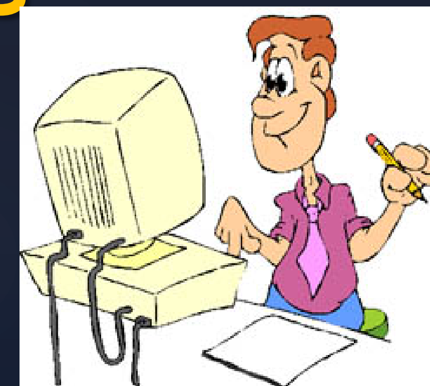
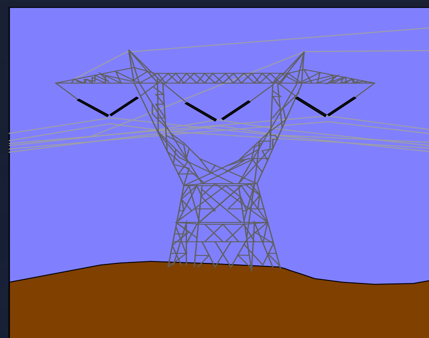
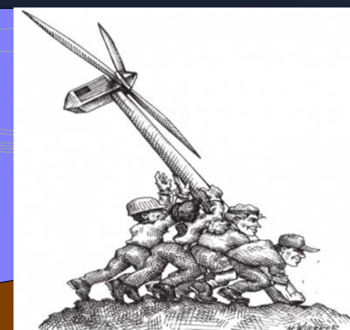
Computational Challenges in Electric Power Markets







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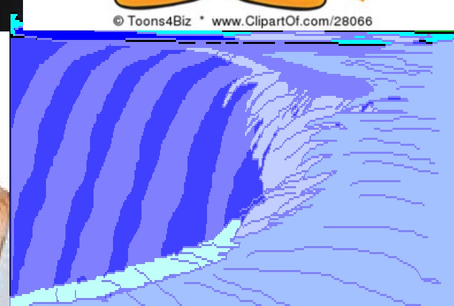
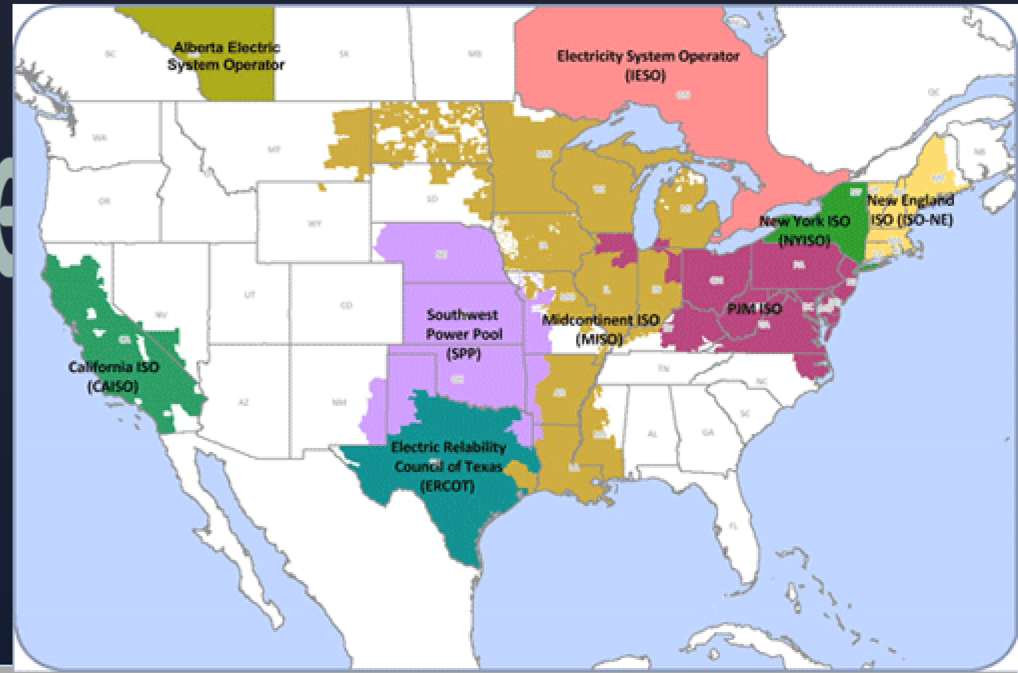
January 11, 2016
Views expressed are not necessarily those of the Commission



fictions, approximations, paradigm changes and politics

- ⇨300 BC: Aristotle's science
  - ⇨Air, Water, Fire, Earth, Aether
  - ⇨'proved' voids impossible therefore no zero
  - ⇨aether fills all potential voids
- ⇨Middle Ages: Roman Church adopts Aristotle
  - ⇨Punished for contrary views
  - ⇨Retards development of algebra in Europe
- ⇨aether gradually disappears
- ⇨Zero appears in Europe
- ⇨21st century recycling
  - ⇨aether theory recycled as dark energy
  - ⇨Keeping zero

Why study Power Markets



- United States Gross Production (2009): ≈4,000 TWh
- At $50/MWh: cost $600 billion/year (world)
  - cost $200B (billion) /year (US)
- At $100/MWh: cost $2,000 billion/year (world)
  - cost $400B/year (US)
- In US 10% savings is about than $20 to $40B/yr
- All current ISO markets are constrained by software ;-(

Source: IEA Electricity Information, 2010.

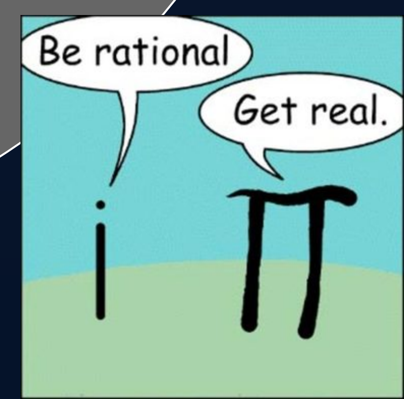
☹ **money can't buy you love**

1960s

Edward Teller on 1965 Blackout:
"power systems need sensors, communications, computers, displays and controls"

software

Engineering judgment



1970 and 1980s

Regulation is cost-of-service

Vertically integrated utilities

Optimize capital investment

software

Engineering judgment

1990s

Open access (FERC Order 888)

ISOs form

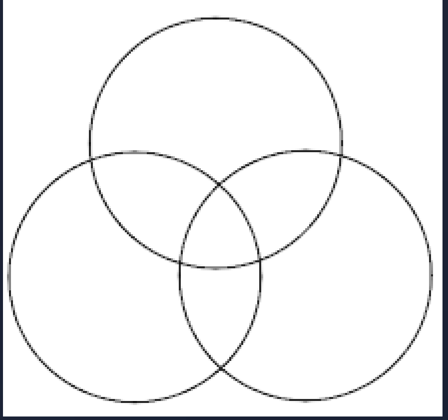
Markets evolve

Efficiency objective

Engineering judgment

software

Market Design
Intersection of Disciplines

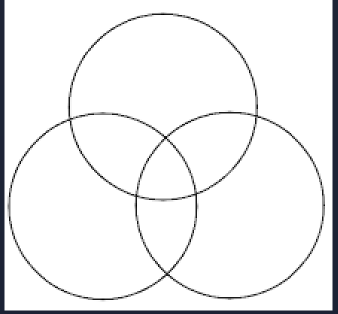


- ⇨ Institutions and Legacies
  - ⇨ Federal commission: just and reasonable rates for wholesales and transmission
  - ⇨ state commissions: eminent domain and rates for retail sales and distribution
  - ⇨ ISOs Stakeholder process: voting rules and coalitions
- ⇨ Game Theory
  - ⇨ Non-cooperative game theory: no coalitions
  - ⇨ Cooperative game theory: non-cooperative with coalitions
- ⇨ Electrical engineering and physics
- ⇨ Economics: primary objective is market efficiency
- ⇨ Optimization over complex algebra and binary variables

