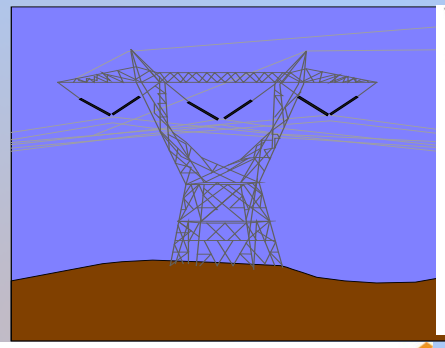
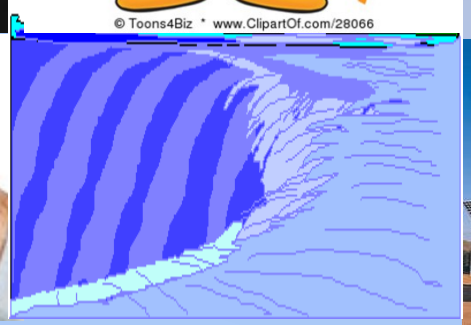
Computational Challenges in Electricity Markets

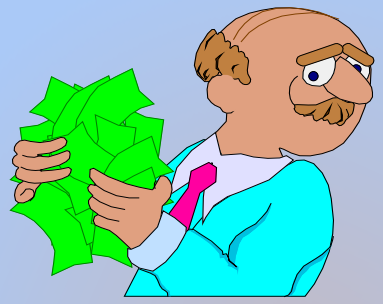


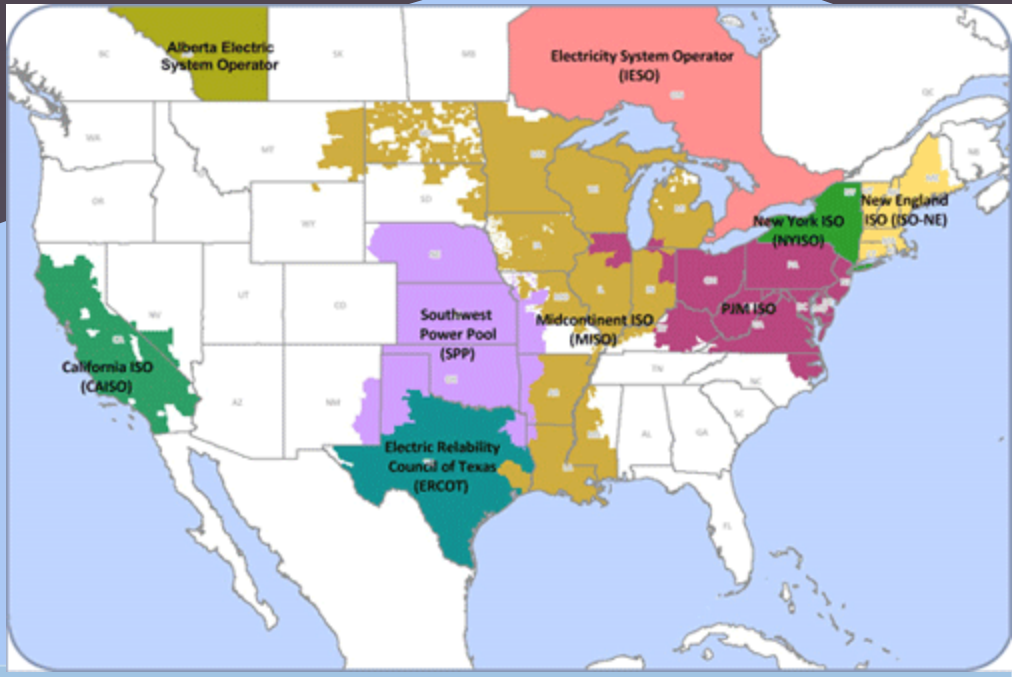
...eill
Chief Economic Advisor
FERC

HEGP
October 1, 2015
Views expressed are not necessarily those of the Commission



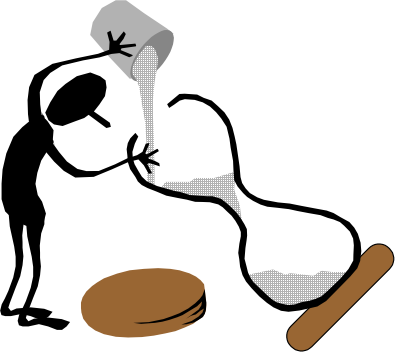
The Potential Impact…



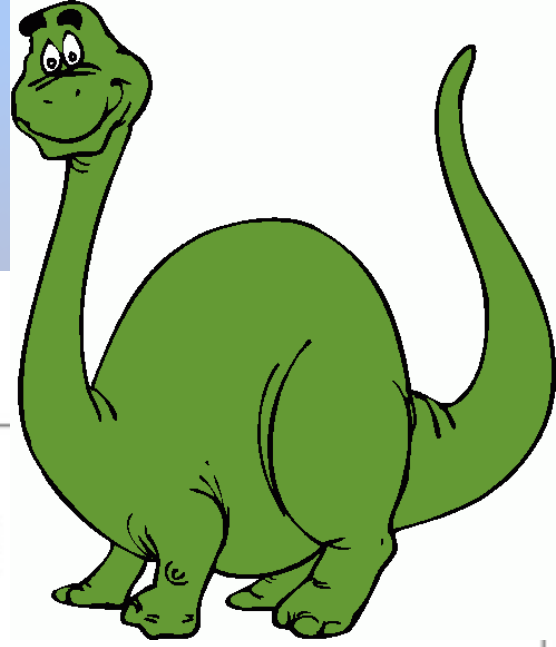


