Next Generation of More Efficient Markets and Planning

Richard O’Neill
Federal Energy Regulatory Commission
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Modeling, Simulation and Optimization for the 21st Century Electric Power Grid
Lake Geneva, Wisconsin

October 23, 2012
Views expressed are not necessarily those of the Commission
paradigm changes: fictions, frictions, inertia and politics

300 BC: Aristotle’s elements
- Air, Water, Fire, Earth, Aether
- 'proved' voids impossible therefore no zero
- aether fills all potential voids

Middle Ages: Roman Church adopts Aristotle’s view
- Punished for contrary views
- Retards the development of algebra

20th century: aether gradually disappears

21st century recycling
- aether theory recycled as dark energy
- Keeping zero
Electricity better fictions, paradigm changes and politics

- **19th century competition:**
  - Edison v. Westinghouse

- **20th century:** Sam Insull’s deal
  - franchise ‘unnatural’ monopoly
  - cost-of-service rates

- **1927 PJM formed a ‘power pool’**

- **1962** Carpentier formulates the ACOPF

- **1965 Blackout:**
  - Edward Teller: “power systems need sensors, communications, computers, displays and controls”

- **2012 still working on it**
End-use markets

got to get you into my life

Consumers receive very weak price signals
- monthly meter; ‘see’ monthly average price
- On a hot summer day
  - wholesale price = $1000/MWh
  - retail price < $100/MWh
- results in market inefficiencies and
- poor purchase decisions for electricity and electric appliances.

Smart meter and real-time price are key
Solution: smart appliances
- real time pricing, interval meters and
- Demand-side bidding
- Large two-sided market!!!!!!!!!!
New markets
new technologies

- Batteries, flexible generators, topology optimization and responsive demand
- Optimally integrated
- Off-peak
  - Generally wind is strongest
  - Prices as low as -$30/MWh
- Ideal for battery charging
More flexible transmission markets

- Thermal capacity is similar to a storage device: manage dynamically
- Relaxation penalties vs dynamic management of transmission assets
- Incentives for transmission owners
<table>
<thead>
<tr>
<th>ISO</th>
<th>Generation megawatts</th>
<th>Transmission Lines (miles)</th>
<th>Population (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAISO</td>
<td>57,124</td>
<td>25,526</td>
<td>30</td>
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<tr>
<td>ISO-NE</td>
<td>33,700</td>
<td>8,130</td>
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<tr>
<td>Midwest</td>
<td>144,132</td>
<td>55,090</td>
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<tr>
<td>NYISO</td>
<td>40,685</td>
<td>10,893</td>
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<tr>
<td>SPP</td>
<td>66,175</td>
<td>50,575</td>
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<tr>
<td>PJM</td>
<td>164,895</td>
<td>56,499</td>
<td>51</td>
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<tr>
<td>Total</td>
<td>506,711</td>
<td>206,713</td>
<td>172</td>
</tr>
</tbody>
</table>
What will be smarter?

- Generators, transmission, buildings and appliances
- Communications, software and hardware
- Markets and incentives

What is the 21st century market design?

- Locationally and stochastically challenged:
  - Wind, solar, hydro
- Fast response: batteries and demand
- Harmonize wind, solar, batteries and demand
- Greater flexibility more options
ISO Markets and Planning

Four main ISO Auctions

- Real-time: for efficient dispatch
- Day-ahead: for efficient unit scheduling
- Generation Capacity: to ensure generation adequacy and cover efficient recovery
- Transmission rights (FTRs): to hedge transmission congestion costs

Planning and investment

- Competition and cooperation

All use approximations due to software limitations

All use approximations due to software limitations
The Potential Impact...

