Dynamic Network Energy Management via Proximal Message Passing

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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

- **gen**
- **charge**
- **load**
- **price**

Graphs showing the power and price profile over time.
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

<table>
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<th>price</th>
<th>load</th>
<th>charge</th>
<th>gen</th>
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</table>
Iteration 1

- gen
- charge
- load
- price

time
**Iteration 2**

- **gen**
  - Continuous line at 1

- **charge**
  - Line starts at 0, rises to 3, then fluctuates around 3

- **load**
  - Line starts at 0, rises to 1, then fluctuates around 1
  - Green line joins the blue line at 35, indicating a change in load

- **price**
  - Line starts at 0, rises to 3, then fluctuates around 3

**time**
- X-axis: 10 to 90
Iteration 3

- **gen**
  - Values: 0, 0, 0, 0, 0, 0, 0, 0, 0, 1

- **charge**
  - Values: 0, 0, 0, 0, 0, 0, 0, 0, 0, 3

- **load**
  - Values: 1, 1, 1, 1, 1, 1, 1, 1, 1, 1

- **price**
  - Values: 0, 0, 0, 0, 0, 0, 0, 0, 0, 3

- **time**
  - Values: 10, 20, 30, 40, 50, 60, 70, 80, 90
Iteration 4

- **gen**: Constant value of 1 across all time points.
- **charge**: Increases from 0 to 3, then decreases to 0.
- **load**: Starts at 0, increases to 1, decreases, and then remains constant.
- **price**: Starts at 0, decreases, then increases, and remains constant.

The graphs show the changes over time for each of the variables.
Iteration 5

- **gen**: A graph showing a steady increase over time, peaking around the 50th minute.
- **charge**: A graph with a gradual increase, peaking at around the 40th minute.
- **load**: A graph showing a significant spike starting at the 40th minute, followed by a gradual decrease.
- **price**: A graph with a slight upward trend over time, starting from a low point and rising steadily.

All graphs are plotted against time, with axes ranging from 10 to 90 minutes.
Iteration 10

- **gen**: The graph shows a steady increase in generation over time, with a slight fluctuation in the middle.
- **charge**: The charging curve starts low, peaks around the middle of the time frame, and then decreases gradually.
- **load**: The load curve is relatively flat with a slight increase around the middle, indicating no significant changes in load demand.
- **price**: The price graph remains relatively constant throughout the time frame, with minor variations suggesting a stable pricing model.

The graphs provide a visual representation of how different variables (generation, charging, load, and price) evolve over time.
Iteration 15

- gen
- charge
- load
- price
Iteration 20

- gen
- charge
- load
- price

Graphs showing the changes over time.
Iteration 25

- Generation (gen):
  - Consistent increase and decrease pattern.

- Charge (charge):
  - Similar pattern to generation with slight fluctuations.

- Load (load):
  - Initial steady state, followed by a significant increase around time 40, then stabilization.

- Price (price):
  - Steady increase throughout the time period.

The graphs illustrate the dynamic changes in generation, charge, load, and price over time, with generation and charge showing synchronous and inverse trends, while load shows a significant peak around the mid-time period.
Iteration 30

- **gen**
- **charge**
- **load**
- **price**

(time)
Iteration 36

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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
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)