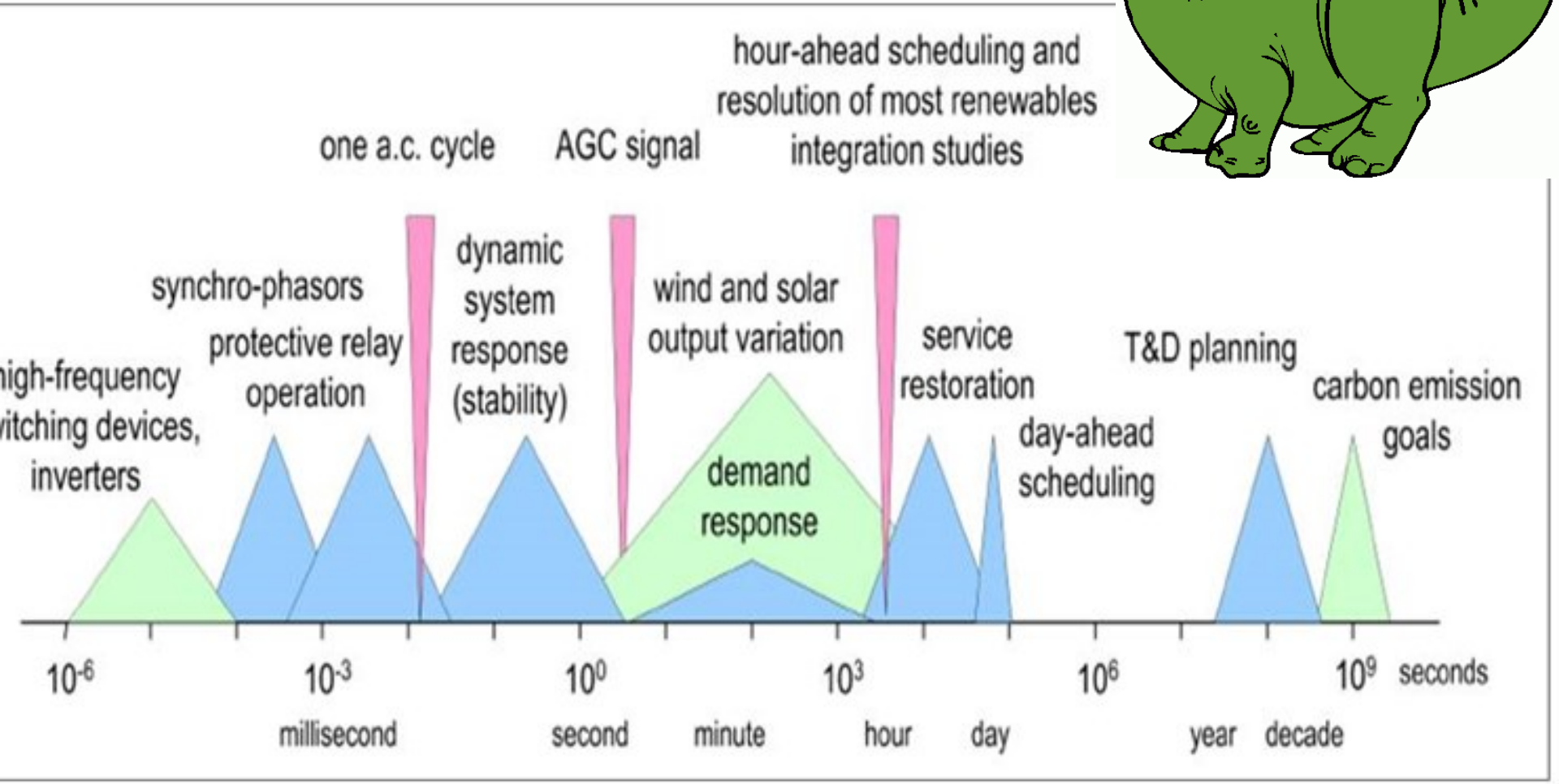
- United States Gross Production (2009): ≈4,000 TWh
- At $50/MWh: cost $600 billion/year (world)
  - cost $200B (billion) /year (US)
- At $100/MWh: cost $2,000 billion/year (world)
  - cost $400B/year (US)
- In US 10% savings is about than $20 to $40B/yr
- All current ISO markets are constrained by software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

Source: IEA Electricity Information, 2010.



