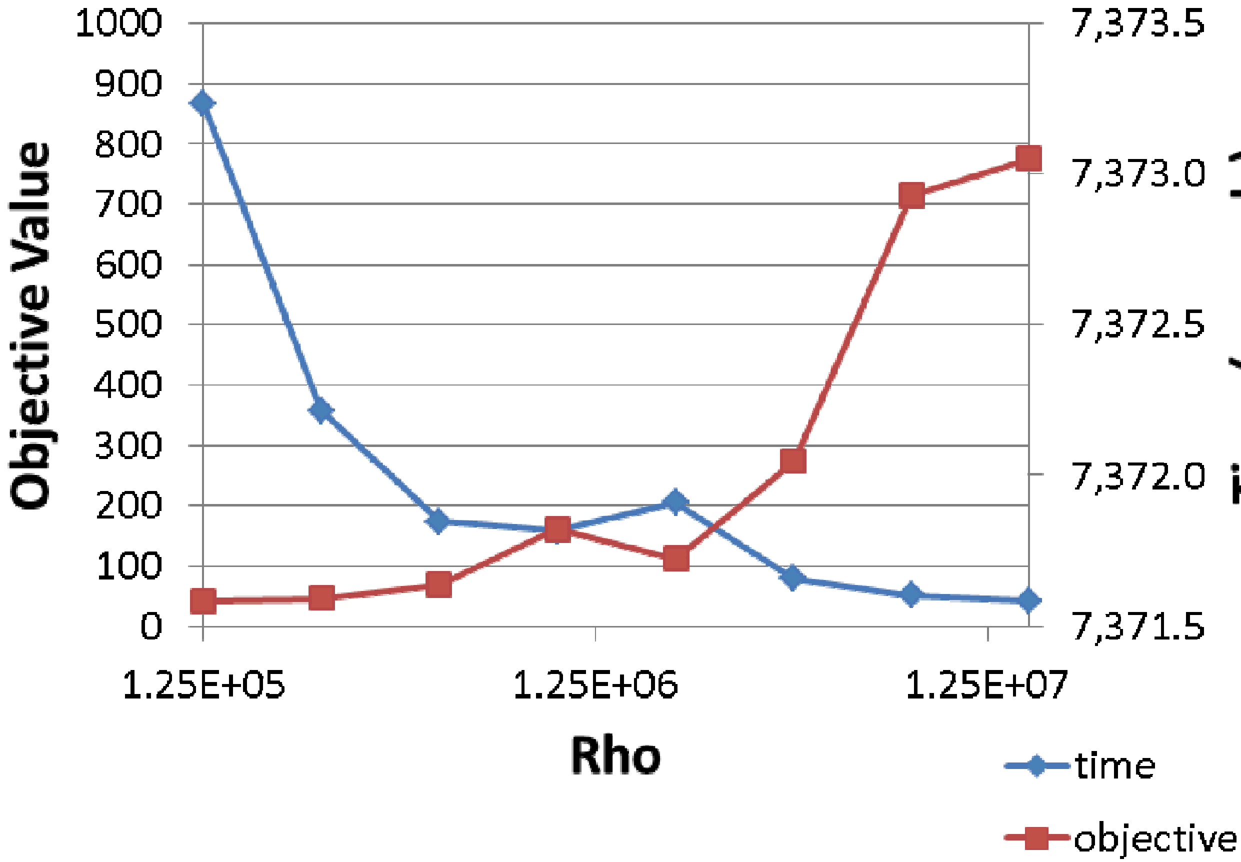


- *Extremely* tight convergence constraint (1E-5)

