Dynamic Network Energy Management via Proximal Message Passing

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CIS AdCom, 11/14/2012

Smart grid

- embed intelligence in energy systems to
  - do more with less
  - reduce CO2 emissions
  - handle uncertainties in generation (wind, solar, . . .)
  - exploit new demand response capabilities
  - handle shift towards EVs
  - extend life of current infrastructure
- cf. current system
  - load is what it is; generation scheduled to match it
  - systems built with large margins for max load

Smart grid critical technologies: The big picture

- physical layer
  - photovoltaics, switches, storage, fuel cells, . . .
- infrastructure/plumbing
  - smart enabled stuff, communication protocols, security, . . .
- **algorithms** (our focus)
  - real-time decision making
- economics layer
  - markets, investment, regulation, . . .

Coordinating devices on the smart grid

- **setting**: a network of smart devices, that can adjust/change/defer their power consumption/generation
- **goal**: coordinate device behavior (generation/consumption) over time

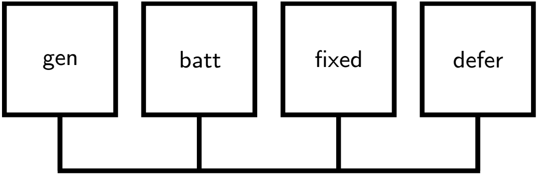
- **method**: use (mathematical) optimization to coordinate devices
- **algorithm**: use message passing to solve optimization problem

Device coordination via optimization

- devices exchange energy at nodes, in multiple time periods
  - generators
  - loads (fixed, deferrable, curtailable)
  - energy storage systems
  - transmission lines
- each device has dynamic constraints, cost function over time
- to coordinate devices, **minimize total cost subject to power balance at each node, in each time period**
- solving this optimization problem gives
  - (optimal) device power schedules
  - locational marginal prices at each node in each time period

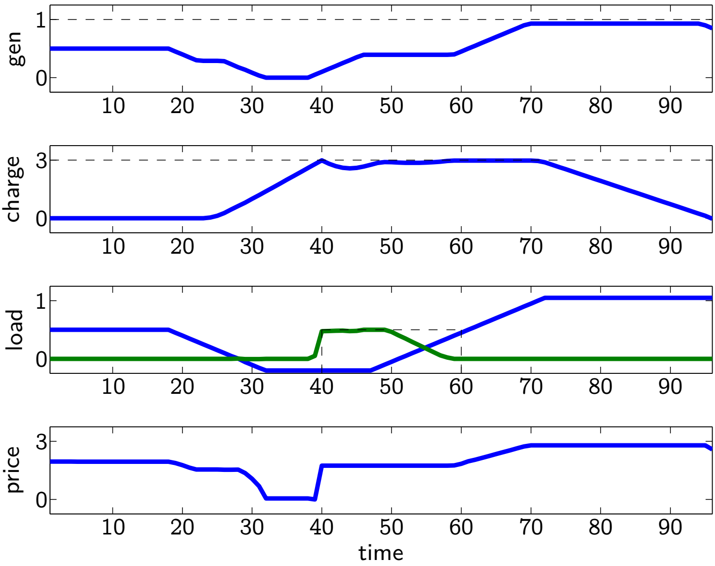
Example

- simple network with 4 devices, 1 power exchange node
- power scheduled over 96 time periods (24 hrs, 15 min intervals)



- generator (cost of generation, max power, ramp rate limits)
- battery (max charge/discharge rates, capacity)
- fixed load
- deferrable load (max power, total work over given time interval)

Optimal power and price profile



How to solve the dynamic energy management problem

- centralized
  - gather all devices' costs and constraints
  - solve on one machine