Time Scales




hour-ahead scheduling and
resolution of most renewables
integration studies
one a.c. cycle
AGC signal
synchro-phasors
protective relay
operation
dynamic
system
response
(stability)
wind and solar
output variation
service
restoration
T&D planning
carbon emission
goals
high-frequency
switching devices,
inverters
day-ahead
scheduling
demand
response
10-6
10-3
100
103
106
109
seconds
millisecond
second
minute
hour
day
year
decade

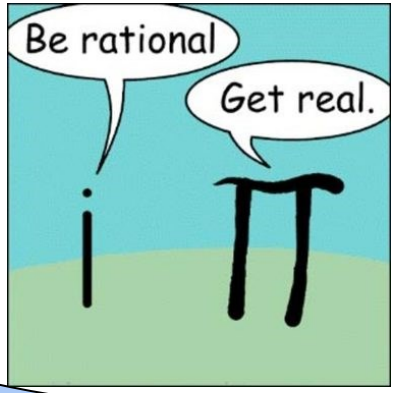
1960

Edward Teller on 1965 Blackout:

"power systems need sensors, communications, computers, displays and controls"

software

Engineering judgment

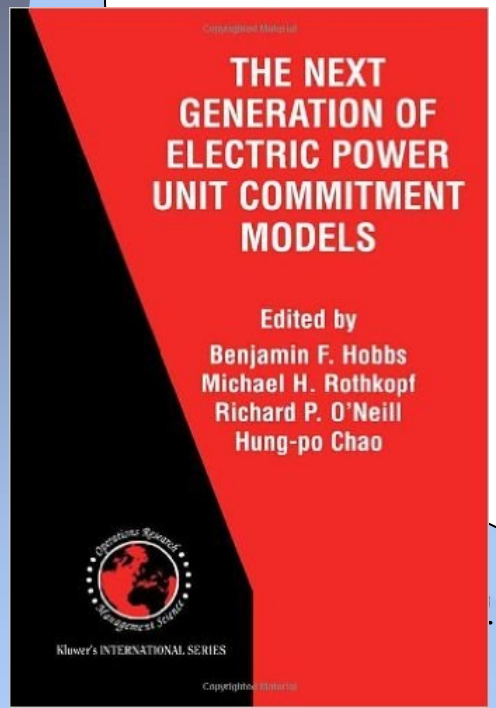


1999

FERC staff conference on the Next Generation of Unit Commitment

software

Engineering judgment



2008

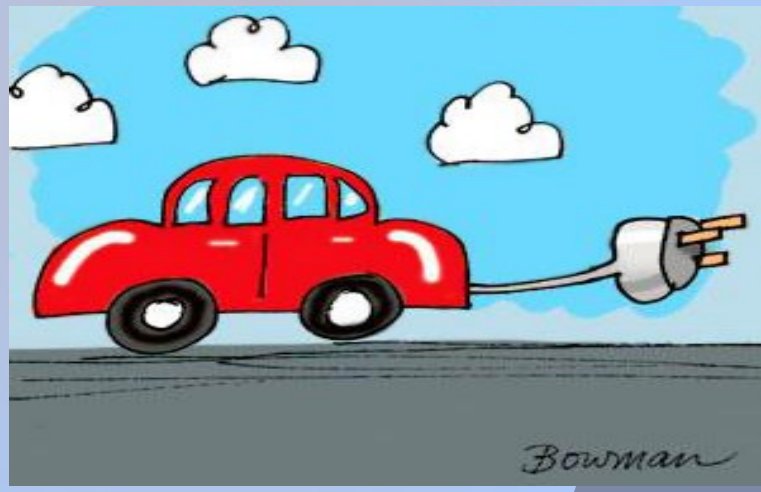
software

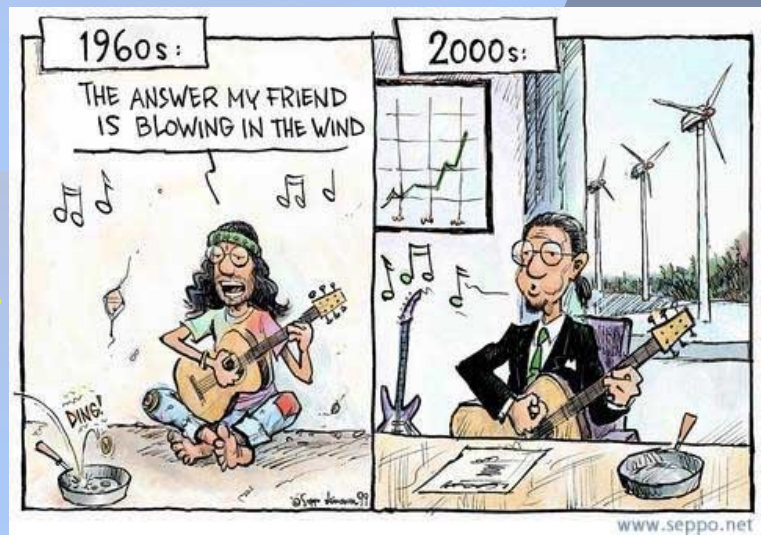
FERC staff introduces
Optimal Transmission
Switching concept
Possible savings > 10%
of dispatch costs

