Decomposed Stochastic Model Predictive Control for Optimal Dispatch of Storage and Generation

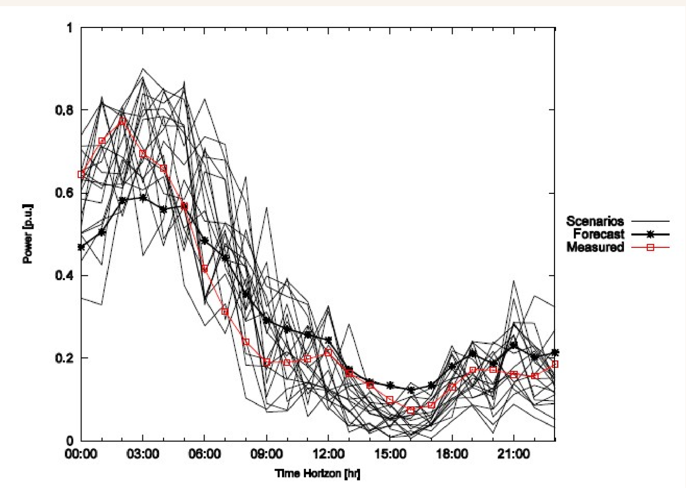
Graduate Student Researcher: Dinghuan Zhu
Academic Advisor: Prof. Gabriela Hug

Introduction

- Motivation & Challenge
  - Uncertainties introduced by variable energy sources, e.g. wind and solar
  - Optimal operation of the emerging large scale energy storage devices
- Objective: safe and optimal scheduling of conventional generation and energy storage in near real time (e.g. 5min) under uncertainties to:
  - reduce ramp rates of generators
  - minimize total operation costs
- Key: uncertainty representation

➢ Expected values
➢ Scenarios

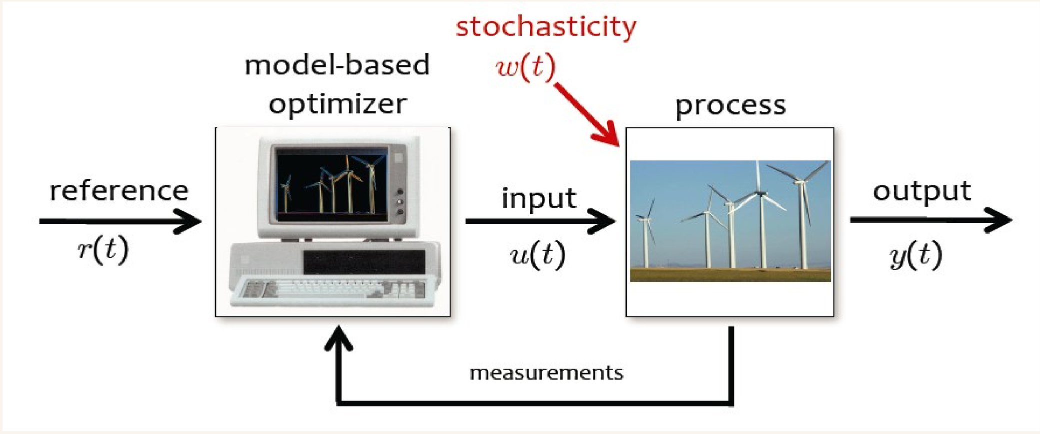
➢ Deterministic
➢ Stochastic



Source: Wind power forecasting: State-of-the-Art 2009, Argonne National Laboratory

SMPC Basics

- Stochastic model predictive control
  - Stochastic optimization
  - Model predictive control
- General concept



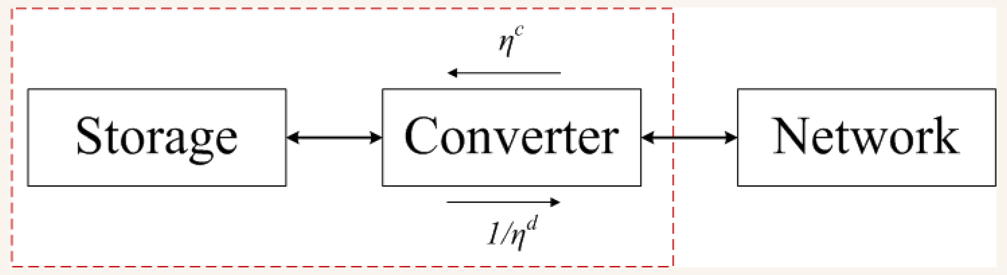
Source: A. Bemporad, "Lecture notes on stochastic MPC"