Electrical engineering myths and shibboleths

- ⇨Physics of AC power (**non-convex over** complex algebra)
- ⇨Traditional approximations and 'good utility practice'
- ⇨Reliability rules imply economic values
  - ⇨VOLL is between $4,000 and $10,000/MWh
- ⇨Misguided objectives:
  - ⇨Volt-Var optimization
  - ⇨Minimize losses
- ⇨ Introduction of new technology is not the internet model.
- ⇨ Entry must run the gantlet of educational inertia, bureaucracy and lack of large-scale testing on real data

Non-convex Auction Market Economics

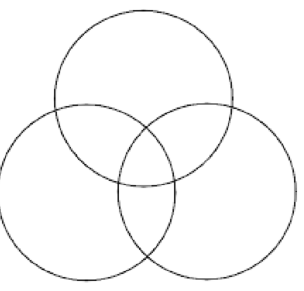


- ⇨ primary objective is market efficiency (max market surplus)
  - ⇨ No 'single market-clearing price'
  - ⇨ Need multi-part pricing
  - ⇨ Internalize externalities
  - ⇨ Market power needs mitigation (cost-based offers)
- ⇨ Secondary objective: good incentives and prices
- ⇨ The distribution of benefits is a separate problem
  - ⇨ Non-confiscatory and revenue neutral
  - ⇨ Incentives for efficient bidding (more important)
  - ⇨ Incentives for efficient investment (less important)
  - ⇨ Investment signals are noisy

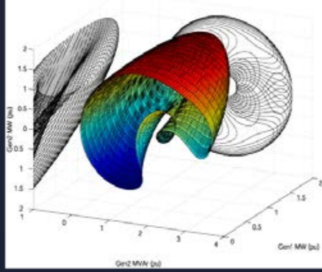
Bad Objectives, Public Goods and Equity

- ⇨Maximize surplus creates a largest benefits
- ⇨Equity: focused subsidies for needy
- ⇨Local public v private goods
  - ⇨Declaring a private good ot be a public good is mischievous

- ⇨Bad objective: Maximize consumer surplus
  - ⇨Is a steel producer more deserving that a solar facility
  - ⇨What if the generator is owned by the Little Sisters of the Poor?
  - ⇨Should we subsidize the heating of swimming pools?



Practical Non-convex Optimization



- ⇨ The optimization on non-convex functions is not well understood
- ⇨ Academic
  - ⇨ NP-hard arguments are only of theoretical concern
  - ⇨ Worst case bounds are of little value
  - ⇨ infinite convergence (10^{-8})
  - ⇨ Local optima
- ⇨ Practical
  - ⇨ Data is noisy
  - ⇨ Approximations are everywhere
  - ⇨ Objective best solution in the time window
  - ⇨ convergence tolerance of 10^{-3} is good

ISO Markets and Planning

- **Four main ISO Auctions**
  - Real-time: for efficient dispatch (every 5 minutes)
  - Day-ahead: for efficient unit scheduling (daily)
  - Generation Capacity: to ensure generation adequacy and cover efficient recovery (annual)
  - Transmission rights (FTRs): to hedge transmission congestion costs (annual)
- **Planning and investment** (annual)
  - Competition and cooperation
- All use approximations due to software limitations

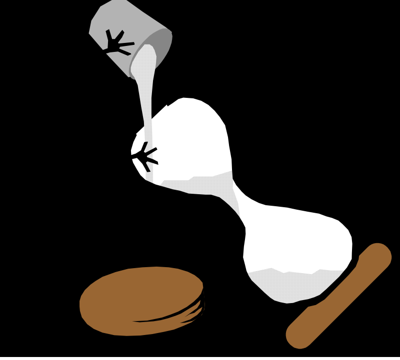
From real time dispatch to investment planning

Mixed Integer Nonconvex Program

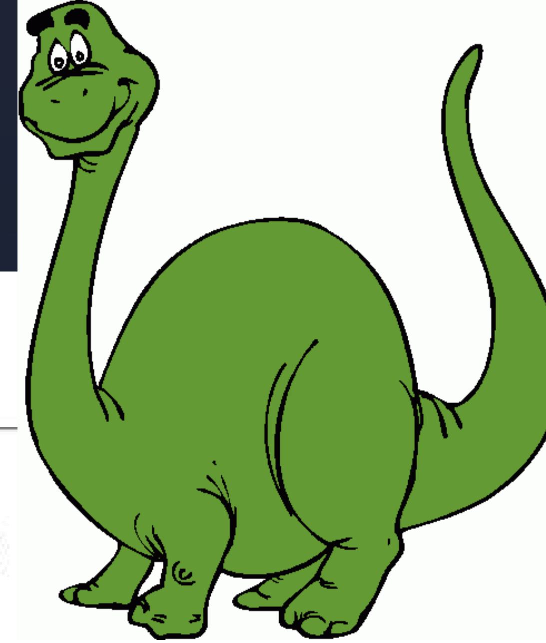
$$
\begin{aligned}
\text{maximize} \quad & c(x) \\
\text{subject to} \quad & g(x) \le 0, \\
& Ax \le b \\
& l \le x \le u, \\
& \text{some } x \in \{0,1\}
\end{aligned}
$$

