Recent Progress on “Holistic” Control for Reactor Systems

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ASI Workshop on Advanced Reactors and the Need for Advanced Controls

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COLLEGE OF ENGINEERING
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Outline

- Background and Problem Description
- Overview of Some Control Algorithms
- Case Studies
  - Economic Optimization of Flexible Power Operation
  - System Health Aware Control Methods
- Summary

Background

Context of this Work

- This work was performed under DOE's NEUP program under contract DE-NE0008975
- In collaboration with
  - Prof. Ben Lindley at UWisc and his staff and students Saeed Alhadrami, Una Baker, and Gabriel Soto; and
  - Prof. Jamie Coble at UTK and her students David Anderson, Matthew Scott, Richard Bisson
  - And Vivek Agarwhal (INL) and Ross Snuggerud (NuScale)
- Project Title: "Innovative Enhanced Automation Control Strategies for Multi-Unit SMRs"

Problem Statement and Objectives

Objective of our Project

- Investigate methods for
  - Supervisory control for flexible power operation
  - "Tactical" control that integrates prognostics and health management into the control problem
  - "Strategic" control of multiple units at a single site.

Objective of this Workshop

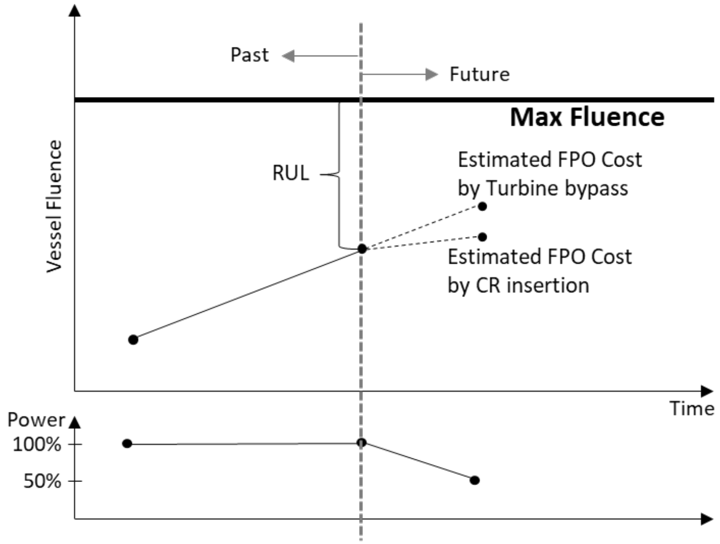
- Discuss the problems, challenges, needs, and state of progress for
- *"increased automation for real-time performance optimization and greater efficiency of operation and maintenance activities beyond traditional base load nuclear power."*

Problem Statement as Questions

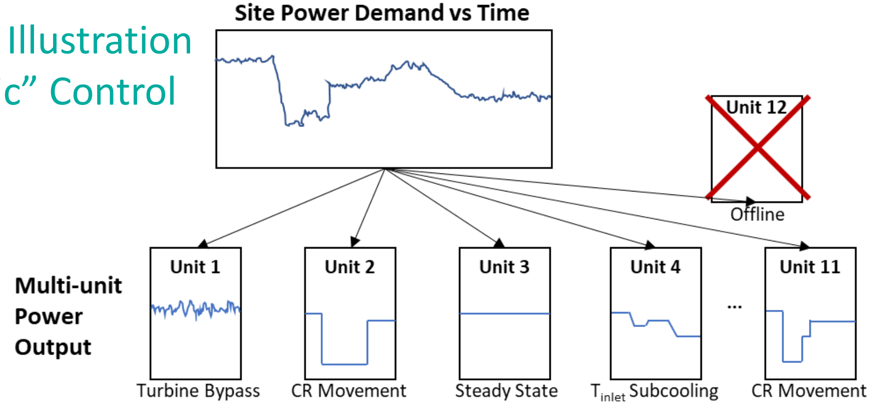
- How should I operate my reactor daily to maximize revenue?

- Subject to the constraints of
  - I need to make my outage window
  - I do not want to “wear out” any components in my plant before my scheduled outage
  - In addition there are the usual expected constraints related to operating envelope, regulatory requirements, environmental conditions