- World Gross Production (2009): 20,000 TWh
- United States Gross Production (2009): 4,000 TWh
- At $30/MWh: cost $600 billion/year (world)
  - cost $120 billion/year (US)
- At $100/MWh: cost $2,000 billion/year (world)
  - cost $400 billion/year (US)
- In US 10% savings is about than $10 to $40 billion/yr
- FERC strategic goal: Promote efficiency through better market design and optimization software


money can't buy me love
From real time dispatch to investment planning

Mixed Integer Nonconvex Program

maximize \( c(x) \)
subject to \( g(x) \leq 0, \)
\( Ax \leq b \)
\( l \leq x \leq u, \)
some \( x \in \{0,1\} \)
c\( (x), g(x) \) may be non-convex

I didn’t know what I would find there
Mixed Integer Program

maximize \( cx \)
subject to \( Ax = b, \)
\( l \leq x \leq u, \)
some \( x \in \{0,1\} \)

And though the holes were rather small
They had to count

Better modeling for
Start-up and shutdown
Transmission switching
Investment decisions

It was twenty years ago today

solution times improved by \( > 10^7 \) in last 30 years
10 years becomes 10 minutes
MIP Paradigm shift:
Let me tell you how it will be

Pre-1999
- MIP can not solve in time window
- Lagrangian Relaxation
  - Solutions are usually infeasible
  - Simplifies generators; no switching

1999 Unit commitment conference and book
- Bixby demonstrates MIP improvements

2011 MIP creates savings > $500 million annually

MIP provides new modeling capabilities
- New capabilities may present new challenges

2015 MIP savings of > $2 billion annually
Combined Cycle Combustion Turbine

CT = combustion turbine
ST = steam turbine

<table>
<thead>
<tr>
<th>Unit</th>
<th>Startup Costs $</th>
<th>Cost per MWh $</th>
<th>Minimum Output MW</th>
<th>Maximum Output MW</th>
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</thead>
<tbody>
<tr>
<td>CT1</td>
<td>4000</td>
<td>60</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>CT2</td>
<td>4000</td>
<td>75</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>CT3</td>
<td>4000</td>
<td>90</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>ST</td>
<td>0</td>
<td>0</td>
<td>130</td>
<td>210</td>
</tr>
</tbody>
</table>
Linear Residual Demand and Local Optimal Solutions

Equilibrium Points - Local Optima

Happy ever after in the market place

'eco min'

Net Benefit

$50,000

$40,000

$30,000

$20,000

$10,000

$0

-$10,000

Marginal Cost

$120

$110

$100

$90

$80

$70

$60

$50

$40

$30

$20

$10

$0

-$10

-$20

Quantity

100 200 300 400 500 600 700

Total Benefits ▲ Local Optima ● Marginal Costs Derived Demand Equilibrium Points
Optimal transmission switching

**Solution:**
- Gen A produces 70
- Gen B produces 30

Cost: $8500

**Solution:**
- Gen A produces 0
- Gen B produces 100

Cost: $5000
Optimal Transmission Switching
DCOPF Formulation

- IEEE 118 bus model
  - 25% savings found [Fisher et al].

- ISONE 5000 bus model (includes NEPOOL, NYISO, NB, NS - costs for NEPOOL only)
  - 5% to 13% savings of $600,000 total cost for NEPOOL for one hour [Hedman et al]

- Does not include N-1 reliability constraints
Optimal Transmission Switching
N-1 DCOPF

- Savings while including reliability constraints

- IEEE 118 Bus Model
  - Up to 16% savings with N-1 DCOPF transmission switching [Hedman et al]

- IEEE 73 (RTS 96) Bus Model
  - Up to 8% savings with N-1 DCOPF transmission switching [Hedman et al]
Transmission switching

Philpott: switching using column generation lowers unit commitment

Ruiz et al: captured up to 96% of potential cost savings with limited computational effort