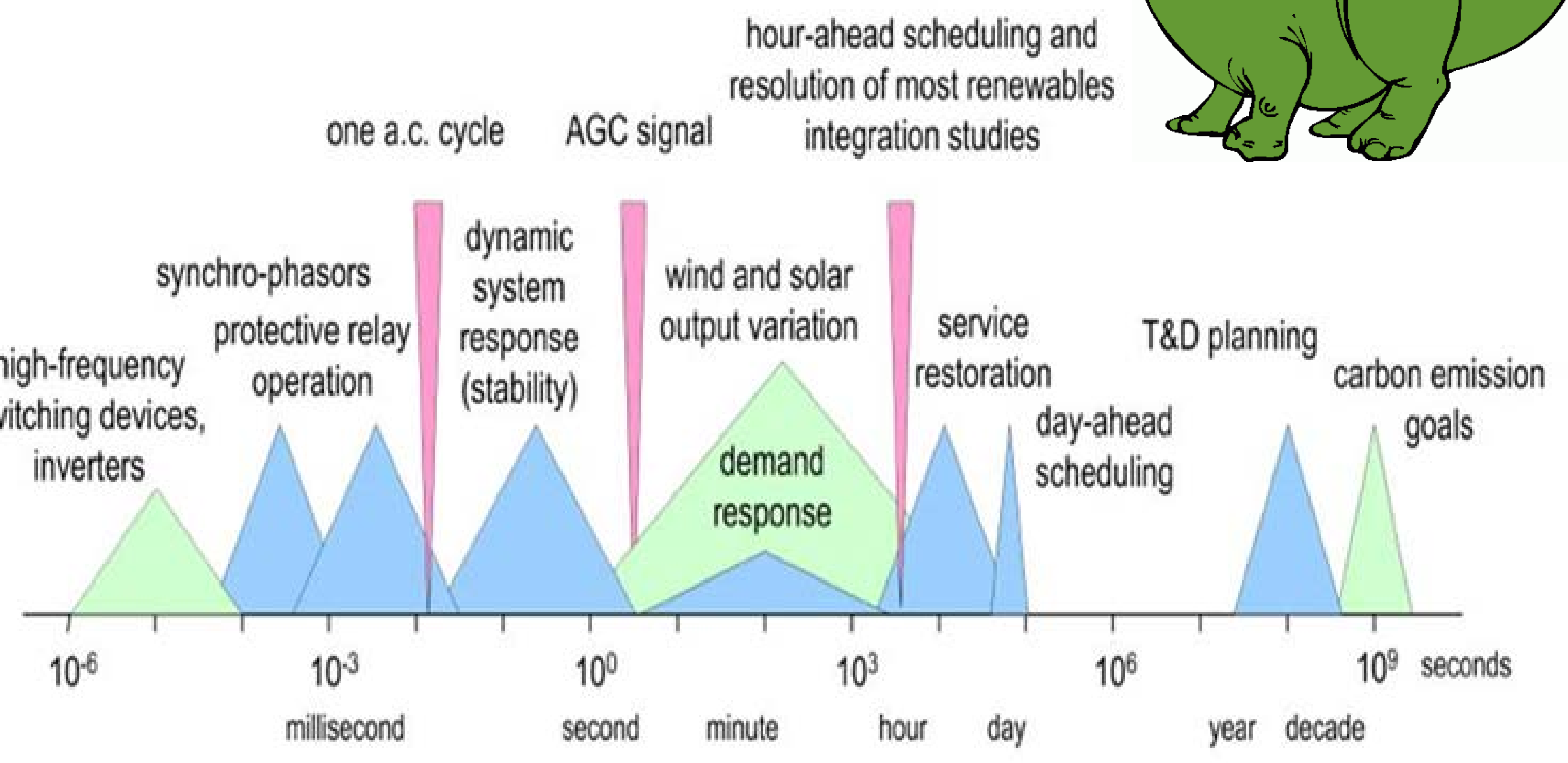
c(x), g(x) may be non-convex

I didn't know what I would find there



Optimization Time Scales





Market Approximation
Mixed Integer Linear 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 them all

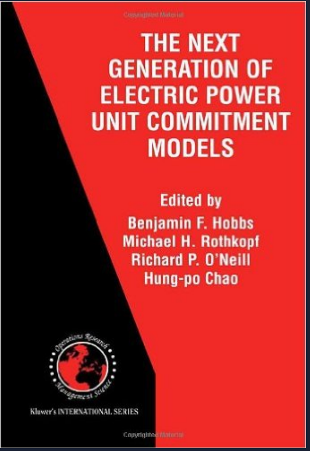
Better modeling for

- 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



Power Markets and MIP the early years

Let me tell you how it will be

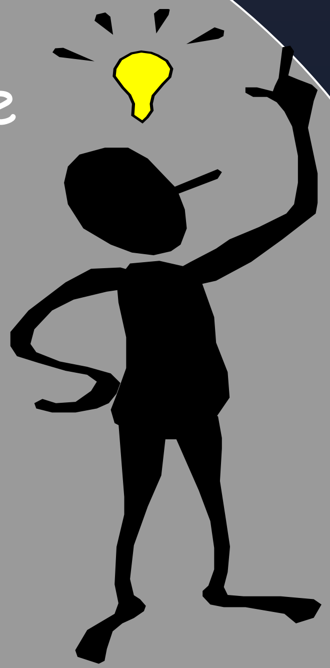
- ⇨Pre-1999, Mixed Integer Programs
  - ⇨MIP can not solve in time window
  - ⇨Lagrangian Relaxation leaves a duality gap
    - ⇨solutions are usually infeasible
    - ⇨Over simplifies generators; no transmission switching
- ⇨1999 Unit commitment conference and book
  - ⇨Bixby demonstrates MIP improvements using CPLEX
- ⇨2005 PJM adopts MIP for market software
- ⇨2015 All ISOs have adopted MIP Annual Savings > $2B

Mixed Integer Programs Development

- ⇨Pre-2000 Aristotelian logic: better branch and bound
- ⇨Improvements since 2000
  - ⇨Presolve – numerous small ideas
  - ⇨better linear program solvers: robust dual simplex
  - ⇨Variable/node selection and bound strengthening
  - ⇨Cuts (planes, zero-half and path)
  - ⇨covers (knapsack, flow and GUB),
  - ⇨integer rounding, cliques, implied bounds,
- ⇨Since 1988 CPLEX and GUROBI (10^7 seconds in a year)
  - ⇨10^7 software improvement
  - ⇨10^4 hardware improvement

2010s

Promote efficient wholesale markets through the exploration of software and hardware that will optimize market operations



software

Engineering judgment

2015

FERC focuses on prices, incentives and cost allocation for settlements mechanisms

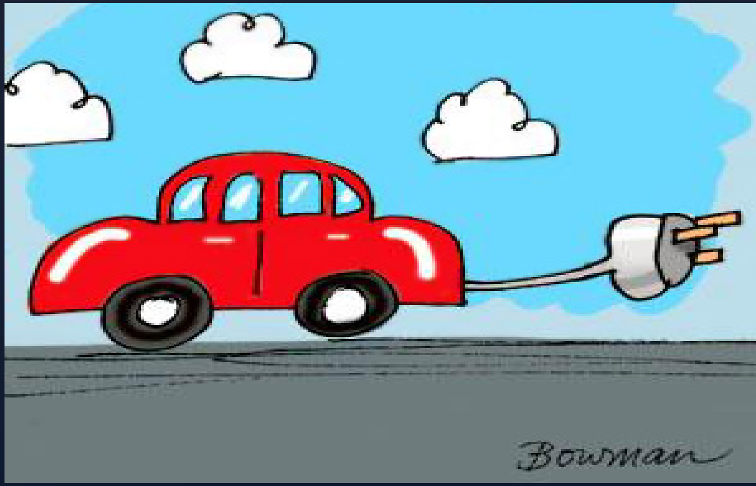
software

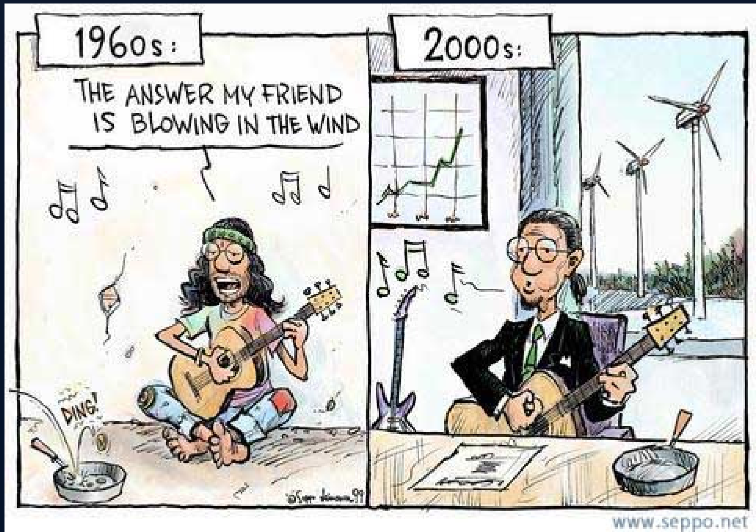
Engineering judgment

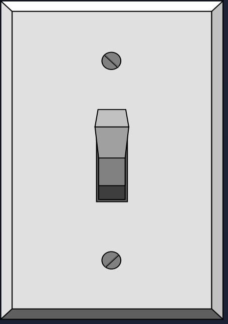
New markets new technologies

- ⇨Wind, solar, batteries,
- ⇨flexible generators
- ⇨topology optimization
- ⇨price responsive demand
- ⇨Need flexibility
- ⇨Where is the peak?

- ⇨First contingency is weather.