Conceptual Illustration of “Tactical” Control Problem



Conceptual Illustration Of “Strategic” Control Problem



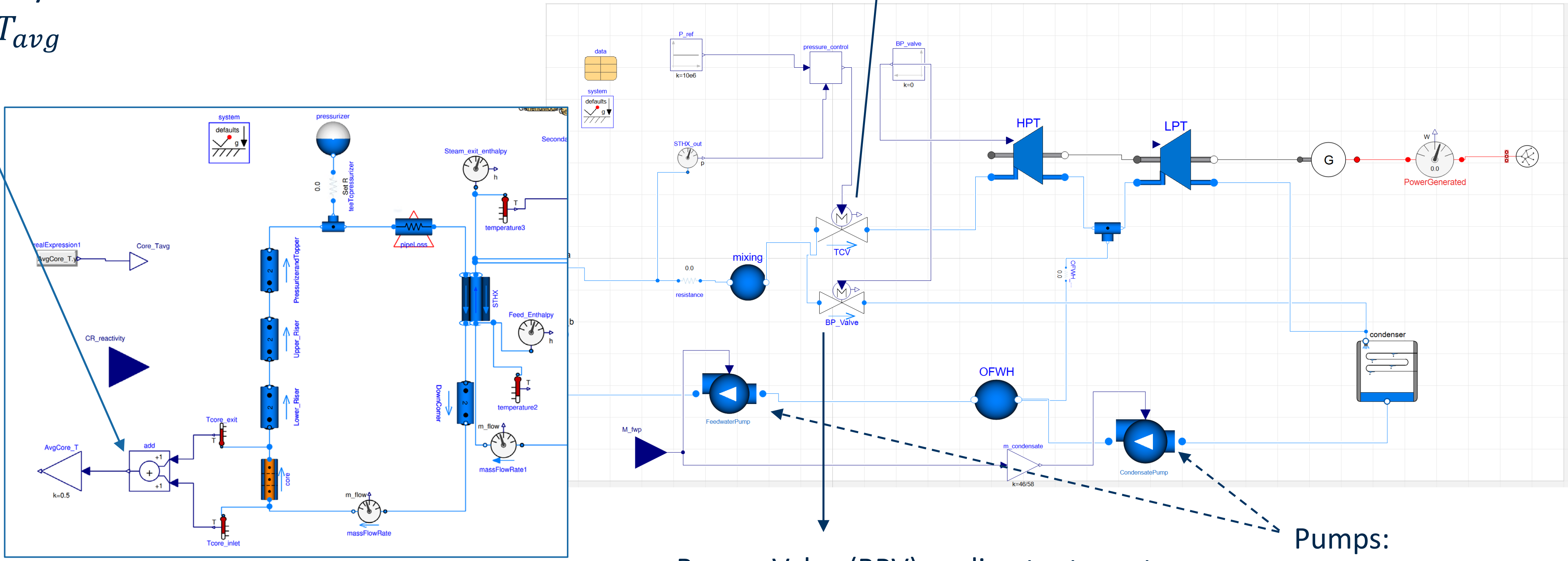
Overview of Some Control Algorithms

This relates to supervisory control

Load Follow Control for Simplified SMR Plant

Turbine control valve (TCV): maintain Turbine inlet pressure

Core reactivity control maintains T_{avg}



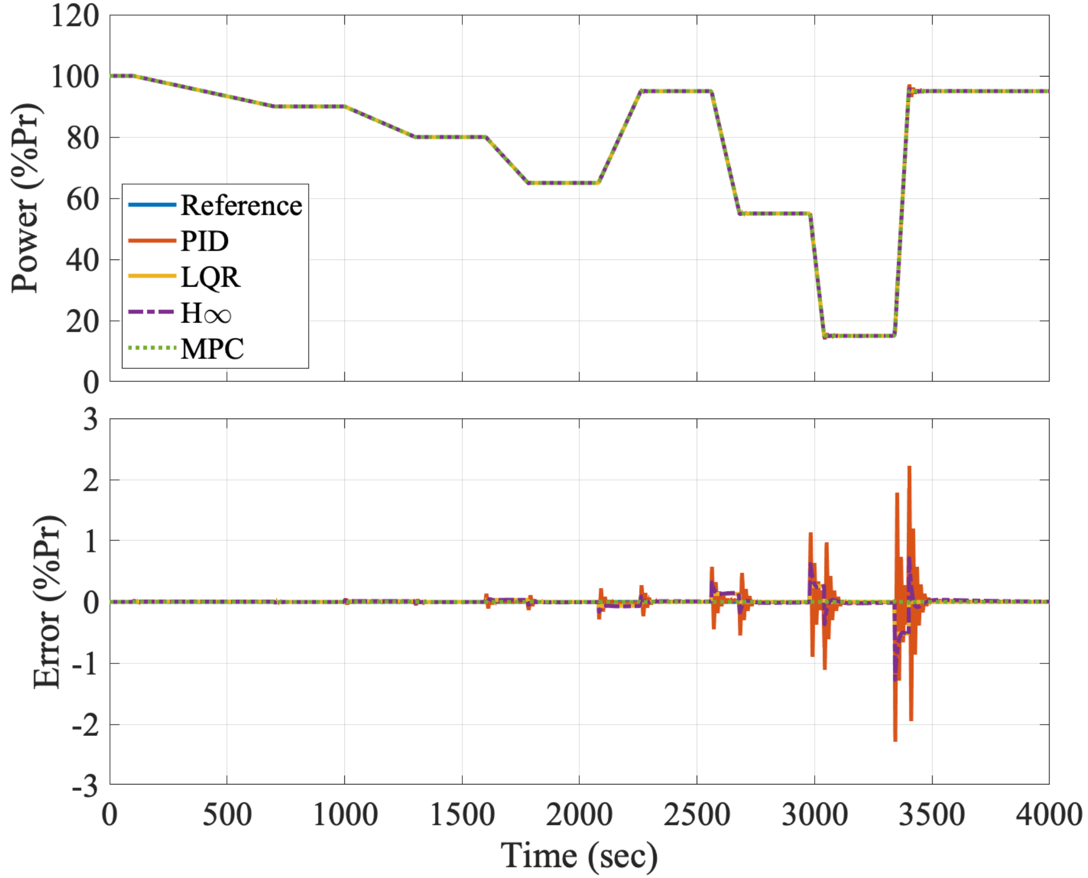
Bypass Valve (BPV): redirects steam to condenser for fast load change (Not used yet)

Pumps:

- Set pump speed based on desired power output

2-closed loop PID controllers
1-open loop controller

Comparison of Control Algorithms



All use a State-Space Model

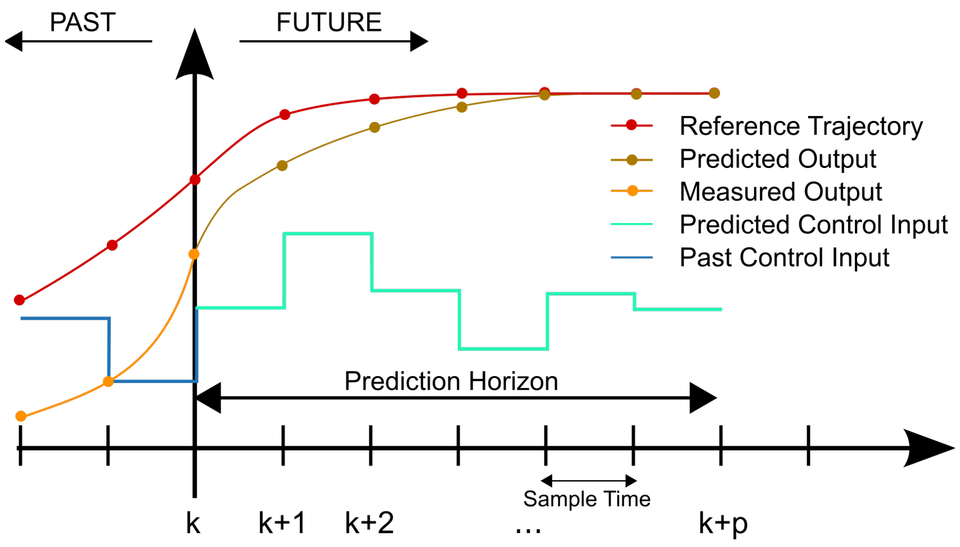
	PID	LQR	H_∞	MPC
Accuracy	Highly depends on tuning	Depends on tuning	Depends on tuning	Depends on tuning
Easy to tune?	Difficult	Easy	Easy	Easy
Able to handle constraints?	Not general	Not general	Not general	Yes
Able to handle MIMO?	Difficult	Yes	Yes	Yes
Calculation cost	Cheap	Expensive	Expensive	The most expensive