Engineering
judgment

New markets new technologies

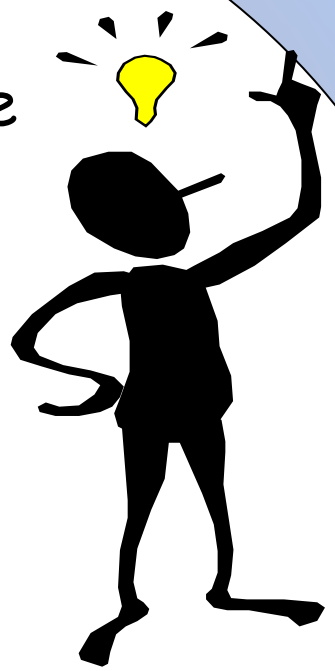
- ⇨Batteries, flexible generators, topology optimization and price responsive demand
- ⇨Need flexibility
- ⇨optimally integrated
- ⇨off-peak
  - ⇨Generally wind is strongest
  - ⇨Prices as low as -$30/MWh
- ⇨Ideal for battery charging





2010

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



software

Engineering judgment

2015

All ISOs have adopted Mixed Integer Programming for Unit Commitment

Annual Savings > $1B

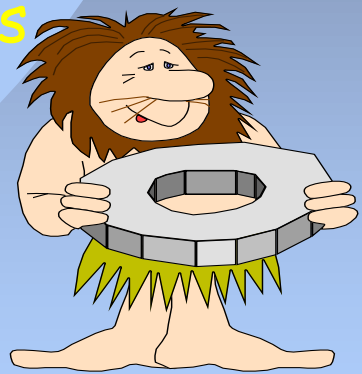
software

Engineering judgment

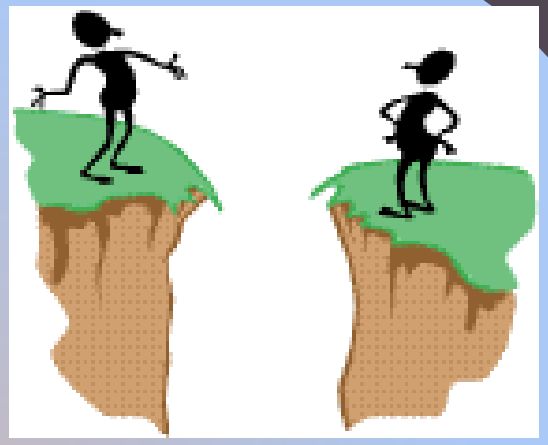
what we do well and what we are working on

- 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



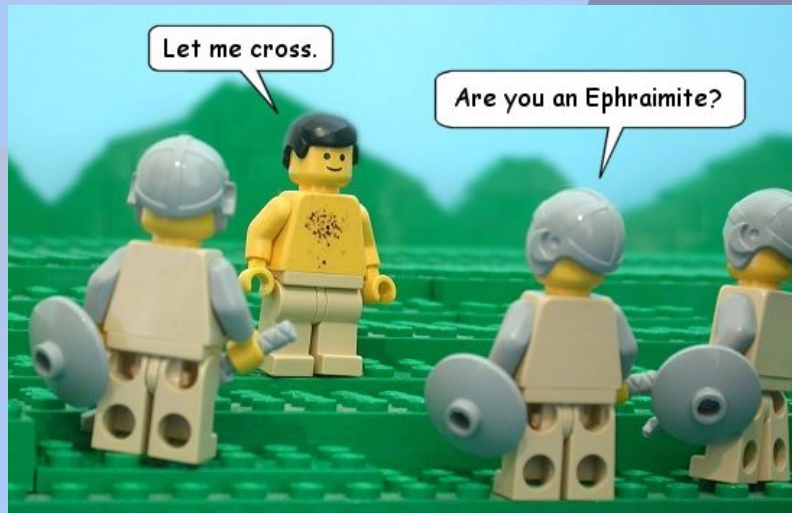
binding constraints on market efficiency