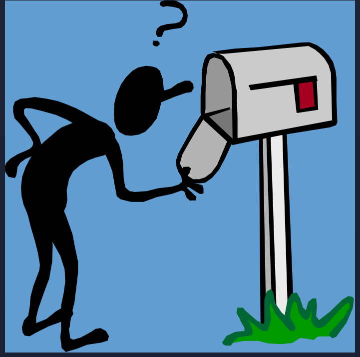


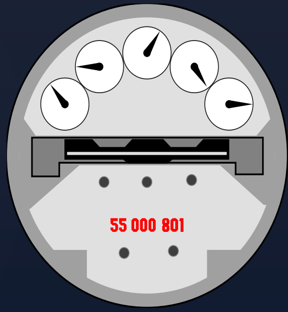




End-use markets

got to get you into my life



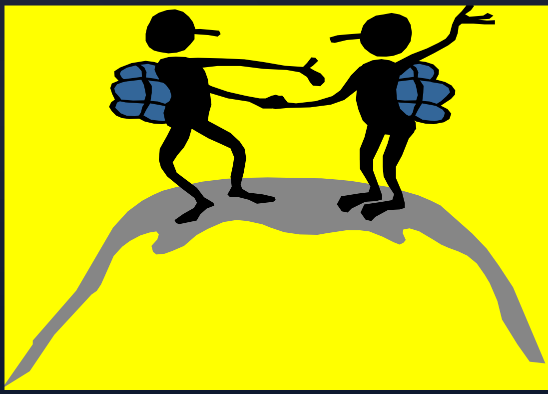


- ⇨Consumers receive very weak price signals
  - ⇨monthly meter; 'see' monthly average price
  - ⇨On a hot summer day
    - ⇨Cost > \$1000/MWh
    - ⇨price < \$100/MWh
  - ⇨ results in market inefficiencies and
  - ⇨ inefficient purchase decisions.
- ⇨Smart meter and real-time price are key
- ⇨Solution: smart appliances
  - ⇨real time pricing, interval meters and
  - ⇨Demand-side bidding
- ⇨Result: Large two-sided market!!!!!!!!!

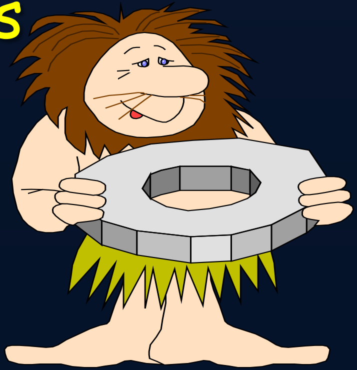
He's as blind as he can be just sees what he wants to see

what we do well and what we are working on

- ⇨What we do well
  - ⇨Solve sparse linear equations
  - ⇨Solve linear optimization problems
  - ⇨Solve convex optimization problems



- ⇨What is more difficult
  - ⇨Problems with binary variables
    - ⇨Startup, min run time,
    - ⇨Optimality gap
  - ⇨Problems with continuous non-convex functions
    - ⇨Local optima
    - ⇨Duality gap



Distribution Factor Model

if z_i is fixed, SCED; if z_i is {0,1}, SCUC

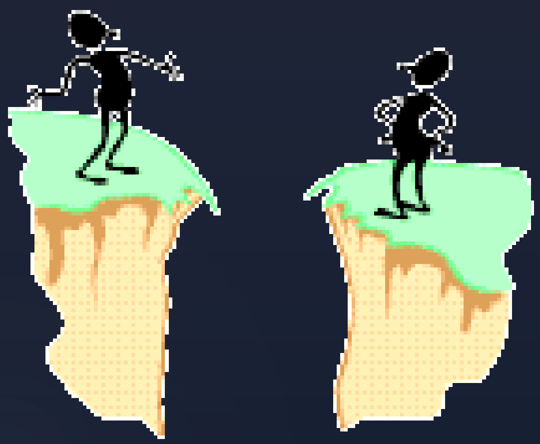
$MS = \max \sum_{i \in D} b_i d_i - \sum_{i \in G} c_i p_i$

	dual variables		
$\sum_{i \in D} d_i - \sum_{i \in G} p_i + \text{losses} = 0$	λ		power bal
$d_i - d^{max}_i \leq 0$	$i \in D$	α^{max}_i	max demand
$-d_i \leq -d^{min}_i$	$i \in D$	α^{min}_i	min demand
$p_i - z_i p^{max}_i \leq 0$	$i \in G$	β^{max}_i	max supply
$-p_i - z_i p^{min}_i \leq 0$	$i \in G$	β^{min}_i	min supply
$\sum_i df_{ki}(p_i - d_i) - p_k = 0$	$k \in K$	τ_k	flow balance
$p_k \leq p^{max}_k$	$k \in K$	μ^{max}_k	flowgate max
$p_k \geq 0$	$k \in K$		

Day-ahead and Real-time Market Process

1. Formulate the distribution factor (DF) unit commitment
2. Solve the unit commitment (SCUC)
3. Solve the security constrained economic dispatch (SCED)
4. Check for AC reliability, e g, N-1-1, voltage limits
5. check for convergence, if so go to step 9
6. If not, create linear constraints for 'violations'
7. add constraints DF
8. go to 2 or 3
9. solve pricing run and post dispatch and prices

