Cornell University

PSERC

Scheduling of Commitment, Energy and Reserves Under Uncertainty in a Two-Settlement Framework

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Consortium for Electric Reliability Technology Solutions

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CONSORTIUM FOR ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

Outline

- Generalized scheduling problem
- MOPS – MATPOWER Optimal Power Scheduler
- Our approach
- Benchmarking stochastic vs. deterministic
- Simulation Results
- Challenges

Problem Characteristics

Many problems we would like to solve in electricity markets, operations and planning are:

- large-scale
- stochastic
- non-linear
- mixed-integer
- multi-stage
- multi-period

Our Formulation

- Generalized extension of combined UC/OPF problem, to include …
  - intertemporal energy constraints for storage, flexible/deferrable demand
  - endogenous, price responsive contingency and ramping reserves
  - multi-stage stochastic approach w/scenario recombination
- Presented here in 2013 and published in [1].

[1] Carlos E. Murillo-Sánchez, Ray D. Zimmerman, C. Lindsay Anderson and Robert J. Thomas, "Secure Planning and Operations of Systems with Stochastic Sources, Energy Storage and Active Demand", *Smart Grid, IEEE Transactions on*, vol.4, no.4, pp.2220-2229, Dec. 2013. Available: http://dx.doi.org/10.1109/TSG.2013.2281001

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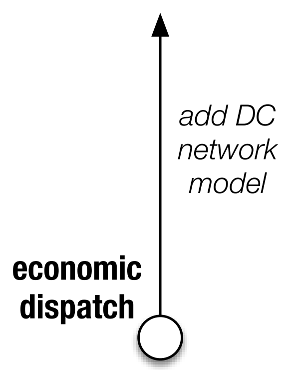
MOPS

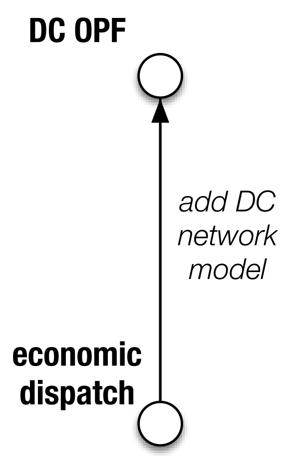
- **M**ATPOWER **O**ptimal **P**ower **S**cheduler
  - Current implementation based on DC power flow model.
  - Being refined and integrated into next major MATPOWER release.
  - AC version still at early prototype stage.

MOPS Continuous
Single Period Problems

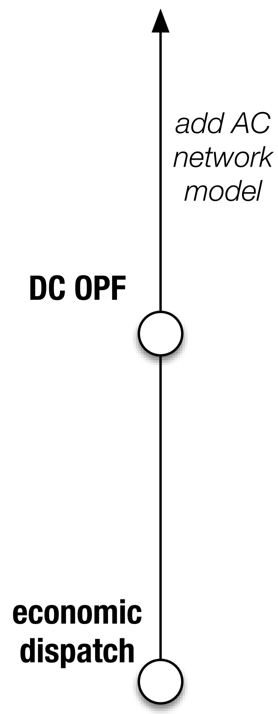
MOPS Continuous
Single Period Problems



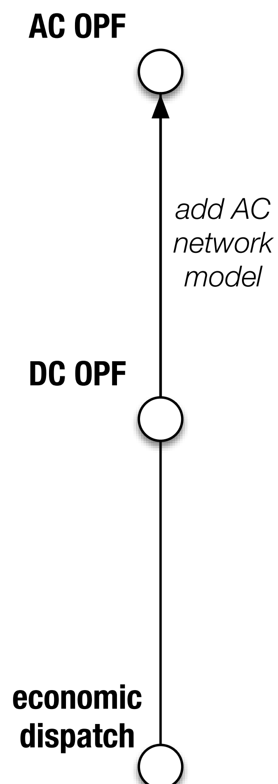
MOPS Continuous
Single Period Problems



MOPS Continuous Single Period Problems



MOPS Continuous
Single Period Problems



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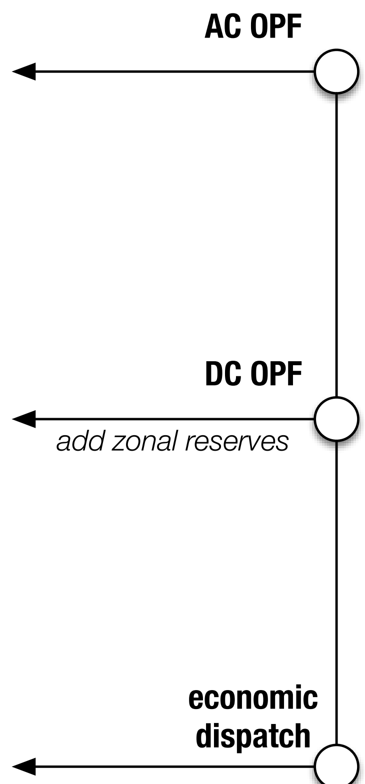

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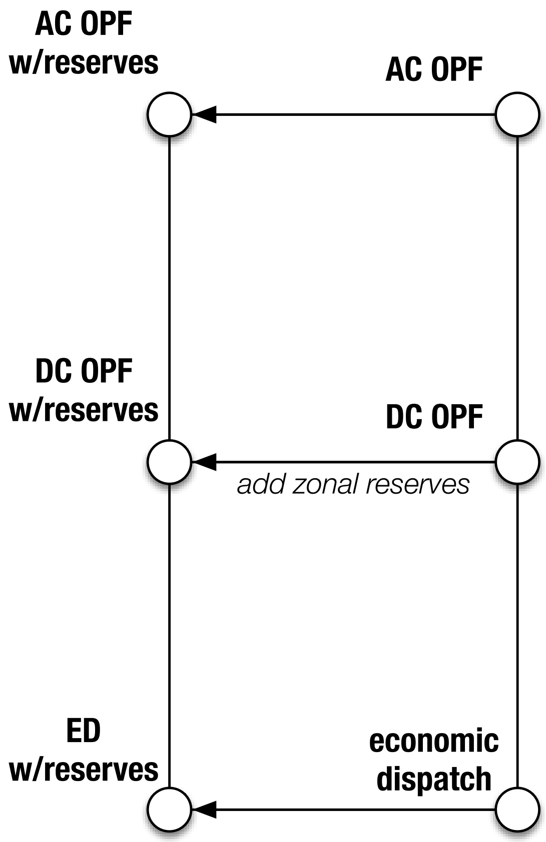
Single Period Problems



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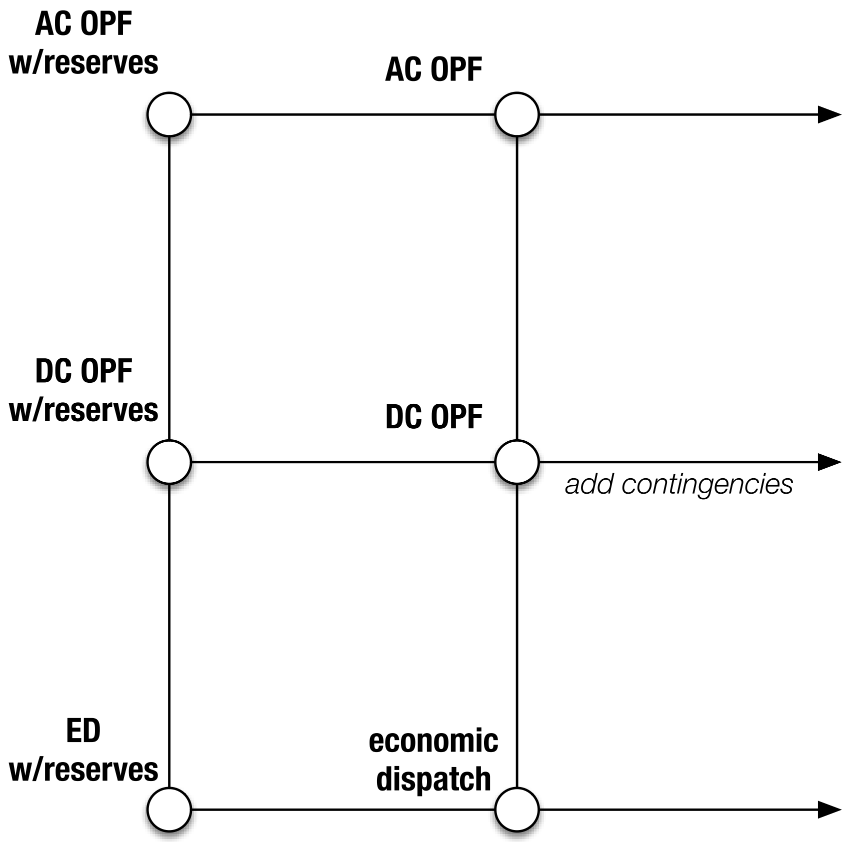

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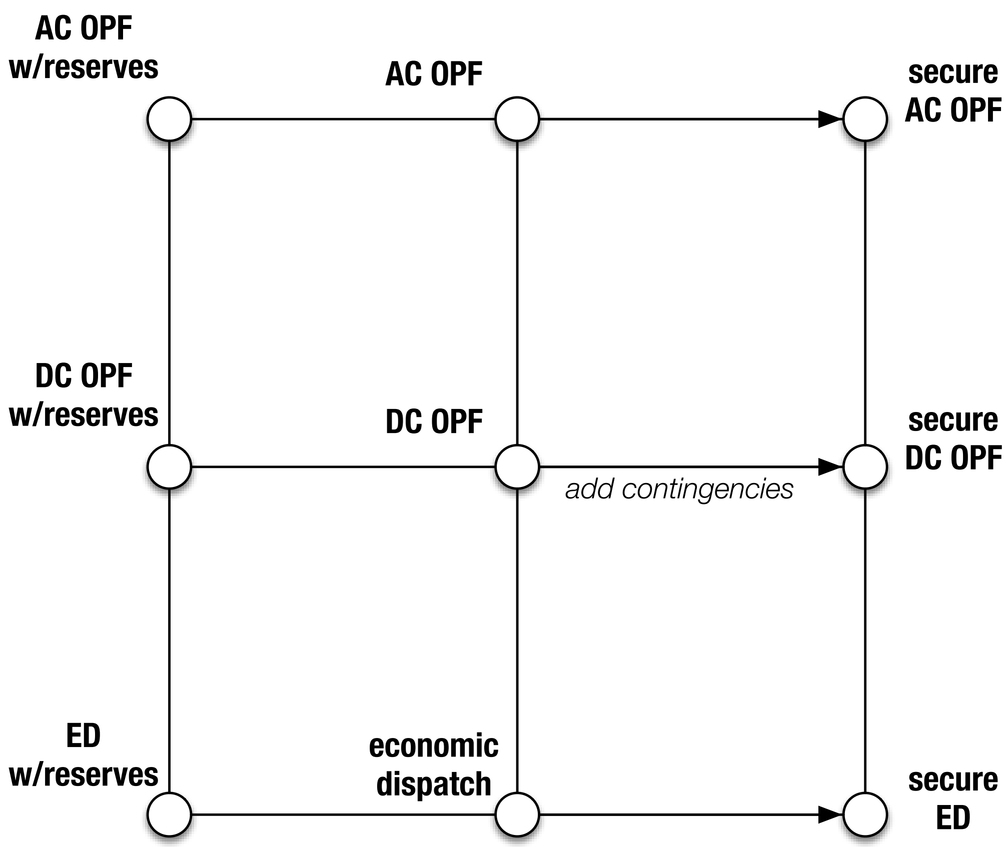
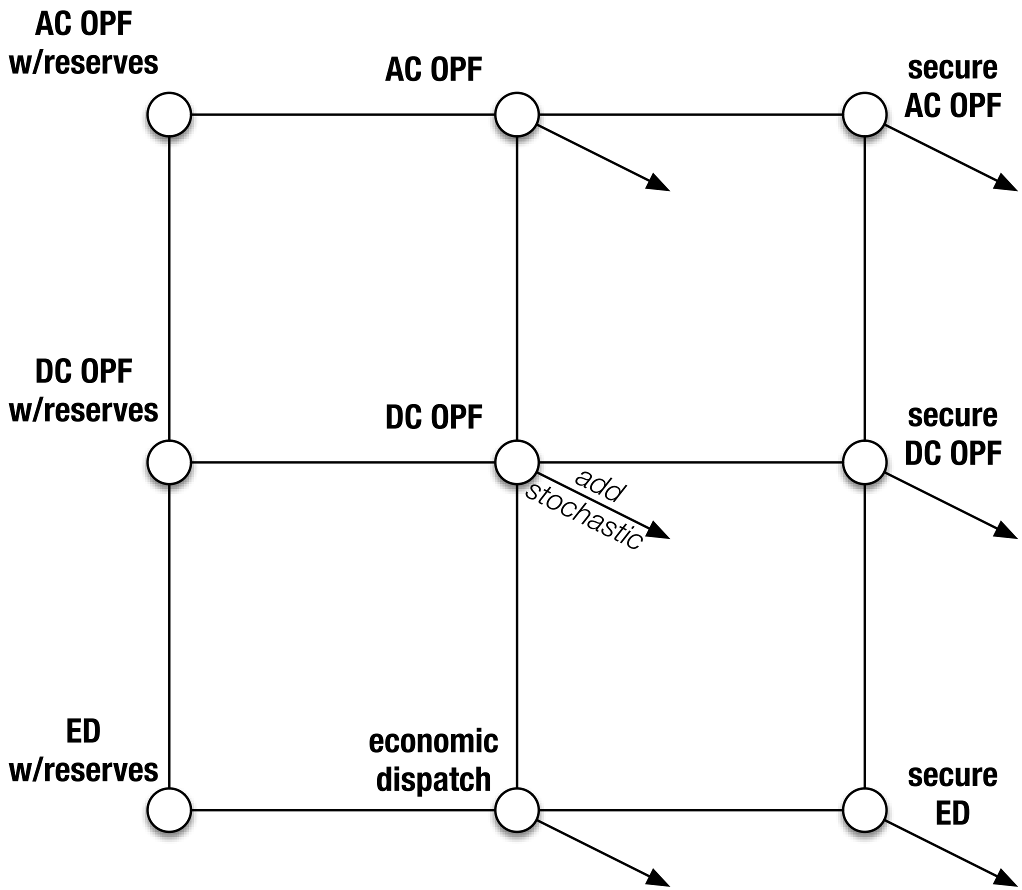