- Mathematical formulation

$$\min \; E_w\{\sum_{k=0}^{N-1} l[y(k+1)-r(k+1),u(k)]\}$$
$$x(k+1) = f(x(k),u(k),w(k))$$
$$y(k) = g(x(k),u(k),w(k))$$
$$\text{s.t.} \quad x^{\min} \le x(k) \le x^{\max}$$
$$y^{\min} \le y(k) \le y^{\max}$$
$$u^{\min} \le u(k) \le u^{\max}$$

Modeling

- Energy storage & converter



- State-space model

$$E(k+1) = \alpha \cdot E(k) + T \cdot [\eta^c \cdot u^c(k) - (\eta^d)^{-1} \cdot u^d(k)]$$
$$u^c(k) \cdot u^d(k) = 0\,, \quad \forall k$$

$E(k)$: energy level at time k
$u^c(k)$: charge power at time k
$u^d(k)$: discharge power at time k
α: related to standby losses
T: time step size

- Conventional generator

$$p(k+1) = p(k) + u^g(k)$$

$p(k)$: generator output power at time k
$u^g(k)$: increment in power output level

- Power network: DC power flow model

Formulation

- Two-stage SMPC problem

$$\min_{x^s(k),u^s(k)} \sum_{s\in\mathcal{N}} \pi^s \left[\sum_{k\in\mathcal{T}} l_k(x^s(k),u^s(k)) + l_{n_H}(x^s(n_H))\right]$$

s.t. $x^s(k+1) = Ax^s(k) + Bu^s(k) \quad \forall s\in\mathcal{N}, k\in\mathcal{T}$ (1a)

$x^{min} \le x^s(k+1) \le x^{max} \quad \forall s\in\mathcal{N}, k\in\mathcal{T}$ (1b)

$u^{min} \le u^s(k) \le u^{max} \quad \forall s\in\mathcal{N}, k\in\mathcal{T}$ (1c)

$h(x^s(k),u^s(k),r^s(k),d^s(k)) \le 0 \quad \forall s\in\mathcal{N}, k\in\mathcal{T}$ (1d)

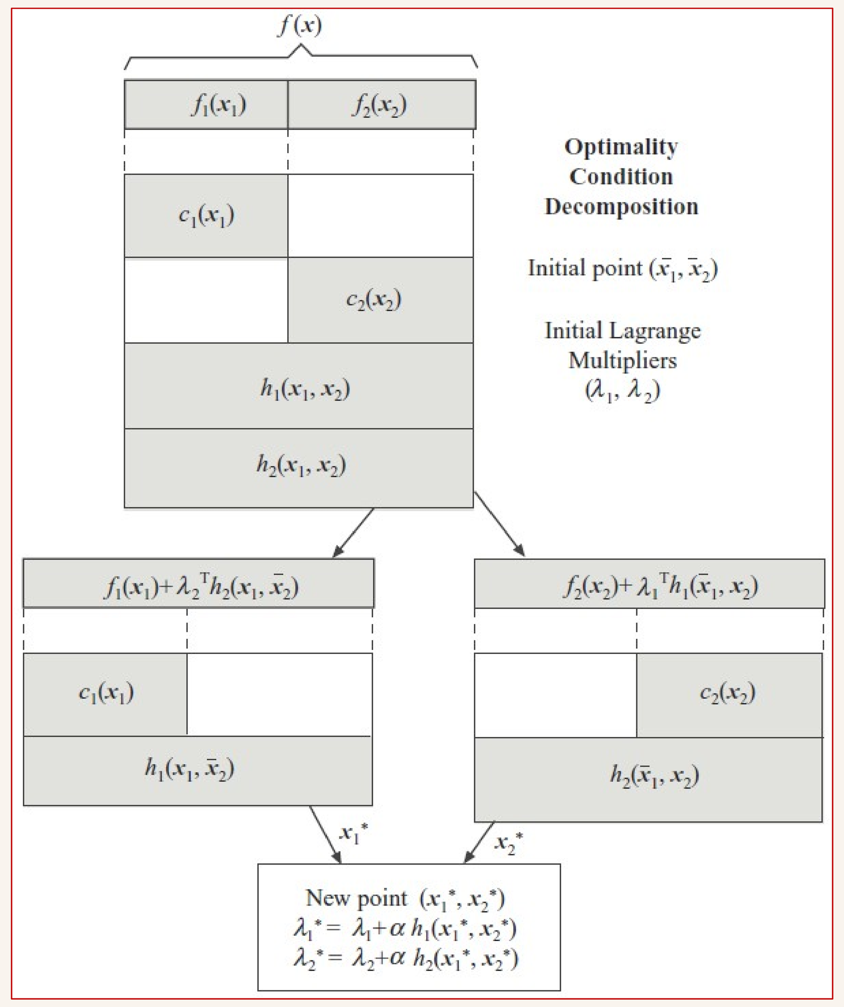
$u^i(0) = u^j(0) \quad \forall i,j\in\mathcal{N}$ (1e)

