Transient Efficiency, Flexibility, and Reliability Optimization of Coal-Fired Power Plants

Contract Number: DE-FE0031767

Final Program Review
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Principal Investigator
Dr. Aditya Kumar
Sr. Principal Engineer
Controls & Optimization
GE Research
1 Research Circle
Niskayuna NY 12309
Email: kumara@ge.com

GE Contracts Manager
Ahsan Zaidi
Contract Administrator
GE Research
1 Research Circle
Niskayuna NY 12309
Email: ahsan.zaidi@ge.com

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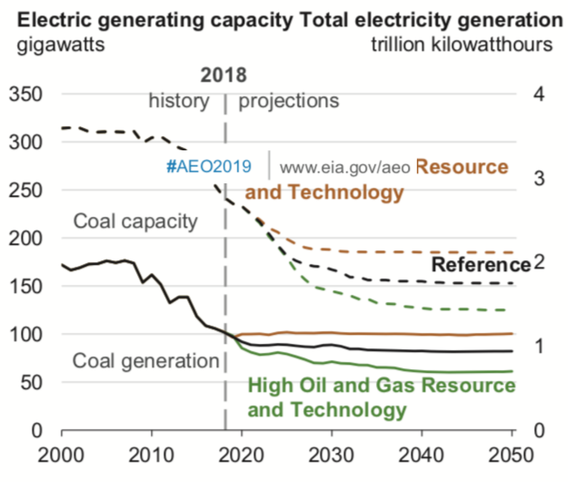
Motivation

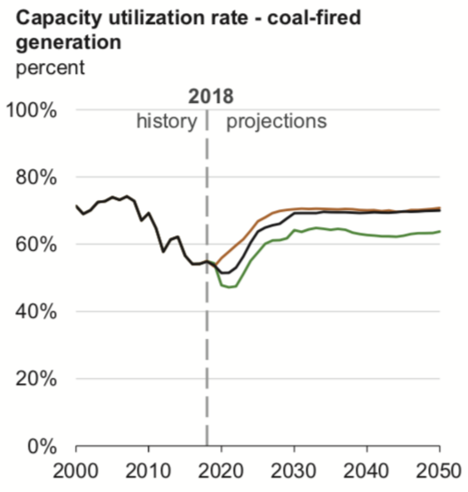
Coal-Fired Power Generation Outlook

Coal-fired power plants (CFPPs) are critical to US power generation infrastructure

- providing diversity at low cost
- hardening the grid against increased penetration of intermittent generation sources

Coal-fired generating capacity is projected to decrease 36%
However, coal-fired generation is projected to decrease 18%
2018 to 2035 (AE2019, EIA)





Remaining active CFPPs will have to:

operate more time at part-load
be more flexible
be more efficient

Program Goal: Build a platform for Digital Twins (UKF + transient model) and Real-Time Optimizers (MPC)
that *estimates* then *optimizes* heat rate at all conditions
optimizes part-load to base-load transitions

Purpose of Project

Project Description

Program Team

GE Research

Dynamic model development

Model Based Estimation

Model Predictive Control

GE Power

Coal-fired power plant operation & design

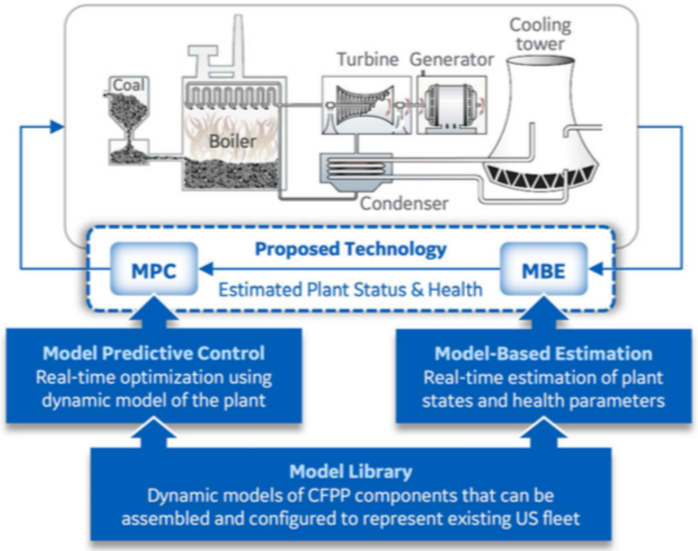
Coal-fired power plant modelling

Relevant Prior Work

- MPC-MBE design for IGCC and CC power plants
- MPC for military aviation applications
- MBE for military aviation applications

Program to develop model-based estimation and predictive control technology for transient optimization and estimation of CFPPs

Program Objective: *Deliver faster ramp rates, higher plant efficiency, and reliability through transient estimation and optimization*



Technical Approach

- Reduced order dynamic models embedded in MBE based on unscented Kalman filtering
- Integrating the MBE with MPC for improved flexibility, efficiency, and reliability

Technical Challenges

- Model library to be able to represent the US installed base coal-fired power plants
- Model, MBE, MPC cohesive integration

Program Deliverables

- Extensive model library for coal-fired power plants
- Integrated MBE-MPC technology
- Hardware in the Loop setup for testing MBE-MPC technology

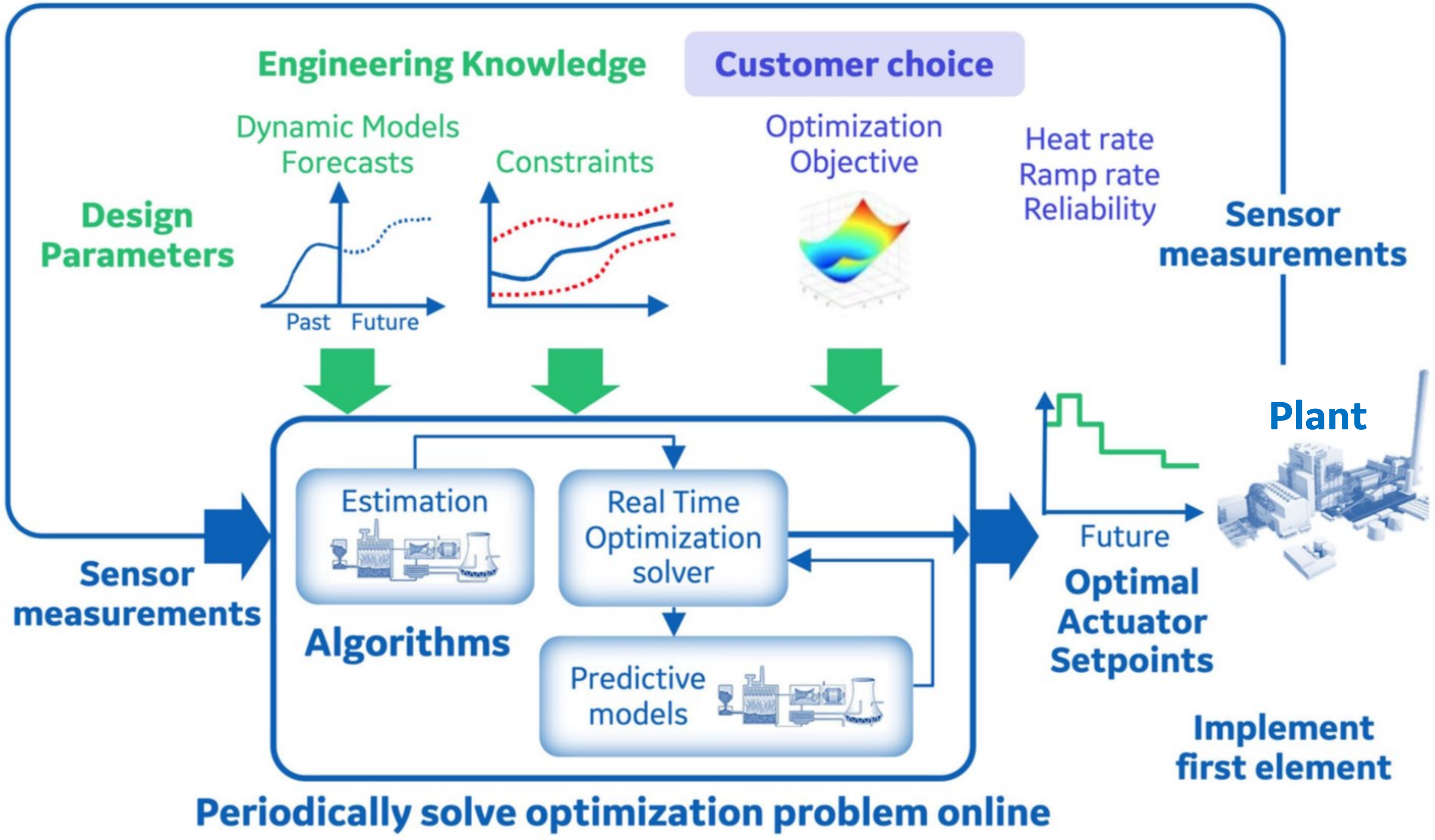
Anticipated Benefits of the Proposed Technology

- Heat rate improvements of up to relative 5%
- Flexibility improvements of up to 30%
- Reliability improvements through power plant component health estimation

Value: 800 MW plant 5%(relative) improvement in heat rate → $2.9M fuel savings/year

* 5% relative improvement for a plant with 37% efficiency amounts to an increase of 1.85% in overall plant efficiency to 38.85%