MOPS Continuous Single Period Problems



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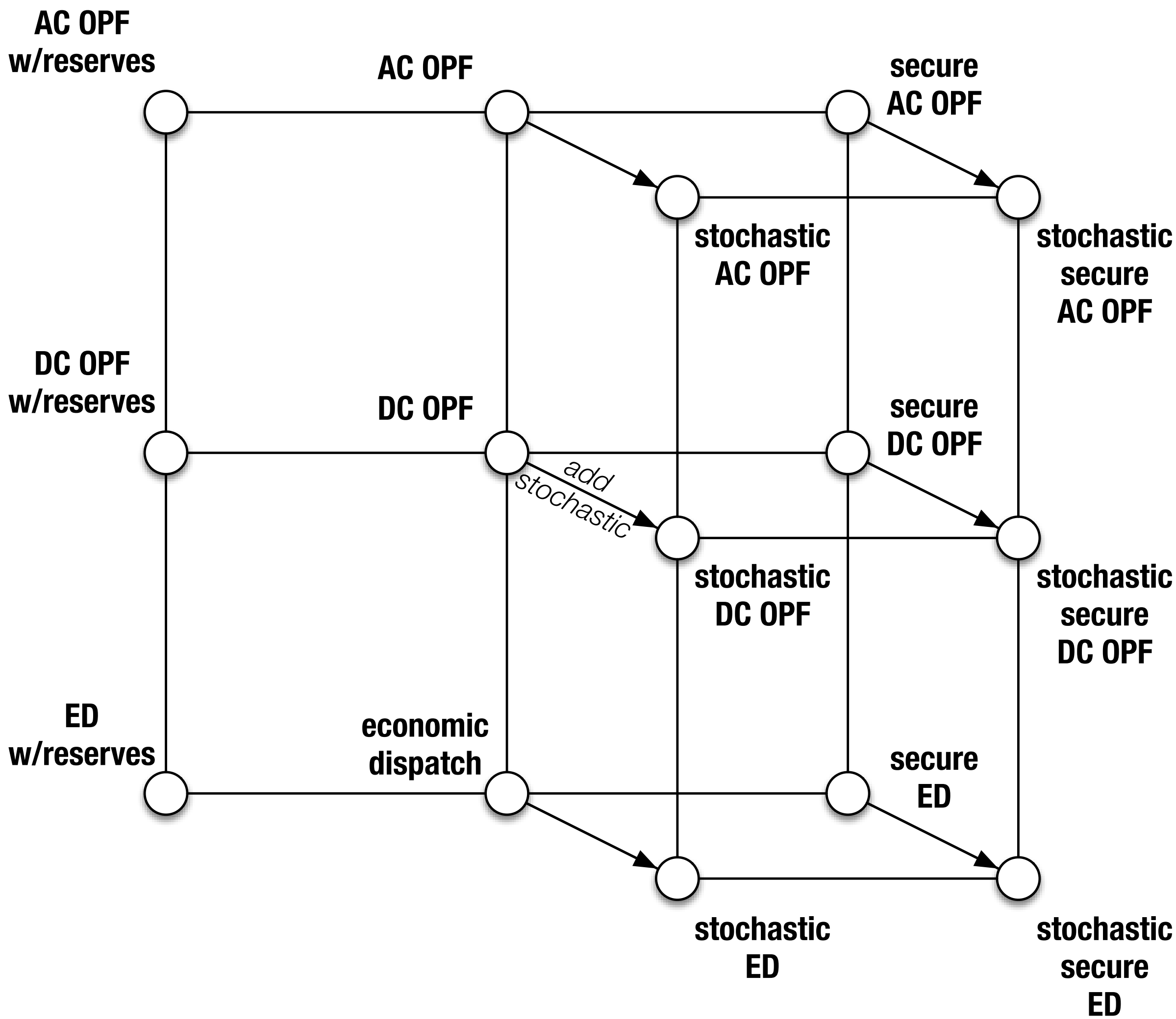

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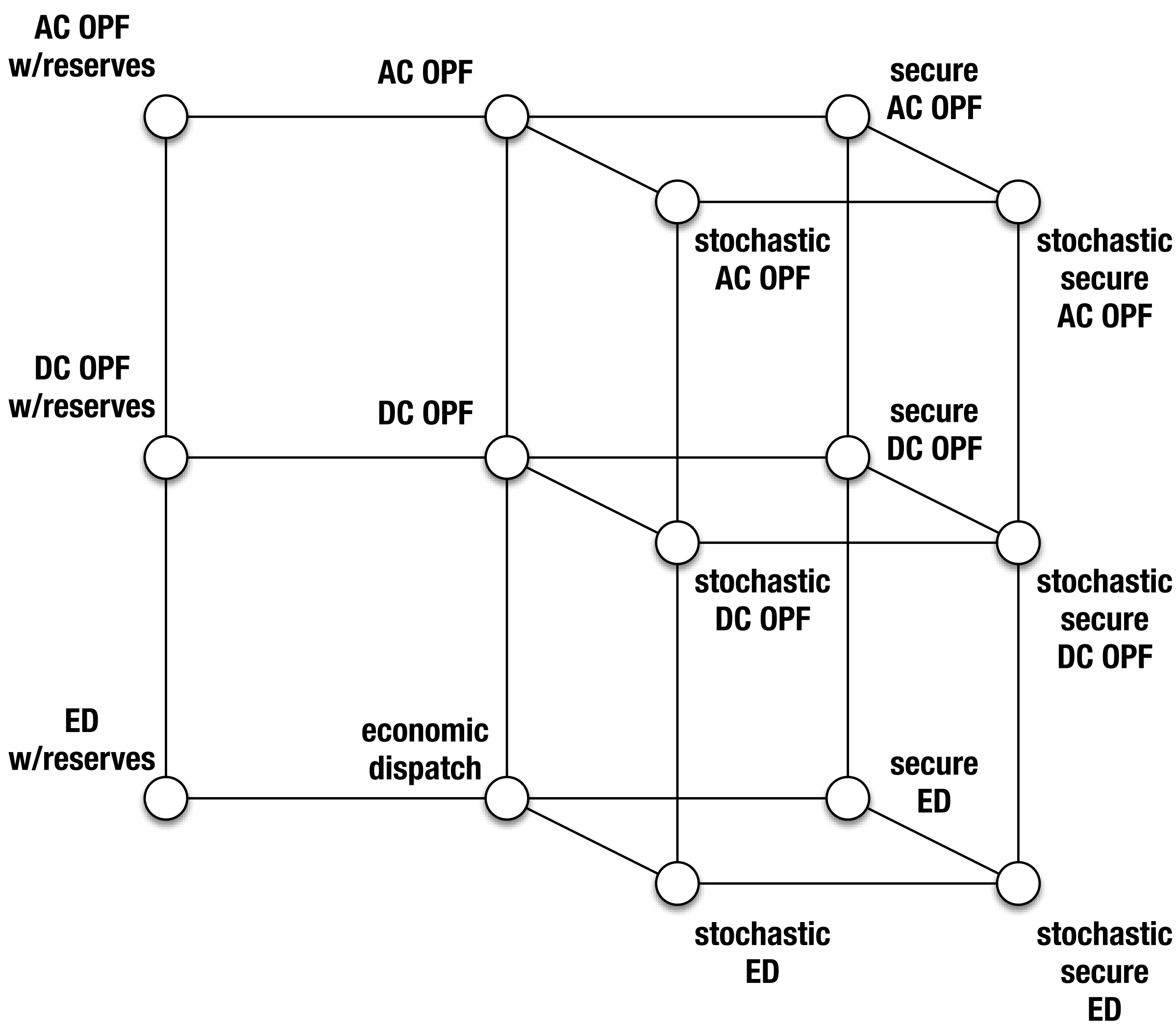

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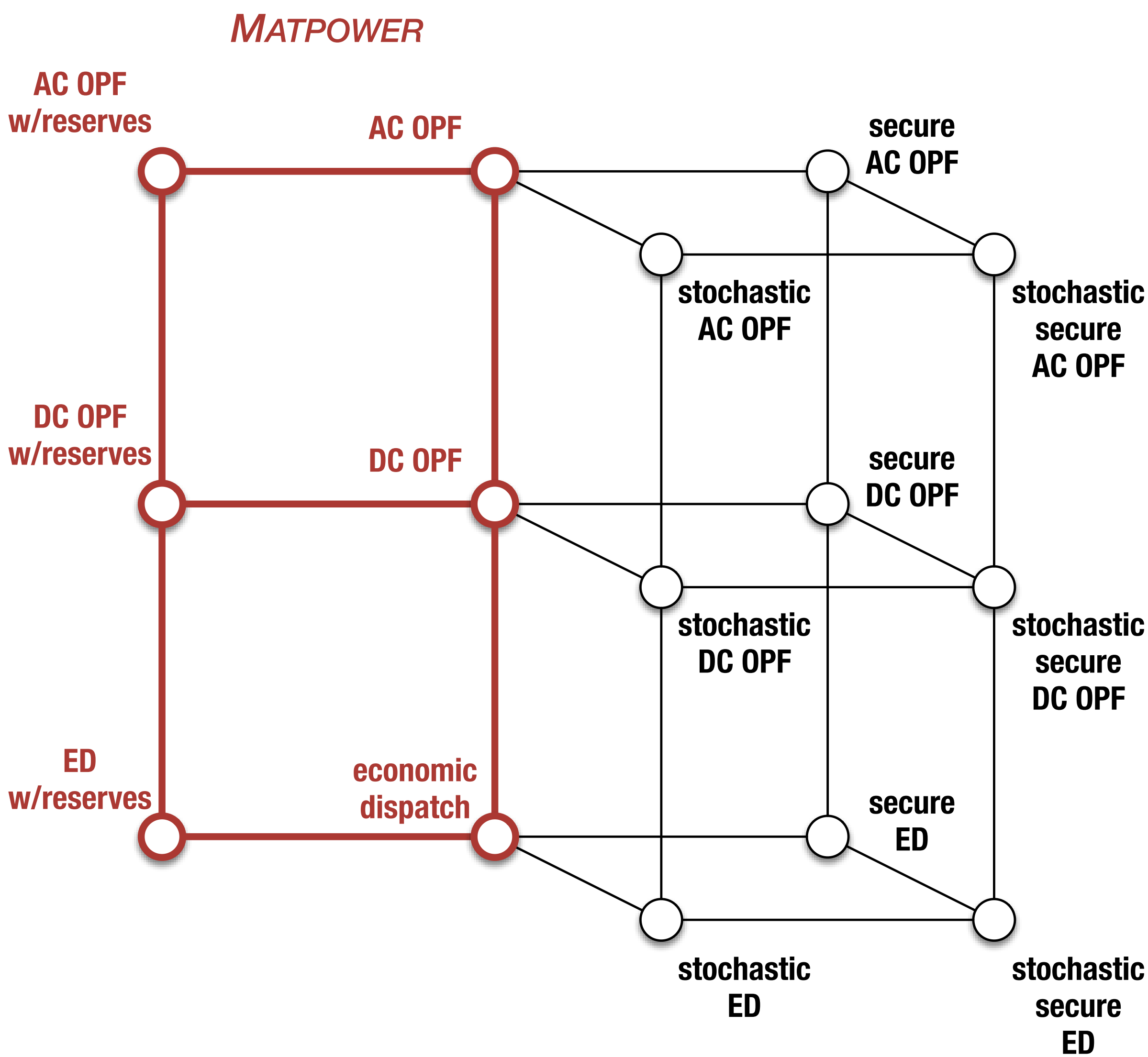
Single Period Problems



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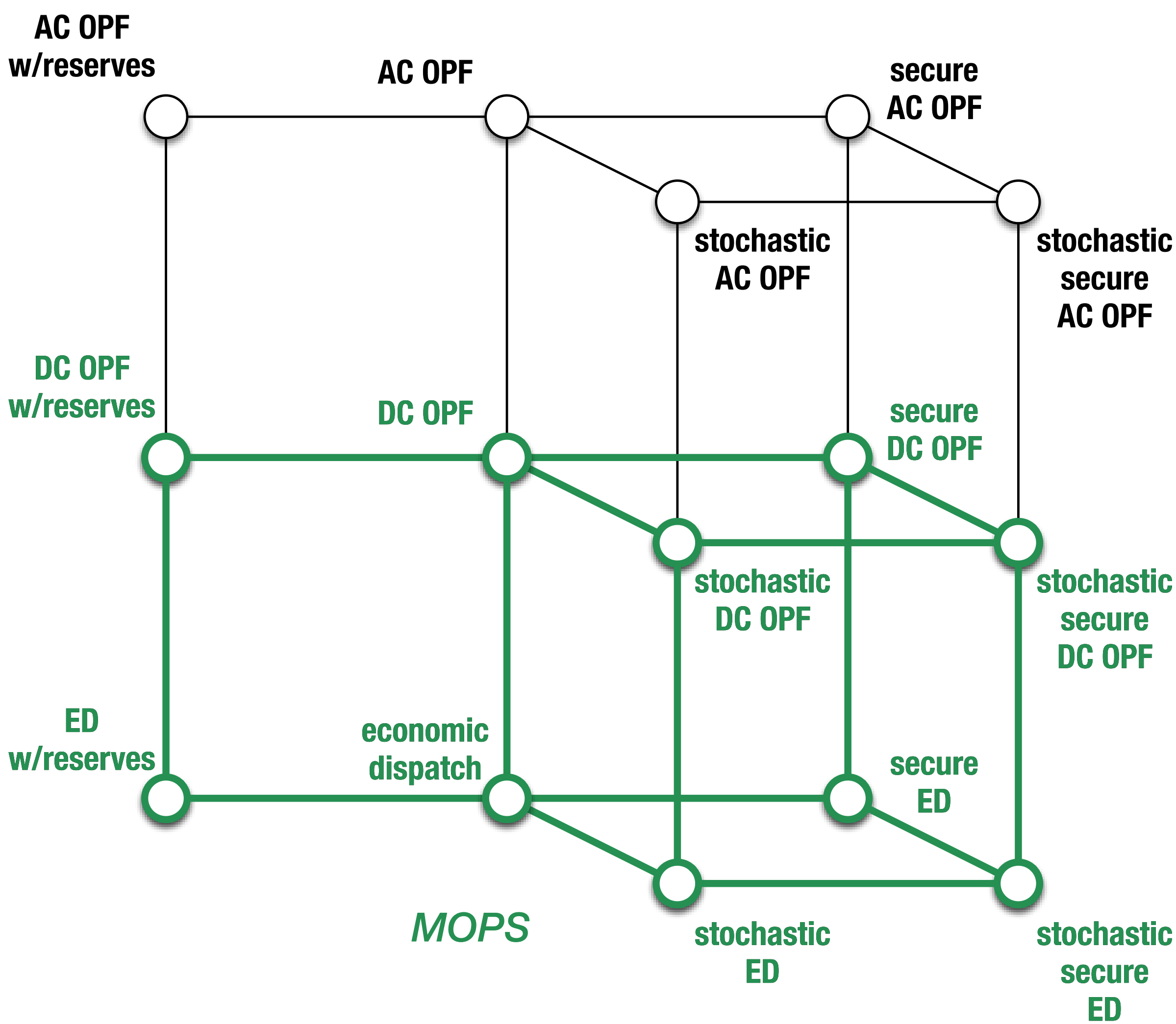