binding constraints on market efficiency

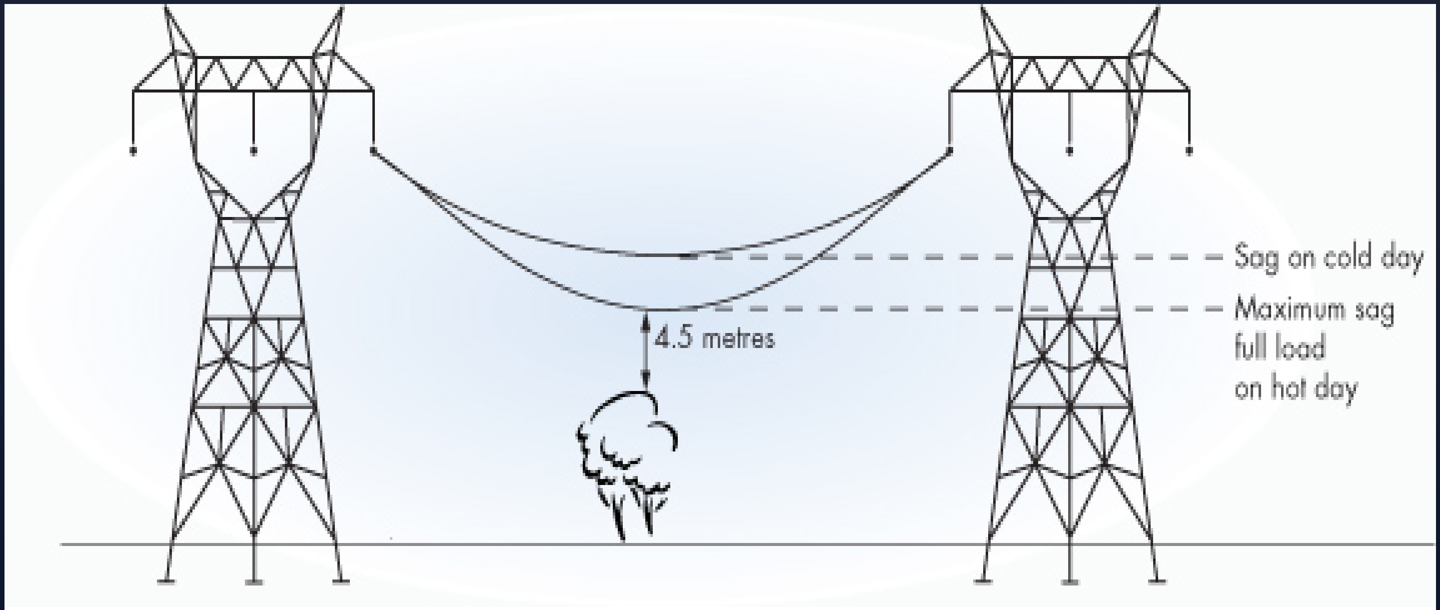


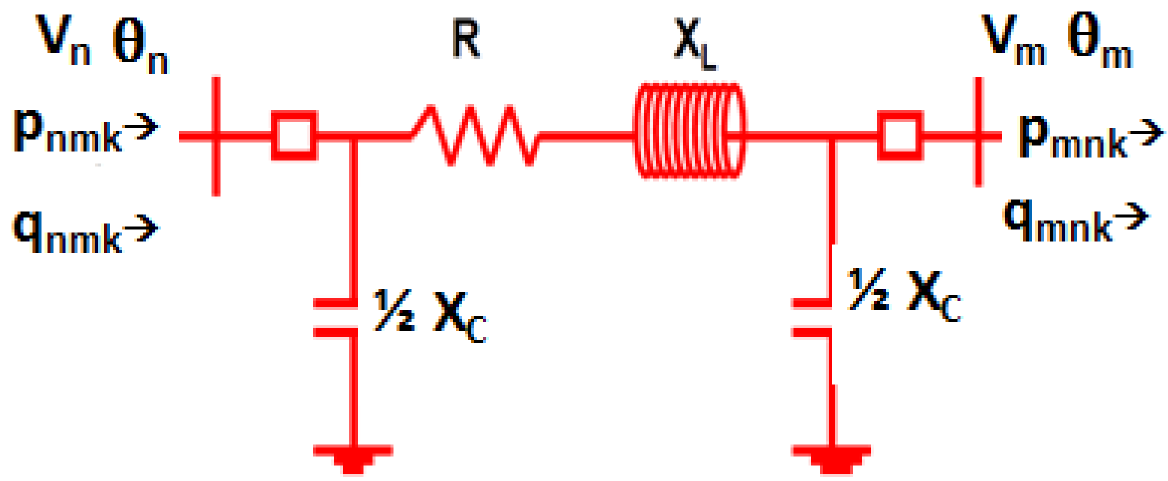
- As
  - computers get faster and cheaper
  - software gets faster and better
  - measurements get better, e g, PMUs
  - information transfer gets faster
- There is the potential significant market efficiency improvement
- binding constraints on market efficiency
  - Software
  - "Good Utility Practice"

Improving the Approximation

- AC v DC (distribution factor or Bθ)
- DF model is 10^2 to 10^3 faster than Bθ
- Better loss approximation
- Introduce reactive power linearization
  - RMR choices are weak
  - Cut sets are a very rough approximation
  - Introduce D-curve and transmission reactive approximation
  - Topology optimization improvement
    - Corrective switching
    - Efficiency improving switching

Alternating Current Optima Power Flow (ACOPF)





AC polar Non-convex network to "DC" linear

AC polar model

$p_n - \Sigma_k p_{knm} = 0$

$q_n - \Sigma_k q_{knm} = 0$

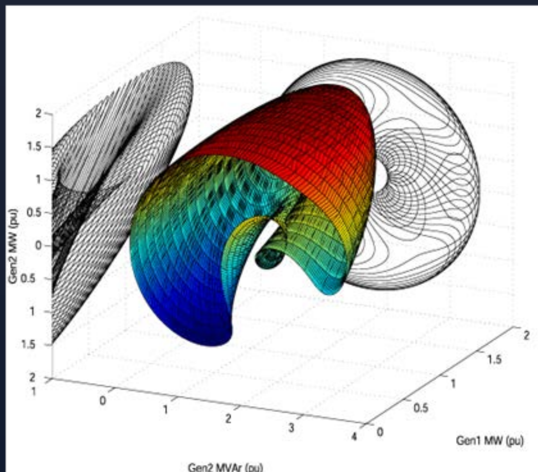
$p_{knm} = v_n v_n g^s_k + v_n v_m [g_k \cos(\theta_{nm}) + b_k \sin(\theta_{nm})]$

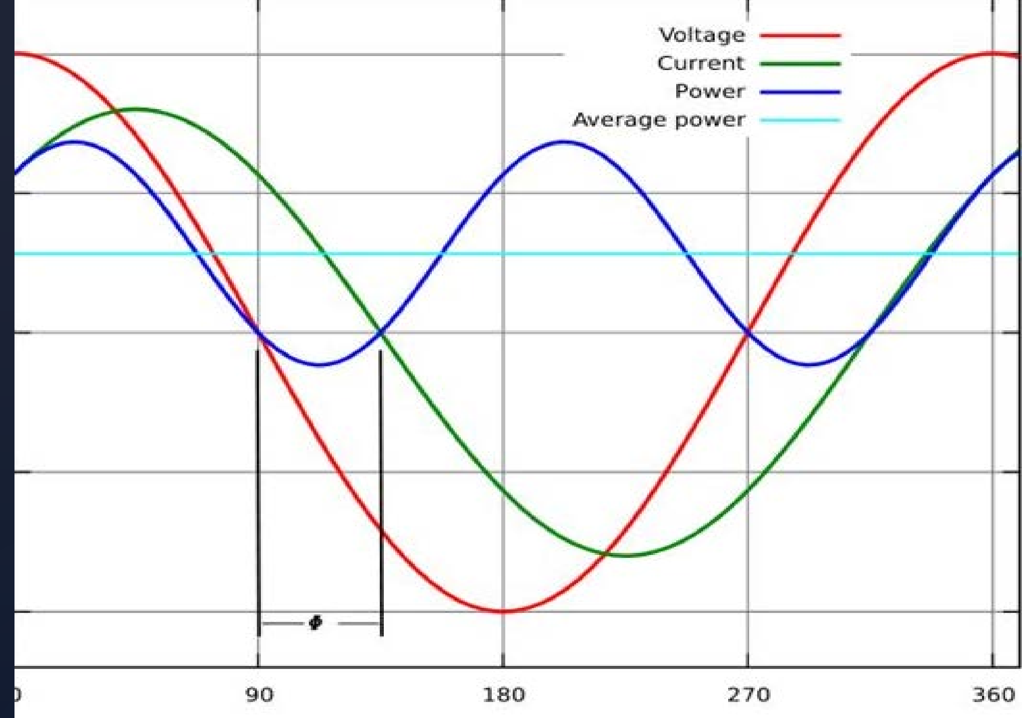
$q_{knm} = v_n v_n g^s_k + v_n v_m [g_k \sin(\theta_{nm}) - b_k \cos(\theta_{nm})]$

Assume $q_n = q_{knm} = 0$, $v_n = v_m = 1$, $\sin(\theta_{nm}) = \theta_{nm}$

$p_{knm} = b_k \theta_{nm}$

ACOPF





- ⇨Includes reactive power, voltage constraints
- ⇨Standard nonlinear solvers are faster

Optimization results can be formulation dependent

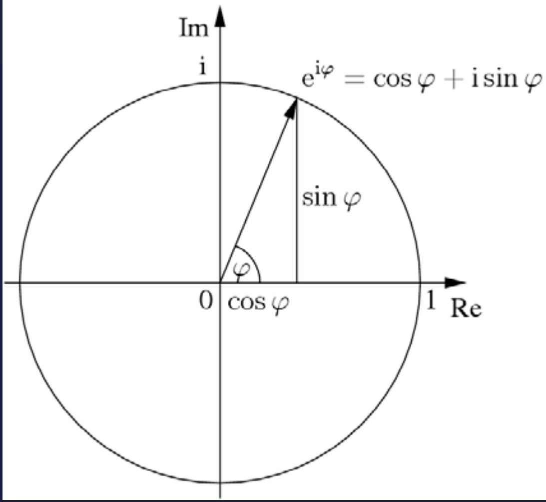
- ⇨IV approximation is linear in the network equation
- ⇨Rectangular formulations solve faster
- ⇨Simple linear equations for state estimator

- ⇨Convex and linear approximations
- ⇨ARPA-E initiative to perform better testing

Operator Intervention

- ⇨ reactive power is it too cheap to meter?
- ⇨ N-1-1 reliability
- ⇨ In load pockets, either operator dispatch or cut set constraints are needed
- ⇨ Causes generators to start up and sit at minimum operating level to produce reactive power
- ⇨ Cost of reactive power is the startup, no-load, minimum operating level, and min runtime costs
- ⇨ Also suppresses the LMP