Project Overview

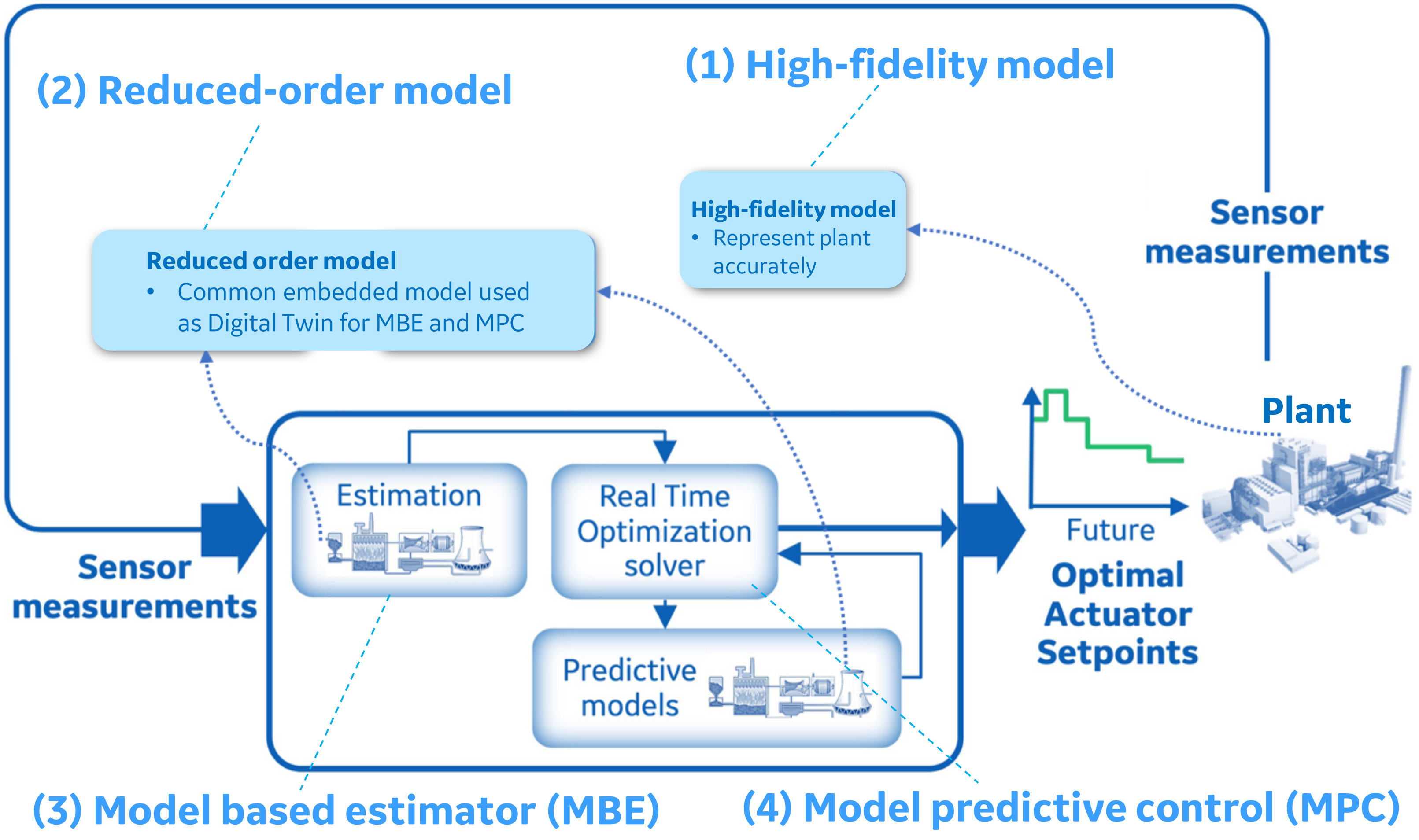


- **Develop & Demonstrate real-time model-based estimation & optimal control technology** (TRL5)
  - Use a simplified, continuously matched model (Digital Twin) to optimize operation of power plant, and monitor plant equipment health

Model-based (Digital Twin) Optimal Controls for Coal Fired Power Plants (CFPP)

- faster ramps (flexibility)
- reduced coal fuel usage (efficiency)
- equipment health monitoring

Key Elements of MBE+MPC Technology



- Physics-based transient models
  - **High-fidelity model in Apros** (1) – simulate plant
  - **Reduced-order model (ROM)** (2) – very fast and robust for use as shared embedded model in MBE & MPC
- **Model-based estimation (MBE)** (3)
  - Real-time adaptation of model parameters and states to match plant measurements (Digital Twin)
- **Model predictive control (MPC)** (4)
  - Real-time optimization – fast load ramps, efficiency

- Develop and test individually – Topical Reports
- Integrate and test overall solution
  - Desktop simulations
  - Deploy and test on Hardware-in-loop (HIL) platform for real-time deployment

MBE+MPC for faster ramps (flexibility), better heat-rate (efficiency), and health monitoring

Overall Program Summary

Program Activities	2019 Q3	2019 Q4	2020 Q1	2020 Q2	2020 Q3	2020 Q4	2021 Q1	2021 Q2	2021 Q3	2021 Q4	2022 Q1	2022 Q2
Task 1: World Design and Simulation Engine for prediction/expectation task	■	■	■	■	■	■	■	■	■	■	■	■
Deliverable: *Upated Project Management Plan*				▽								
Deliverable: *Updated Technology Maturation Plan*								▽				
Deliverable: *Final Project Report*												▽
Phase 1: Task 2: Generic Transient Model Development												
2.1: Develop transient models of key components of coal-fired power plant from existing steady-state performance models	■	■										
2.2: Validation of transient model of the overall CFPP using site data and refine component models (if necessary) to meet accuracy limits		■	■									
Deliverable: *Modeling methodology of key component models and validation results*			▽									
Milestone: *Models available for key components of coal-fired power plants*			◆									
Task 3: Transient Model-based Estimator Design (MBE)												
3.1: Develop and test model-based estimator to estimate parameters of the coal-fired power plant model			■	■								
3.2: Validate MBE with site data at steady-state and transient conditions				■	■							
Deliverable: *Model-based estimation technology applied to a coal-fired power plant to estimate parameters resulting in a digital twin CFPP model*					▽							
Task 4: Model Predictive Control (MPC) Design												
4.1: Develop and test MPC technology using the digital twin CFPP model to optimize heat rate at steady state and ramp-rates at part-load conditions					■	■						
4.2: Integrate and apply MPC and MBE technologies on the nominal CFPP model						■	■					
Deliverable: *Integrate MBE and MPC solution to estimate states and control operation of CFPP*							▽					
Milestone: *Model-based estimation and controls methodology and simulation results using nominal CFPP model*							◆					
Phase 2: Task 5: Deployment of Integrated Solution												
5.1: Integrate MBE and MPC solution on the tuned digital twin model								■	■			
5.2: Deployment of Integrated Solution on GE's EdgeOS platform									■	■		
5.3: Hardware-in-loop (HIL) simulation to test different optimization formulations										■	■	
Deliverable: *Deployment process and optimization results of HIL studies peformed on GE's Edge OS platform*											▽	
Milestone: *Integrated solution on the tuned digital twin model, deployment process on GE's Edge OS platform and HIL results*											◆	

◆ Denotes ***Milestone*** ▽ Denotes ***Deliverable***

Task 1: Project Management
- *Final Report - in progress*

Task 2: Transient Model Development
- High-fidelity APROS model (based on reference 820 MW plant)
- Reduced order model (>100x faster than real time)
- *Submitted Topical Reports*

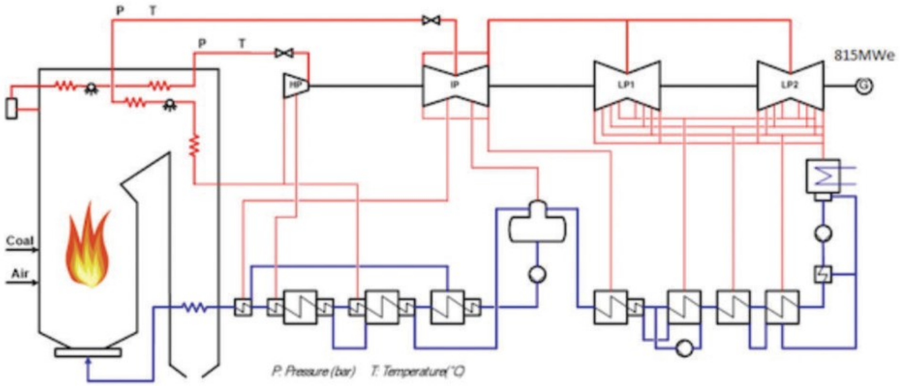
Task 3: Unscented Kalman Filter development
- Develop and test with ROM and Apros model as plant for measurements
  - Match ROM with high-fidelity plant model – Digital Twin
- *Submitted Topical Report*

Task 4: Model Predictive Control platform development
- Develop and test with ROM as plant for fast ramps, efficiency improvement
- *Submitted Topical Report*

Task 5: Integrated Hardware-in-loop (HIL)-like environment
- Desktop simulation studies with ROM+MBE+MPC+Apros
- Real-time deployment on with Linux+Docker containers for HIL
- Demonstrate real-time application and key benefits
  - **Fast load ramps** – up to 4%/min
  - **Efficiency improvement** – up to 5.5% reduction in coal at 50% load
  - **Component health monitoring** – track estimated component health parameters
- *Final report – in progress*

High-Fidelity Transient Model in Apros

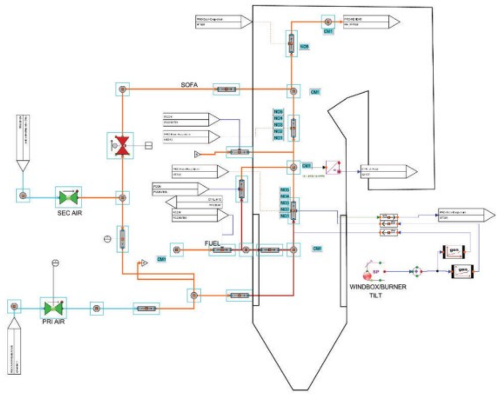
Reference Plant (820MW) architecture



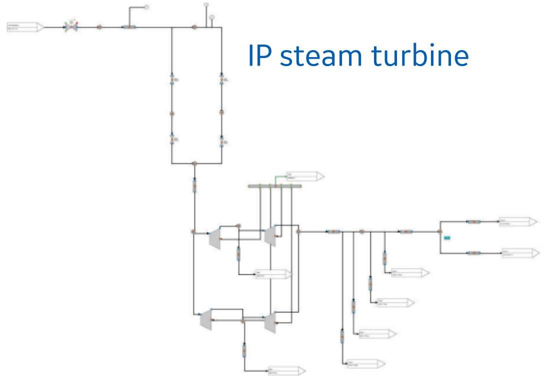
- Reference plant design configuration & specifications at 100% load (TMCR)