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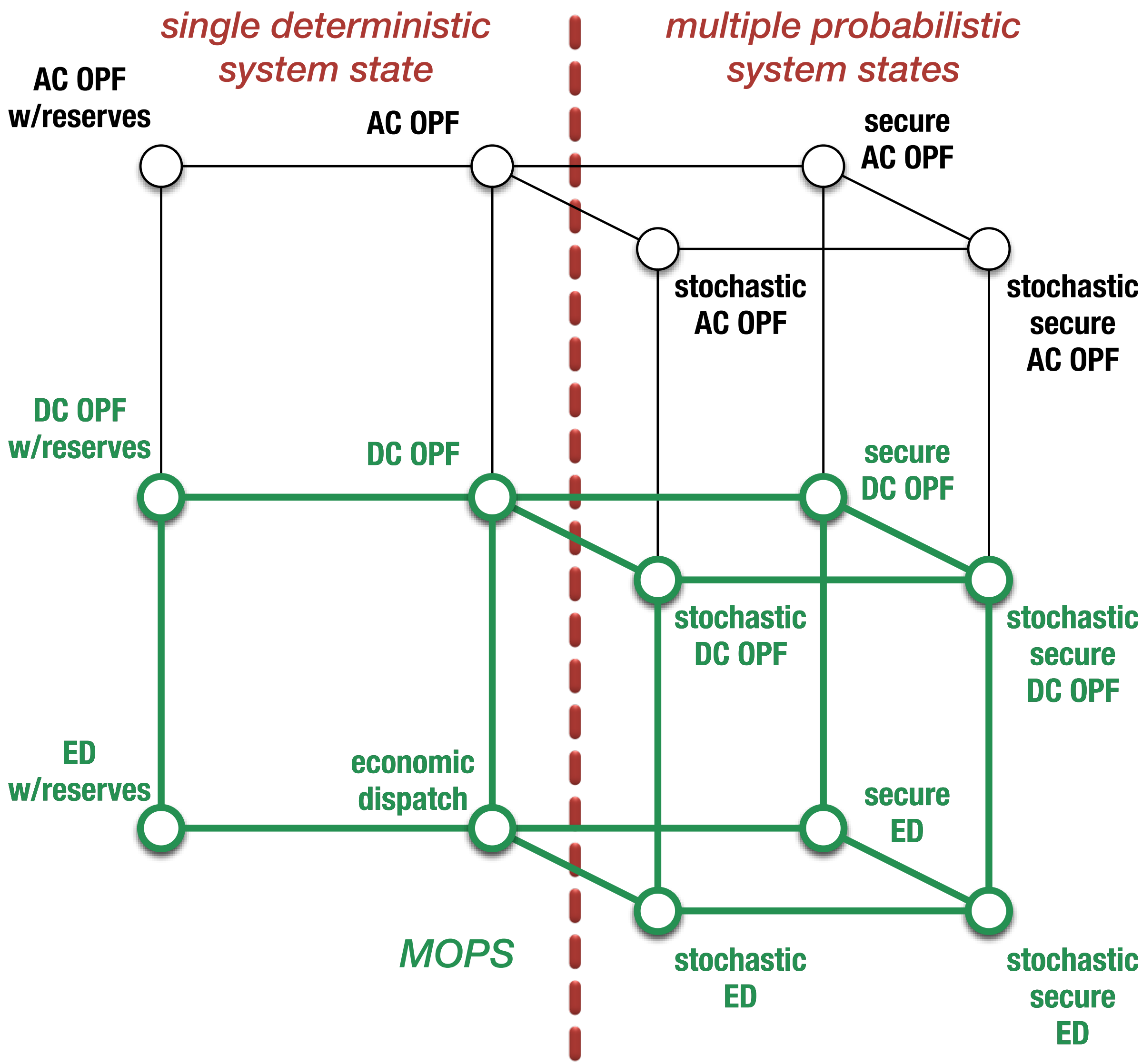
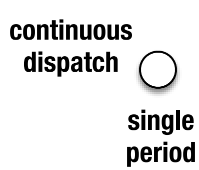


MOPS Mixed Integer and Multi-Period Problems



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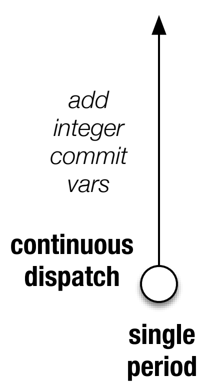

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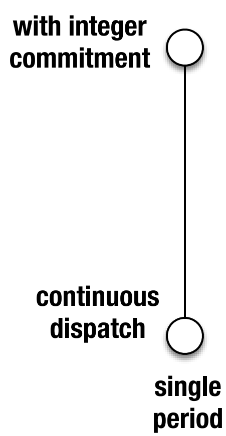

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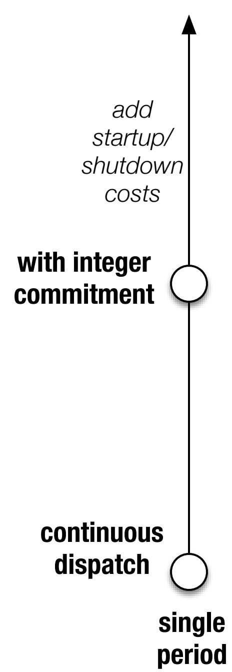

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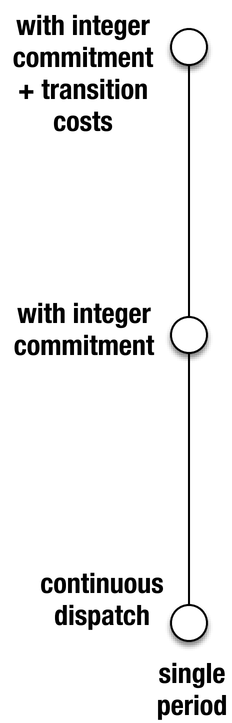

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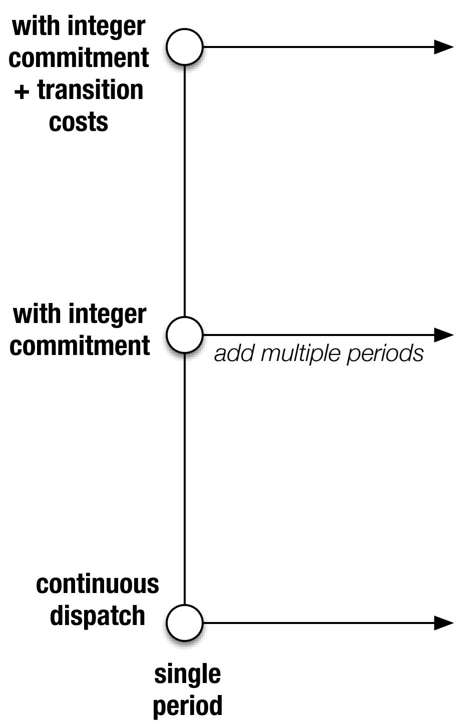

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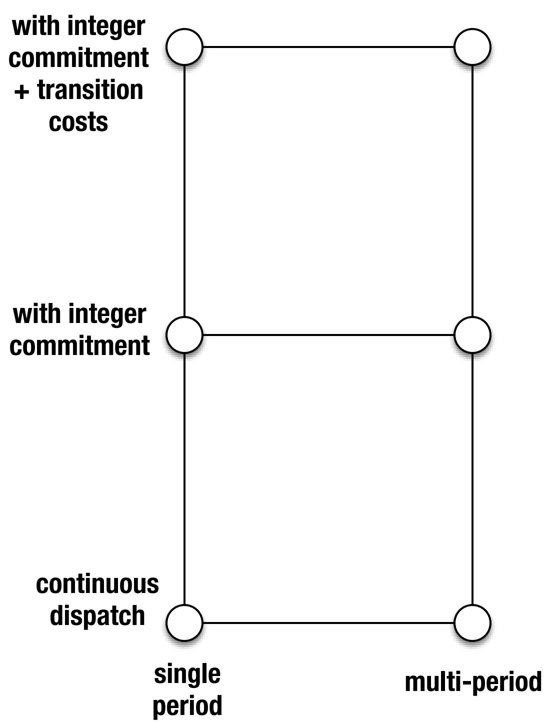

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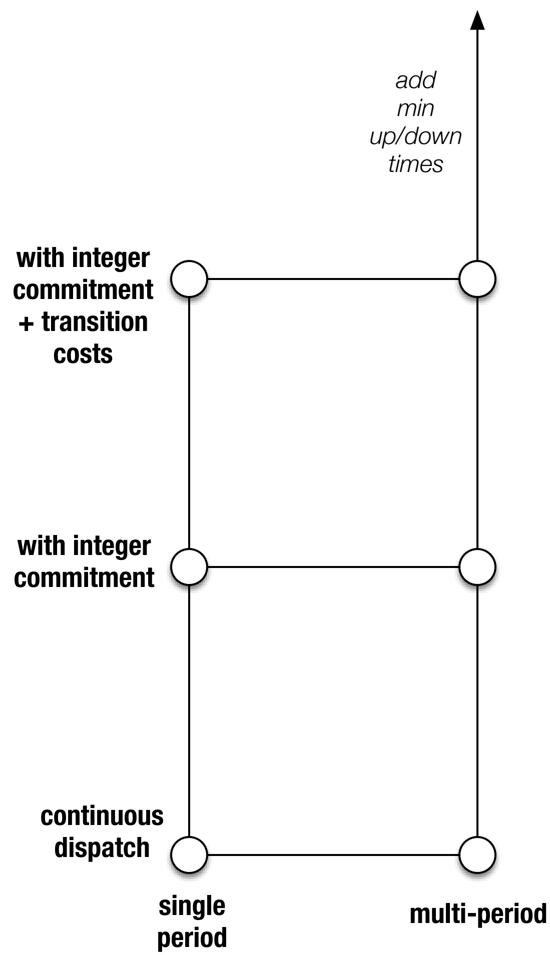

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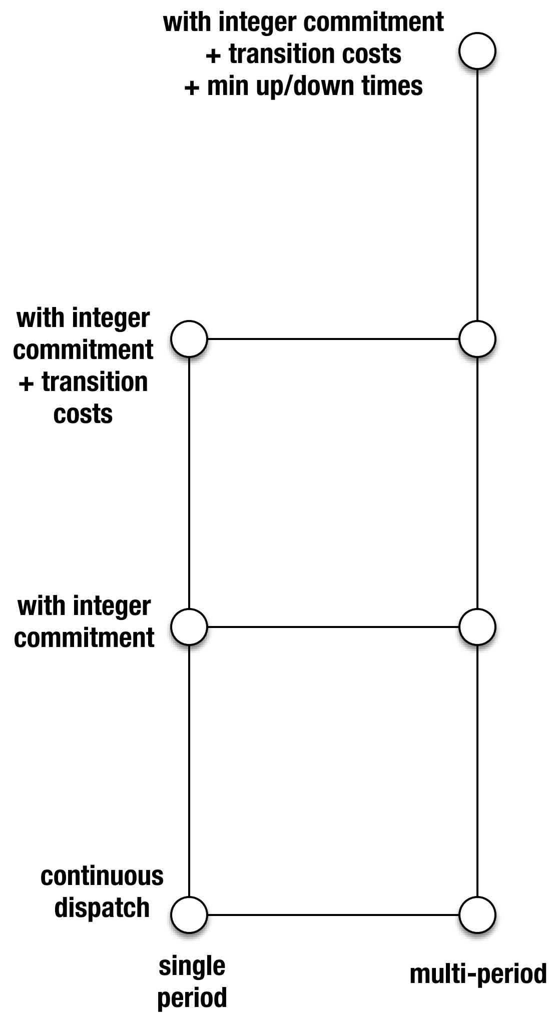

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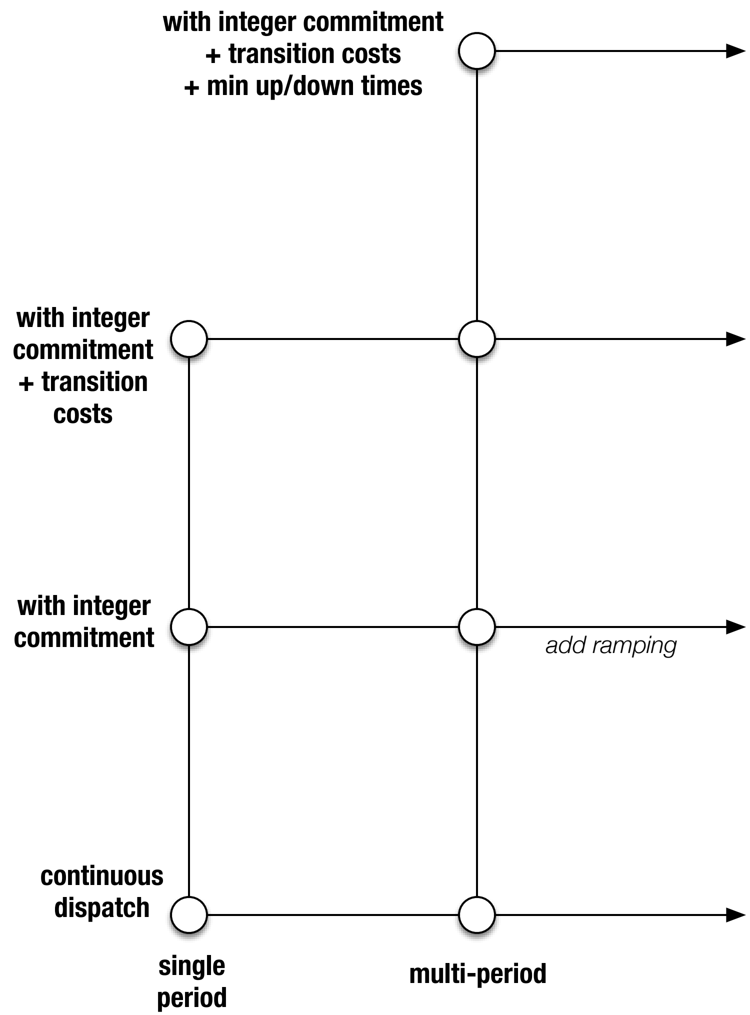