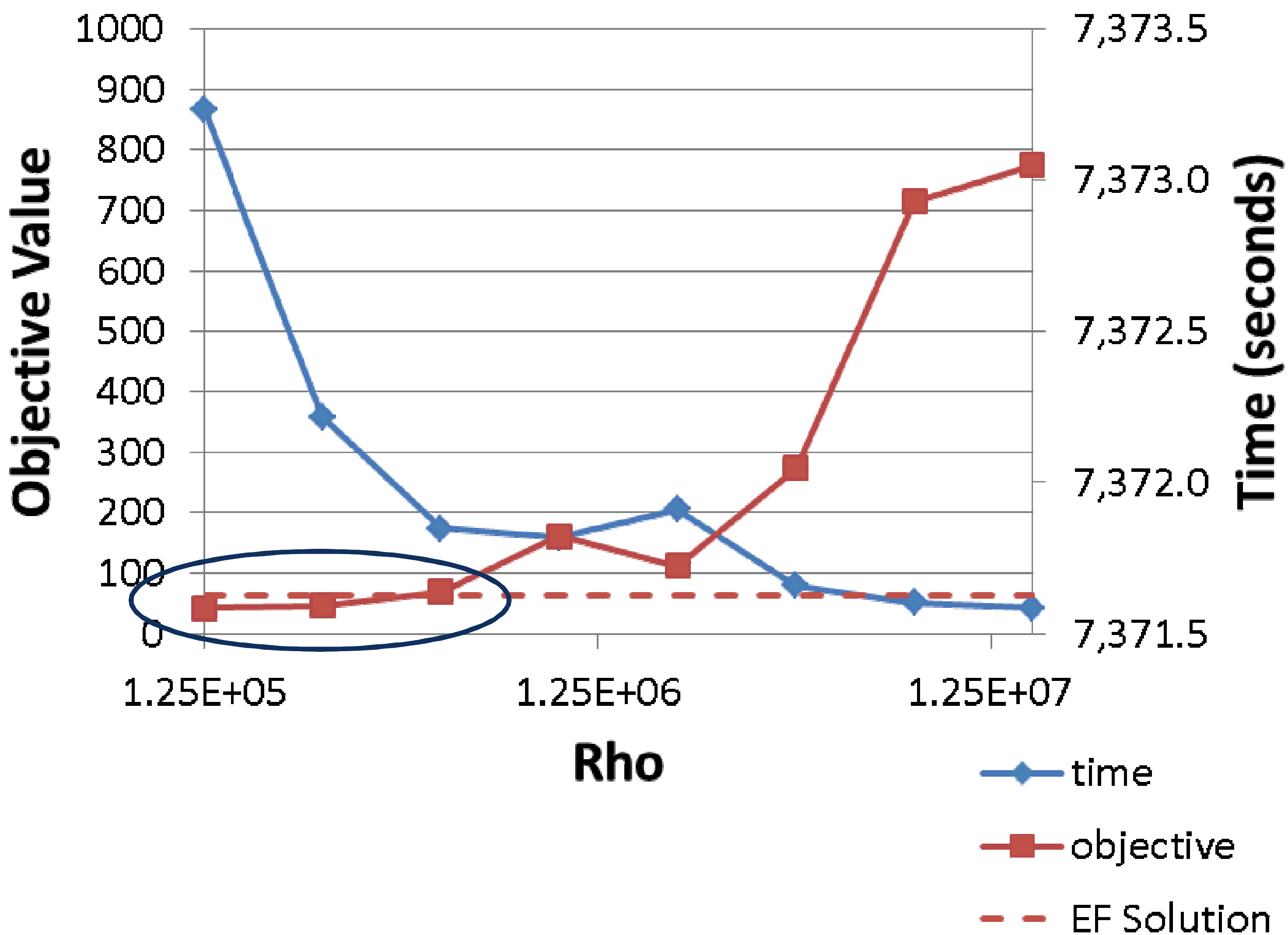
- 10x – 80x improvement in wall clock time