High-fidelity modular components – use design specifications

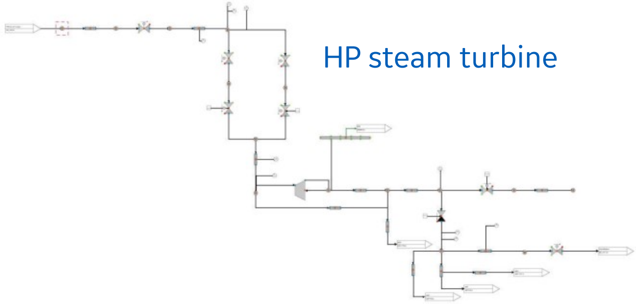
Combustor – 2 combustion zones + SOFA



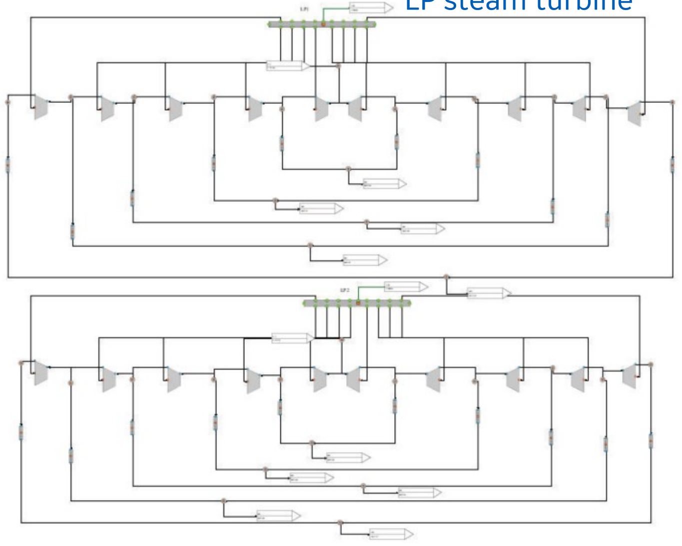
IP steam turbine



HP steam turbine



LP steam turbine

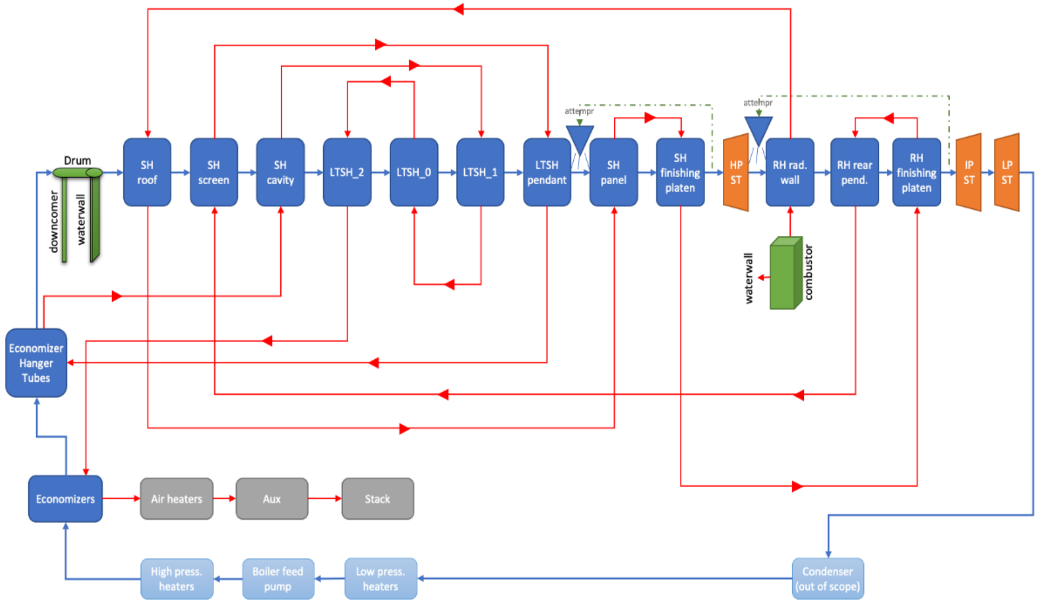


- Detailed modules (boiler, superheater/reheater, HP/IP/LP turbine, air preheaters, water preheaters, economizer
- Detailed baseline schedules & controls to enable steady-state and transient (load changes) simulations
- I/O hooks for measurements (to MBE) and control knobs (from MPC)
- Real-time two-way communication for I/O with MBE+MPC using Apros API

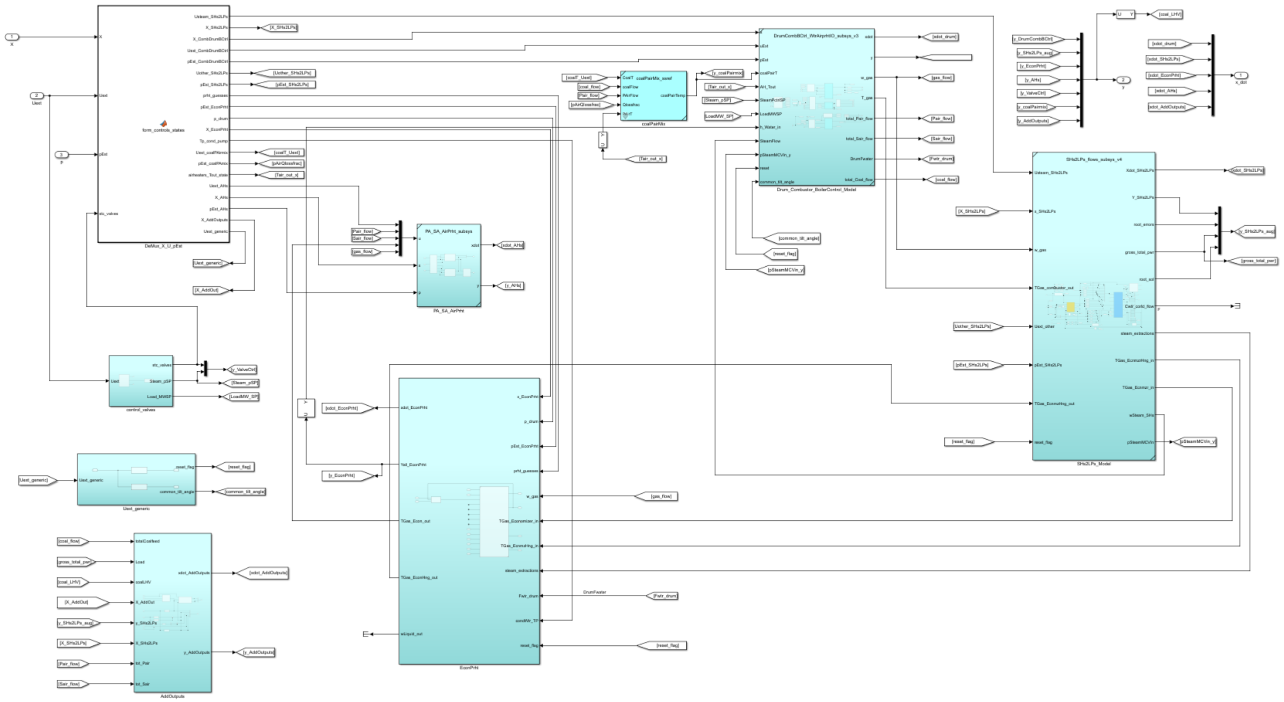
Detailed, real-time transient model – run between 100%-40% TMCR as plant model

Reduced-Order Model (ROM)

Reference CFPP (820MW) architecture



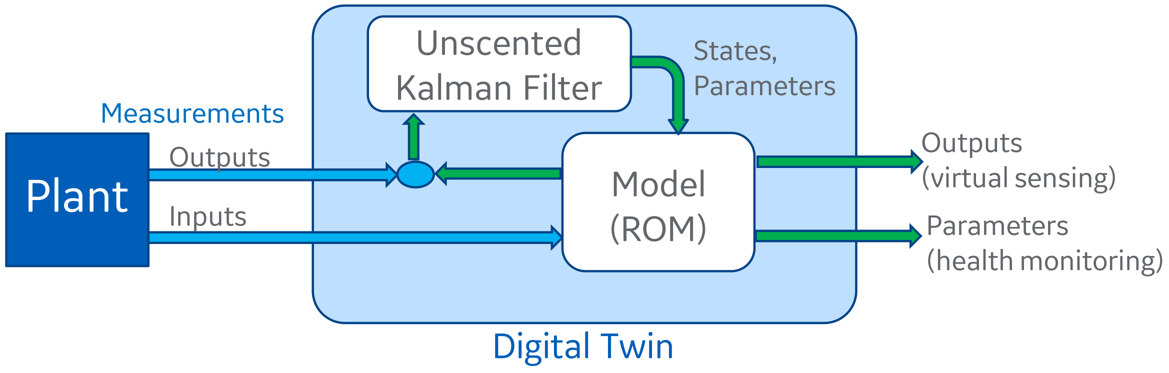
Modular, configurable, parameterized ROM in Simulink



- Simplified physics with relevant dynamics, modular, & configurable – combustor, drum, SH/RH, HP/IP/LP ST, air/water preheater
- Simple P/PI unit-level controllers – drum level, steam P, MW, …
- Tuning parameters in each module (e.g., scale factors on heat transfer coefficients, efficiency,…) to allow matching simplified model with plant measurements to get a Digital Twin ~66 parameters available (select subset to tune via MBE)