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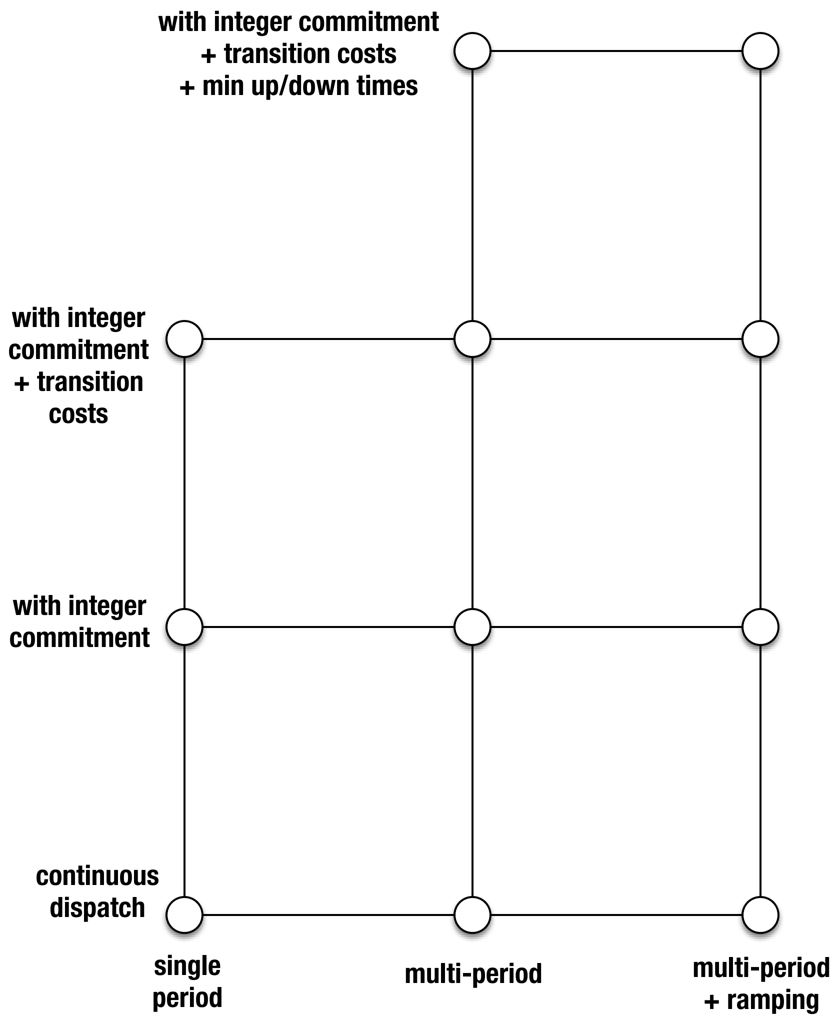

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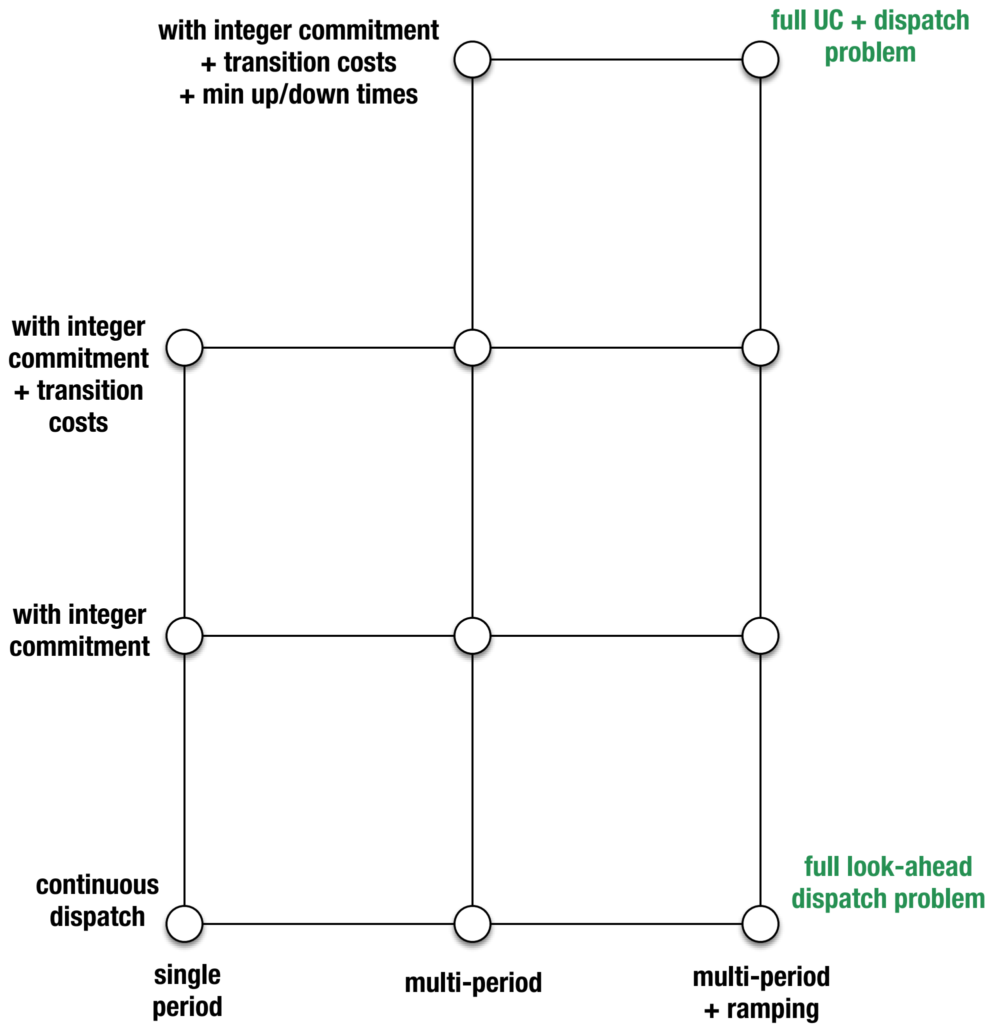

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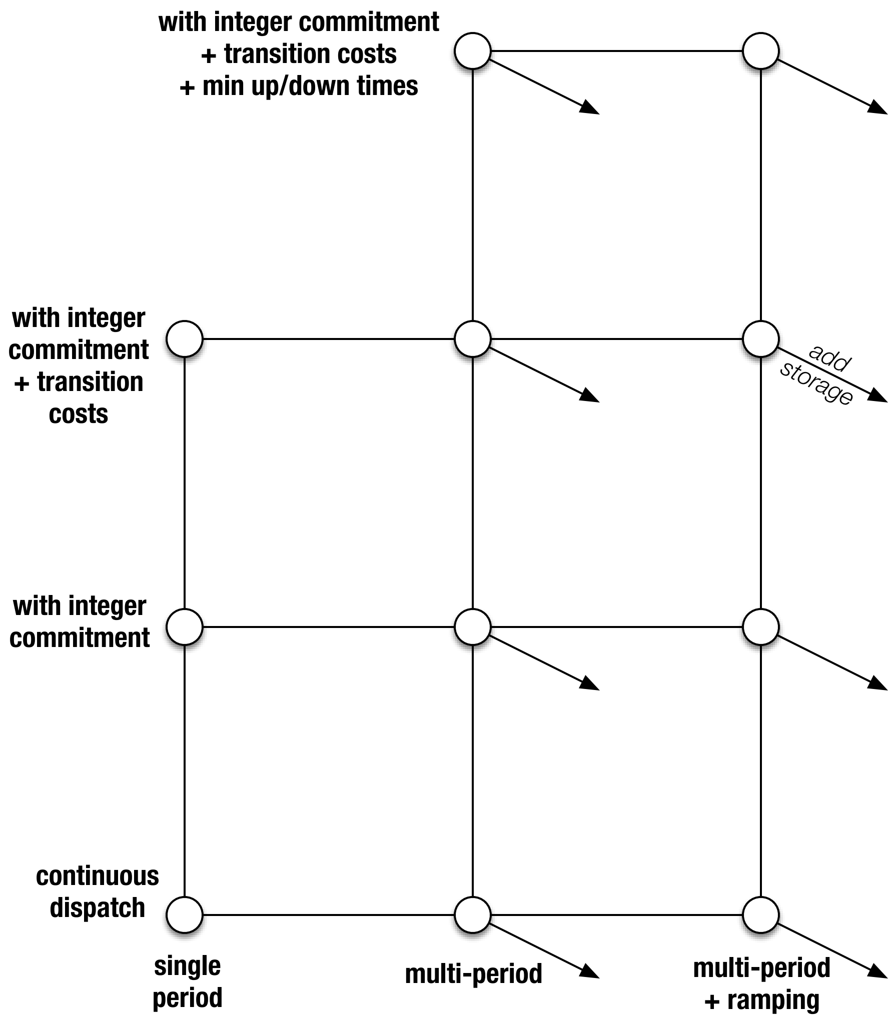

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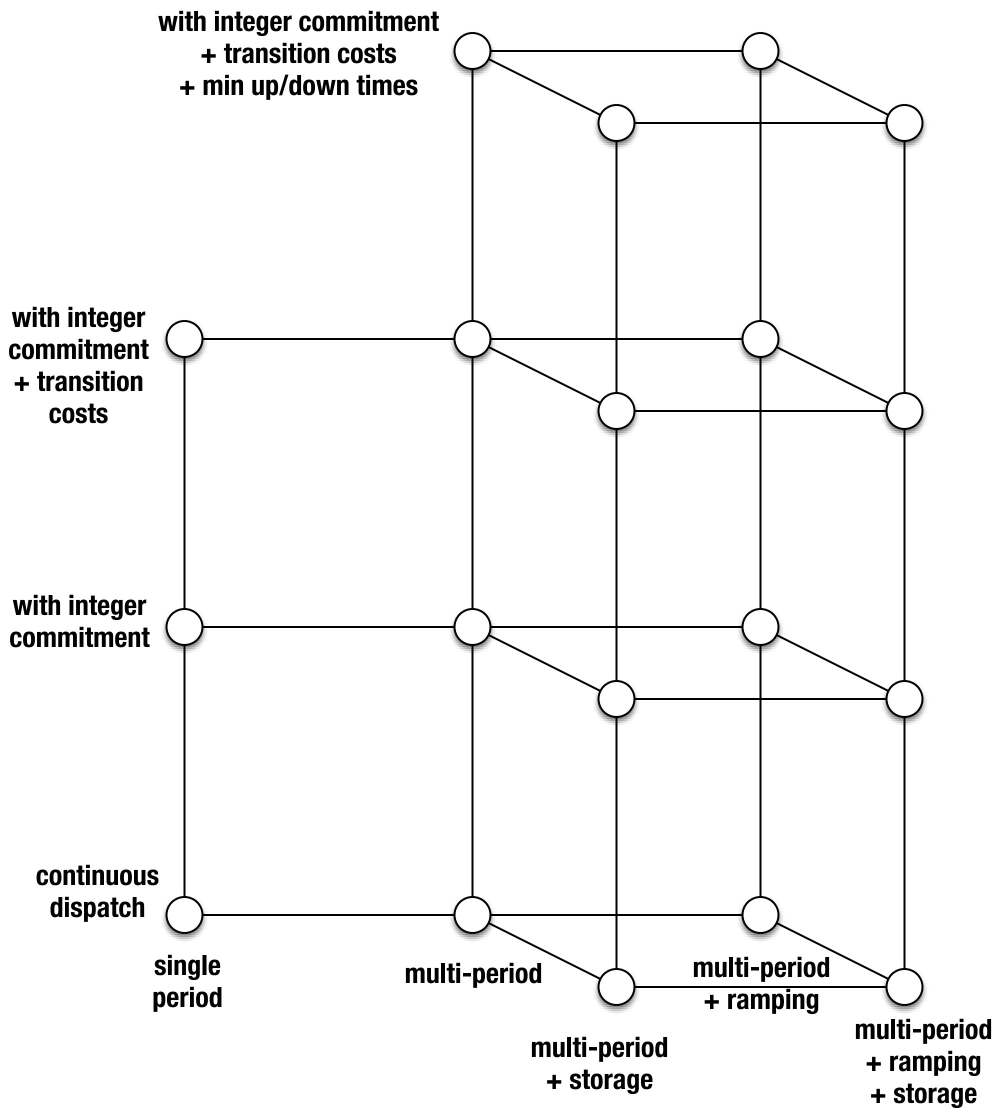


Objective Function

$$\min_x f(x) \qquad \text{where}$$

(1) expected active power dispatch and re-dispatch costs

(2) contingency reserve costs

(3) expected ramping wear & tear costs

$$f(x) = f_p(p, p_+, p_-) + f_r(r_+, r_-) + f_\delta(p) + f_{\mathrm{lf}}(\delta_+, \delta_-) + f_s(p_{\mathrm{sc}}, p_{\mathrm{sd}}) + f_{\mathrm{uc}}(v, w)$$

(4) load following ramp reserve costs

(5) expected cost/value of leftover stored energy in terminal states

(6) startup and shutdown costs

Constraints

(1) standard OPF constraints
- nonlinear AC power balance equations
- nonlinear transmission flow and voltage limits, other OPF inequalities

(2) contingency constraints
- reserve, redispatch and contract variables
- ramping limits on transitions from base to contingency cases

(3) intertemporal constraints
- load following ramping limits and reserves
- energy storage constraints

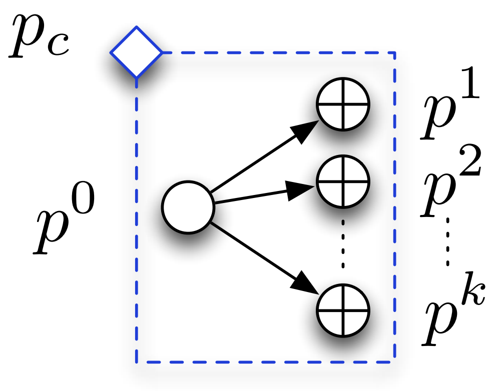
(4) unit commitment constraints
- injection limits vs. commitment variables
- startup/shutdown events
- minimum up/down times

Uncertainty

Begin with single period problem, that is, making the OPF stochastic and secure.