	PID	LQR	H_∞	MPC
Elapsed time (sec)	0.09	0.16	0.17	1.67

S. Choi et al., "COMPARATIVE STUDY FOR LOAD-FOLLOW OPERATIONS \\OF THE HOLOS MICROREACTOR" Proc. of M&C 2021

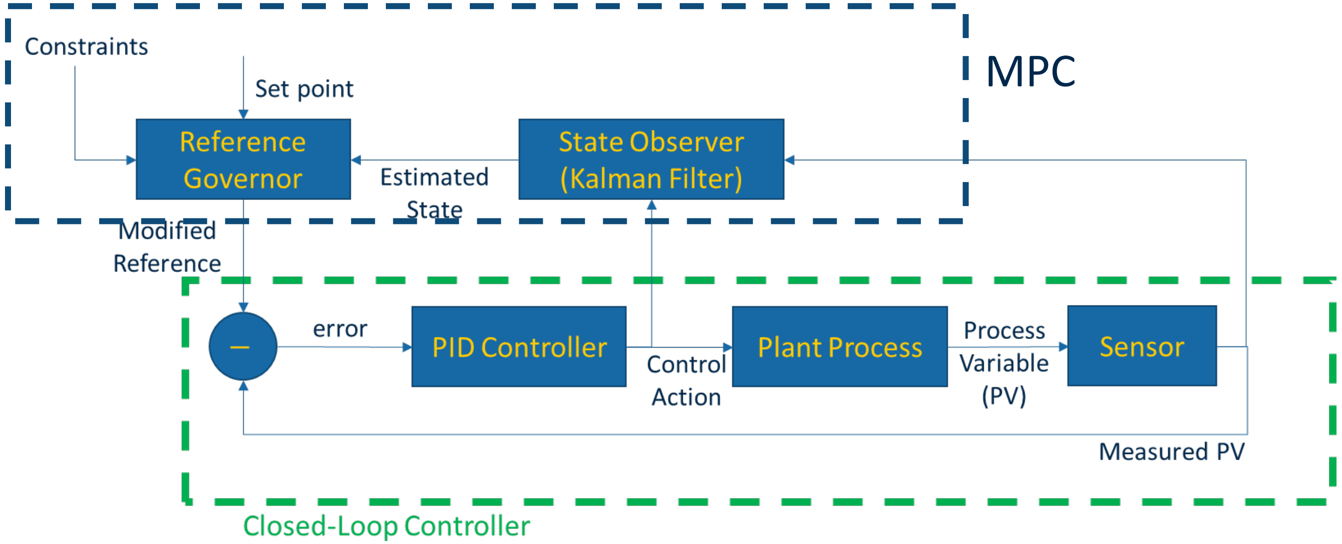
Supervisory Control with Model Predictive Control

Concept of Model Predictive Control

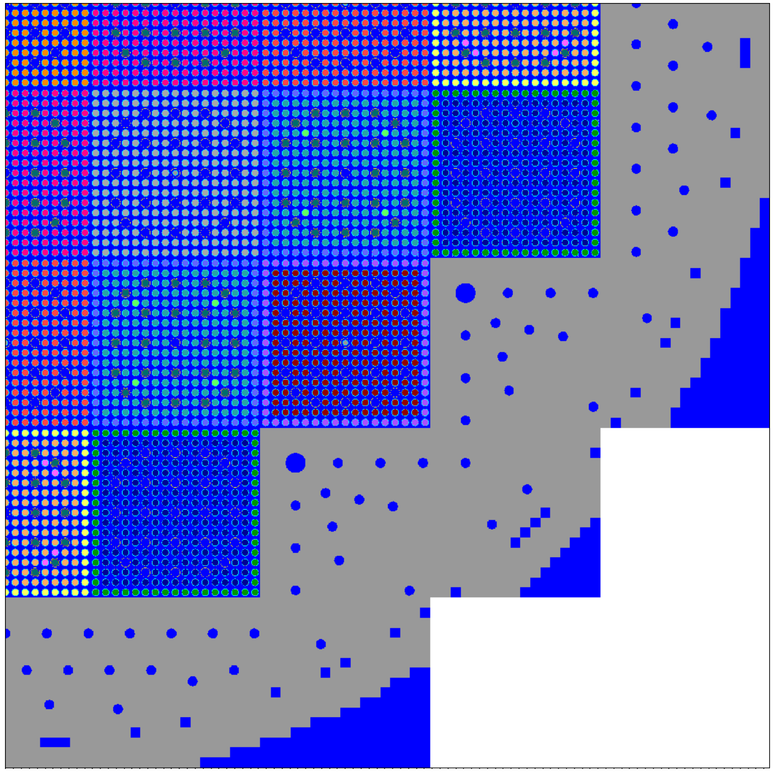


For each Prediction Horizon solve optimization problem to Minimize Cost Function

Reference/Command Governors



Cost Function = Tracking Error + Control Action + Smoothness (variation in control input)



NuScale-SMR

Applications

1. How do I do supervisory control that's "health-aware"?
2. How do I maximize revenue?

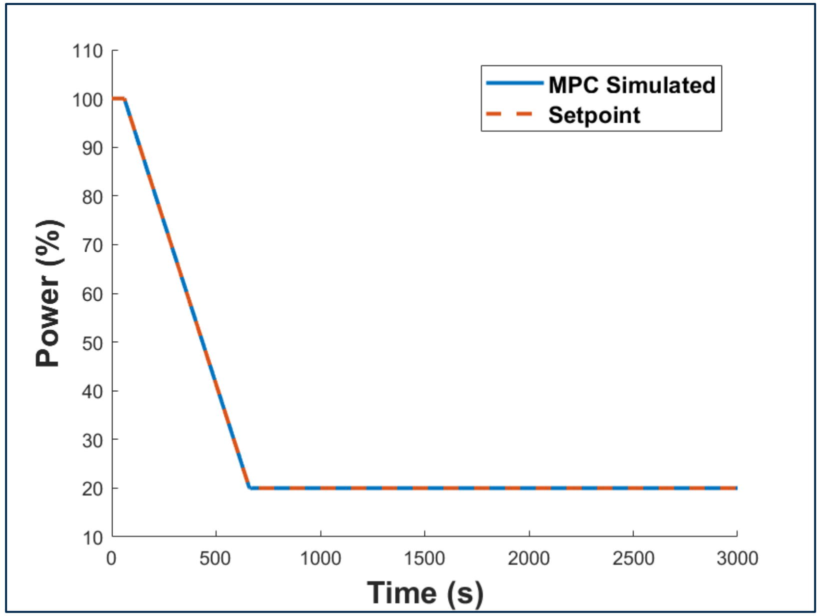
Health-aware MPC Description

- Basic Idea: Modify MPC cost function and state-space to have system/component "health" (remaining useful life)

  Cost Function = Tracking Error + Control Action
  + Smoothness (variation in control input)
  + Damage (decrement to RUL)