Polar PQ formulation
Carpentier 's 1962 formulation



Min $c(p, q)$

$$p_n = \sum_{mk} v_n v_m (g_{nmk} \cos\theta_{nm} + b_{nmk} \sin\theta_{nm})$$
$$q_n = \sum_{mk} v_n v_m (g_{nmk} \sin\theta_{nm} - b_{nmk} \cos\theta_{nm})$$
$$p^{min}{}_n \le p_n \le p^{max}{}_n$$
$$q^{min}{}_n \le q_n \le q^{max}{}_n$$
$$v^{min}{}_n \le v_n \le v^{max}{}_n$$
$$\theta^{min}{}_{nm} \le \theta_n - \theta_m \le \theta^{max}{}_{nm}.$$

n, m are bus indices

Network equations are quadratic and trigonometric

Bus equations linear

Rectangular Network Equations

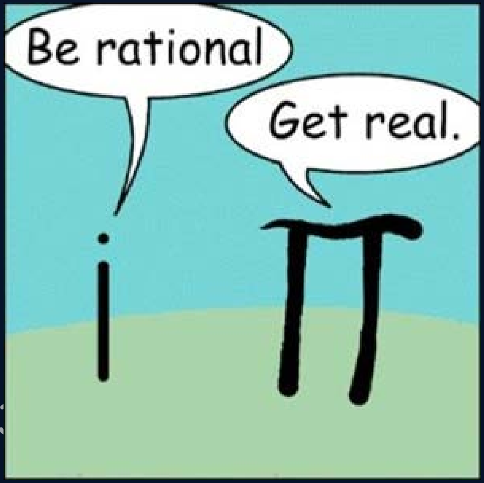
IV network equations are linear: $I = YV$

$i^r_n = \sum_{m \in N} g_{nm} v^r_m - \sum_{m \in N} b_{nm} v^j_m$

$i^j_n = \sum_{m \in N} b_{nm} v^r_m + \sum_{m \in N} g_{nm} v^j_m$

P, Q equations in rectangular form are quadratic:

$S = I \cdot V = YV \cdot V$



Rectangular ACOPF-IV Formulation

Network-wide objective function: Min c(P, Q)

Network-wide constraint: I = YV

at each bus non-convex bilinear constraints

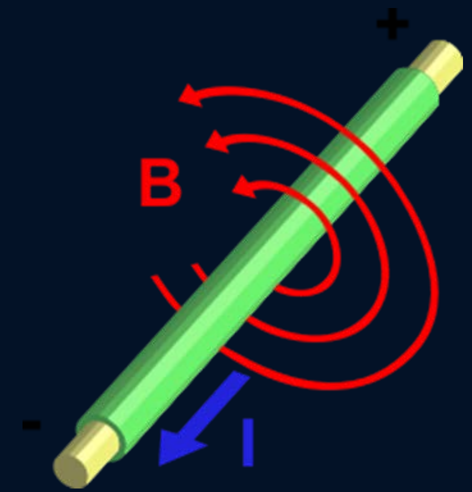
$$v^r i^r + v^j i^j \le p^{max}$$

$$p^{min} \le v^r i^r + v^j i^j$$

$$v^j i^r - v^r i^j \le q^{max}$$

$$q^{min} \le v^j i^r - v^r i^j$$

$$(v^{min})^2 \le v^r v^r + v^j v^j$$ Optimization drives voltage higher

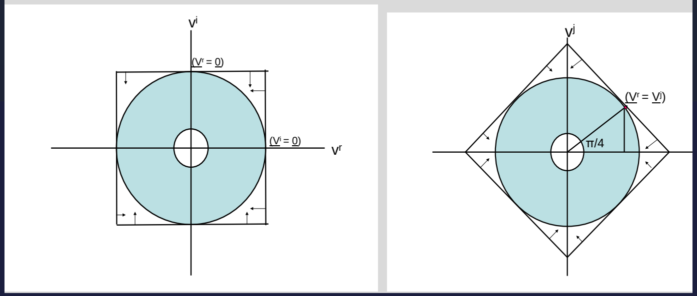


Convex bilinear constraints

$$v^r v^r + v^j v^j \le (v^{max})^2$$

$$(i^r)^2 + (i^j)^2 \le (i^{max})$$

$$(v^r{}_m)^2 + (v^j{}_m)^2 \le (v^{max}{}_m)^2$$



Convex Constraints

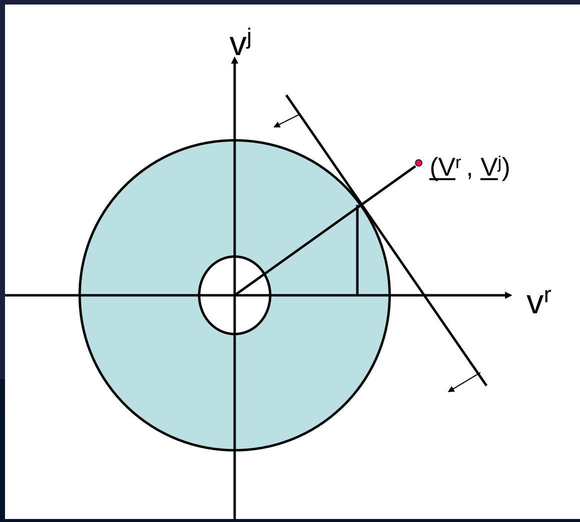
If the constraint is convex, preprocessed cuts

Add iterative tight cuts cutting off previous LP optimum

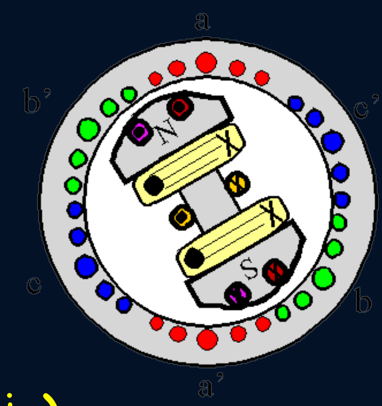
For each node, add a tight linear constraint:

$$\underline{v}^r v^r + \underline{v}^j v^j \le (v^{max})^2$$

cuts off the linear program solution, is tangent to and contains to convex constraint



Real and Reactive Power Conversions.



We can linearize around $\underline{v}^r_n$, $\underline{v}^j_n$, $\underline{i}^r_n$, $\underline{i}^j_n$

$$p^{\approx} = \underline{v}^r_n i^r_n + \underline{v}^j_n i^j_n + v^r_n \underline{i}^r_n + v^j_n \underline{i}^j_n - (\underline{v}^r_n \underline{i}^r_n + \underline{v}^j_n \underline{i}^j_n)$$

$$q^{\approx} = \underline{v}^j_n i^r_n - \underline{v}^r_n i^j_n - v^r_n \underline{i}^j_n + v^j_n \underline{i}^r_n - (\underline{v}^j_n \underline{i}^r_n - \underline{v}^r_n \underline{i}^j_n)$$

We add step-size constraints:

$$p^{min} \le p^{\approx} \le p^{max}$$

$$q^{min} \le q^{\approx} \le q^{max}$$

and drop the previous approximation

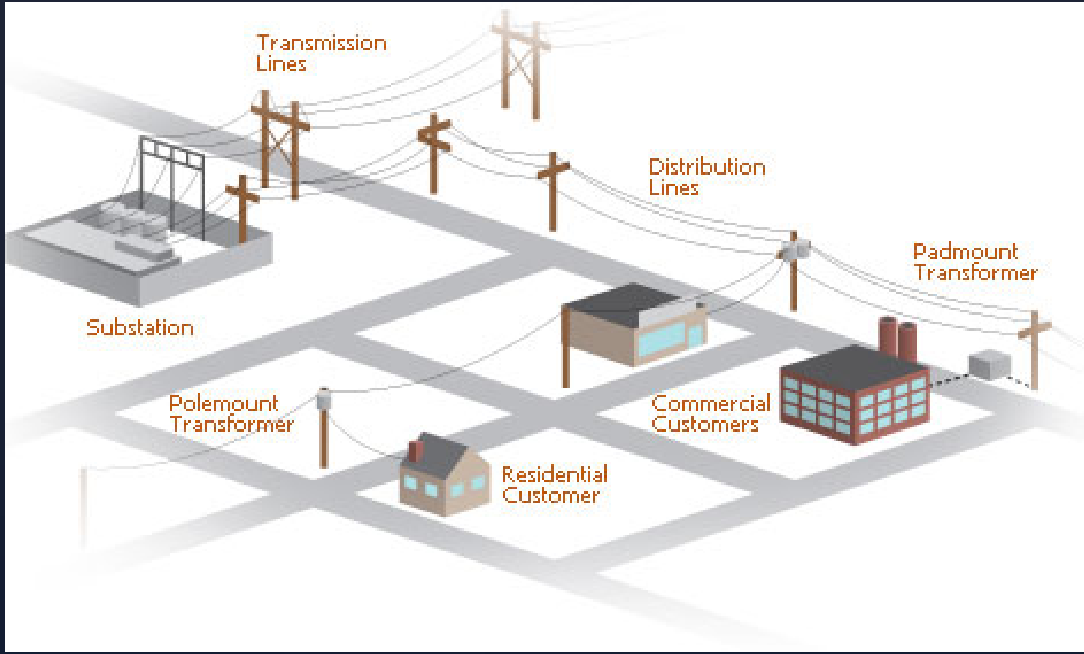
Computational experience

- IV SLP faster than most commercial non-linear solvers
- best parameters are problem-dependent

ACOPF Using Semi-definitive Programs

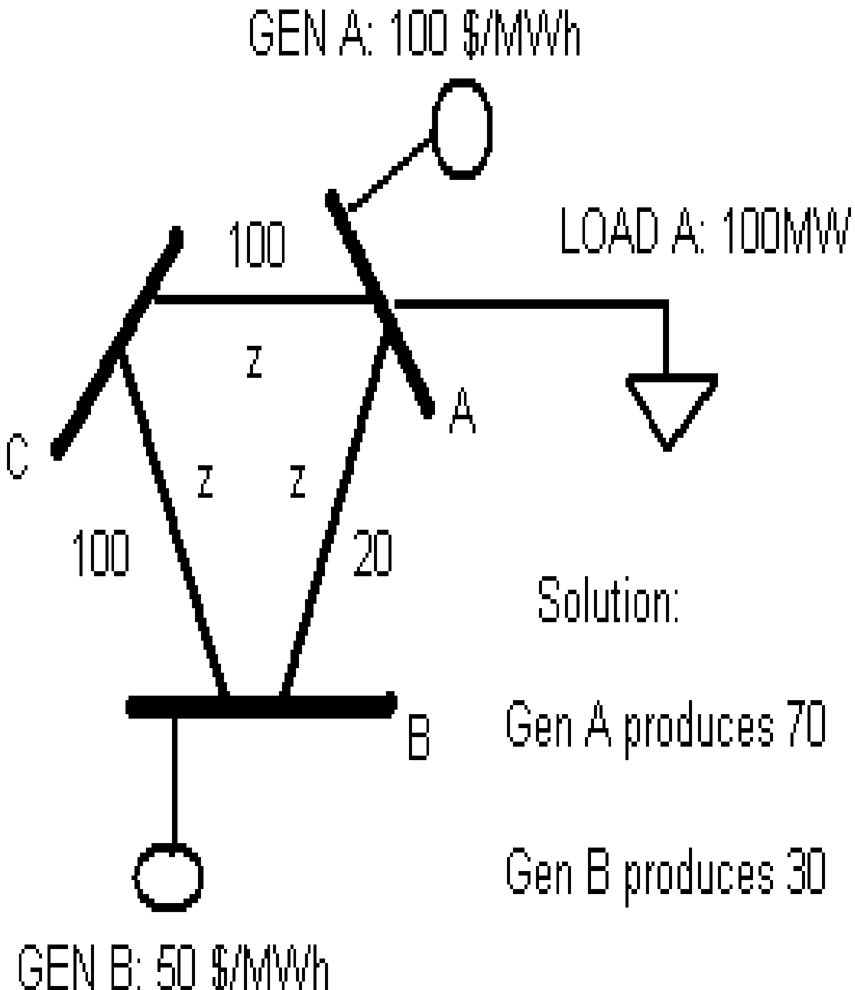
- Javad Lavaei et al
- received the INFORMS Optimization Society Prize
- Convex approximation
- Global optimal solutions For
  - standard test problems
  - Networks with enough Phase Shifters
  - Acyclic networks with positive LMPs
  - Penalized reactive power on ‘problematic’ lines
- SDP algorithms are getting faster

distribution optimization



- ⇨Decentralized markets
- ⇨Distribution systems generally are trees and simple cycle networks
- ⇨Smart grids and markets
- ⇨Losses can be high, e g, 30%
  - ⇨Reconfiguration switching
  - ⇨Locating new assets
- ⇨Lowering losses lowers prices on the entire line

Optimal Transmission Switching

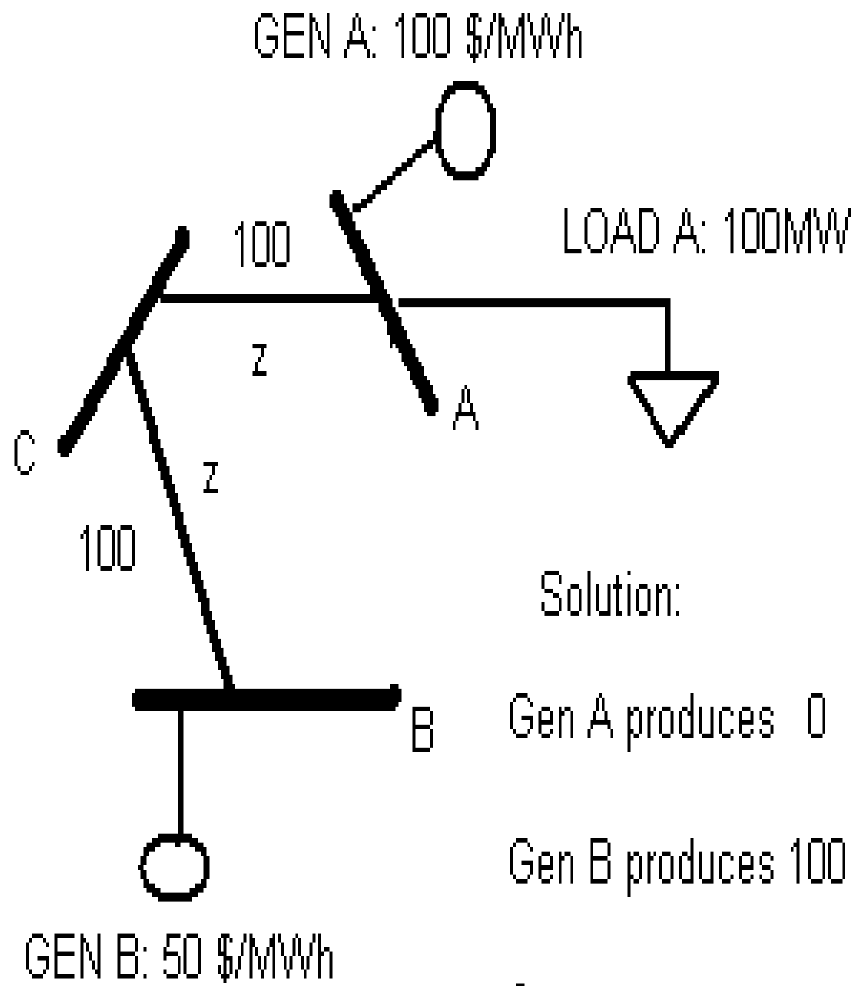


Solution:

Gen A produces 70

Gen B produces 30

Cost: 8500



Solution:

Gen A produces 0

Gen B produces 100

Cost: 5000

Optimal Transmission Switching DC Formulation

- Fisher et al IEEE 118 bus model 25% savings found.
- Hedman et al
  - ISONE 5000 bus model **13% savings**
- N-1 reliability constraints
- Hedman et al
  - IEEE 118 Bus Model 16% savings
  - IEEE 73 (RTS 96) Bus Model 8% savings

Beneficial transmission switching

- ⇨2015 Ruiz et al limited to 6 opens and 6 closes per hour
  - ⇨savings of about $100 million in RT and
  - ⇨$150 million in DA. 96% of savings with fast heuristic

- ⇨2015 Hedman et al corrective switching eliminates post-contingency violations
  - ⇨In PJM, eliminates post-contingency violations ~70%
  - ⇨Estimated savings: $100M/year
- ⇨Ostrowski et al (RTS96) anti-islanding > 10x
- ⇨In 5 years solutions are 100 times faster
- ⇨Now considered part of the smart grid
- ⇨Still potential for improvements
- ⇨Fuller AC v. DC switching

Optimal Topology

problem	current	next decade
Corrective switching	little	Real-time
Topology estimator		
Real-time market	Pre-studied	Real-time
day-ahead market	Pre-studied	Day ahead
Maintenance scheduling	none	monthly
Optimal planning	none	annual

AC IV Transmission Switching

Transmission flow equations

$$i^r_{nmk} - g_{nmk}(v^r_n - v^r_m) + b_{nmk}(v^j_n - v^j_m) = 0$$

$$i^j_{nmk} - b_{nmk}(v^r_n - v^r_m) - g_{nmk}(v^j_n - v^j_m) = 0$$

$$(i^r_{nmk})^2 + (i^j_{nmk})^2 \leq (i^{max}_{nmk})^2$$

Transmission switching equations: $z_k = 0$ (out) ; $z_k = 1$ (in)

$$i^r_{nmk} - g_{nmk}(v^r_n - v^r_m) + b_{nmk}(v^j_n - v^j_m) \leq M(1 - z_k)$$

$$i^r_{nmk} - g_{nmk}(v^r_n - v^r_m) + b_{nmk}(v^j_n - v^j_m) \geq -M(1 - z_k)$$

$$i^j_{nmk} - b_{nmk}(v^r_n - v^r_m) - g_{nmk}(v^j_n - v^j_m) \leq M(1 - z_k)$$

$$i^j_{nmk} - b_{nmk}(v^r_n - v^r_m) - g_{nmk}(v^j_n - v^j_m) \geq -M(1 - z_k)$$

$$(i^r_{nmk})^2 + (i^j_{nmk})^2 \leq z_k(i^{max}_{nmk})^2$$

Modeling For Long-term Planning

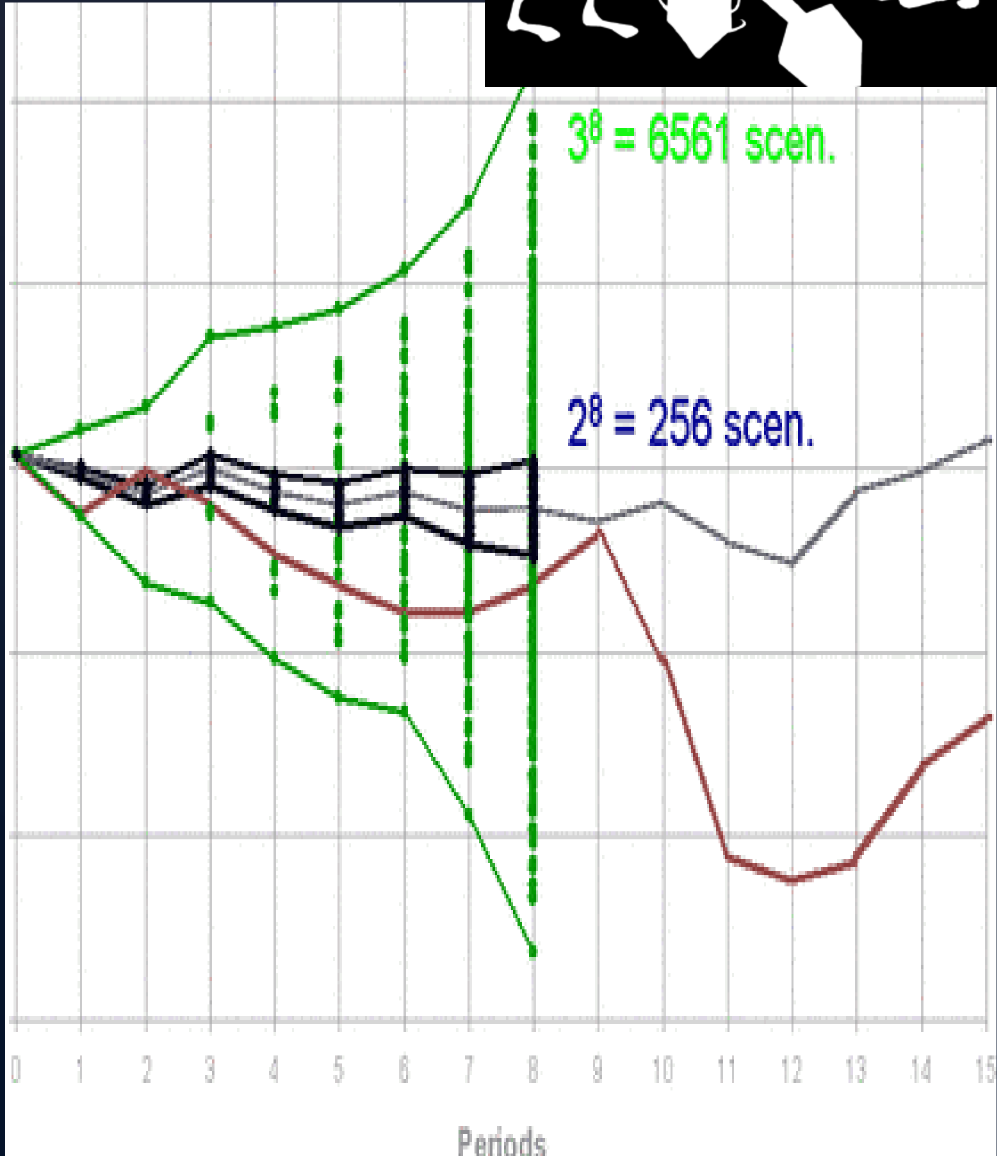
- ⇨Epistemology: what do we know about the future?
- ⇨Representation of uncertainty
- ⇨Weather (wind, solar, temperature)
  - ⇨interactions
- ⇨Generator failure is a function of
  - ⇨Weather
  - ⇨Maintenance

Modeling for long-term planning

- **transmission expansion**
- Reduced network
- No binaries, eg, unit commitment result less flexible generators (CTs)
- Ramping issues
- Price-responsive demand
- Representative time periods
  - Peak only
  - Peak, off peak
  - Representative weeks
  - Seasons (summer, fall, winter, spring)
- Scenarios

stochastic issues

- ⇨Old
  - ⇨Forced outage model of generation
  - ⇨Estimating tomorrow's demand with temperature forecast
  - ⇨Estimating long term demand with GPD forecast
- ⇨New
  - ⇨Ramp rate model of generation
  - ⇨Weather forecasts
  - ⇨temperature
  - ⇨wind
  - ⇨cloud cover



2020

software

better software and hardware

- ⇨ Price-responsive demand
- ⇨ Better look ahead in real-time market
- ⇨ Reactive power approximation
- ⇨ Transmission supply function

Engineering judgment

2030

software

better software and hardware

- ⇨ Unit commitment for demand
- ⇨ ACOPF
- ⇨ Distribution systems optimization

Engineering judgment

Computational Research Questions

- ⇨ 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

Thanks

References at

http://www.ferc.gov/industries/electric/indus-act/market-planning/opf-papers.asp