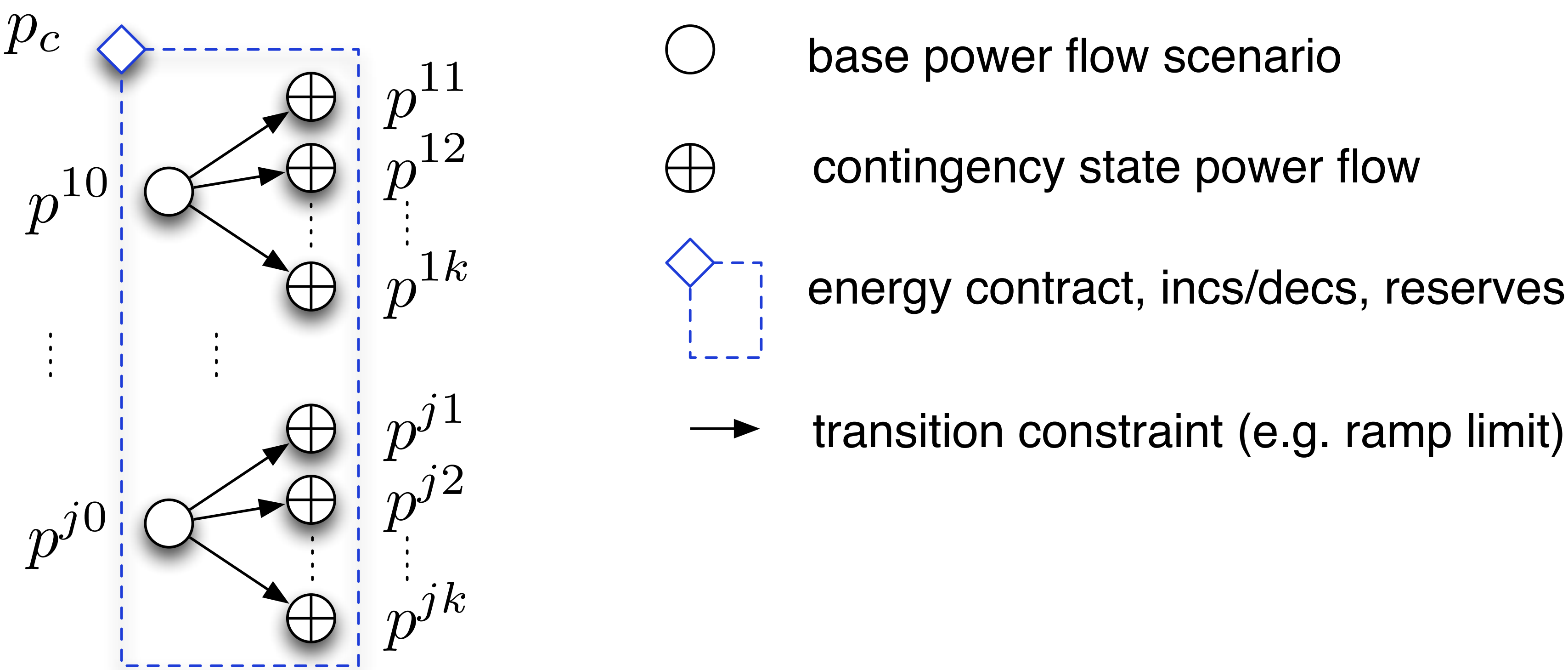
- two types of uncertainty
  - wind, load (continuous, distribution)
  - contingencies (discrete, low probability)
- both handled by selecting sets of individual probability weighted scenarios, so that:
  - overall stochastic cost is approximated adequately,
  - credible, low probability, high impact events are included to ensure security,
  - number of scenarios is minimized to keep computational cost reasonable.

Problem Structure – Contingencies

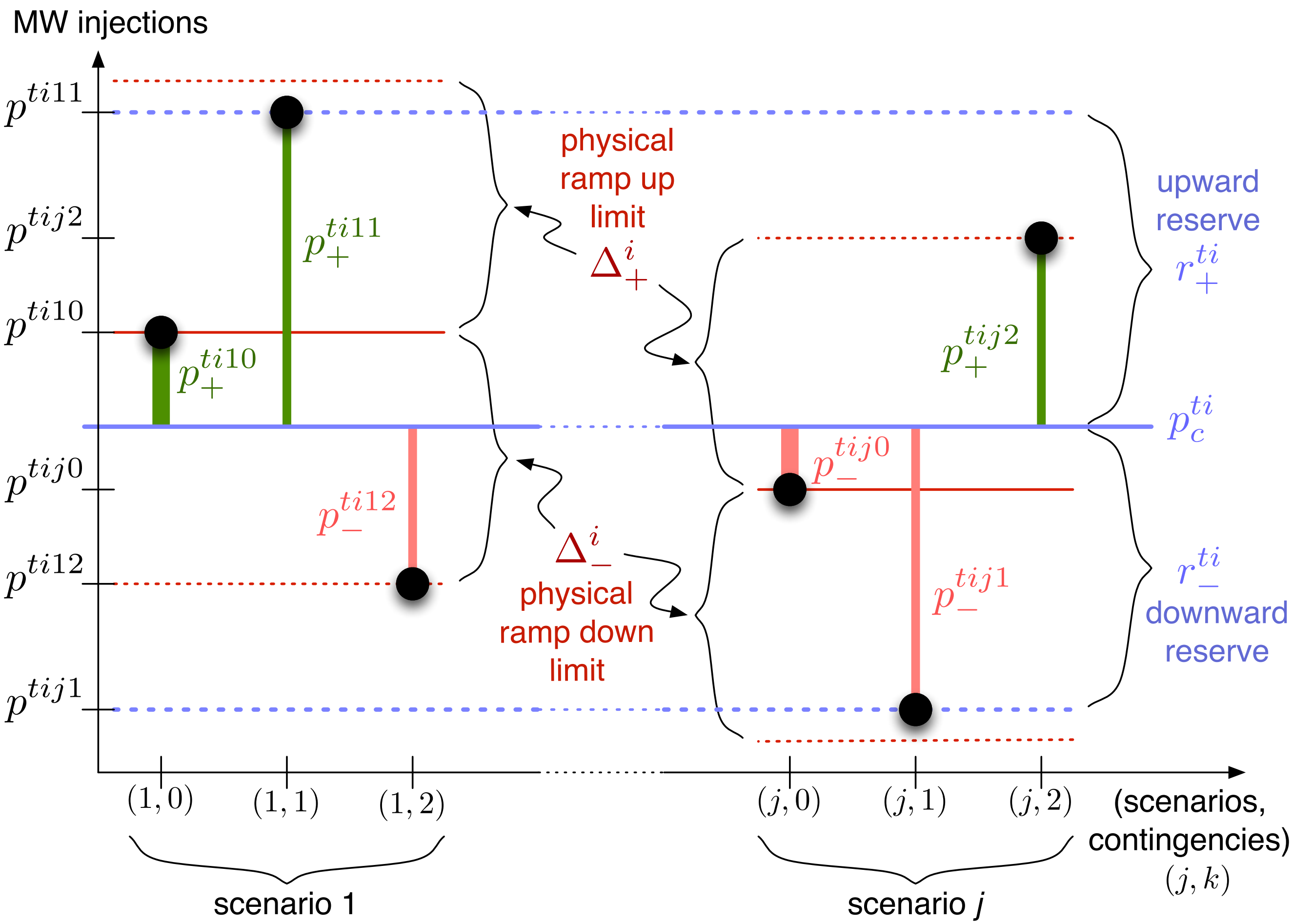


- base power flow scenario
- contingency state power flow
- energy contract, incs/decs, reserves
- transition constraint (e.g. ramp limit)

Problem Structure – Wind



Reserves

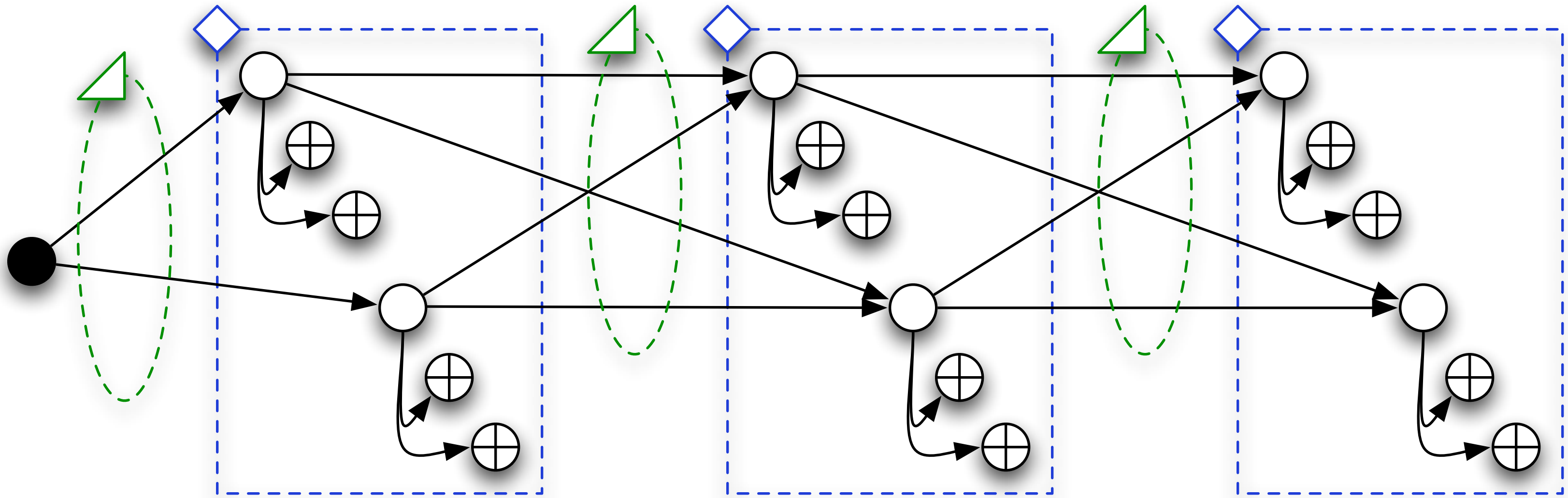


MW injections
p^{ti11}
p^{tij2}
p^{ti10}
p^{tij0}
p^{ti12}
p^{tij1}
p_+^{ti11}
p_+^{ti10}
p_-^{ti12}
physical
ramp up
limit
Δ_+^i
Δ_-^i
physical
ramp down
limit
p_+^{tij2}
p_-^{tij0}
p_-^{tij1}
upward
reserve
r_+^{ti}
p_c^{ti}
r_-^{ti}
downward
reserve
$(1, 0)$
$(1, 1)$
$(1, 2)$
$(j, 0)$
$(j, 1)$
$(j, 2)$
(scenarios,
contingencies)
(j, k)
scenario 1
scenario *j*

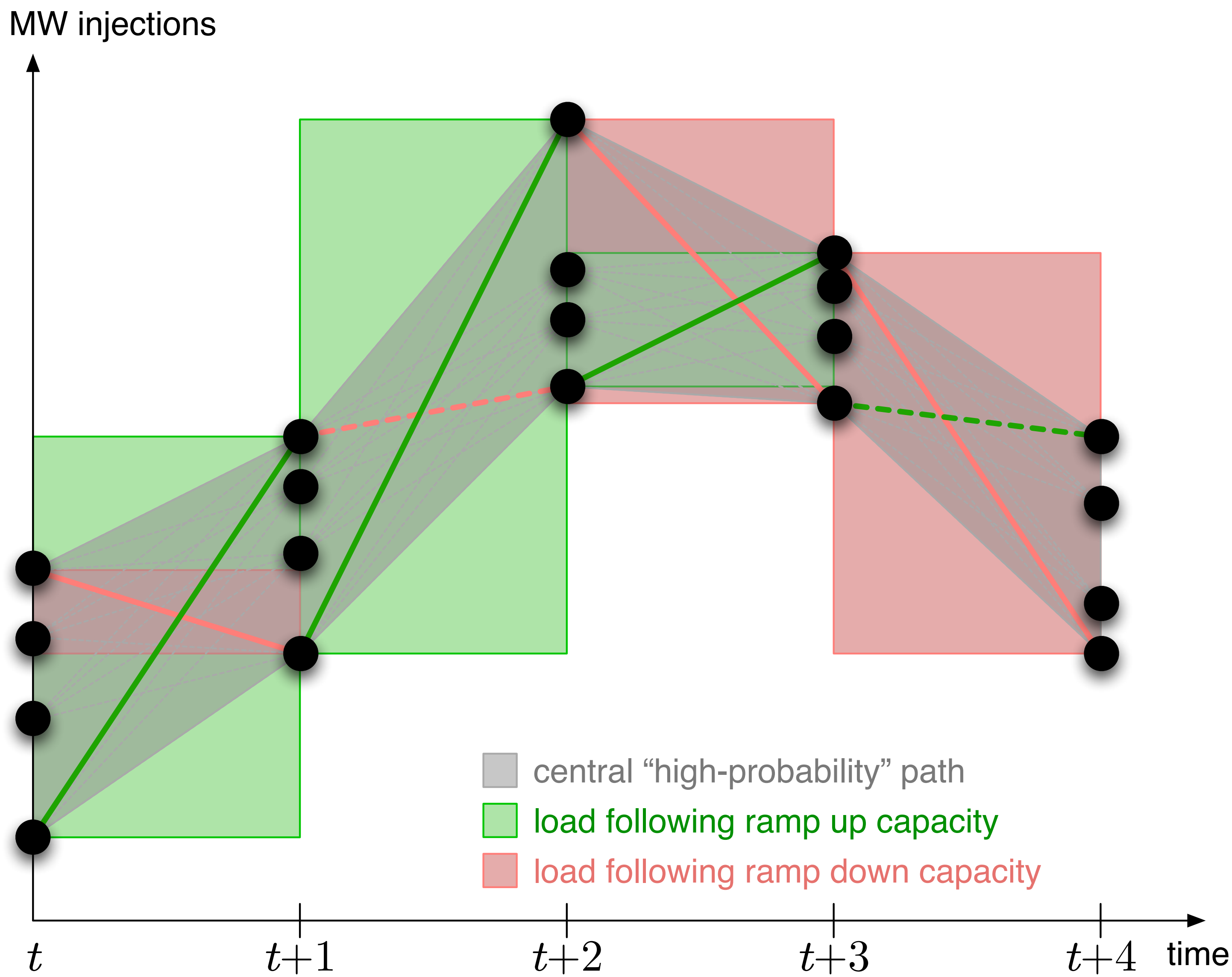
Extending to Multiple Periods

- number of possible states explodes due to path dependence
- treating each trajectory as a scenario requires too many trajectories to capture the range of possible outcomes in each period
- our approach – enforce feasibility of a central path, the high probability path defined by the set of base scenarios