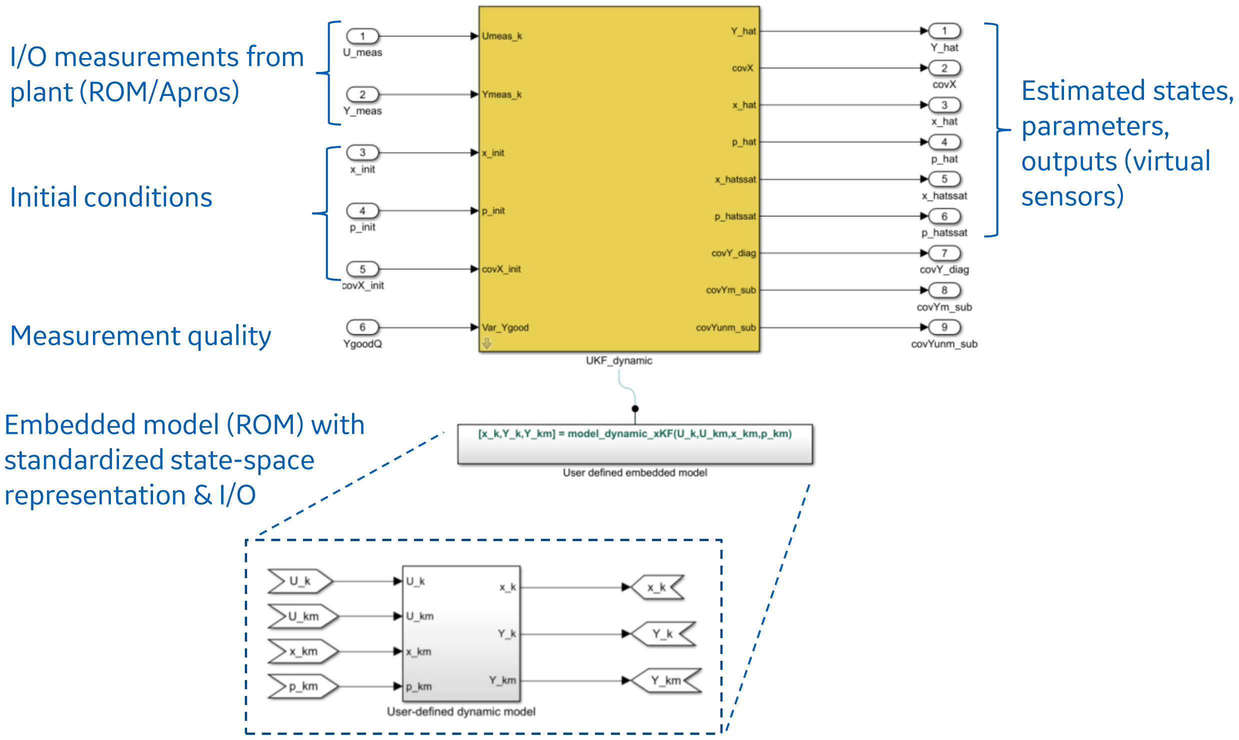
Very fast (>100x real-time!) and robust model – enable real-time MBE & MPC

Model-Based Estimation(MBE)



- Use unscented Kalman filter (UKF) for joint state & parameter estimation
- Excel-based configuration – measurements, estimated parameters, tuning
- Enable desktop simulation studies, code generation and deployment in HIL

Standardized Estimation library in Simulink



Select measurements, Apros signal names & units, UKF tuning

Outputs	Unit	Measure	Estimate	Nomina	R	Name	Coun	APROS Name	APROS Unit
fluegas xwO2		1	0	0.030	0.50	Outlet flue gas fraction of O2		/SPU-BOILER/Process/PRO-FUEL_AIR/GI02#ME_OUTPUT_VALUE	MassFrac
xll	ft	1	0	3.300	0.15	Liquid level		/SPU-BOILER/Process/PRO-Econ-Evap-drum/TAH03#TA12_LIQ_LEVEL	m
pd	psi	1	0	2775.628	3.00	Drum Steam P		/SPU-BOILER/Process/PRO-Econ-Evap-drum/TAH03#TA12_PRESSURE	Mpa
Total_primair_flow	lb/s	1	0	414.321	2.00	Total Primary Air flow		/SPU-BOILER/Process/PRO-AIR-PREHEATER/APHPIP01#PI12_MIX_MASS_FL	kg/s
Total_secair_flow	lb/s	1	0	1062.067	2.00	Total Secondary Air flow		/SPU-BOILER/Process/PRO-AIR-PREHEATER/APHPIP08#PI12_MIX_MASS_FL	kg/s
Total_coal_flow	lb/s	1	0	230.178	2.00	Total Coal Flow		/SPU-BOILER/Process/PRO-FUEL_AIR/PIP28@1#PI12_MIX_MASS_FLOW	kg/s
tSteam_in_SH_panel	deg F	1	0	795.370	2.00			/SPU-BOILER/Process/PRO-Superheater/SH_PO42#PO11_TEMPERATURE	deg C
tSteam_out_SH_fnshpltn	deg F	1	0	1054.915	1.00	Steam Temperature out Superheater finishing platen		/SPU-ST/STHP/STHPPO03#PO11_TEMPERATURE	deg C
pSteam_out_SH_fnshpltn	psi	1	0	2427.492	5.00	MCV inlet Steam P - same as SH fnshpltn outlet		/SPU-ST/STHP/STHPPO03#PO11_PRESSURE	Mpa
wLiquid_DeSH	lb/s	1	0	17.428	3.00	Liquid flow in superheater attemperator		/SPU-BOILER/Process/PRO-Superheater/SH_PIP32#PI12_LIQ_MASS_FLOW	kg/s
wSteam_MCV	lb/s	1	0	1410.701	1.00	MCV Steam flow		/SPU-ST/STHP/STHPPIP01#PI12_MIX_MASS_FLOW	kg/s
tSteam_out_RH_fnshpltn	deg F	1	0	1052.255	1.00	Steam Temperature out of Reheater Finishing Platen		/SPU-BOILER/Process/PRO-REHEAT/RH_PO144#PO11_TEMPERATURE	deg C
wLiquid_DeRH	lb/s	1	0	6.074	3.00	Liquid flow in reheater attemperator		/SPU-BOILER/Process/PRO-REHEAT/RH_PIP109#PI12_LIQ_MASS_FLOW	kg/s
wSteam_ICV	lb/s	1	0	1272.862	1.00	ICV steam flow		/SPU-ST/STIP/STIPPIP01#PI12_MIX_MASS_FLOW	kg/s
pSteam_out_ICV	psi	1	0	569.951	2.00	Steam Pressure out of ICV		/SPU-ST/STIP/STIPPO22#PO11_PRESSURE	Mpa

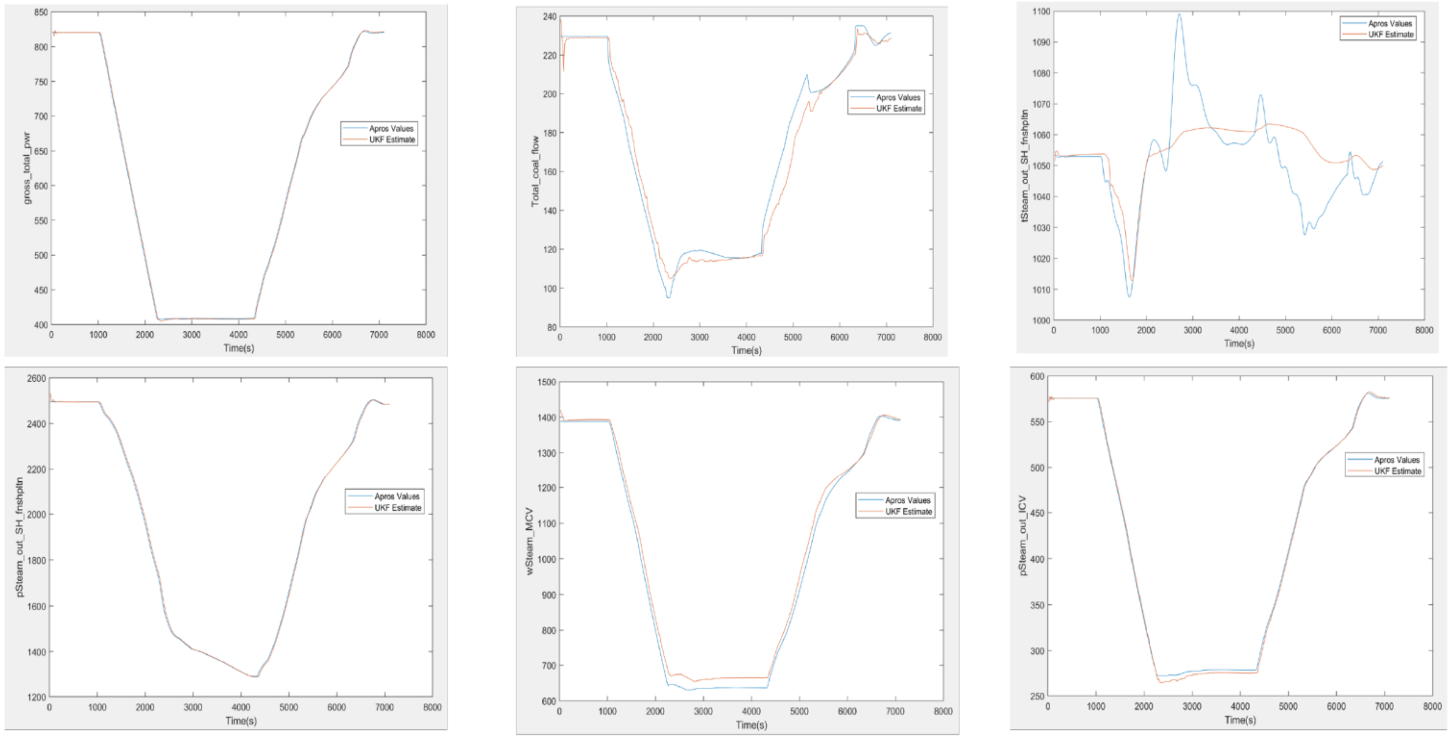
Select estimated parameters, min/max limits, UKF tuning

Parameters	Estimated	Upper Boun	Nominal	Lower Boun	P_0	Q	TauMarko	TauMovA	CovPss
Comb UAconvrad sf	1	1.7	1	0.5	0.001	0.01	600	3000	0.001
Primary_air_Scaling	1	1.15	1	0.9	0.005	0.001	600	3000	0.003
Secondary_air__Scaling	1	1.1	1	0.95	0.005	0.001	600	3000	0.003
SteamPSP_bias	1	2	0	-2	0.5	0.01	400	3000	0.003
FgasxwO2SP_bias	1	0.015	0	-0.01	0.003	0.01	600	3000	0.001
drumLevelSP_bias	1	1	0	-1	0.05	0.01	150	500	0.03
htcGas_totalsf_LTSH1	1	4	1.00	0.05	0.1	0.01	600	3000	0.002
htcGas_totalsf_SH_panel	1	11	3.774884029	0.05	1.5	0.01	600	2000	0.1
flow_extr_sf_HPST	1	2.5	1	0.5	0.05	0.001	600	3000	0.002
cv_sf_HPST	1	2	1	0.3	0.1	0.001	600	3000	0.02
htcGas_totalsf_RH_fnshpltn	1	10	1	0.05	1	0.01	600	3000	0.02