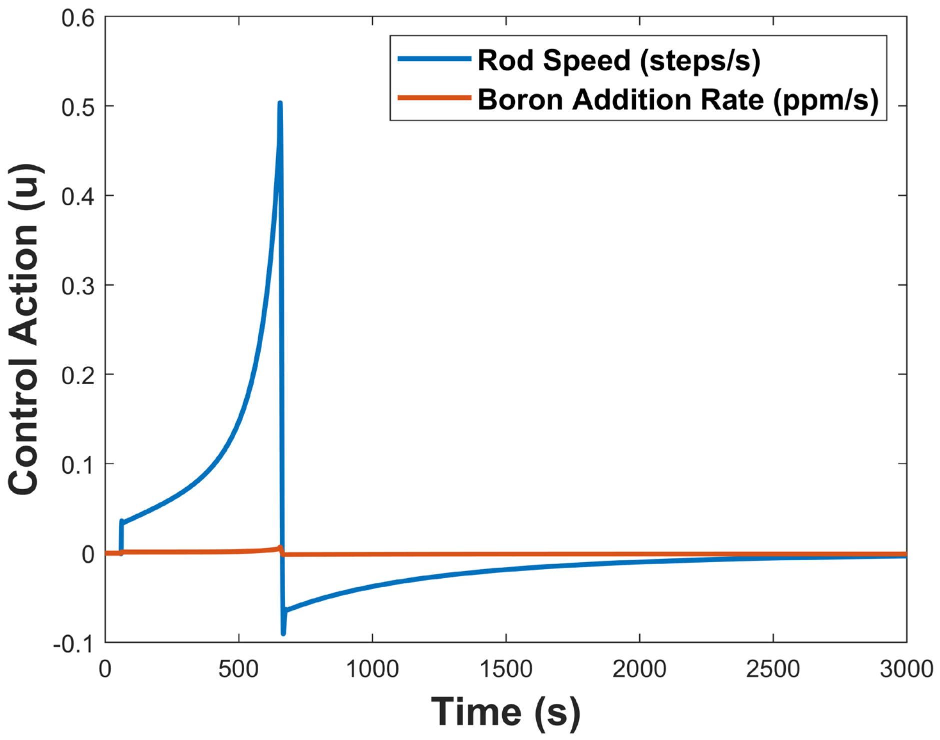
- Requires we be able to write a simple mathematical expression for damage accumulation
  - MPC cannot treat an arbitrarily large number of components explicitly
  - Need to reduce to some system-level remaining useful life (e.g. choose the limiting component for each prediction interval)

Power Maneuver

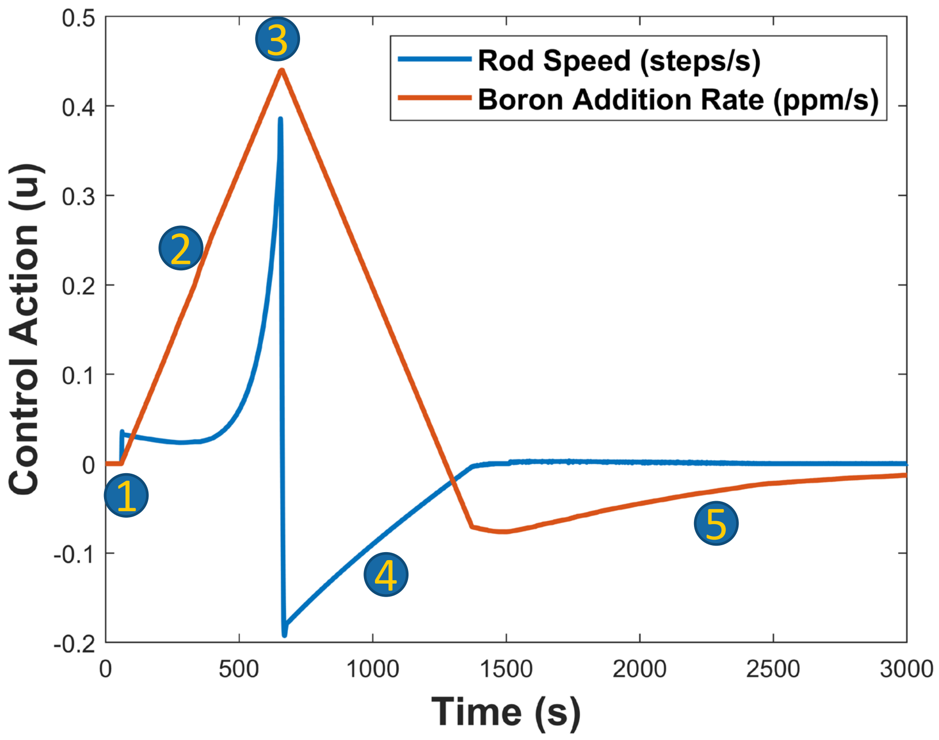


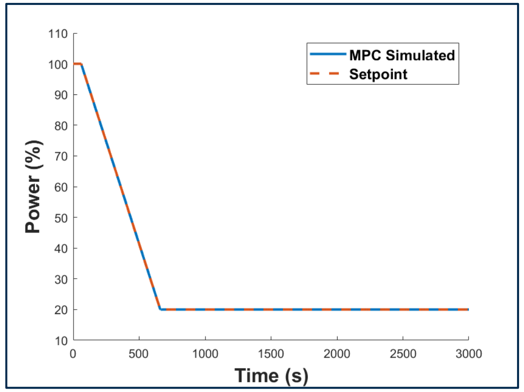
Health-aware MPC Numerical Demonstration

Reactivity Control with No PHM



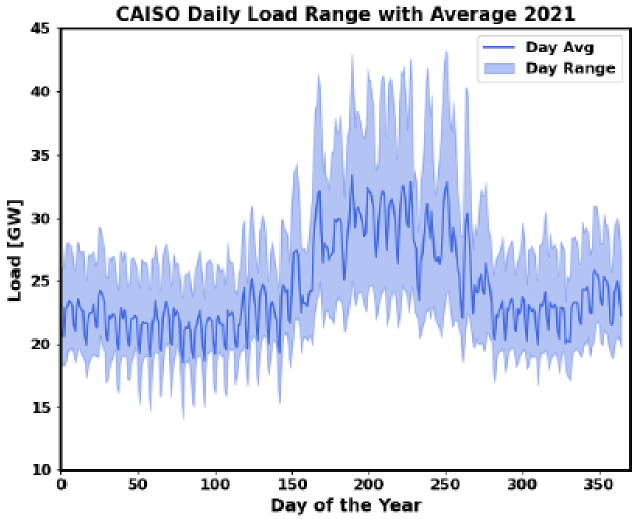
Reactivity Control with Hypothetical PHM (moving control rod is 200x worse than boron)

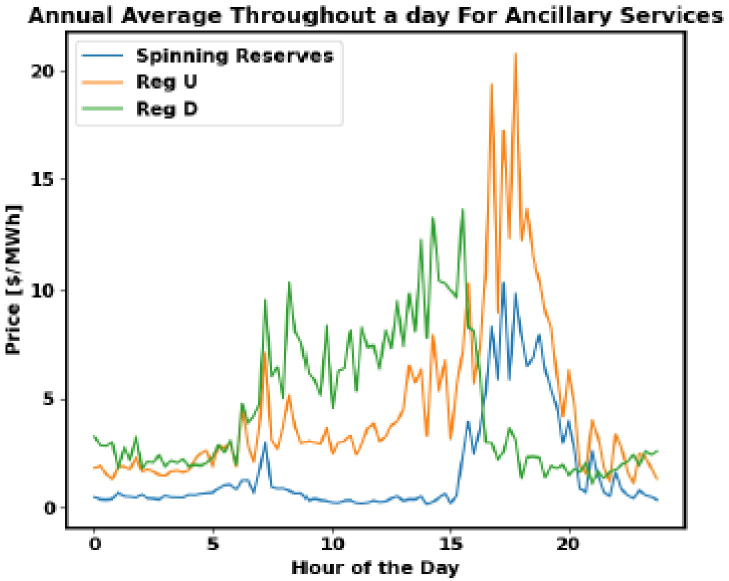




Strategic Control: Economic Optimization

- De-regulated Market Revenues
  - Cost of electricity
  - Ancillary Services
    - Spinning Reserves
    - Regulation Up/Down
    - Etc.
- Two Dispatch Optimizations by Grid Operators
  - Day-ahead Market
  - Hourly Dispatch
  - Minimum Market Price is ~$20/MWh