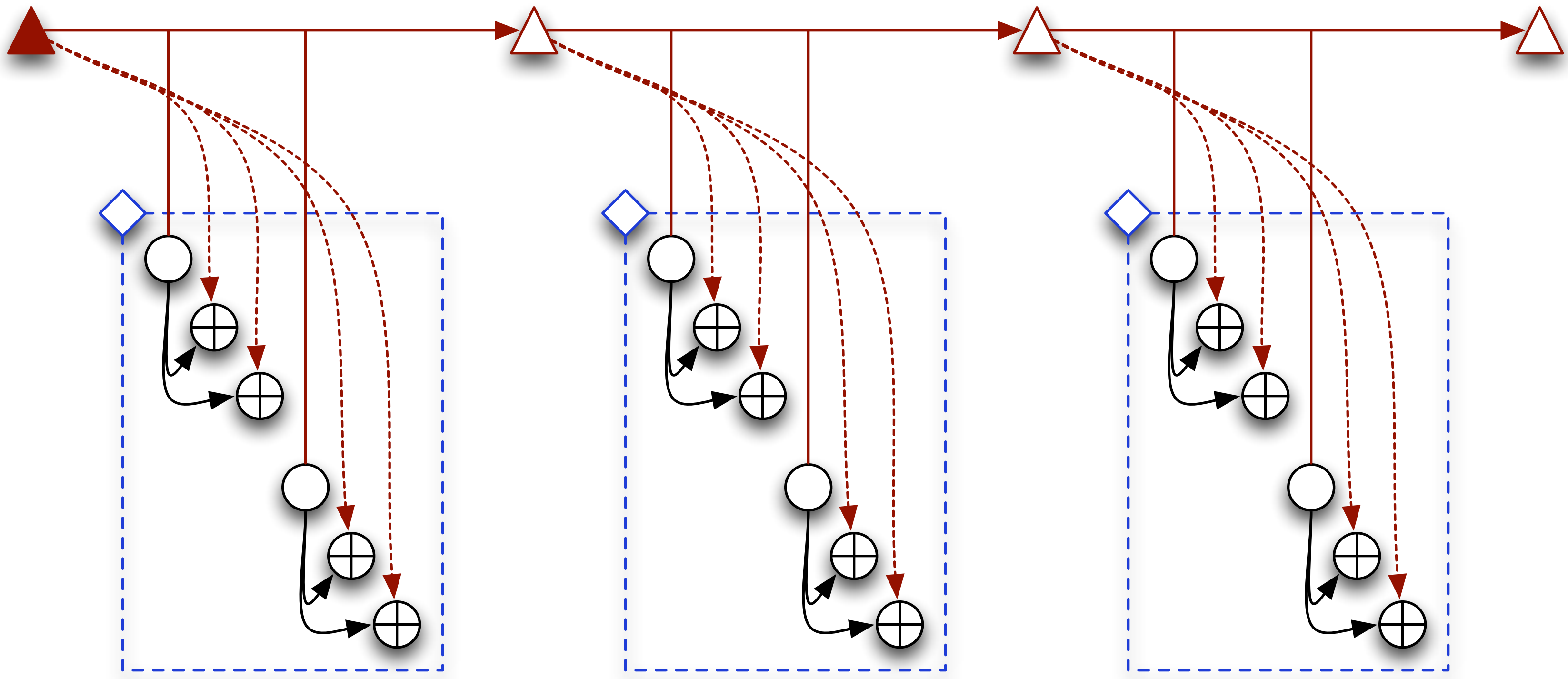
Ramping



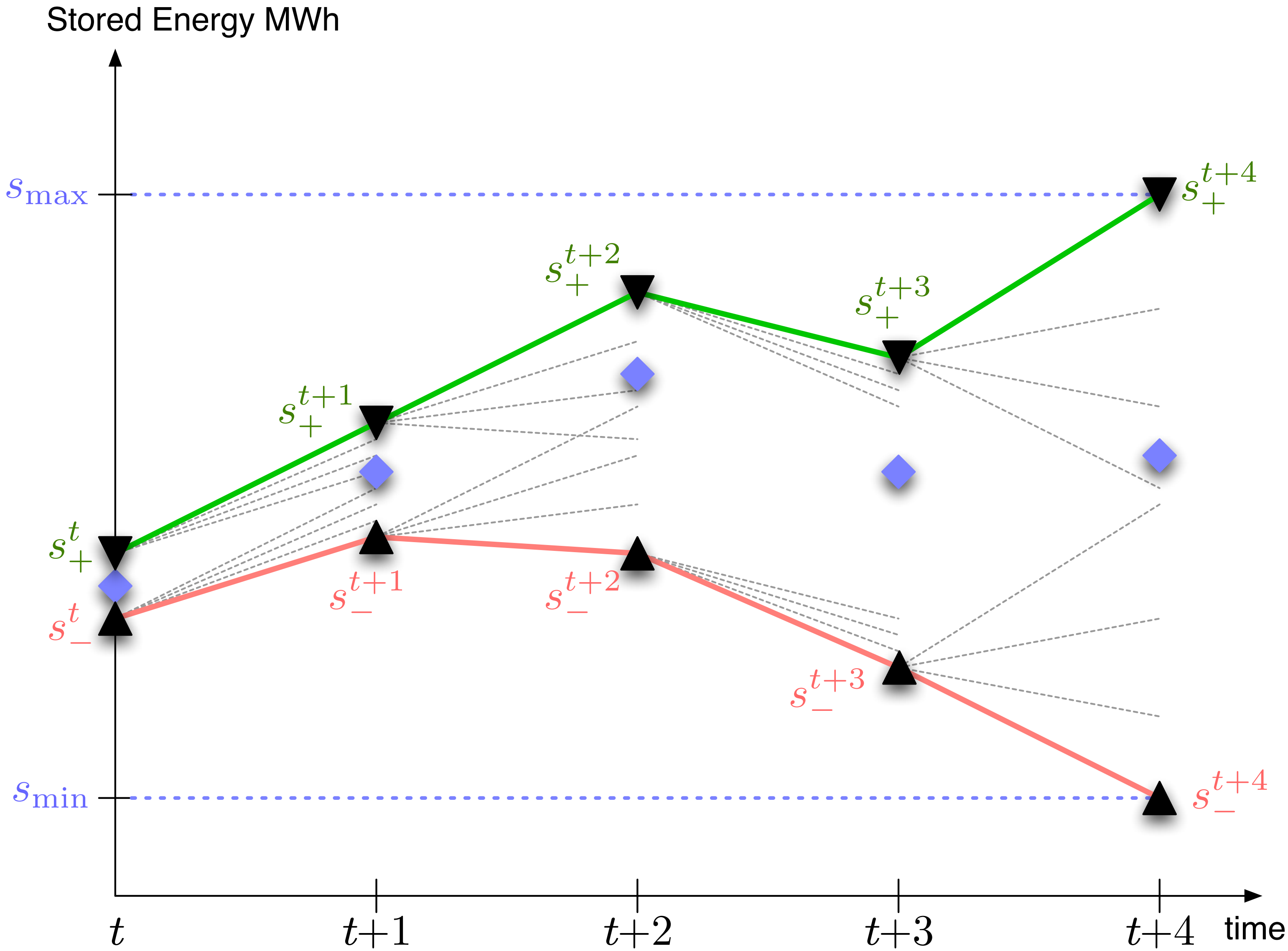
Ramping – Load Following Reserve



Storage



Storage



Stored Energy MWh
$s_{\max}$
$s_{\min}$
s_+^t
s_-^t
s_+^{t+1}
s_-^{t+1}
s_+^{t+2}
s_-^{t+2}
s_+^{t+3}
s_-^{t+3}
s_+^{t+4}
s_-^{t+4}
t
$t+1$
$t+2$
$t+3$
$t+4$
time

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Application Context

- In system operations, we have multi-stage decisions (focus on day-ahead commitments through 5-minute dispatch), with uncertainty revelation along the way.

The Challenge – Testing MOPS

Stochastic

Secure UC+OPF

- multiple scenarios for demand and renewable availability
- explicit contingencies for security

Deterministic

UC+OPF

- single scenario with expected demand and renewable availability
- zonal reserve requirements for security

Ideal Comparison

- Our stochastic approach in a receding horizon context vs. current ISO practice with realistic forecasting of uncertain inputs (time varying distributions).
  - Under uncertainty, allowing recourse in decision-making can dramatically improve efficiency
  - Tests should reflect potential real-world benefits
- Both are too complex
- Data problem is massive

Tradeoffs

- Two settlement structure
  - 1st settlement : solves a multi-period plan resulting in day-ahead commitment decisions and reserve allocations
  - 2nd settlement : solves single-period problem to determine energy dispatch and contingency reserve allocation subject to UC decisions from 1st settlement, dispatch from previous period 2nd settlement and newly revealed uncertainty
  - Ideally, should have 3rd phase to simulate "what actually happens" but for now we assume 2nd settlement approximates that well enough

Distinctive Features of Our Approach

- MOPS formulation
  - design does not preclude AC network model
  - multi-stage scenario tree w/scenario recombo vs. individual trajectories as scenarios
    - smaller number of scenarios required to capture range of outcomes
    - preserves non-anticipativity of dispatch decisions
  - scenarios linked by reserves, ramping, storage as well as unit commitment
- Benchmarking structure
  - 2nd settlement decisions are sequential (causal) as in real world

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Testing Structure

- Given:
  - historical temp, wind, demand up to today *(any selected day of interest)*
  - ARIMA model of temp, wind, demand that can generate potential realizations of the operating day
- For each approach:
  1. Solve 1st settlement problem for the day (based on uncertainty predicted by the ARIMA model).
  2. Select *N* realizations of the day generated by ARIMA model, for each solve 2nd settlement problems sequentially for each hour, subject to 1st settlement.

First Settlement

Stochastic

- n_j base wind/load scenarios per period
- n_c contingencies for each base scenario
- base scenarios selected based on ARIMA model
- n_j x n_c x 24 OPF problems tied together by ramping, UC and additional variables, costs, constraints

Deterministic

- based on single expected wind/load scenario per period
- zonal reserve requirements to handle largest outage + forecast errors, no explicit contingencies
- base scenario based on ARIMA model
- 24 OPF problems tied together by ramping and UC

Second Settlement

Stochastic

- 1 base scenario with realized wind/load
- n_c contingencies
- UC from 1st settlement
- dispatch constrained by ramp from previous period
- n_c OPF problems tied together by additional variables, costs, constraints

Deterministic

- 1 base scenario with realized wind/load
- zonal reserve requirements to handle largest outage, no explicit contingencies
- UC from 1st settlement
- dispatch constrained by ramp from previous period
- single OPF problem