MBE tuned using ROM / Apros as plant model for robust real-time estimation

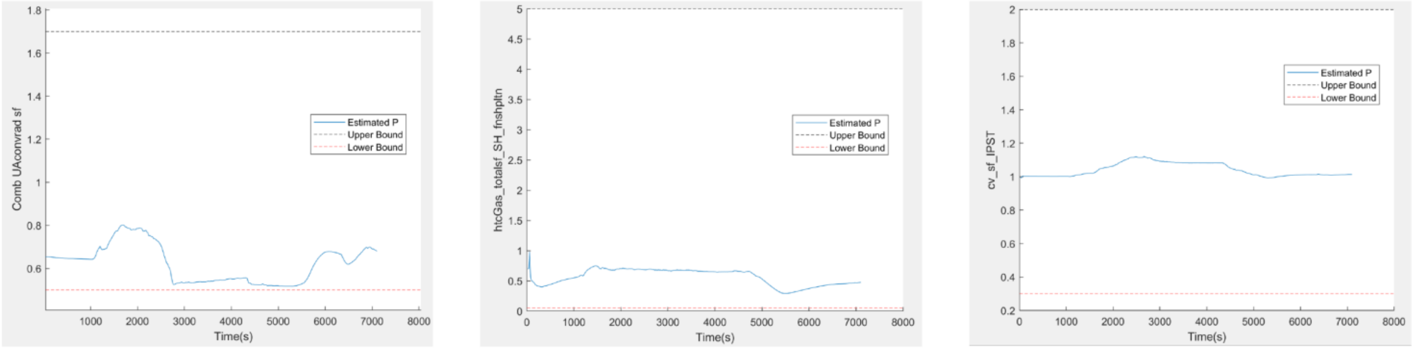
Model-Based Estimation(MBE)

– Representative results with Apros Plant model (100% → 50% → 100% load transient)

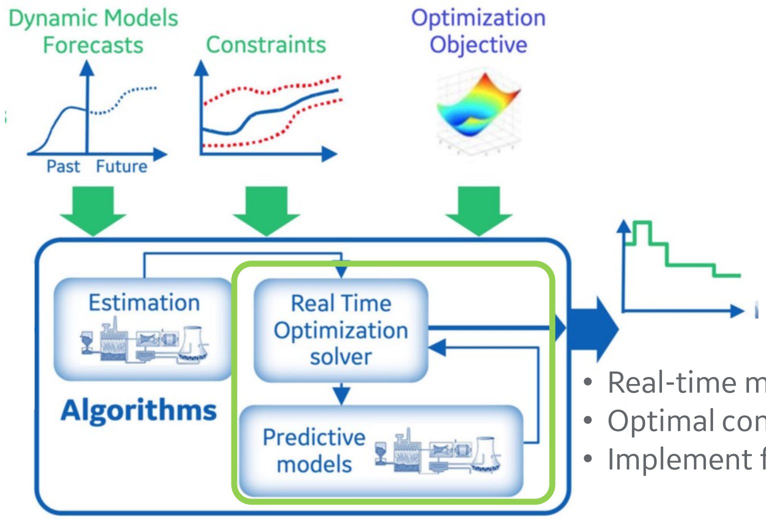


Matching measured output variation

Estimated parameter variation

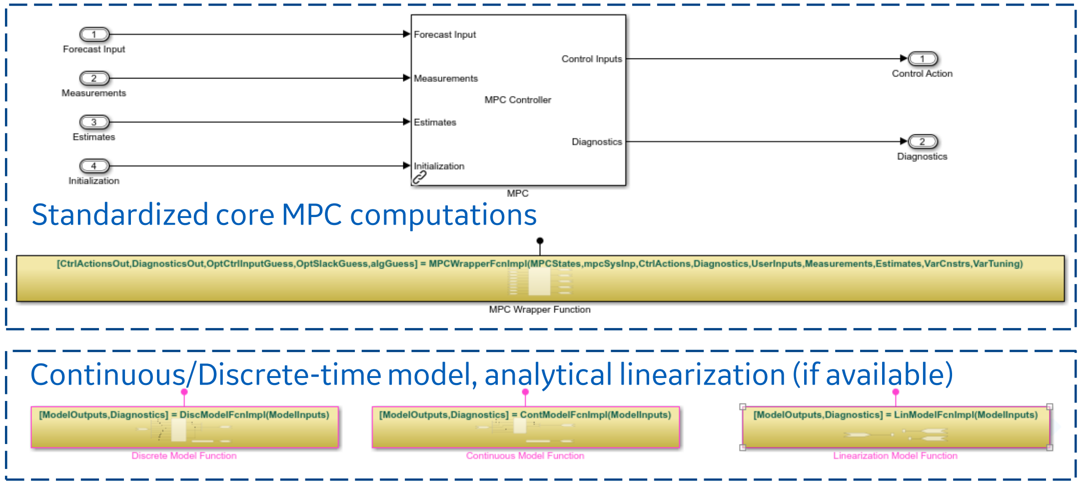


Model Predictive Control (MPC)



- Real-time model prediction & optimization
- Optimal control over future horizon
- Implement first move & repeat

Standardized MPC library in Simulink



- Use hybrid (nonlinear prediction + linear/QP optimization) – fast & robust
  - Nonlinear discrete-time model for prediction + analytical (if available) or numerical model (continuous/discrete-time) linearization
  - *Dual objective*: *tracking* (load ramp) + *performance* (min coal) optimization – tracking is the primary objective
  - Input & output constraints
- Excel-based configuration – control inputs & outputs, weights, input & output constraints (soft output constraints with weights)
- Enable desktop simulation studies, code generation and deployment in HIL

Select outputs (tracking, performance, constraints) and tuning, LB/UB limits

Outputs	Unit	MPC Track	MPC Perforn	MPC Con	Q_ii - tracking	L_ii - perform	Qslack_ii - const	Lslack_ii - constr	y-UB	y-LB
fluegas xwO2		0	0	1	10	0	8	2	0.05	0.01
tSteam_out_SH_fnshpltn	deg F	0	0	1	10	0	8	2	1160	700
tSteam_out_MCV	deg F	0	0	1	10	0	8	2	1160	700
sat_ratio_HPST		0	0	1	10	0	8	2	0.95	0.001
tSteam_out_ICV	deg F	0	0	1	10	0	8	2	1160	700
sat_ratio_IPST		0	0	1	10	0	8	2	0.95	0.001
sat_ratio_LPST		0	0	1	10	0	8	2	1.2	0.9
gross_total_pwr	MW	1	0	0	3	0	8	2	10000	-10000
y_Econ_gasout_T	deg F	0	0	1	10	0	8	2	1800	300
total_coal_flow_filtered	lb/s	0	1	0	0	8	8	2	1000	0

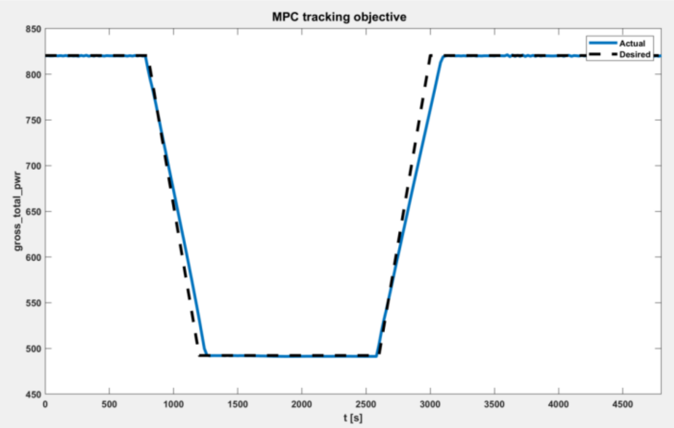
Select control inputs – tuning, magnitude and rate LB/UB limits

Inputs	Unit	MPC knobs	R_ii - control cost	u-UB	u-LB	delta_u-UB / sec	delta_u-LB / sec
Steam_pSP	psi	1	4	2550	1100	1.8	-1.8
stc_MCV	[%]	1	13	100	10	0.2	-0.2
common_delta_tilt	deg	1	5	15	-15	0.025	-0.025

MPC tested for fast load ramps (tracking) and coal minimization (performance) with ROM

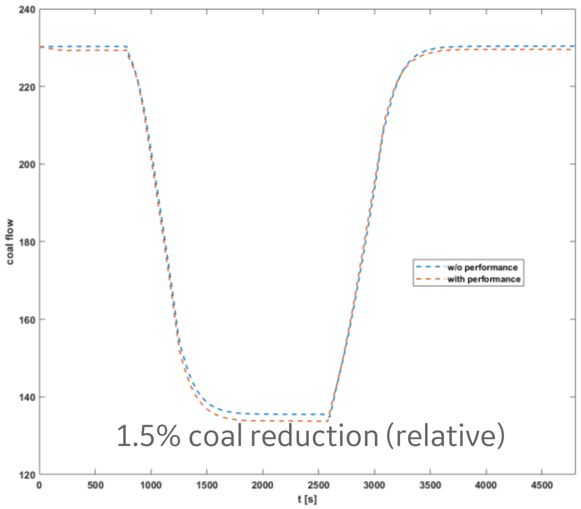
Model-Based Estimation(MBE)