Ostrowski et al Anti-Islanding on RTS-96

<table>
<thead>
<tr>
<th>TS problem w/o connectivity</th>
<th>with connectivity constraints</th>
<th>with N-1 connectivity constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>Nodes</td>
<td>Time (s)</td>
</tr>
<tr>
<td>524</td>
<td>11,306</td>
<td>204</td>
</tr>
<tr>
<td>32</td>
<td>179</td>
<td></td>
</tr>
</tbody>
</table>
Better solutions found quickly
In 5 years solutions are 100 times faster
Now considered part of the smart grid
Potential
- solutions have optimality gaps
- higher savings may be found
- still takes too long to solve to optimality
- Better solutions are acceptable
Useful in many applications
Next step: AC switching
<table>
<thead>
<tr>
<th>Problem</th>
<th>Current</th>
<th>Next Decade</th>
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</thead>
<tbody>
<tr>
<td>Corrective switching</td>
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<td>Real-time</td>
</tr>
<tr>
<td>Real-time market</td>
<td>Pre-studied</td>
<td>Real-time</td>
</tr>
<tr>
<td>Day-ahead market</td>
<td>Pre-studied</td>
<td>Day ahead</td>
</tr>
<tr>
<td>Maintenance scheduling</td>
<td>none</td>
<td>monthly</td>
</tr>
<tr>
<td>Optimal planning</td>
<td>none</td>
<td>annual</td>
</tr>
</tbody>
</table>
Enhanced wide-area planning models

- more efficient planning and cost allocation through a mixed-integer stochastic program.
- Integration into a single modeling framework
- Better models are required to
  - economically plan efficient transmission investments
  - compute cost allocations
- in an environment of competitive markets with locationally-constrained variable resources and criteria for contingencies and reserve capacity.
Complete ISO market design
Not quite there yet

- Smarter markets
  - Full demand side participation with real-time prices
  - Smarter hardware, e.g., variable impedance
  - Better approximations, e.g., DC to AC
  - Flexible thermal constraints and transmission switching
  - Smarter software with Petaflop computers

- ISO electric network optimization has roughly
  - $10^5$ nodes
  - $10^6$ constraints
  - $10^5$ binary variables

- Potential dispatch costs savings: 10 to 30%
Electric Network Markets

April 4, 2013
Air traffic controller as system operator

- Trip from DC to LA
  - 1/3 goes thru Toronto on Air Canada
  - 1/3 goes thru Chicago on United
  - 1/3 goes thru Dallas on American

- Trip time: milliseconds
- Who gets the money from the ticket?
- Is your Mother-in-law fungible?
Power Flow and Admittance

AC Model  
(Physics)  
\[ \text{Pik} = G_k V_i^2 - G_k (V_i V_j) \cos(\Theta_i - \Theta_j) - B_k (V_i V_j) \sin(\Theta_i - \Theta_j) \]
\[ \text{Qik} = -B_k V_i^2 - G_k (V_i V_j) \sin(\Theta_i - \Theta_j) + B_k (V_i V_j) \cos(\Theta_i - \Theta_j) - \text{Bcapik} V_i^2 \]

DC Model  
(Market model approximation. Can we do better?)  
\[ \text{Pik} = -B_k (\Theta_i - \Theta_j) \]

\[ G = \frac{R}{R^2 + X^2} \]
\[ B = \frac{-X}{R^2 + X^2} \]
AC Optimal Flow Problem

“DC OPF” formulations linearize the nonlinearities.

'ACOPF' formulation is a continuous nonconvex optimization problem
Most nonlinear solvers find at best local optimal solutions

Linear IV approximation to ACOPF
If promising, it can be embedded in binary formulations:
unit commitment models, and optimal topology models.
allows the use of exceptionally fast and robust MIP algorithms
Power Flow Equations

Polar Power-Voltage: 2N nonlinear equality constraints

\[ P_n = \sum_{mk} V_n V_m (G_{nmk} \cos \theta_{nm} + B_{nmk} \sin \theta_{nm}) \]

\[ Q_n = \sum_{mk} V_n V_m (G_{nmk} \sin \theta_{nm} - B_{nmk} \cos \theta_{nm}) \]

Rectangular Power-Voltage: 2N quadratic equality constraints

\[ S = P + jQ = \text{diag}(V) I^* = \text{diag}(V)[YV]^* = \text{diag}(V)Y^*V^* \]

Rectangular Current-Voltage (IV) formulation.