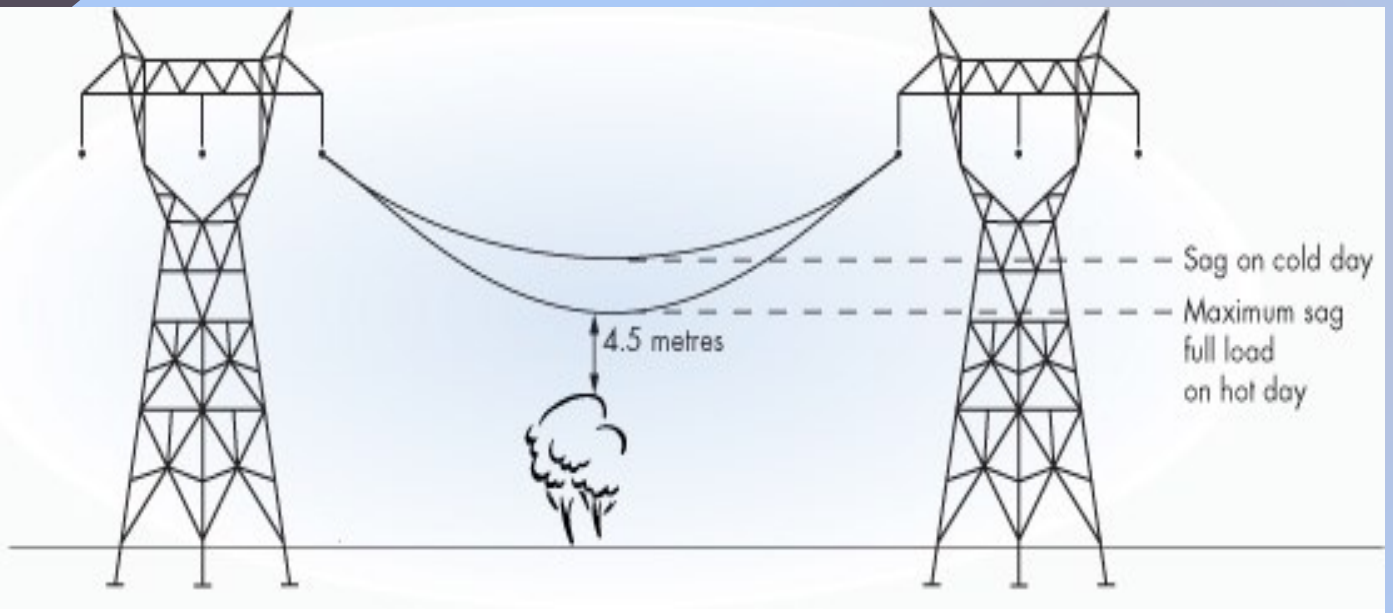
- As
  - computers gets faster and cheaper
  - software gets faster and better
  - measurements get better, eg, PMUs
  - information transfer gets faster
- There is the potential significant market efficiency improvement
- binding constraints on market efficiency
  - Software
  - "Good Utility Practice"

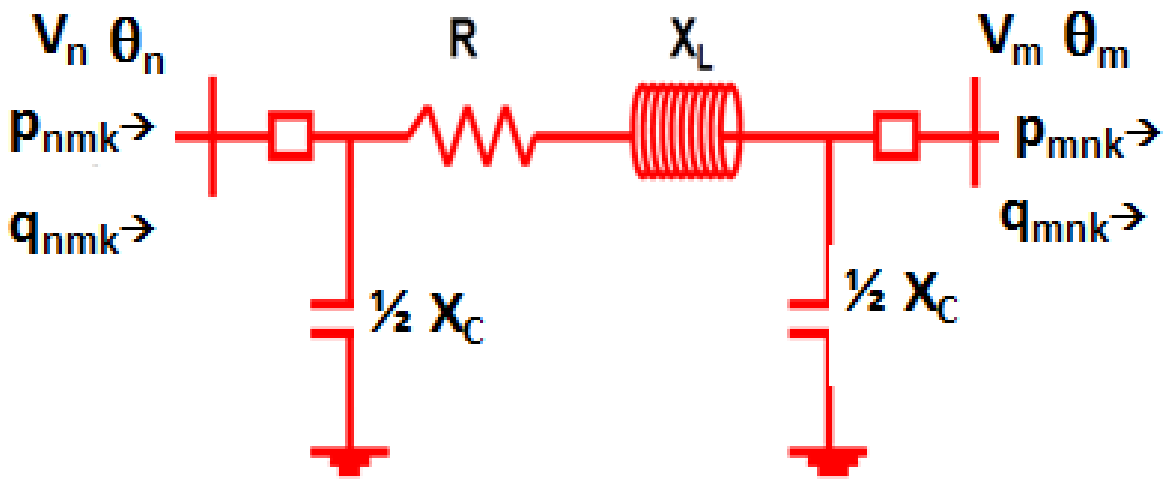
myths, shibboleths and good utility practice

- Introduction of new technology is not the internet model
- Entry must run the gantlet of
  - Educational inertia: Sr. management is 30 years out of school
  - Bureaucracy
  - Large-scale testing on real data
  - Reliability myths and shibboleth