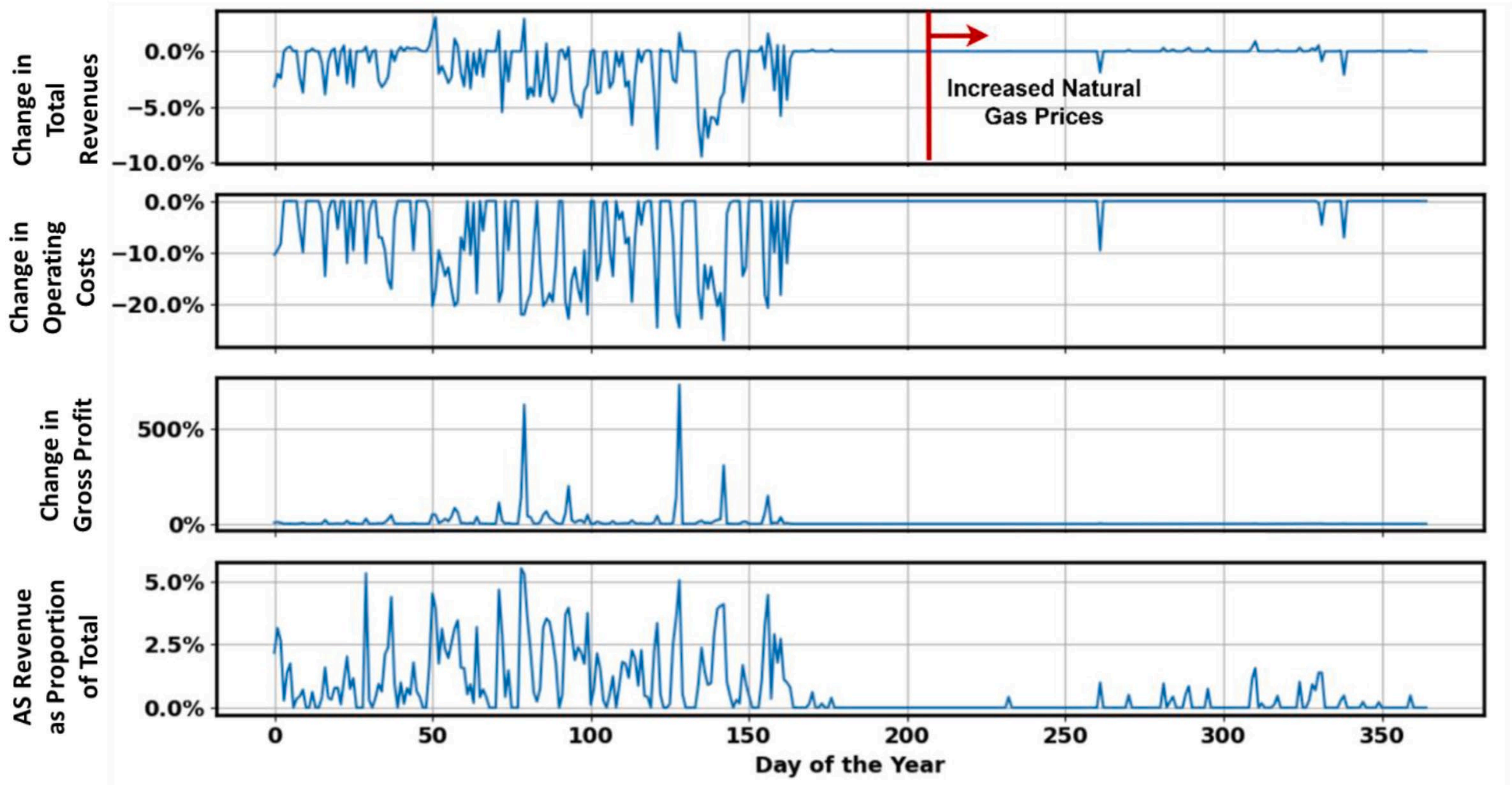




Basic Solution: Setup and solve a very complex optimization problem

Alhadhrami, Soto, Lindley, "Dispatch Analysis of Flexible Power Operation with Multi-Unit SMRs"
Recently published online in *Energy* https://doi.org/10.1016/j.energy.2023.128107

Economic Dispatch Optimization Results



Alhadhrami, Soto, Lindley, “Dispatch Analysis of Flexible Power Operation with Multi-Unit SMRs”
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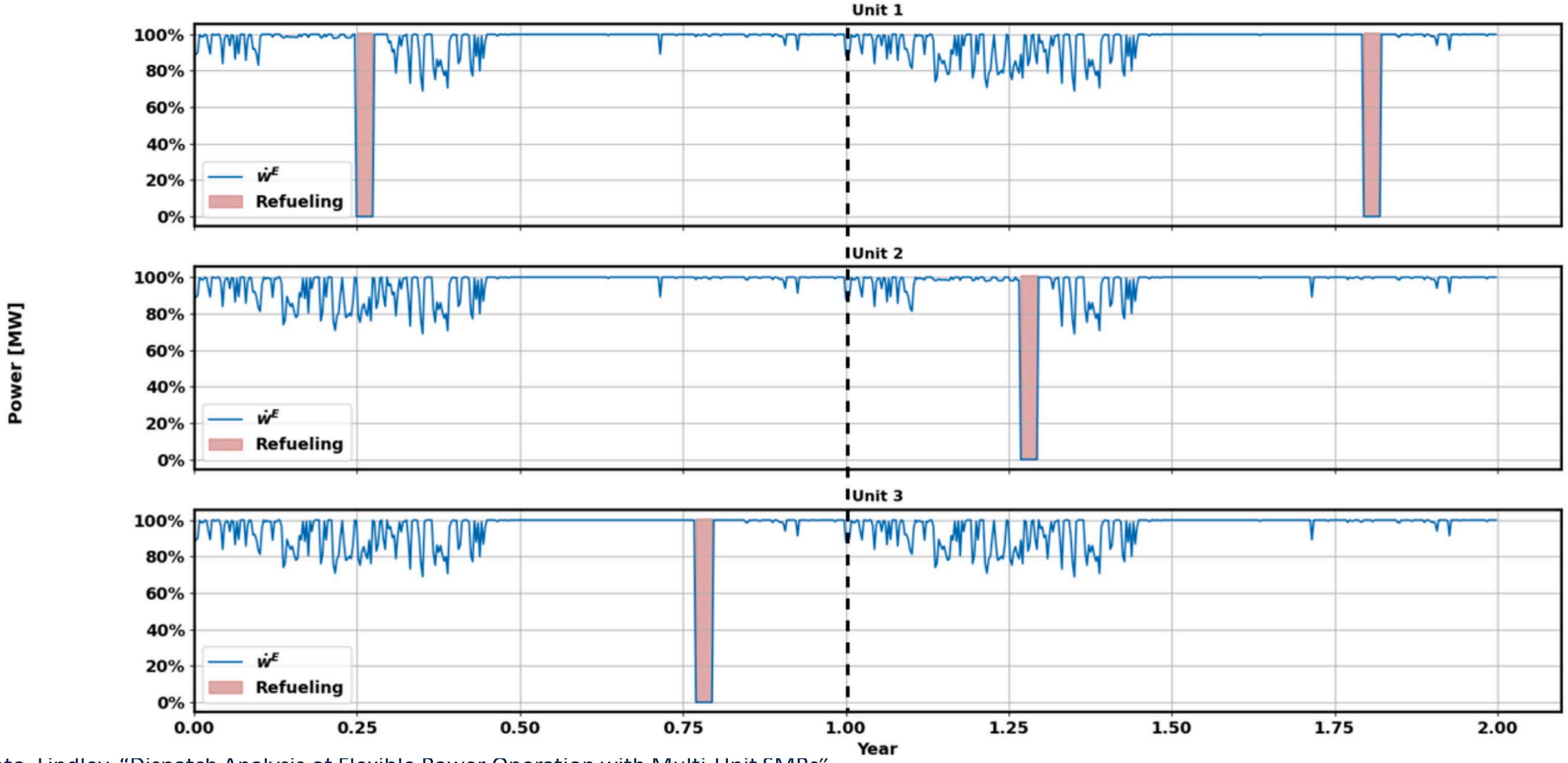
Multi-Unit Site Optimization