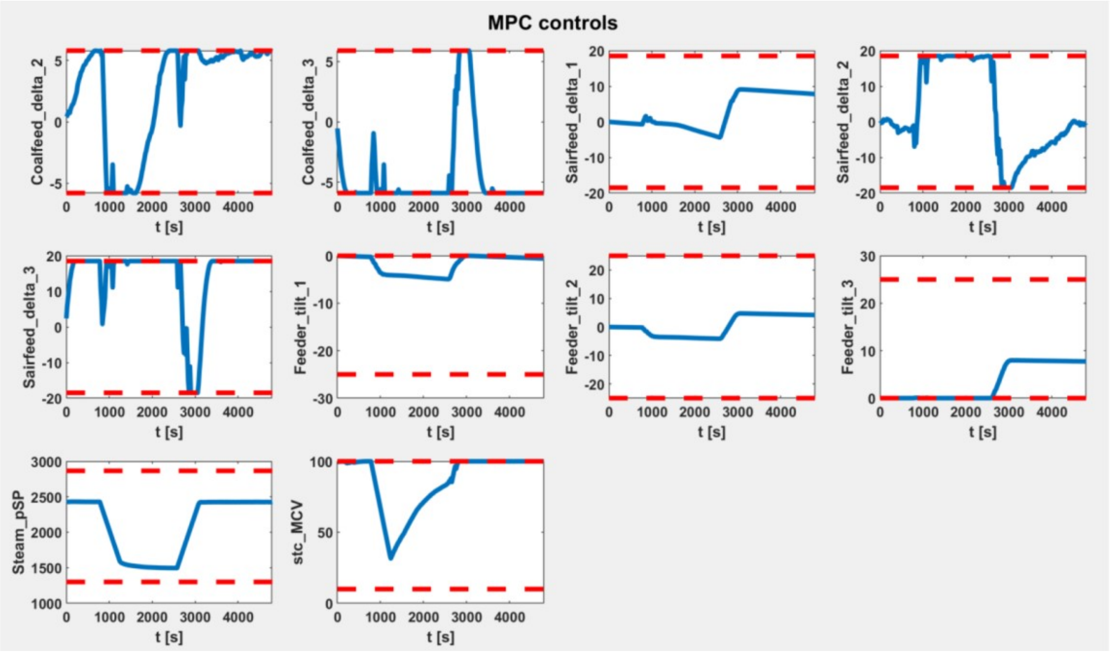
– Representative results with ROM Plant Model (100% → 60% → 100% at 6%/min)



← Load ramp tracking

Coal minimization →
(max efficiency)





Potential (exploratory) control knobs – coal/air feed trim, feed tilt in each of 3 combustor zones

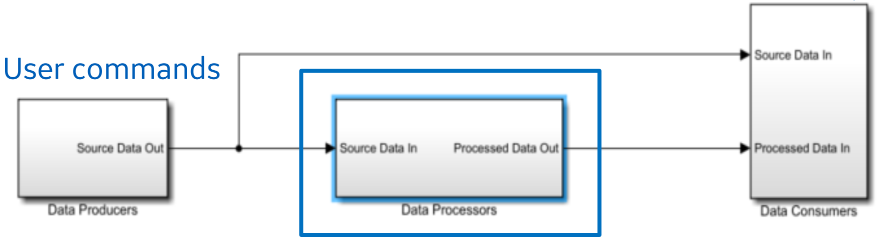
- consolidated to single “common” feed tilt for runs with Apros

Main control knobs (steam pressure SP, MCV)

Integrated (MBE+MPC+Plant) – Simulink Test Harness for desktop simulations

Data save, scopes

User commands



Plant model

- Option1: Use ROM as plant for initial design/testing
- Option2: Bridge to Apros high-fidelity model via two-way real-time comms over GRC network
    - Read sensor measurements for MBE
    - Write MPC optimal control

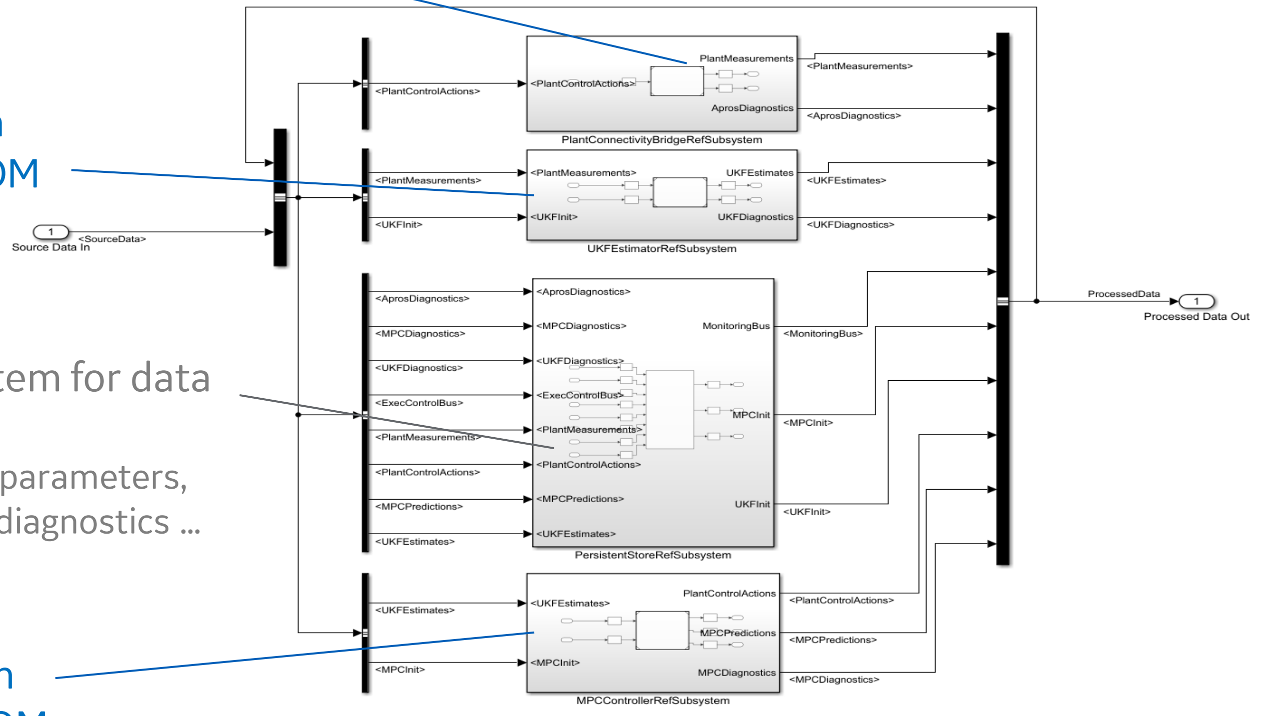
MBE based on embedded ROM

Auxiliary system for data persistence

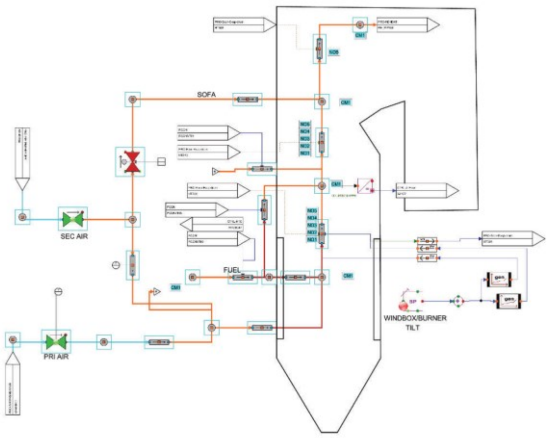
- Store states, parameters, covariances, diagnostics …