Alternating Current Optima Power Flow (ACOPF)





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

$$S = P + \mathbf{j}Q = \mathrm{diag}(V)I^* = \mathrm{diag}(V)[YV]^* = \mathrm{diag}(V)Y^*V^*$$

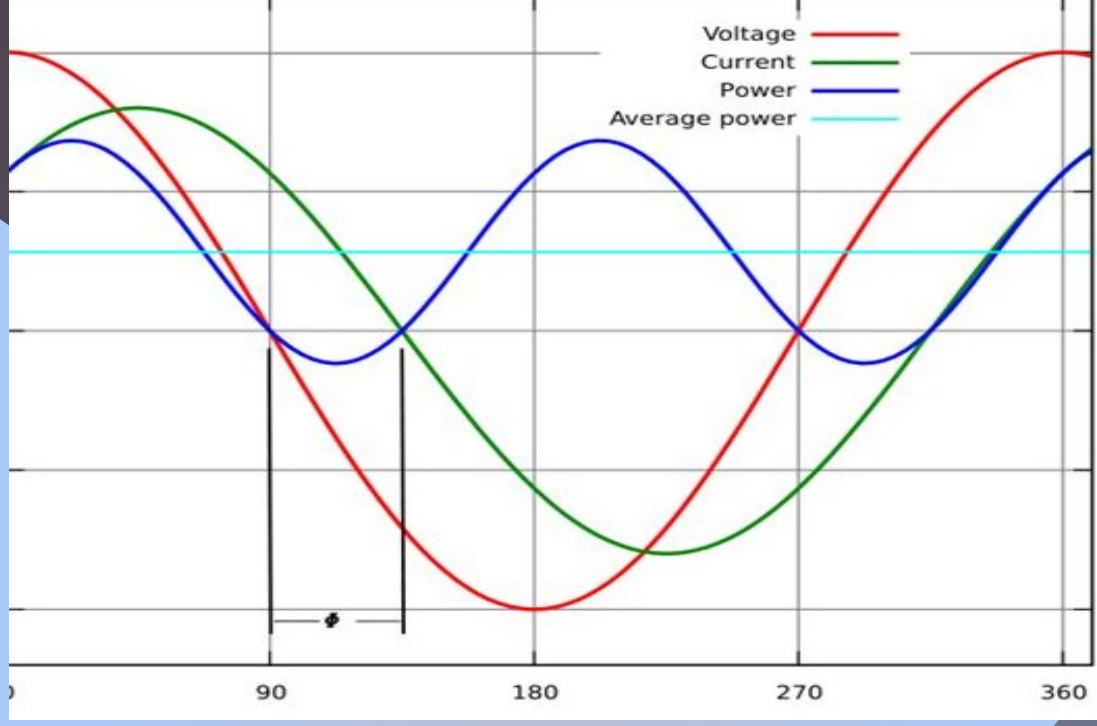
Rectangular Current-Voltage (IV) formulation.

Network-wide ***LINEAR*** constraints: 2N linear equality constraints

$$I = YV = (G + \mathbf{j}B)(V^r + \mathbf{j}V^j) = GV^r - BV^j + \mathbf{j}(BV^r + GV^j)$$

where $I^r = GV^r - BV^j$ and $I^j = BV^r + GV^j$

ACOPF



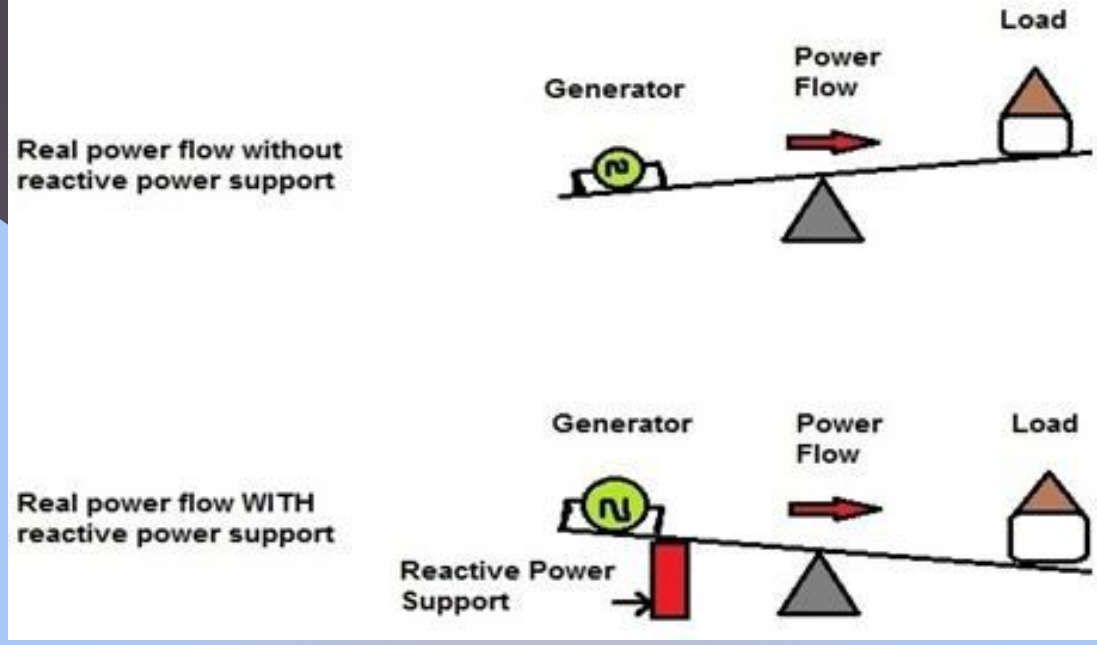
- ⇨Includes reactive power, voltage constraints
- ⇨Standard nonlinear solvers are faster