Network-wide \textit{LINEAR} constraints: 2N linear equality constraints

\[ I = YV = (G + jB)(V^r + jV^j) = GV^r - BV^j + j(BV^r + GV^j) \]

where \( I^r = GV^r - BV^j \) and \( I^j = BV^r + GV^j \)
Rectangular ACOPF-IV formulation.

Network-wide objective function: \( \text{Min } c(P, Q, I, V) \) \hspace{1cm} (50)

Network-wide constraint: \( I = YV \) \hspace{1cm} (51)

Bus-specific constraints:

\[ P = V^r \cdot I^r + V^j \cdot I^j \leq P^\max \] \hspace{1cm} (54)
\[ P^\min \leq P = V^r \cdot I^r + V^j \cdot I^j \] \hspace{1cm} (55)

\[ Q = V^j \cdot I^r - V^r \cdot I^j \leq Q^\max \] \hspace{1cm} (56)
\[ Q^\min \leq Q = V^j \cdot I^r - V^r \cdot I^j \] \hspace{1cm} (57)

\[ V^r \cdot V^r + V^j \cdot V^j \leq (V^\max)^2 \] \hspace{1cm} (58)
\[ (V^\min)^2 \leq V^r \cdot V^r + V^j \cdot V^j \] \hspace{1cm} (59)

\[ (i^n_{mk})^2 \leq (i^\max_k)^2 \text{ for all } k \] \hspace{1cm} (60)

\[ [\Theta^\min_{nm} \leq \arctan(v^j_n/v^r_n) - \arctan(v^j_m/v^r_m) \leq \Theta^\max_{nm}] \] \hspace{1cm} (61)

\[ V^r \geq 0 \] \hspace{1cm} (62)
(51) are 2N linear equality constraints that apply throughout the network,

(54) - (57) are quadratic and non-convex.

(58) are convex quadratic inequality constraints, but

(59) are non-convex quadratic inequality constraints.

(61) could be eliminated and the problem becomes quadratic with linear network equations.
**Generator and Load Constraints.**

The lower and upper bound constraints for generation and load are:

\[
P_{\text{min}} \leq P \leq P_{\text{max}} \quad (24) \quad Q_{\text{min}} \leq Q \leq Q_{\text{max}} \quad (26)
\]

In terms of \( V \) and \( I \),

\[
V^r \cdot I^r + V^j \cdot I^j \leq P_{\text{max}} \quad (28) \quad P_{\text{min}} \leq V^r \cdot I^r + V^j \cdot I^j \quad (29)
\]

\[
V^j \cdot I^r - V^r \cdot I^j \leq Q_{\text{max}} \quad (30) \quad Q_{\text{min}} \leq V^j \cdot I^r - V^r \cdot I^j \quad (31)
\]

(28)-(31) are non-convex constraints.
Voltage constraints.

in rectangular coordinates

\[(v^r_m)^2 + (v^i_m)^2 \leq (v^{\text{max}}_m)^2\]

\[(v^{\text{min}}_m)^2 \leq (v^r_m)^2 + (v^i_m)^2\]

Voltage magnitude bounds are generally in the range, \([.95, 1.05]\).

High voltages are often constrained by circuit breakers capabilities.

Low voltage constraints can be due operating requirements of motors or generators.
Line Flow Constraints

Power Line Flow Constraints.

\[
(s_{nmk}^r)^2 + (s_{nmk}^i)^2 = |s_{nmk}|^2 \leq (s_{max_k})^2 \tag{37}
\]

Current Line Flow Limitations.

\[
(i_{nmk}^r)^2 + (i_{nmk}^i)^2 \leq (i_{max_{nmk}})^2 \tag{38}
\]

convex quadratic and isolated to the complex current at the bus.

Voltage Angle Constraints.

\[
\theta_{min_{nm}} \leq \theta_n - \theta_m \leq \theta_{max_{nm}}. \tag{39}
\]

(38) appears to be the best choice
The Linear Approximations to the IV Formulation

We take three approaches to constraint formulation.