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Summary

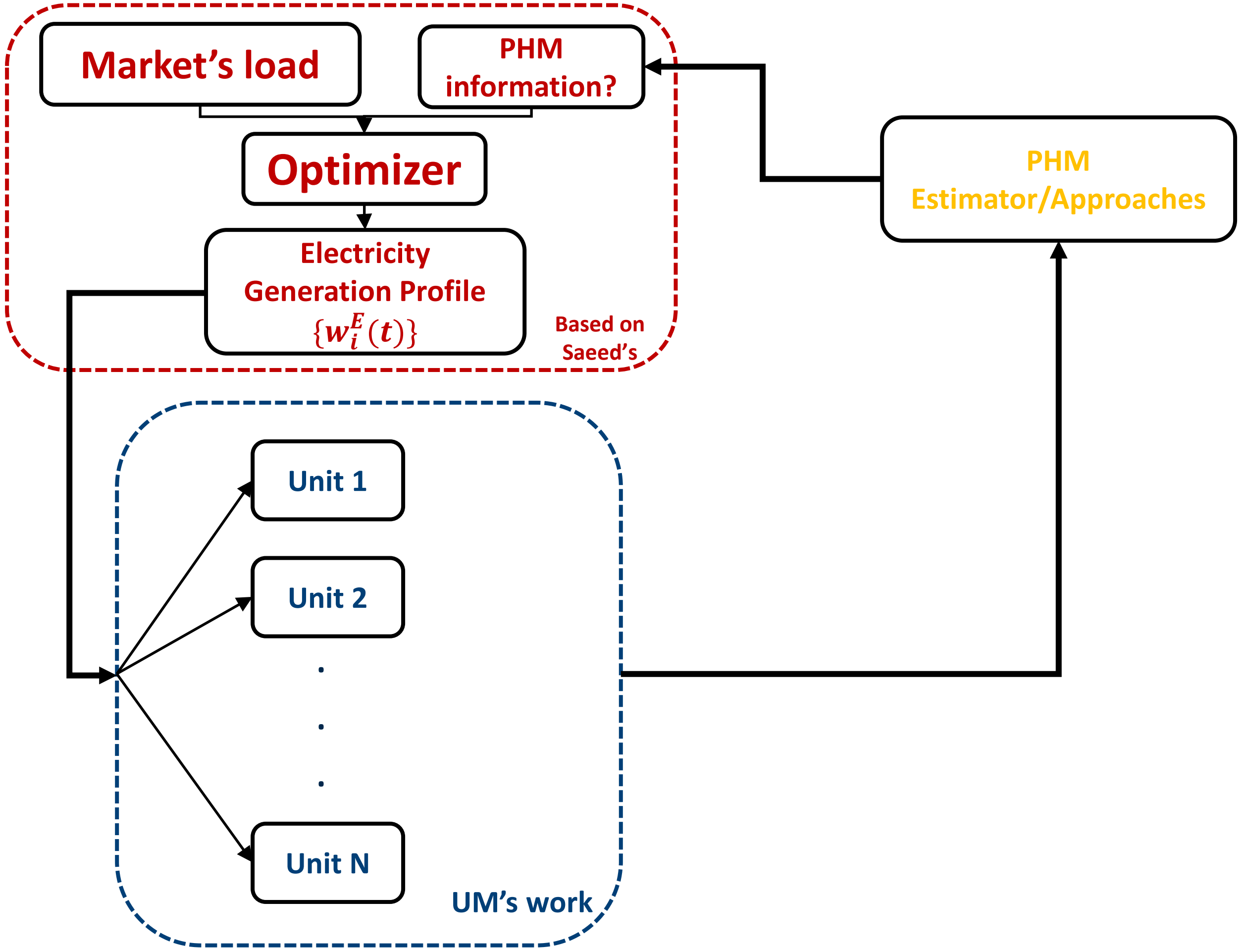
Summary and Future Work

- Some advancements
  - Demonstrated Model Predictive Control as supervisory control directly
    - Possibility to use as an “add-on” to PID system as a Command Governor
  - Demonstrated MPC can (rather easily) integrate prognostics for “health-aware” control
  - Studied Economic Optimization Problem for multi-unit SMR to see how much FPO can help revenues
    - We observed ancillary services do not provide significant revenue increases over baseload
- Some thoughts on Future work, needs, challenges
  - Integrate strategic/economic optimization with tactical control
  - Perform more realistic control problems
    - Consider more components or subsystems, more degradation modes for components, ncertainty in prognostics
    - Introduce noise
    - Evaluate robustness
    - Test as Command Governors
  - How good to prognostics models need to be?