Optimization is formulation dependent

- ⇨ IV approximation is linear in the network equation
- ⇨Rectangular formulations solve faster

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

reactive power is it too cheap to meter?



- 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
- Is it too cheap to meter?

Day-ahead and Real-time Market Process

⇨Primary objective: market efficiency
⇨Secondary objective: good incentives and signals

Iterative decomposition and recomposition

1. Solve the DF unit commitment
2. Check for AC reliability
3. If not, modify DF and go to 1

improving the linear approximation

- ⇨Better losses approximation
- ⇨Introduce reactive power linearization
  - ⇨RMR choices are weak
  - ⇨Cut sets are a very rough approximation
  - ⇨Introduce D-curve and transmission reactive approximation
  - ⇨Topology improvement
  - ⇨Corrective switching

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 PSTs
  - Acyclic networks with positive LMPs
  - Penalized reactive power on 'problematic' lines
- Algorithms are getting faster

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

optimal transmission switching

- 2008 Fisher et al 118 bus model 25% savings found.
- Hedman et al ISONE model 13% savings
- 2009 Hedman et al N-1 reliability constraints 8% savings
- 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.
- 2015 Hedman et al corrective switching eliminates post-contingency violations
  - In PJM, eliminates post-contingency violations ~70%
  - Estimated savings: $100M/year

joint optimization

⇨2005 PJM and MISO commit to joint optimization

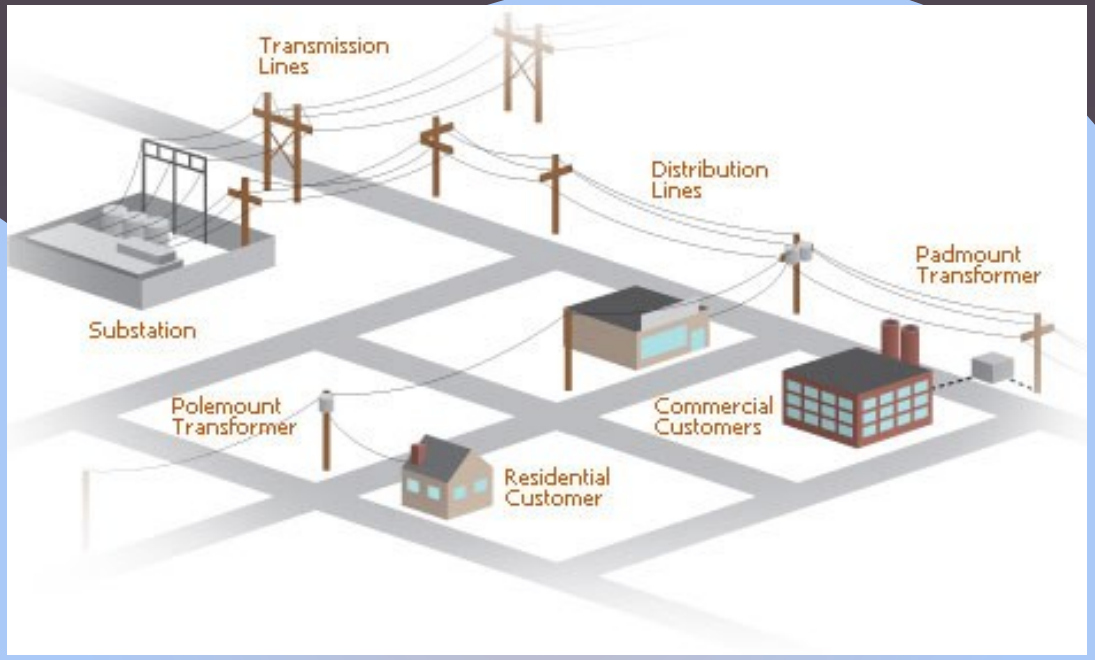
⇨2006 PJM and MISO decommit to joint optimization