If the constraint is nonlinear,

use the first order Taylor series approximation

updated at each LP iteration

If the constraint is convex,

add linear cutting planes to remove from the linear feasible

Can we guarantee feasibility with this approach?
Linear Voltage Approximations.

A first order Taylor's series approximation about \((V^r, V^j)\)

\[V^r \cdot V^r + V^j \cdot V^j \approx 2V^r \cdot V^r + 2V^j \cdot V^j - V^r \cdot V^r - V^j \cdot V^j\]

Since higher losses occur at lower voltages, the natural tendency of the optimization will be toward higher voltages.
Preprocessed Linear Voltage and Current Constraints.

\[(v^r_m)^2 + (v^i_m)^2 \leq (v^{\text{max}}_m)^2\]

Current constraint set has no hole

Iterative Voltage and Current Constraints.

Adding a maximum-voltage linear constraint.
Non-Convex Minimum Voltage Constraints.

\[(v_{\text{min}}^r)^2 \leq (v_r^r)^2 + (v_r^i)^2\]

non-convex, the linear approximation is problematic.

approximation and eliminates parts of the feasible region

This is probably not a good idea, but maybe.
Real Power Constraints. At each bus

first order approximation at bus n around $v^r_n, i^r_n, v^j_n, i^j_n$

$$p^\sim_n = v^r_n i^r_n + v^j_n i^j_n + v^r_n i^r_n + v^j_n i^j_n - (v^r_n i^r_n + v^j_n i^j_n)$$

hessian is

\[
\begin{pmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0
\end{pmatrix}
\]

eigenvalues: 2 are 1 and 2 are -1
Reactive Power Constraints. At each bus

First order approximation around $v^r_n, i^r_n, v^i_n, i^i_n$

$$q^\sim_n = v^i_n i^r_n - v^r_n i^i_n - v^r_n i^i_n + v^i_n i^r_n - (v^i_n i^r_n - v^r_n i^i_n)$$

The Hessian is

$$\begin{bmatrix}
0 & 0 & 0 & -1 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 \\
-1 & 0 & 0 & 0 \\
\end{bmatrix}$$

Eigenvalues: 2 are 1 and 2 are -1.
Computational experience

MINOS, CONOPT, IPOPT, KNITRO SNOPT

All nonlinear except Knitro find the 'optimal' solution

Ten random starting points, the average cpu time

14 bus: GUROBI < all nonlinear solvers
30 bus: GUROBI < 2 of 5 nonlinear solvers
57 bus: GUROBI < all nonlinear solvers
118 bus: CPLEX and GUROBI < all but one nonlinear solver
300 bus: CPLEX and GUROBI < all but two nonlinear solver

For the naïve approximation and implementation,

LP approach is faster or competitive with nonlinear solvers
ACOPF 2020

software

Engineering judgment
# Software technology impact on markets

<table>
<thead>
<tr>
<th>Problem algorithm</th>
<th>Corrective dispatch</th>
<th>Real-time market</th>
<th>day-ahead market</th>
<th>RUC capacity</th>
<th>planning</th>
</tr>
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<tbody>
<tr>
<td>Optimal topology</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Unit Commitment</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Stochastic models</td>
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<td>ACOPF</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

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Decomposition and Grid (parallel) computing
- Real/reactive
- Time

Good approximations
- Linearizations
- Convex

Avoiding local optima
Nonlinear prices
Better tree trimming
Better cuts
Advance starting points

If you really like it you can have the rights
It could make a million for you overnight
Future ISO Software

Real-time:
- AC Optimal Power Flow with <5 min dispatch, look ahead and explicit N-1 reliability

Day-ahead:
- explicit N-1 ACOPF with unit commitment and transmission switching with <15 min scheduling

Investment/Planning:
- extension of day-ahead market
- Greater detail and topology
- more time to solve
Market Design

Expected Optimal AC Topology and Unit Commitment

"Everything should be made as simple as possible ... but not simpler."  Einstein

The magical mystery tour is waiting to take you away, waiting to take you away.