MPC based on embedded ROM

- Can be enabled/disabled



Apros high-fidelity model



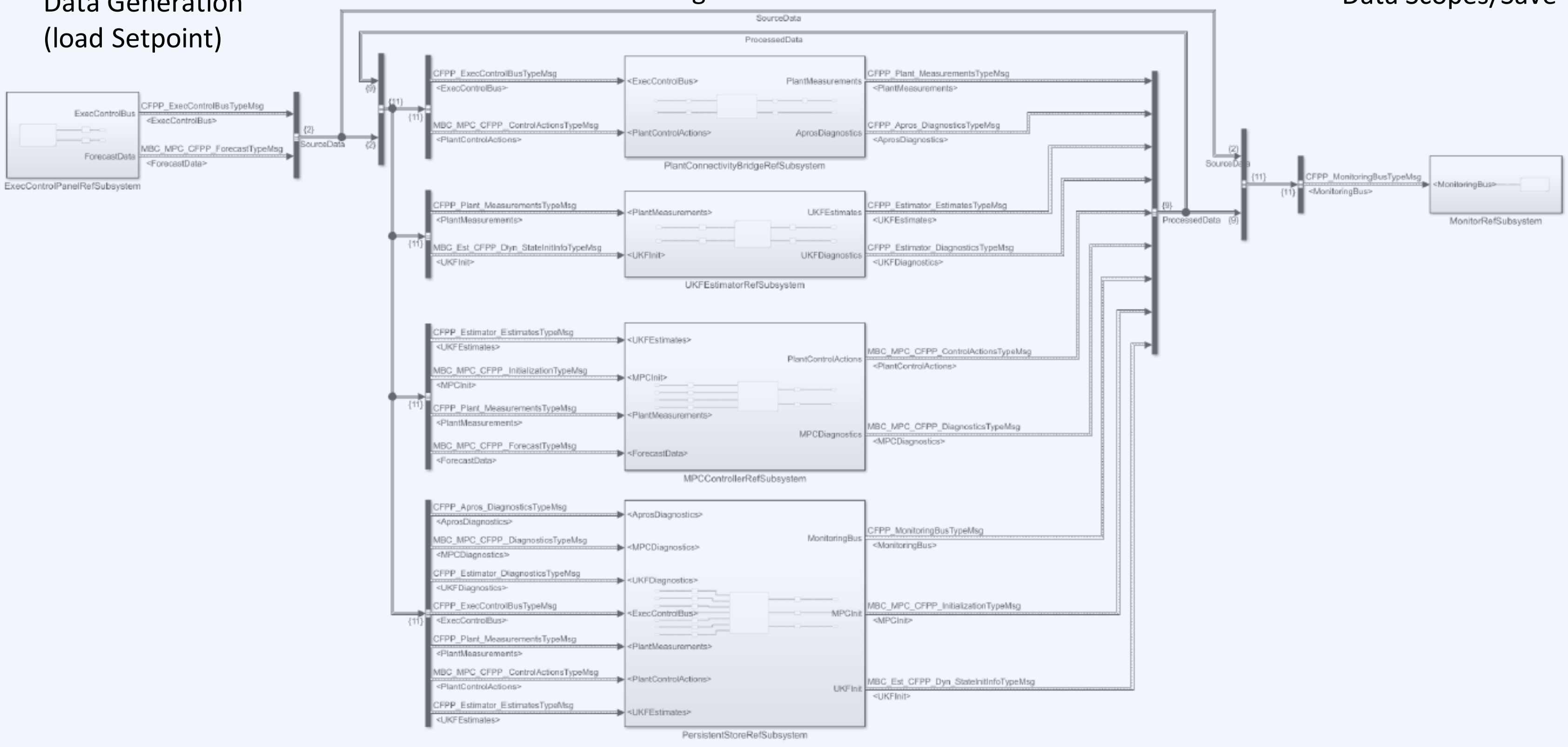
GRC intranet

Integrated (MBE+MPC+Plant) – HIL deployment and testing

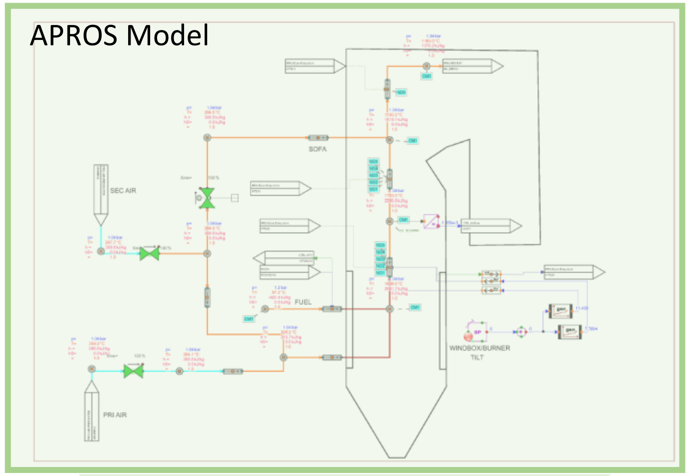
Data Generation (load Setpoint)

Core Algorithm Modules

Data Scopes/Save



APROS Model



- Auto-code generation (C) + Docker containers (no re-work needed for HIL)
- Deployed for real-time on Linux VM
- Test with ROM /Apros as plant model
- Live two-way communication with Apros model

Ubuntu Linux VM

Docker Containers for core algorithm modules

- APROS Bridge, Store, MBE, MPC
- Data generation (load changes, forecast)
- Data scopes, save results to file

virtual Ethernet communication with Linux VM

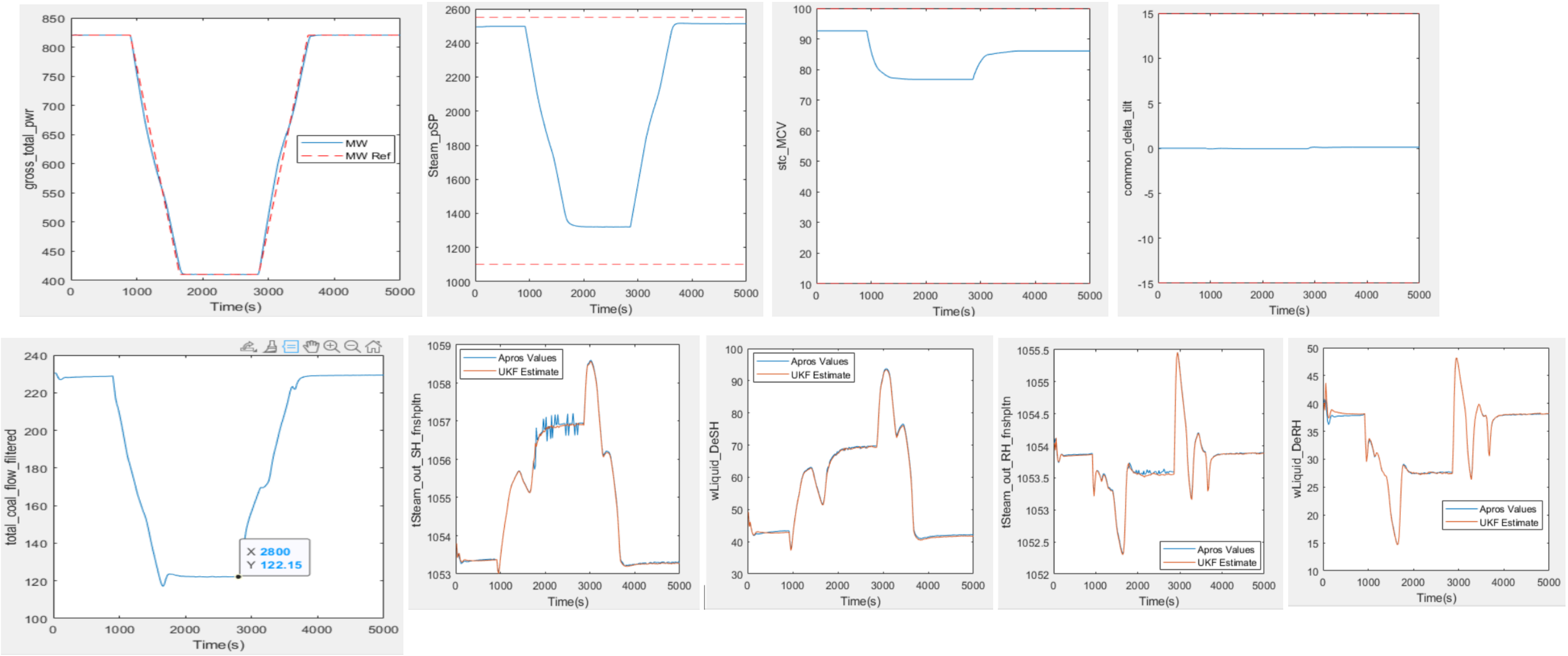
Windows PC

- APROS model & API client
- Linux VM

Desktop & HIL simulations

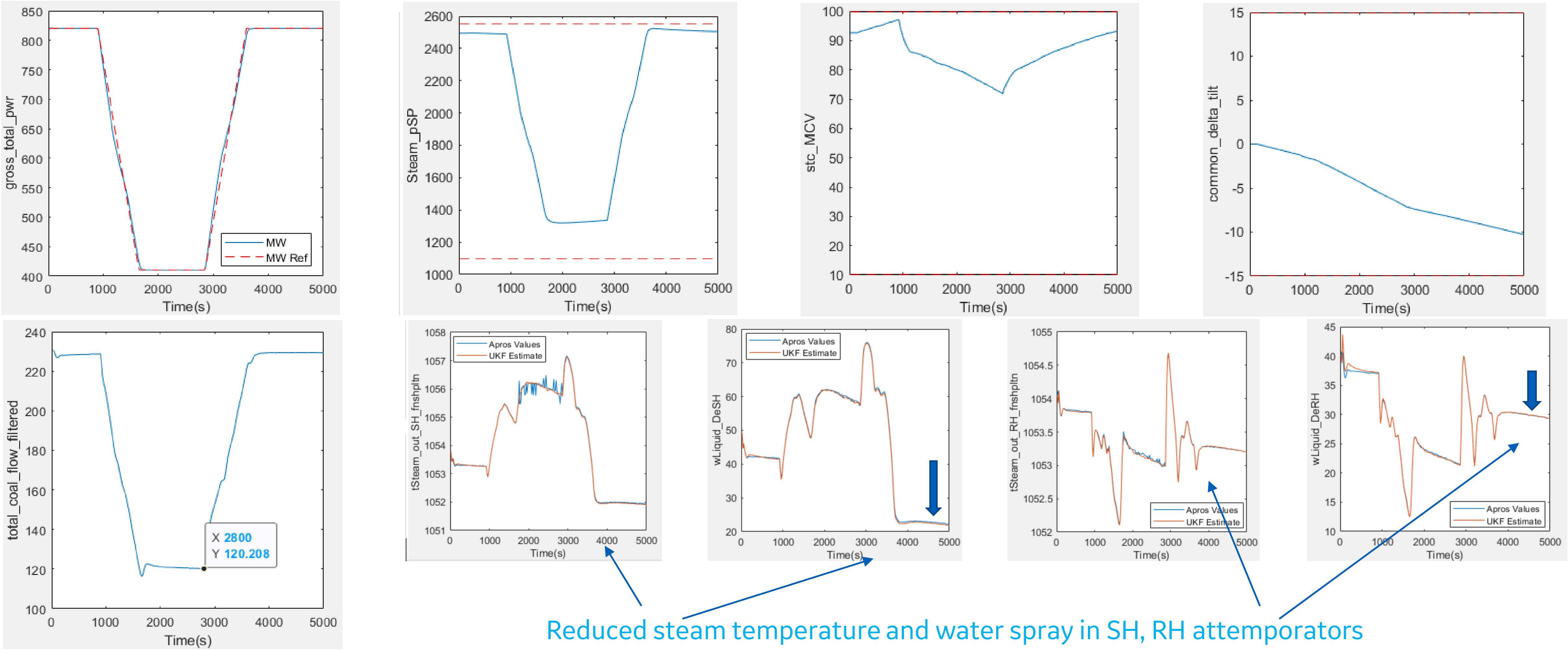
- ROM as plant model

Desktop Simulation - load tracking, NO weight for performance



- 100% → 50% → 100% at 4%/min ramp rate - good tracking
- Minimal use of tilt angle (with no weight on performance optimization)
- Baseline run with no performance metric – coal use at 50% load ~122.2 lb/s