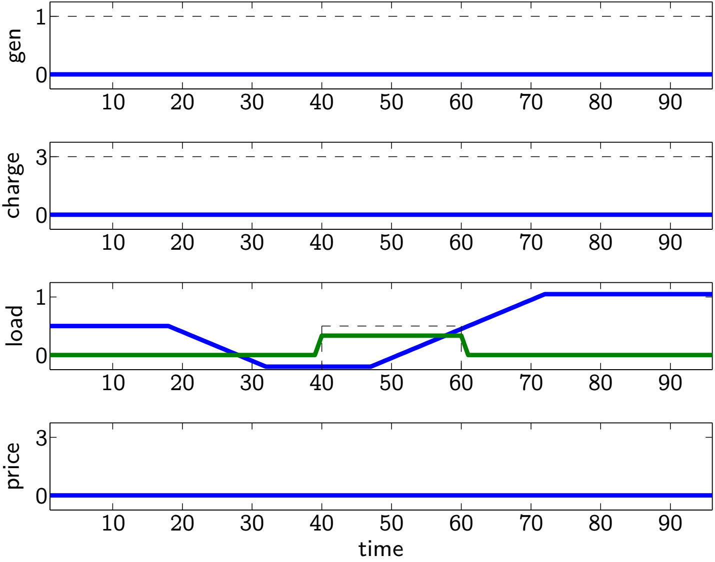
- **decentralized**
  - each device has its own solver
  - devices exchange messages with neighbors
  - coordinate local behavior to obtain global solution

Message passing algorithm

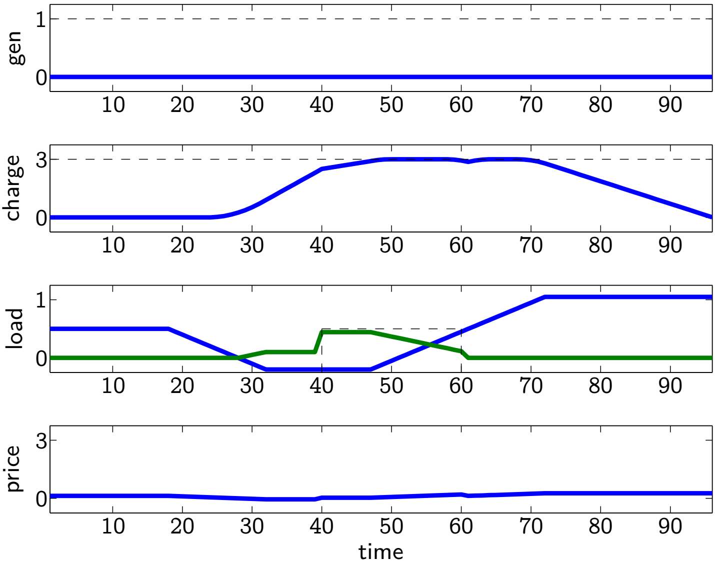
- repeat until convergence:
  - each device optimizes its cost function subject to its constraints, taking into account node prices
  - at each node, devices exchange proposed energy profiles, update node price

- device power profiles and node prices are messages passed between adjacent devices and nodes
- devices don't need to know about other devices (except through their effect on common nodes)
- (when done right) algorithm converges to an optimal solution