Progressive hedging: tuning ρ

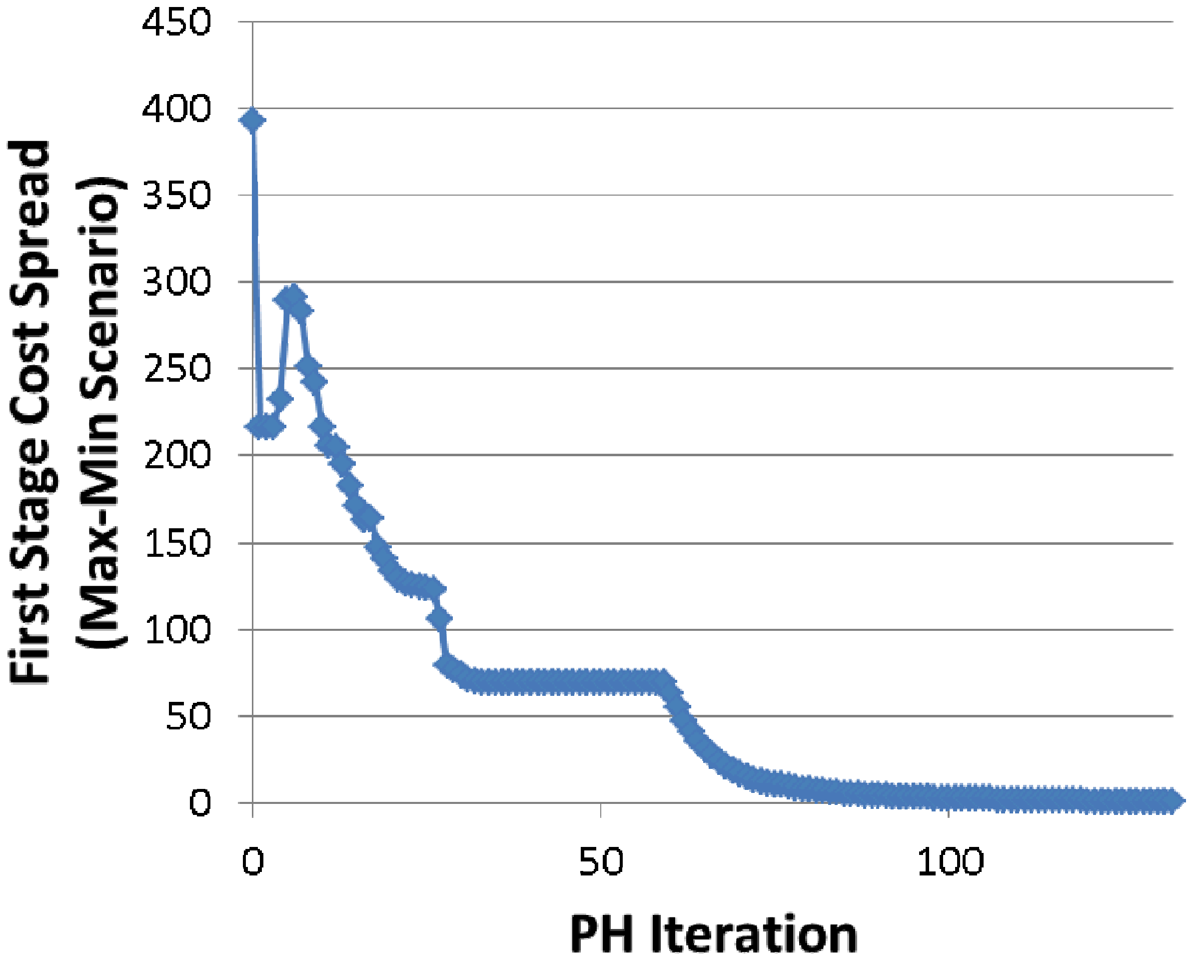
- “Surprisingly” high rho required
  - (118 bus, 16 scenario, 1e-5 convergence)



Impact of nonconvexity



Impact of nonconvexity (2)



Summary

- Stochastic ACOPF has the potential to significantly impact grid operations
  - Integration of renewable (nondispatchable) generation
  - Pricing ramping products?
- Extensive Form convergence a concern
- Progressive Hedging (with appropriate tuning) effective at getting high-quality solutions in tractable time

- *Significant tuning, formulation, and algorithmic opportunities remain*