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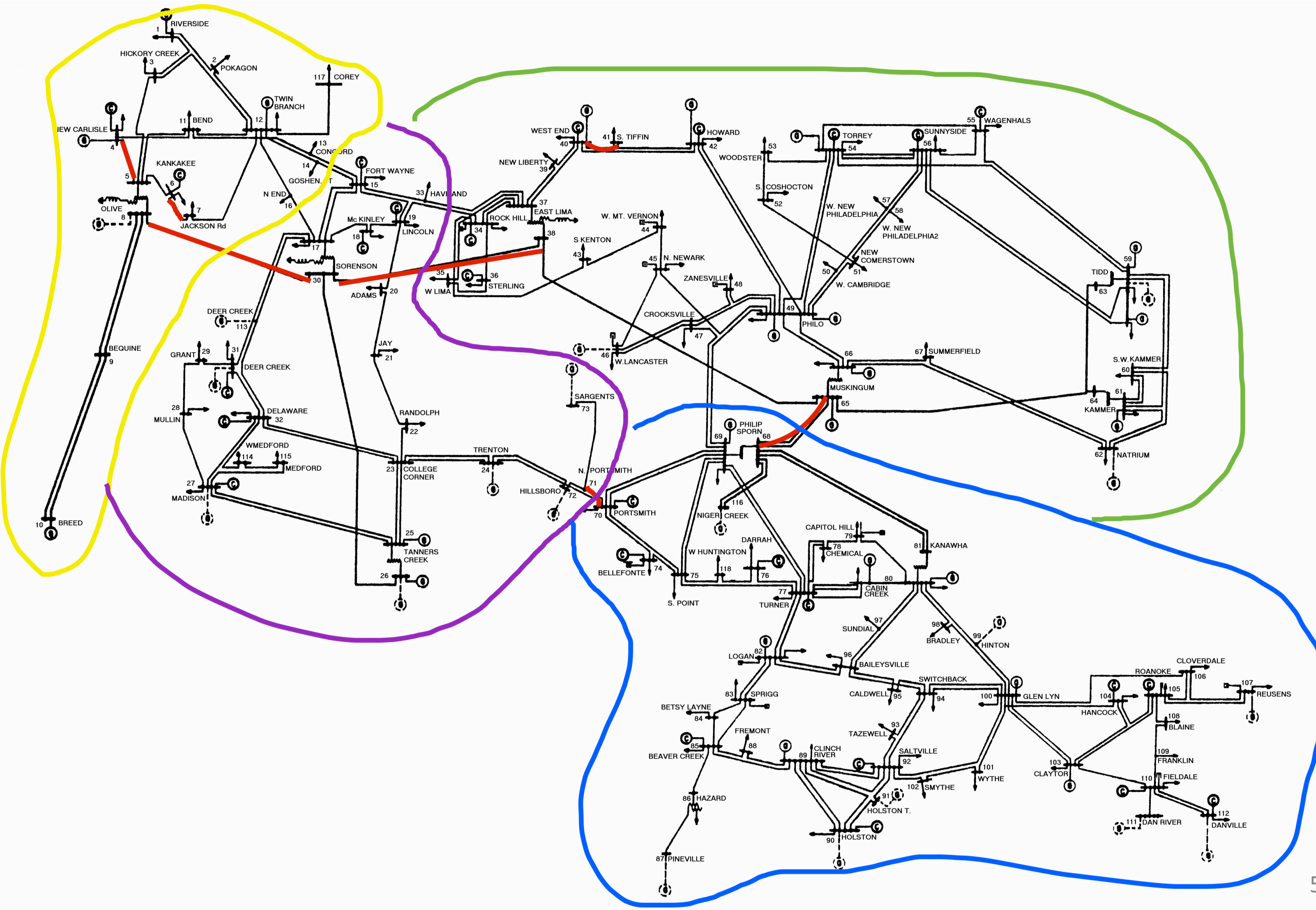
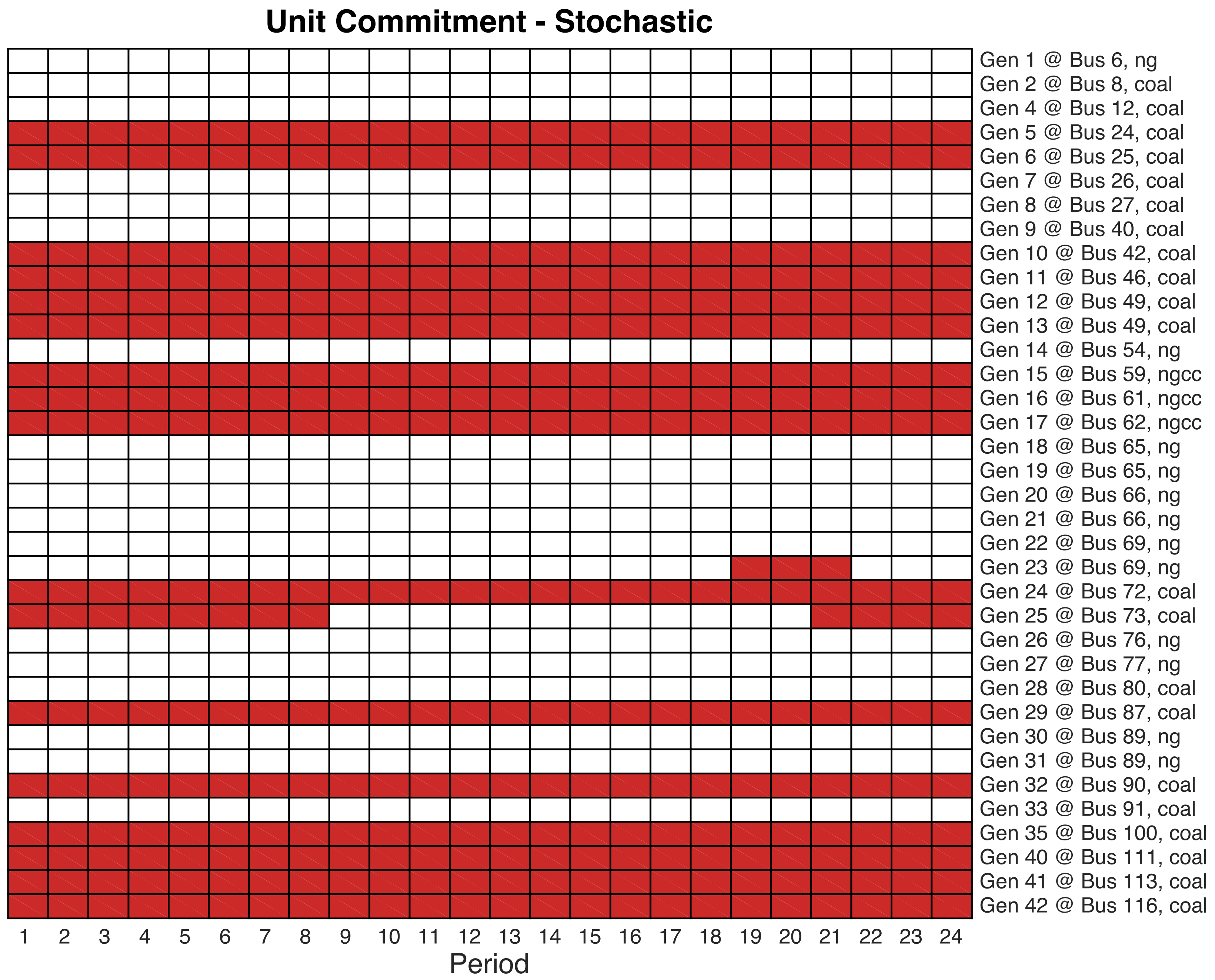
118-bus Test System

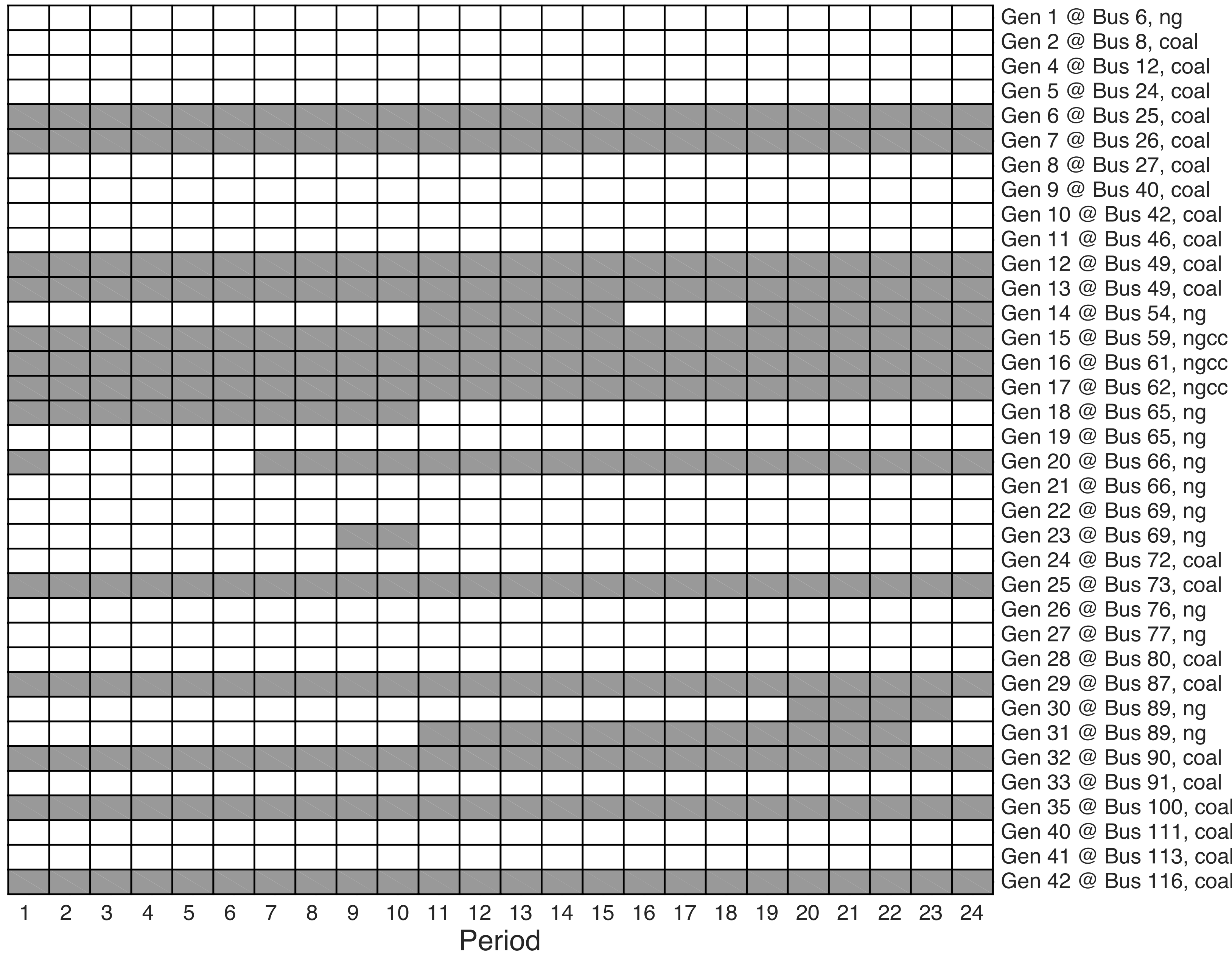


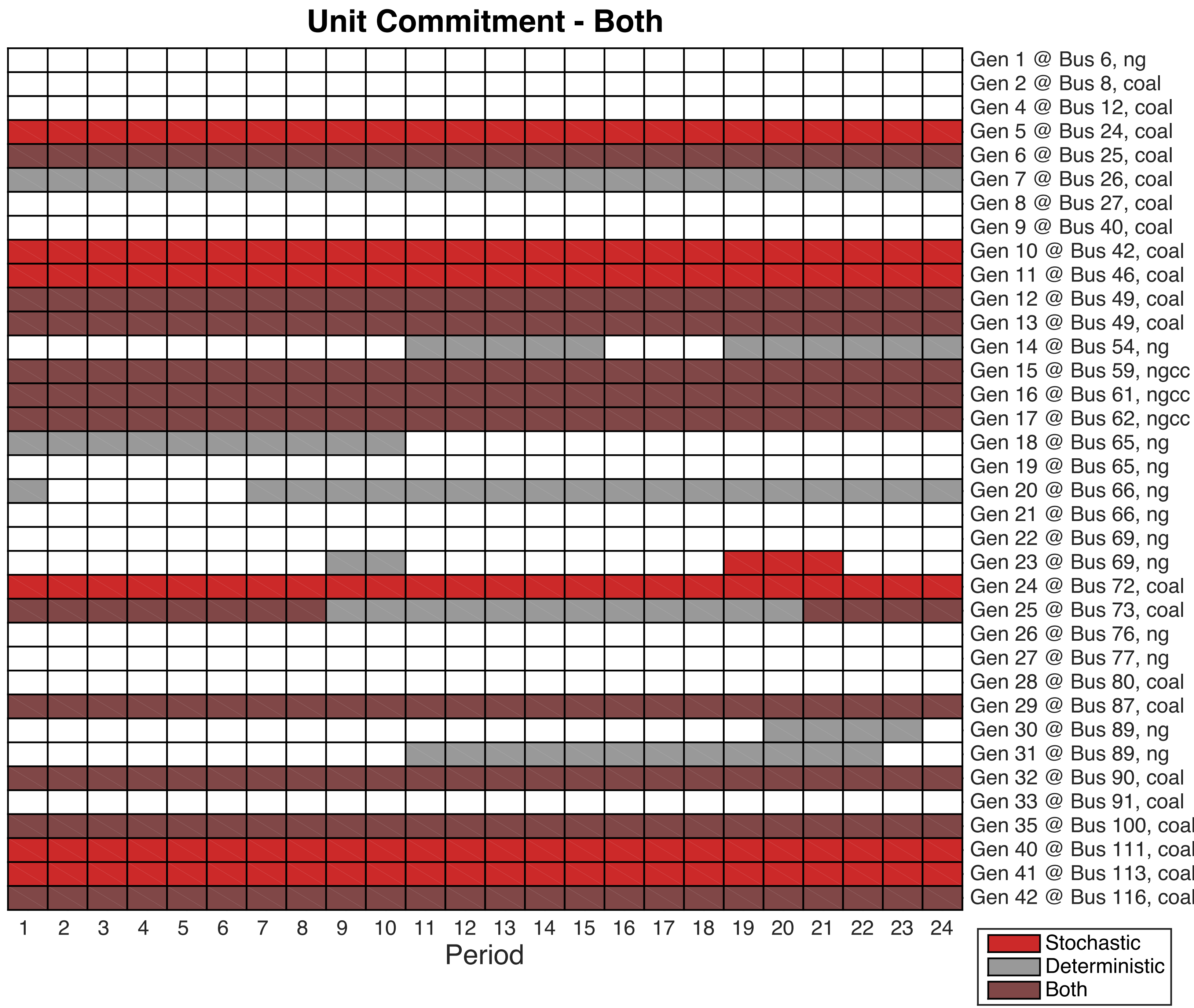
DC Network Example

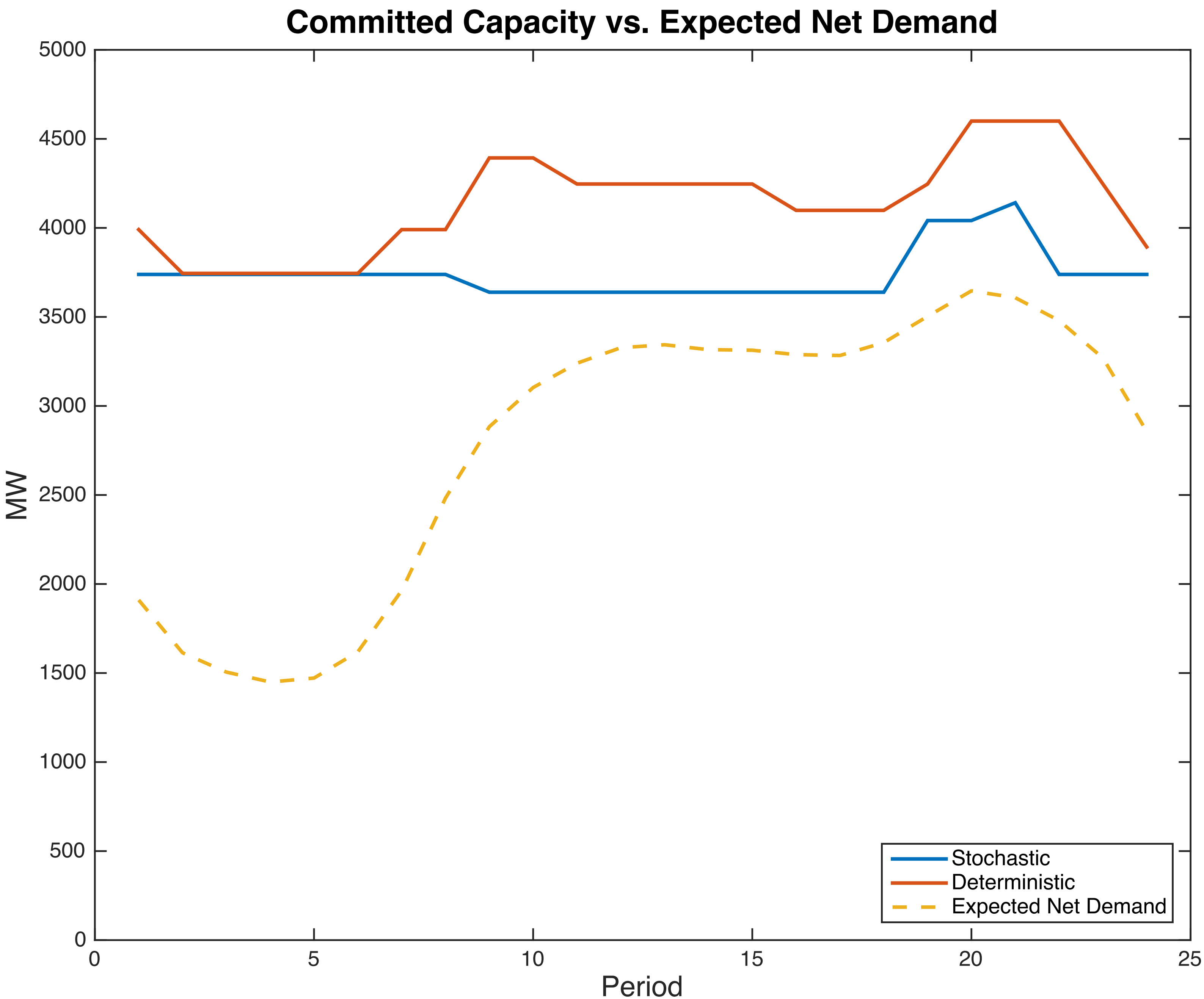
number of …	
buses	118
conventional generators	42
wind farms	12
grid-level storage units	0
curtailable loads	99
periods in horizon, $\|T\|$	24
scenarios per period, $\|J^t\|$	5
contingencies per scenario, $\|K^{tj}\| - 1$	7
variables in resulting MIQP	582,990
constraints in resulting MIQP	1,536,006