$\mathcal{N}$: set of all scenarios, $\mathcal{N} \triangleq \{1,\cdots,N\}$,
$\mathcal{T}$: set of the receding horizon, $\mathcal{T} \triangleq \{0,\cdots,n_H-1\}$,
π^s : probability associated with Scenario s,
$x^s(k)$: storage energy levels and generator output levels,
$u^s(k)$: control input for storages and generators,
$r^s(k)$: power output of variable generation in Scenario s,
$d^s(k)$: demand at time k in Scenario s.

- Objective function
  - Generator production cost
  - Generator ramping cost
  - Cost for storage conversion losses
- Nonanticipativity constraints in (1e)

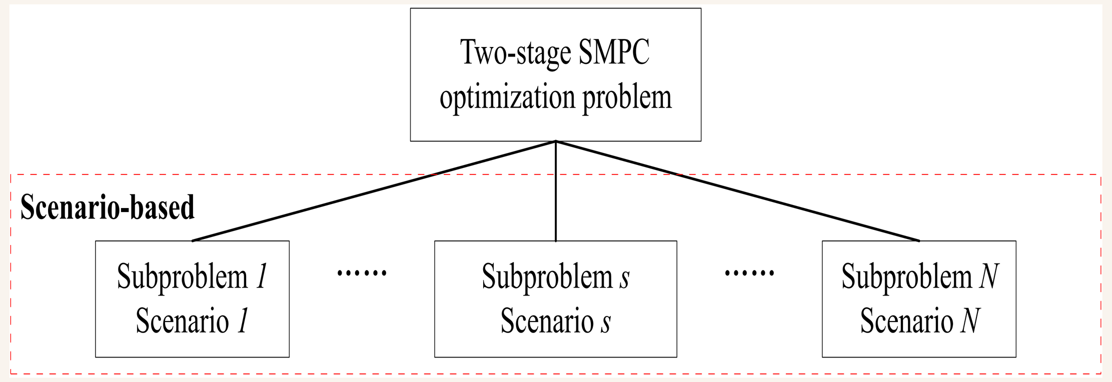
OCD-based Solution Approach

- Graphical illustration of OCD



Source: A. J. Conejo, E. Castillo, R. Minguez, and R. Garcia-Bertrand, Decomposition Techniques in Mathematical Programming, Springer, 2006.

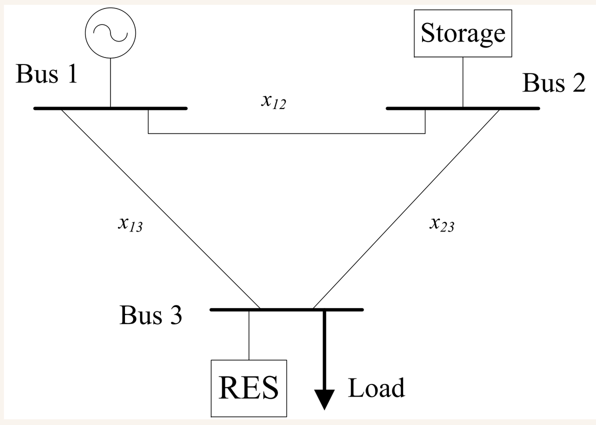
- Scenario-based decomposition



- Complicating constraints → (1e)
- Algorithm
  1) Initialize all decision variables and Lagrangian multipliers;
  2) Solve subproblems in parallel;
  3) Update values of decision variables and multipliers obtained in Step 2);
  4) If stopping criteria are fulfilled, stop. Else, go to Step 2).