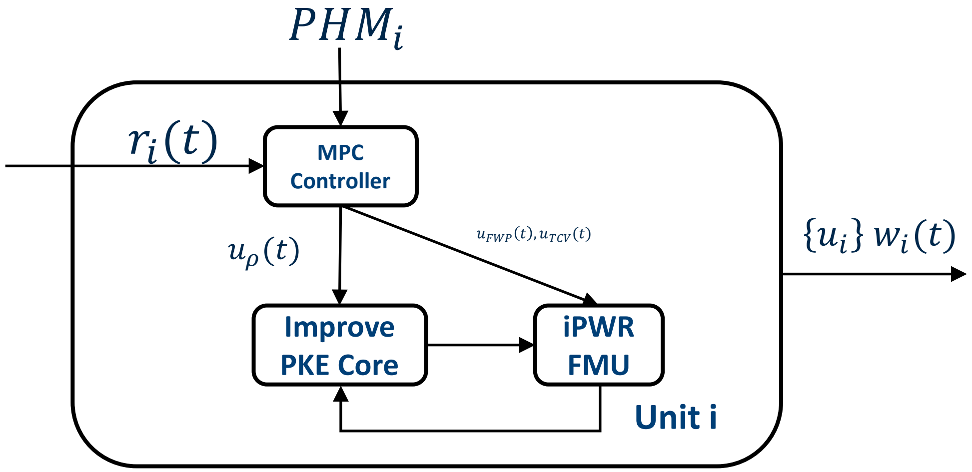
Questions?

Backup

Integrating Strategic & Tactical Controllers



Overall Diagram



Zoomed-in Unit

Plant Model

- 6-group PKE model with Xenon dynamics and two-region temperature model.

$$\frac{dn(t)}{dt} = \frac{\boldsymbol{\rho}(\boldsymbol{t}) - \beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t),$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t), i = 1 \dots 6.$$

6-group PKE

$$\frac{dI(t)}{dt} = \gamma_I \Sigma_f v n(t) - \lambda_I I(t)$$

$$\frac{dX(t)}{dt} = \gamma_X \Sigma_f v n(t) + \lambda_I I(t) - \lambda_X X(t) - \sigma_X v n(t) X(t)$$

Xenon dynamics

$$m_f c_f \frac{dT_f(t)}{dt} = q Q_0 \bar{n}(t) - K_{fc}\big(T_f(t) - T_c(t)\big)$$

$$m_c c_c \frac{dT_c(t)}{dt} = (1-q) Q_0 \bar{n}(t)$$

$$+ K_{fc}\big(T_f(t) - T_c(t)\big) - 2\dot{m}_c c_c (T_c(t) - T_{in})$$

Temperature model

- The total reactivity $\rho(t)$ is the sum of the external reactivity and the reactivity feedback from xenon concentration and temperature

$$\rho(t) = \rho_f(t) + \rho_c(t) + \rho_X(t) + \rho_{in}(t)$$

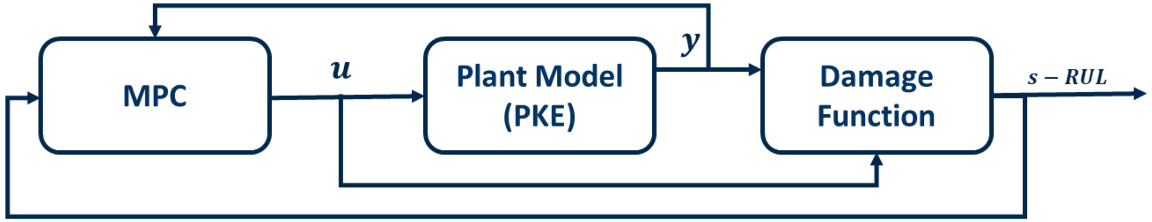
$$= \alpha_f \left(T_f(t) - T_f(0)\right) + \alpha_c \left(T_c(t) - T_f(0)\right) - \frac{\sigma_X}{v\Sigma_f}\big(X(t) - X(0)\big) + \rho_{in}(t),$$

- Control inputs adjust the external reactivity

$$\frac{d\rho_{in}}{dt} = \sum_i a_i u_i$$

MPC Model

- MPC controller is adaptive
  - State-space model is obtained by linearizing nonlinear model adaptively.
  - Control input--u_{cr} control rod speed and u_b boron concentration addition rate
- PHM-informed MPC



- Hypothetical RUL Model

$$RUL_{k+1} = RUL_k - \sum_i b_i u_i^2(k)$$

$$\Delta RUL = -\sum_i b_i u_i^2(k)$$

- Positive u—rod insertion or boron concentration addition

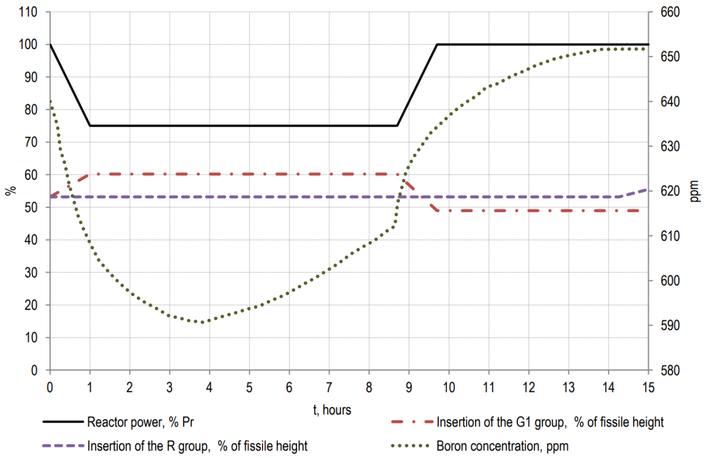
- Objective function for MPC

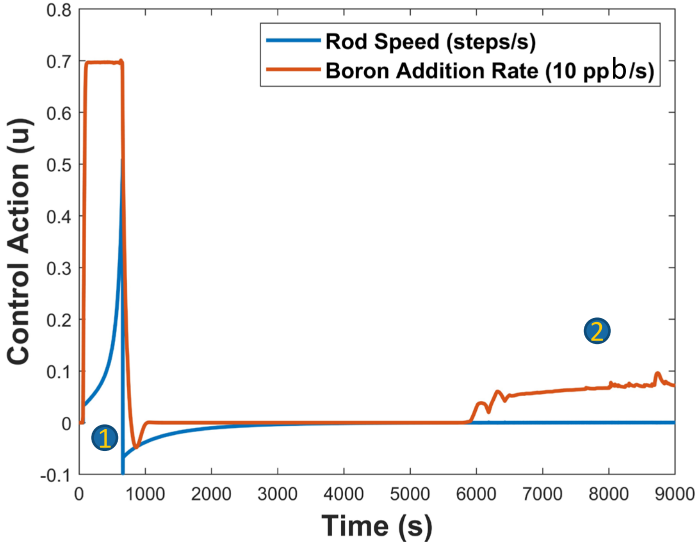
$$\min_{u_k} \sum_{i=0}^{N_p} \|e(k+i|k)\|_{W_e}^2 + \sum_{i=0}^{N_p} \|\Delta RUL(k+i|k)\|_{W_r} + \sum_{i=0}^{N_c} \left(\|u(k+i|k)\|_{W_u}^2 + \|\Delta u(k+i|k)\|_{W_{\Delta u}}^2\right)$$