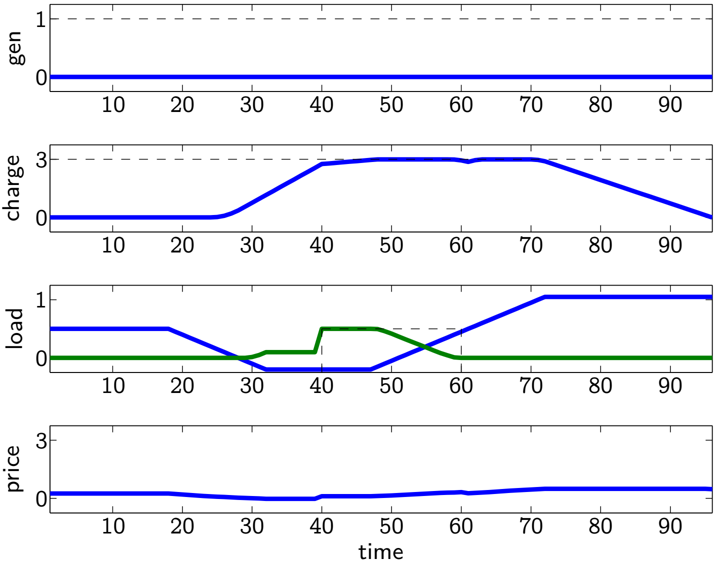
Iteration 0



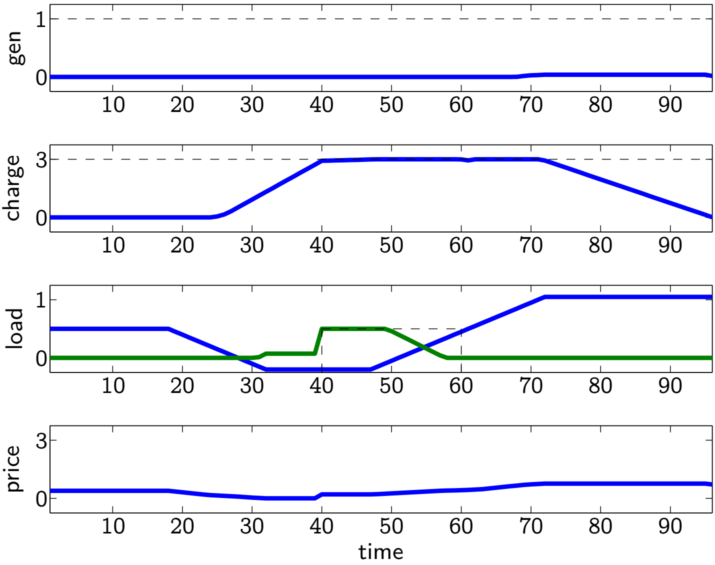
Iteration 1



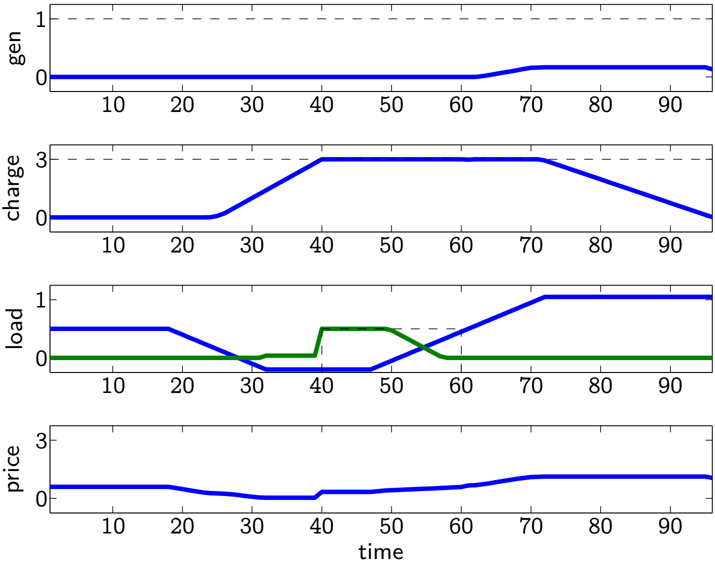
Iteration 2



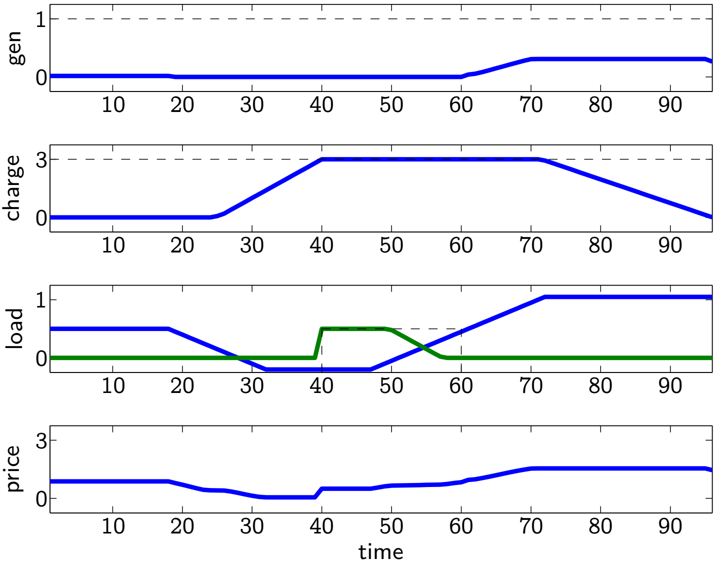
Iteration 3



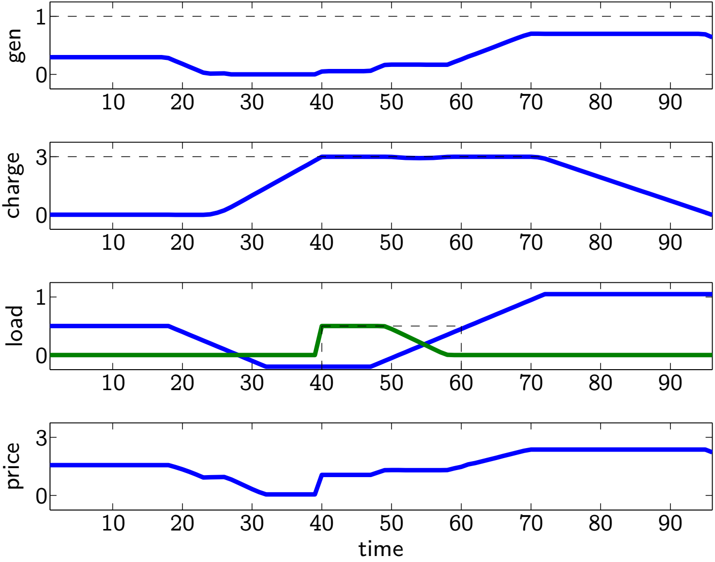
Iteration 4



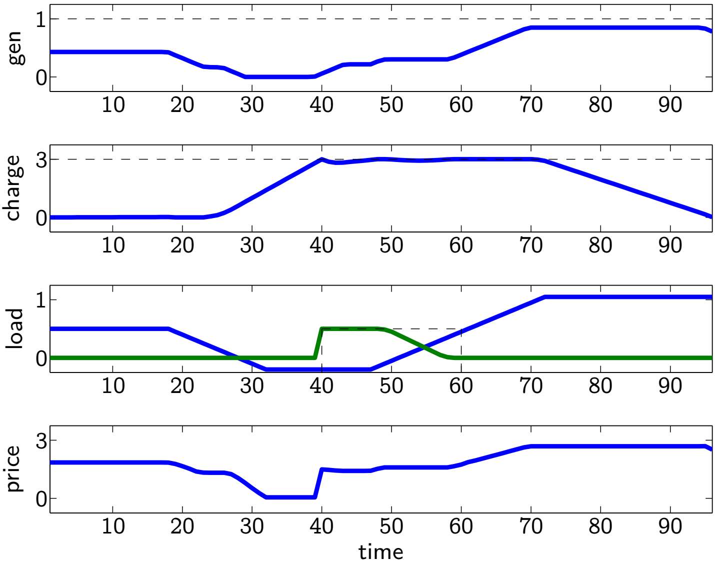
Iteration 5



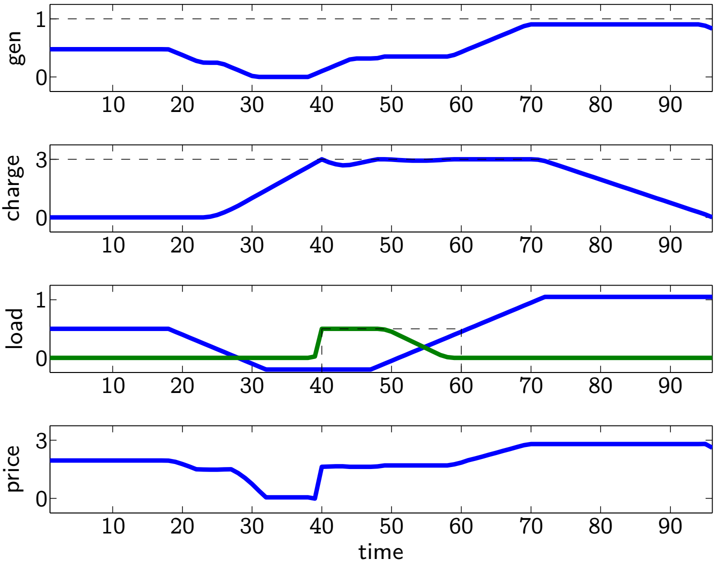
Iteration 10



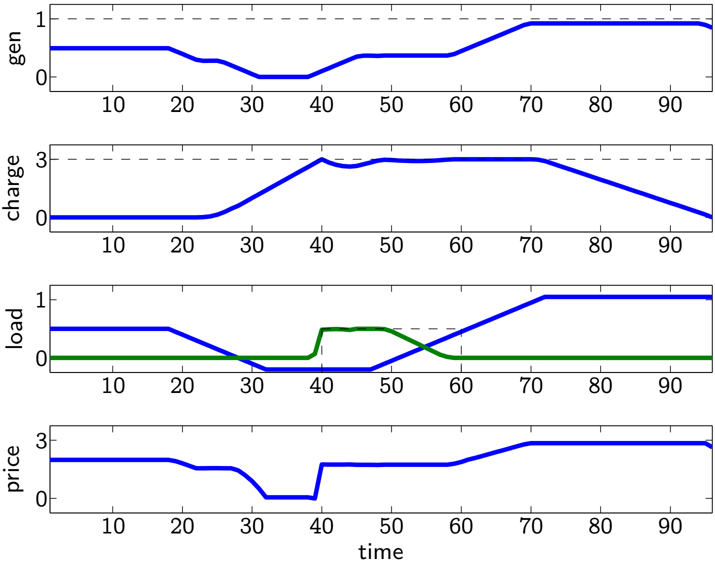
Iteration 15



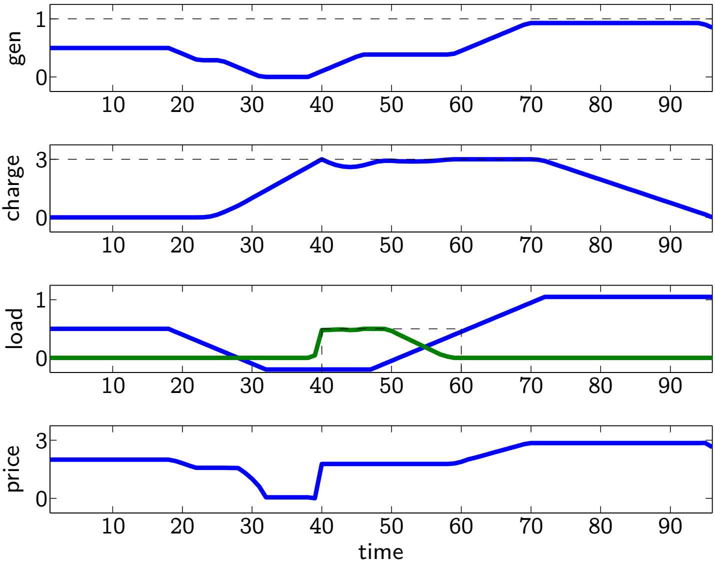
Iteration 20