⇨2015 still working on it

⇨About half the transactions crossing borders go against the price differences

⇨To set benchmarks for evaluating approximation

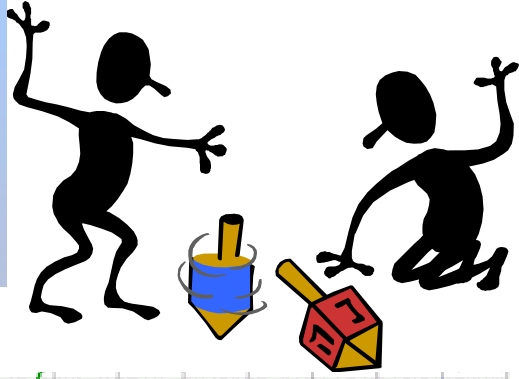
distribution optimization

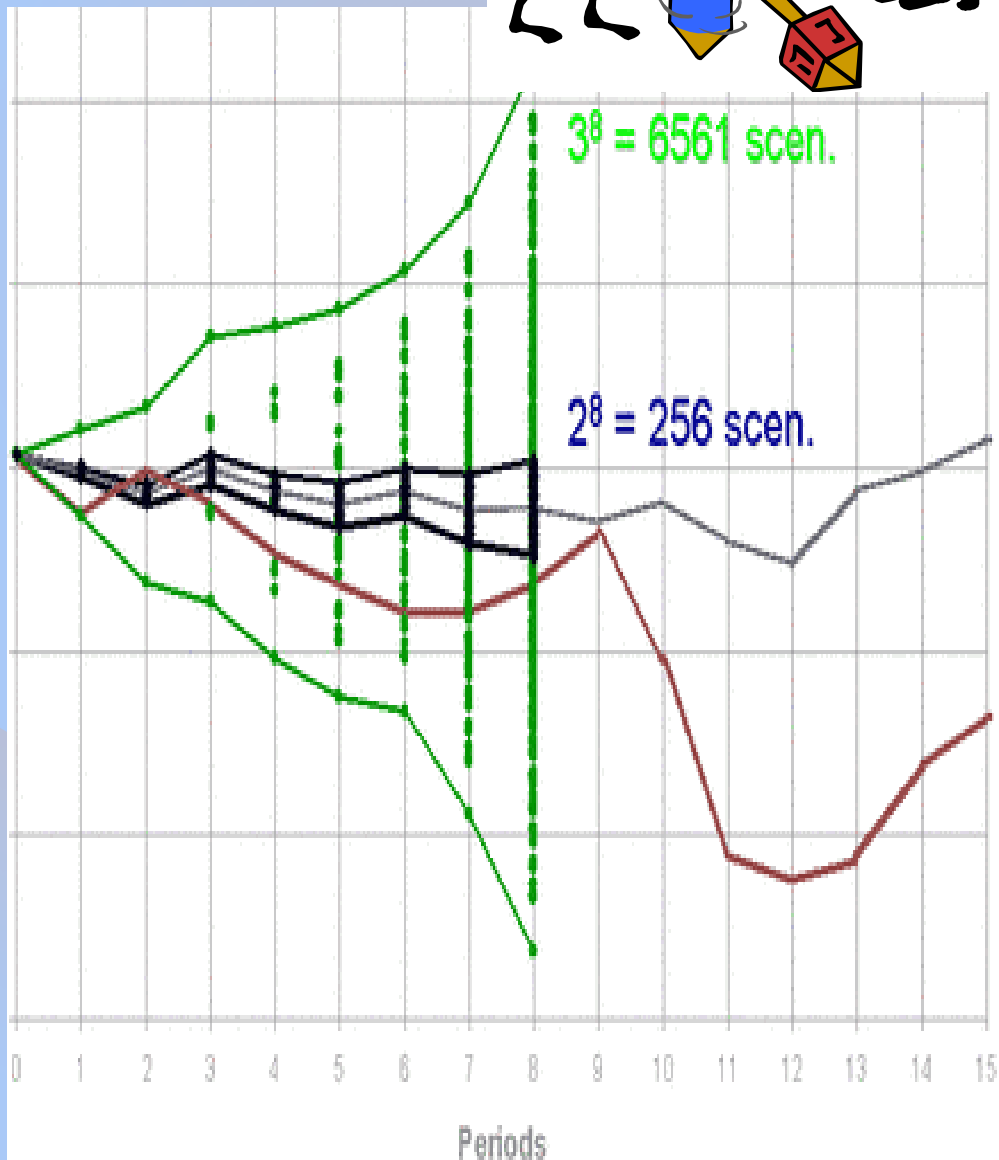


- ⇨Decentralized markets
- ⇨Distribution systems generally are trees and simple cycle networks
- ⇨Smart grids and markets
- ⇨Losses can be high, e g, 30%
  - ⇨Reconfiguration switching
  - ⇨Locating new assets
- ⇨Lowering losses lowers prices on the entire line

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

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

better software and hardware

Engineering judgment

2030

software

better software and hardware

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

Engineering judgment