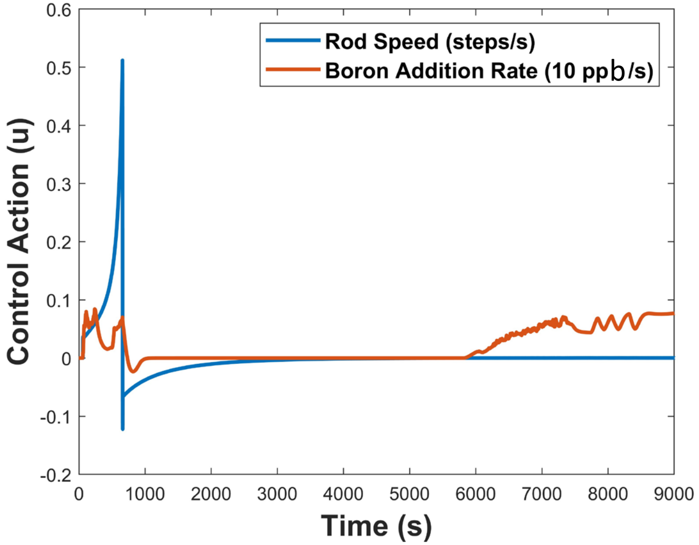
New Results

$$\min_{u_k} \sum_{i=0}^{N_p} \|e(k+i|k)\|_{W_e}^2 + \sum_{i=0}^{N_p} \|\Delta RUL(k+i|k)\|_{W_r} + \sum_{i=0}^{N_c} (\|u(k+i|k)\|_{W_u}^2 + \|\Delta u(k+i|k)\|_{W_{\Delta u}}^2)$$

$$\Delta \mathrm{RUL_k} = \max a_i \left|u_{i,k}\right|^2$$







1) Power tracking—moving control rods with boron addition rate reaches maximum.
2) Slow xenon feedback—boron concentration

Larger damage from moving rod

Smaller damage from moving rod

- Maximum boron concentration addition rate 25ppm/hr—based on OECD FPO report[1]

1. Technical and Economic Aspects of Load Following with Nuclear Power Plants. OECD

Sensitivities on Reduced Order Model Parameters

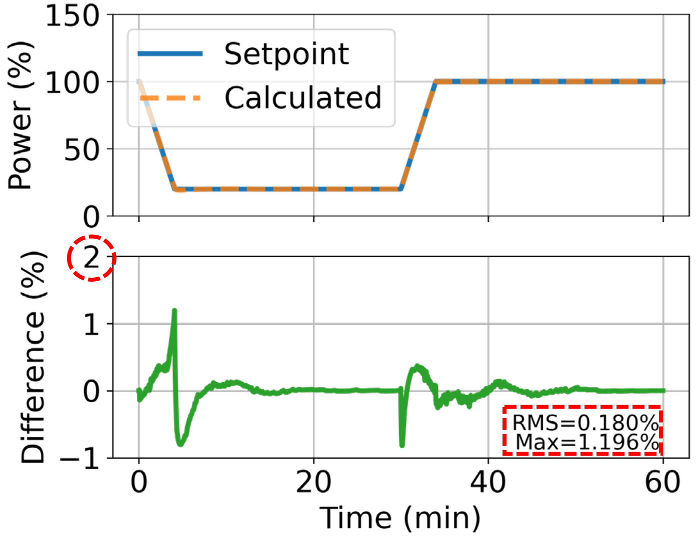
- Even though observer may correct some degree of error, MPC still needs to have a reasonable ROM for accurate and stable simulation results
- Control drum differential worth and β_i have larger sensitivities than other parameters
- ROM parameters may have pretty large margin (30%)
- Standard MPC causes large error since it cannot predict time-varying component

Description	Tracking difference (%)		Control cost	
	RMS	Max	Velocity (deg/s)	Acceleration (deg/s^2)
3D core simulation	0.027	0.234	2.22E-02	5.55E-03
2D core simulation (Base case)	0.017	0.170	2.03E-02	5.10E-03
Standard MPC	0.180	1.196	1.81E-02	2.03E-03
Position-dependent drum worth	0.019	0.166	2.03E-02	5.26E-03
Drum worth −60%	0.106	0.790	9.95E-02	1.93E-01
Drum worth −30%	0.022	0.326	2.04E-02	7.54E-03
Drum worth +30%	0.031	0.172	2.03E-02	4.49E-03
Drum worth +60%	0.049	0.226	2.02E-02	4.06E-03
β_i −30%	0.020	0.145	2.02E-02	4.29E-03
β_i +30%	0.019	0.267	2.03E-02	6.31E-03
λ_i −30%	0.021	0.176	2.05E-02	5.66E-03
λ_i +30%	0.016	0.165	2.04E-02	4.79E-03
Λ −30%	0.017	0.170	2.03E-02	5.10E-03
Λ +30%	0.017	0.170	2.03E-02	5.10E-03
α_f, α_m −30%	0.030	0.221	2.03E-02	5.10E-03
α_f, α_m +30%	0.019	0.170	2.03E-02	5.11E-03
$c_{p,f}, c_{p,m}, c_{p,c}$ −30%	0.020	0.171	2.03E-02	5.10E-03
$c_{p,f}, c_{p,m}, c_{p,c}$ +30%	0.022	0.192	2.03E-02	5.10E-03
Ramp rate 5%/min	0.012	0.097	1.23E-02	1.65E-03
Ramp rate 10%/min	0.014	0.112	1.52E-02	2.78E-03
Ramp rate 30%/min	0.021	0.384	2.59E-02	8.29E-03
Power 100%→140%→100%	0.015	0.140	8.14E-03	1.21E-03

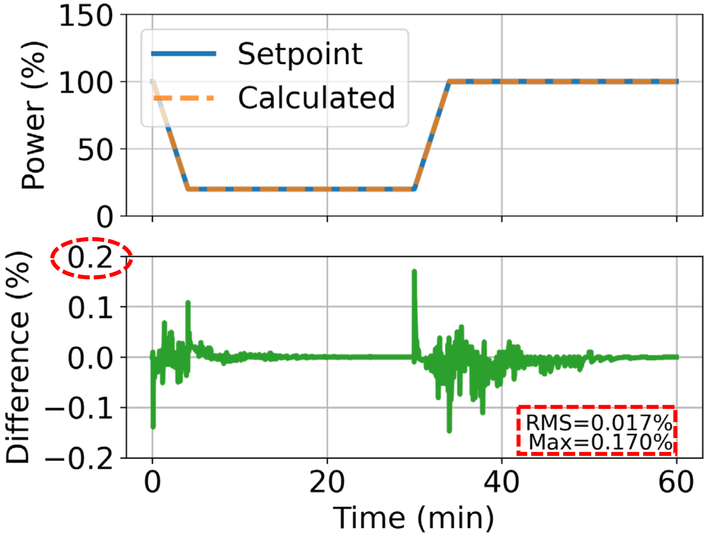
Adaptive MPC vs. Standard MPC

- Ignoring time-varying elements in standard MPC may degrade accuracy
- Successive linearization in adaptive MPC can consider these nonlinearity in ROM

Standard



Adaptive



Time-varying elements from Adaptive MPC