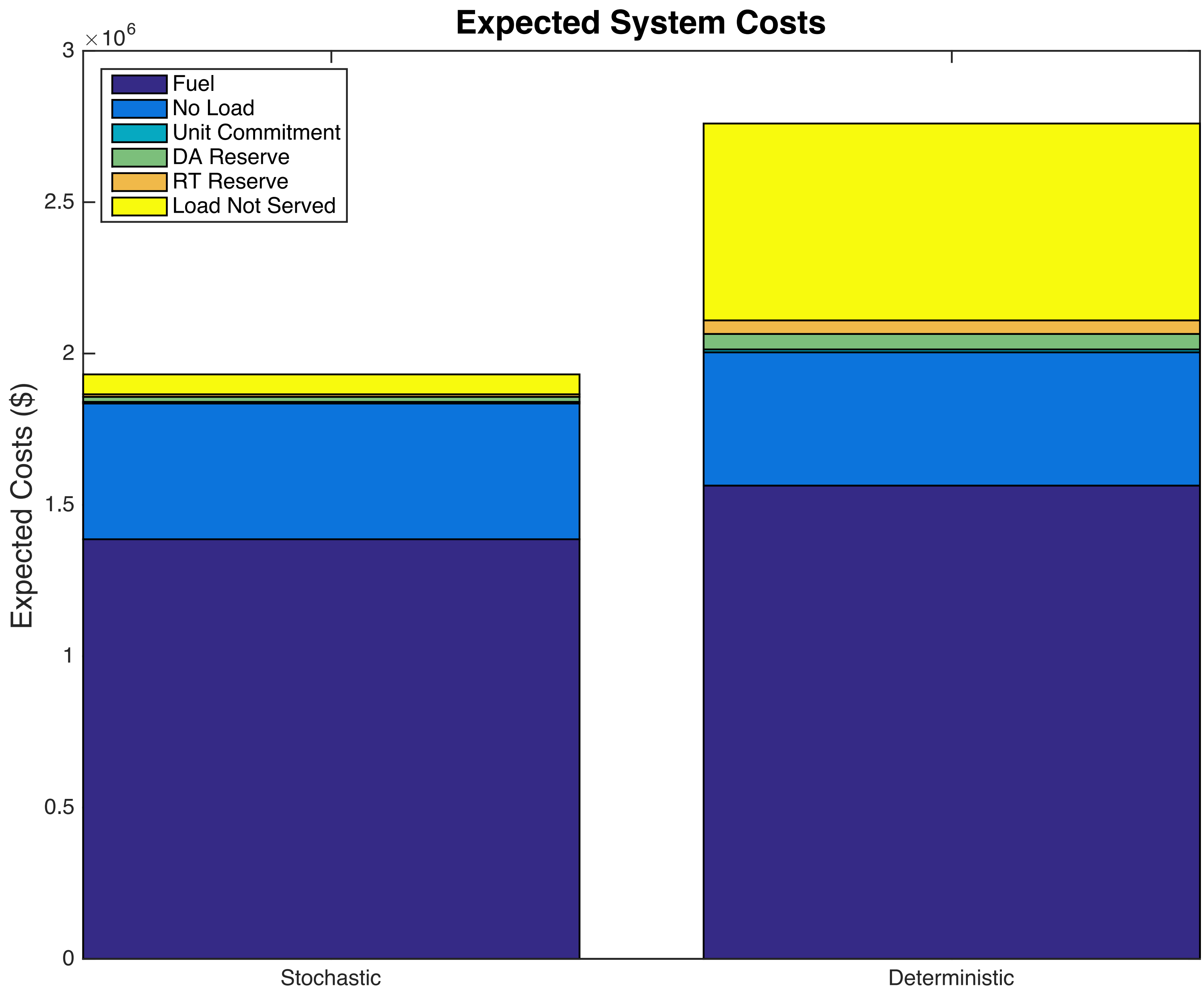

Unit Commitment - Stochastic
Gen 1 @ Bus 6, ng
Gen 2 @ Bus 8, coal
Gen 4 @ Bus 12, coal
Gen 5 @ Bus 24, coal
Gen 6 @ Bus 25, coal
Gen 7 @ Bus 26, coal
Gen 8 @ Bus 27, coal
Gen 9 @ Bus 40, coal
Gen 10 @ Bus 42, coal
Gen 11 @ Bus 46, coal
Gen 12 @ Bus 49, coal
Gen 13 @ Bus 49, coal
Gen 14 @ Bus 54, ng
Gen 15 @ Bus 59, ngcc
Gen 16 @ Bus 61, ngcc
Gen 17 @ Bus 62, ngcc
Gen 18 @ Bus 65, ng
Gen 19 @ Bus 65, ng
Gen 20 @ Bus 66, ng
Gen 21 @ Bus 66, ng
Gen 22 @ Bus 69, ng
Gen 23 @ Bus 69, ng
Gen 24 @ Bus 72, coal
Gen 25 @ Bus 73, coal
Gen 26 @ Bus 76, ng
Gen 27 @ Bus 77, ng
Gen 28 @ Bus 80, coal
Gen 29 @ Bus 87, coal
Gen 30 @ Bus 89, ng
Gen 31 @ Bus 89, ng
Gen 32 @ Bus 90, coal
Gen 33 @ Bus 91, coal
Gen 35 @ Bus 100, coal
Gen 40 @ Bus 111, coal
Gen 41 @ Bus 113, coal
Gen 42 @ Bus 116, coal
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Period

Unit Commitment - Deterministic



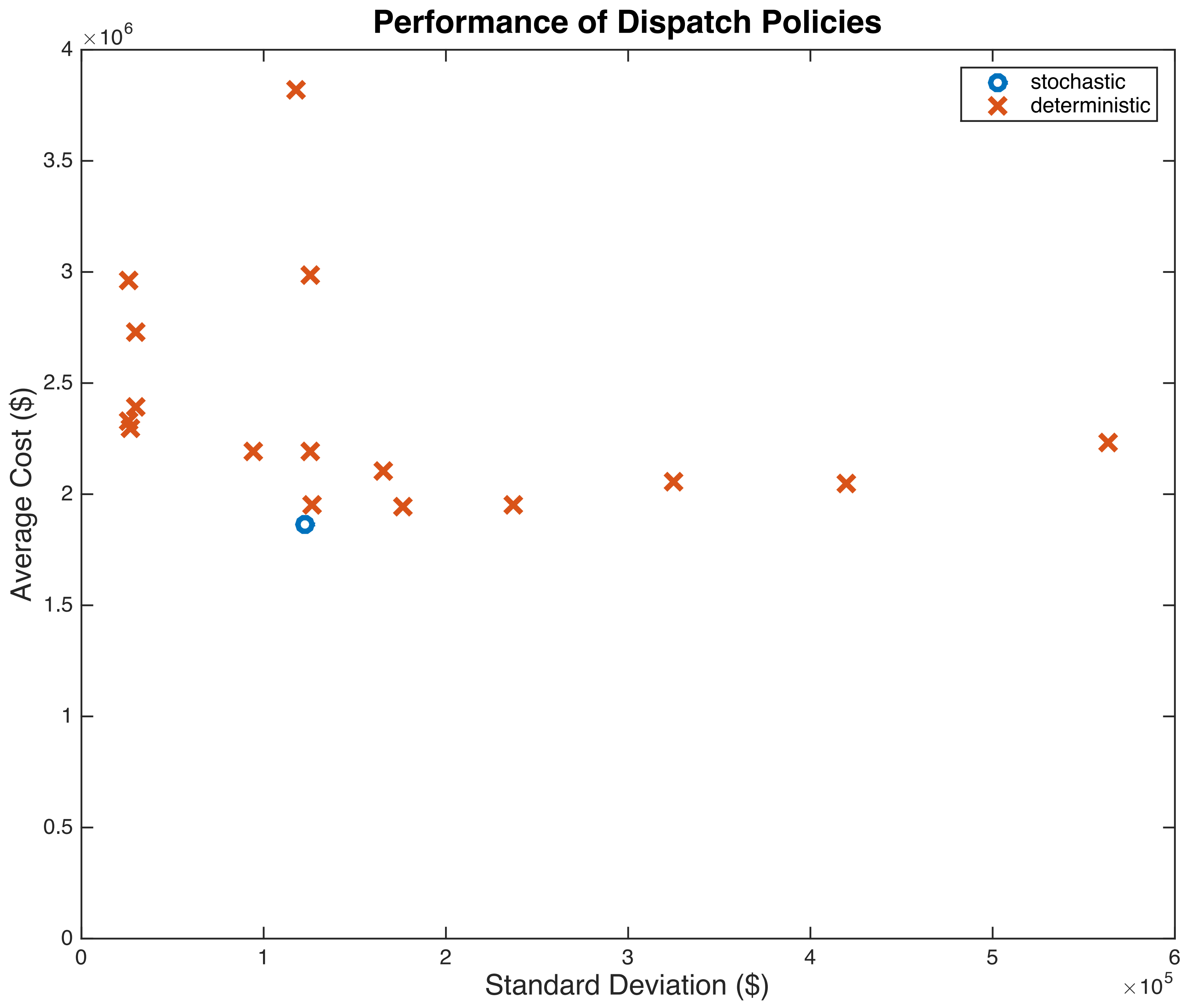

Unit Commitment - Both
Gen 1 @ Bus 6, ng
Gen 2 @ Bus 8, coal
Gen 4 @ Bus 12, coal
Gen 5 @ Bus 24, coal
Gen 6 @ Bus 25, coal
Gen 7 @ Bus 26, coal
Gen 8 @ Bus 27, coal
Gen 9 @ Bus 40, coal
Gen 10 @ Bus 42, coal
Gen 11 @ Bus 46, coal
Gen 12 @ Bus 49, coal
Gen 13 @ Bus 49, coal
Gen 14 @ Bus 54, ng
Gen 15 @ Bus 59, ngcc
Gen 16 @ Bus 61, ngcc
Gen 17 @ Bus 62, ngcc
Gen 18 @ Bus 65, ng
Gen 19 @ Bus 65, ng
Gen 20 @ Bus 66, ng
Gen 21 @ Bus 66, ng
Gen 22 @ Bus 69, ng
Gen 23 @ Bus 69, ng
Gen 24 @ Bus 72, coal
Gen 25 @ Bus 73, coal
Gen 26 @ Bus 76, ng
Gen 27 @ Bus 77, ng
Gen 28 @ Bus 80, coal
Gen 29 @ Bus 87, coal
Gen 30 @ Bus 89, ng
Gen 31 @ Bus 89, ng
Gen 32 @ Bus 90, coal
Gen 33 @ Bus 91, coal
Gen 35 @ Bus 100, coal
Gen 40 @ Bus 111, coal
Gen 41 @ Bus 113, coal
Gen 42 @ Bus 116, coal
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Period
Stochastic
Deterministic
Both


Committed Capacity vs. Expected Net Demand
MW
Period
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
5
10
15
20
25
Stochastic
Deterministic
Expected Net Demand


Expected System Costs
×10^6
3
2.5
2
1.5
1
0.5
0
Expected Costs ($)
Fuel
No Load
Unit Commitment
DA Reserve
RT Reserve
Load Not Served
Stochastic
Deterministic

Expected Cost Comparison

	Stochastic	Deterministic	Difference
fuel	$1,386,000	$1,564,000	9%
no load	$449,000	$440,000	0%
UC	$5,000	$9,000	0%
DA Reserve	$17,000	$51,000	2%
RT Reserve	$8,000	$45,000	2%
LNS	$66,000	$650,000	30%
Total	$1,931,000	$2,760,000	43%


Performance of Dispatch Policies
×10^6
4
3.5
3
2.5
2
1.5
1
0.5
0
Average Cost ($)
0
1
2
3
4
5
6
×10^5
Standard Deviation ($)
stochastic
deterministic

Outline

- Generalized scheduling problem
- MOPS – MATPOWER Optimal Power Scheduler
- Our approach
- Benchmarking stochastic vs. deterministic
- Simulation Results
- Challenges

Challenges

- Began with the idea that 1st settlement contracts for commitment, energy, reserves and ramping would provide "look-ahead view" for single-period 2nd settlement problem
  - too restrictive
  - resulted in shedding load when unused (just not contracted) capacity was available
  - consequence of simplified uncertainty model

Challenges

- Ideally, 2nd settlement would also be multi-period, look-ahead with finer time step
  - not what has typically been done
  - data requirements are quite high
- Is there a way to incorporate "look-ahead" information from the solution of a multi-period problem to guide a subsequent single period recourse problem without being unnecessarily restrictive?

Questions?