Preliminary Simulation

- Consider an SMPC at a specific time step
- Test system setup



2 scenarios
6-step look-ahead horizon
5-min interval length
60 decision variables
231 constraints in total

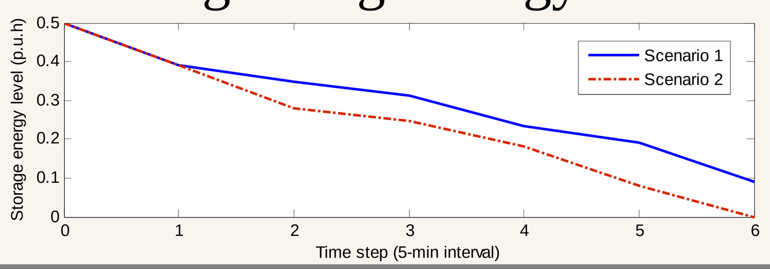
System costs

- Generator production cost $p^2(k)+2p(k)$
- Generator ramping cost $10\cdot(u^g(k))^2$
- Cost for conversion losses $T\cdot[(1-\eta^c)u^c(k)+(\eta^{-d}-1)u^d(k)]$

- System constraints

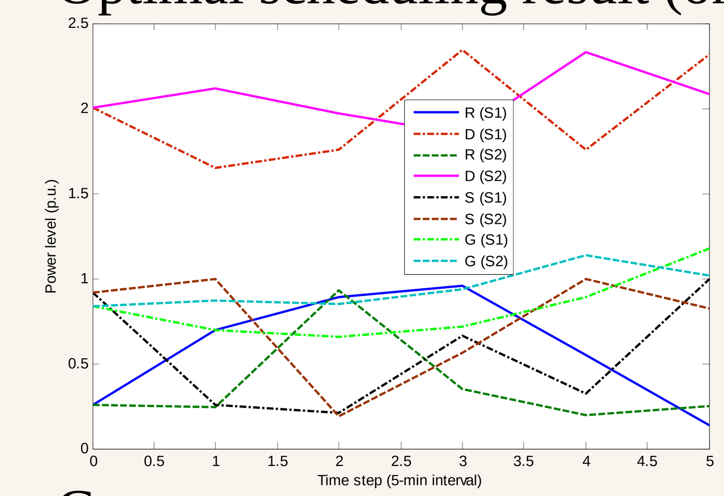
$-1.5 \le line\ flow \le 1.5$ p.u.
$0.5 \le p(k) \le 2$ p.u, $\; -0.5 \le u^g(k) \le 0.5$ p.u.
$0 \le E(k) \le 1$ p.u.h, $\; 0 \le u^c(k), u^d(k) \le 1$ p.u.

- Yielding storage energy level



Nonanticipativity constraints fulfilled

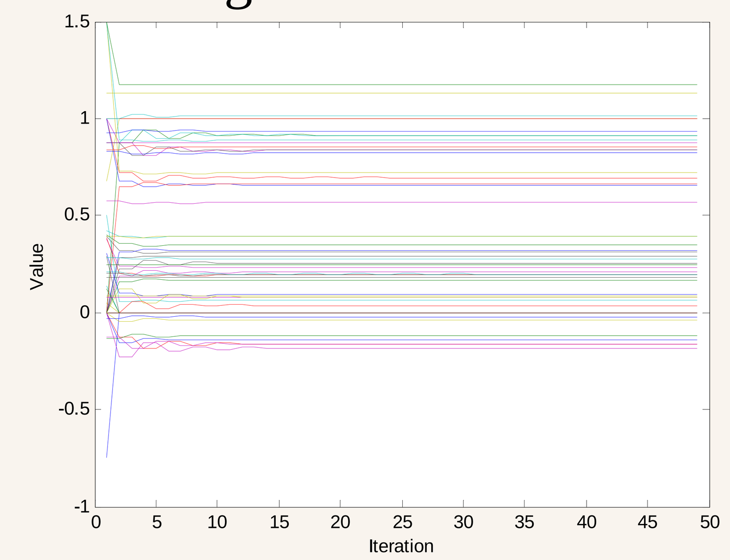
- Optimal scheduling result (only apply $u(0)$)



R: renewable output
D: demand
S: storage output
G: generator output
S1: scenario 1
S2: scenario 2

Nonanticipativity constraints fulfilled

- Convergence



For all 60 decision variables and 3 Lagrangian multipliers

Convergence within 30 iterations