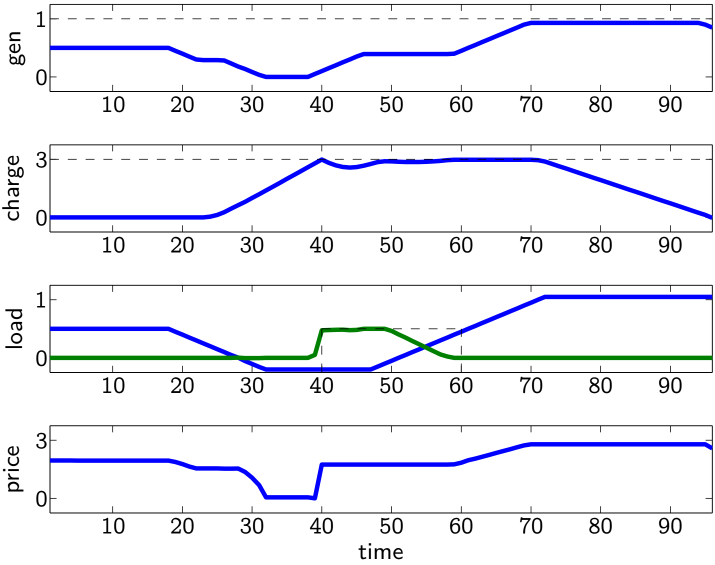
Iteration 25



Iteration 30

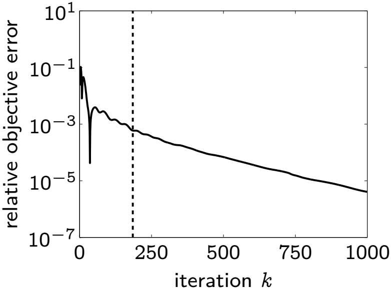


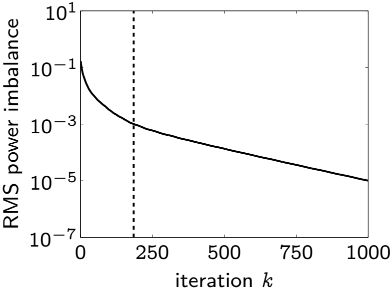
Iteration 36



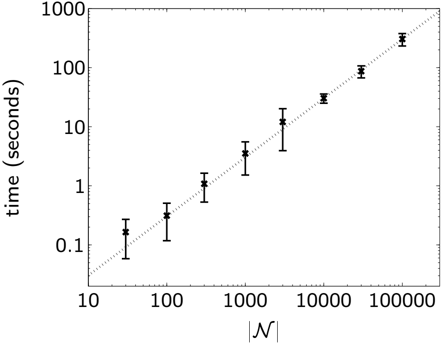
Larger example

- network with 8000 devices exchanging power at 3000 nodes (mixture of generators, batteries, smart loads, transmission lines, ...)
- coordinate devices over 96 time periods
- $\sim$ 1 million variables in optimization problem





Solve time scaling



- serial multi-threaded implementation on 32-core machine with 64 independent threads
- best fit exponent is 0.996
- fully decentralized computation would result in sub second solve time for **any size** network

Handling uncertainty via receding horizon control

- in every time period
  - each device forecasts future costs/constraints over some horizon
  - devices coordinate (optimize) using forecasts to obtain **consumption/generation plan**
  - devices execute first period consumption/generation in plan

- reacts to changes in constraint/objective forecasts
- same method used in chemical process control, supply chain optimization, ...

Summary and vision

- we've developed a completely decentralized method for optimal power exchange/consumption/generation on a smart grid
- decentralized computation allows for sub second solve times independent of network size
- when combined with receding horizon control, can be used for real-time network operation
- we envision a plug-and-play system that is robust, self-healing (internet of power)