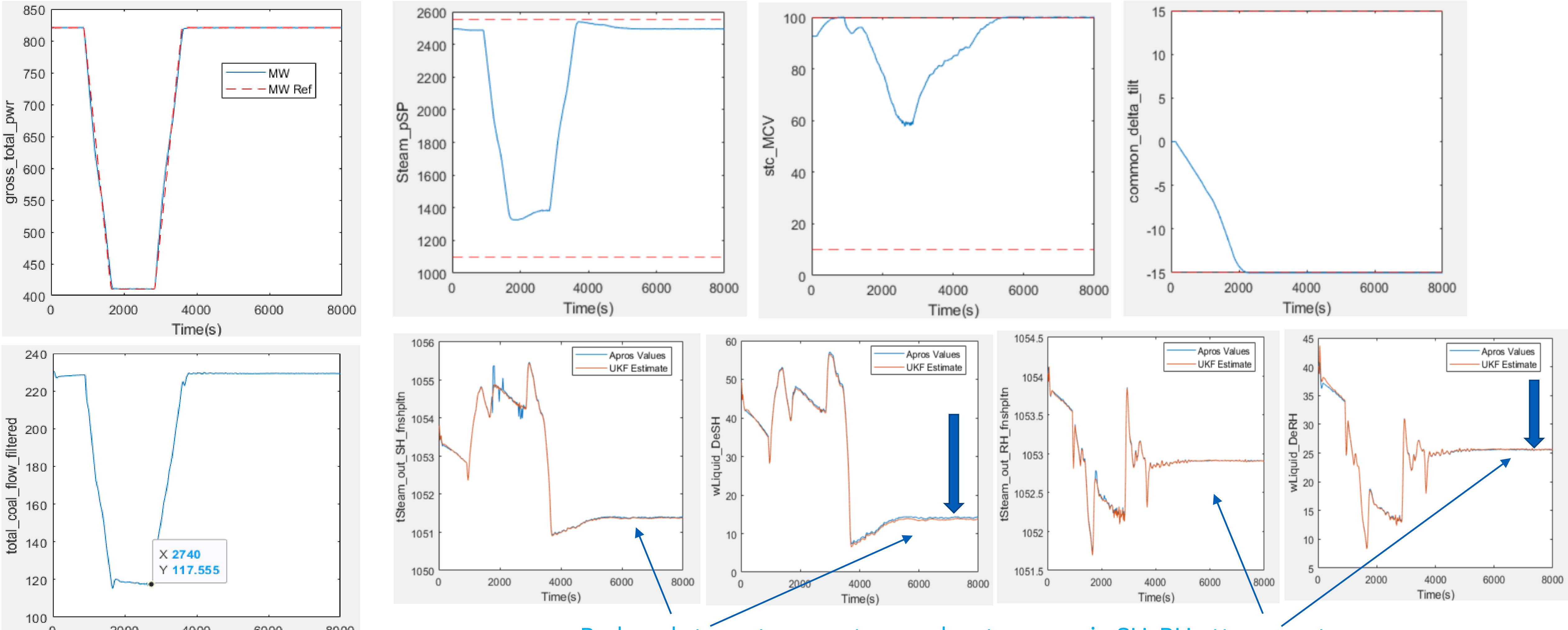
Desktop Simulation - load tracking, LOW weight for performance



~1.6% reduction in coal (relative)

- 100% → 50% → 100% at 4%/min ramp rate - good tracking
- MPC reduced Tilt, i.e., favor steam generation vs superheating → reduce attemporation
- Low emphasis on coal reduction ~ 1.6% reduction vs. baseline run (relative)

Desktop Simulation - load tracking, HIGH weight for performance

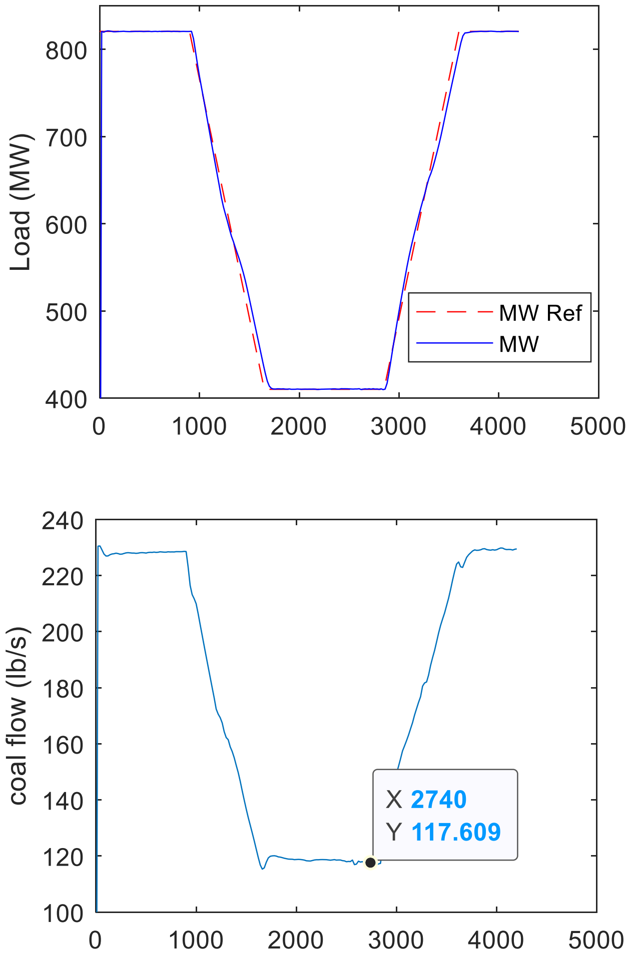


Reduced steam temperature and water spray in SH, RH attemporators

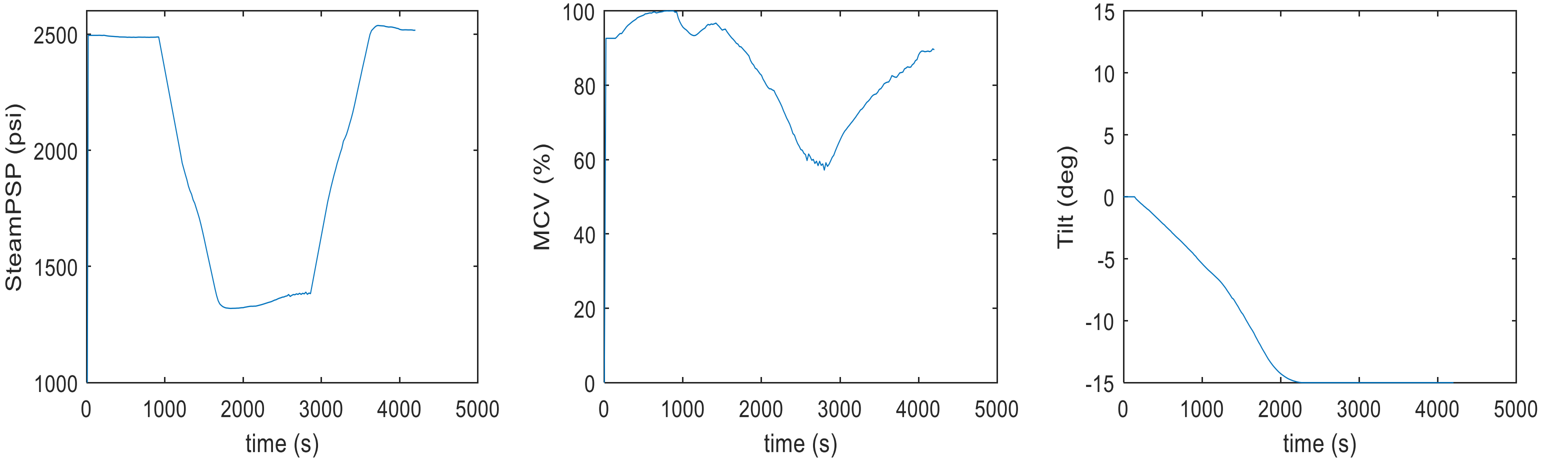
~3.8% reduction in coal (relative)

- 100% → 50% → 100% at 4%/min ramp rate - good tracking
- MPC reduced Tilt to min limit (-15 deg), i.e., favor steam generation vs superheating → reduce attemporation
- High emphasis on coal reduction ~ 3.8% reduction vs. baseline run (relative)

HIL Simulation - load tracking, HIGH weight for performance



Simulation run on Linux VM for 4200s



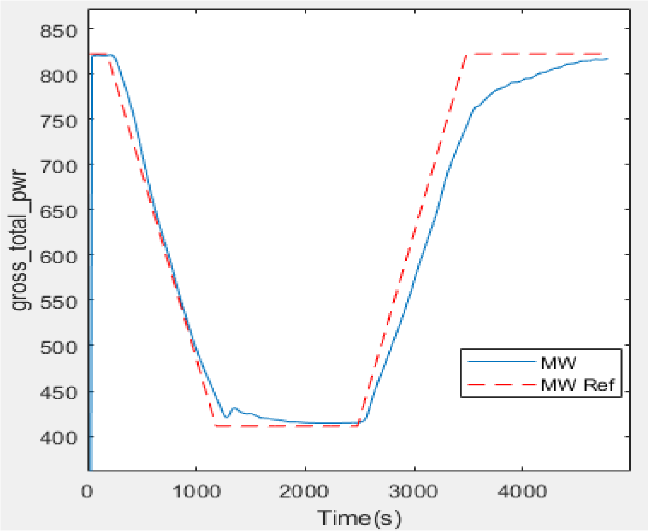
- Reproduce same result as Desktop simulation
- Core computation ~3x faster than real-time even on a Linux VM (would be faster on native Linux PC)

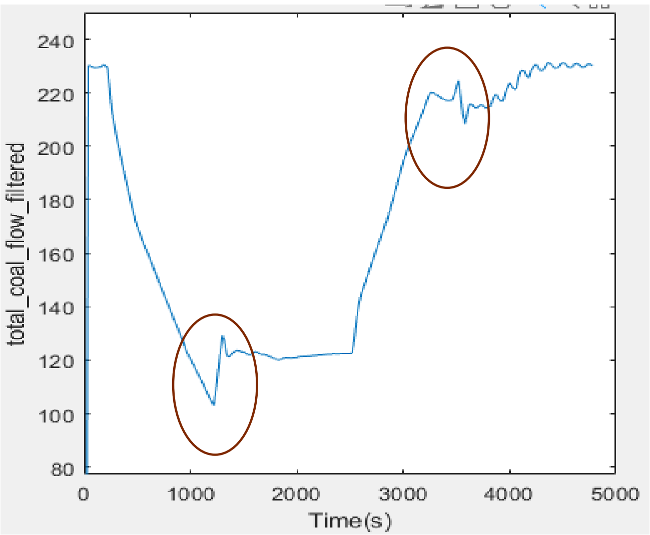
Desktop & HIL simulations

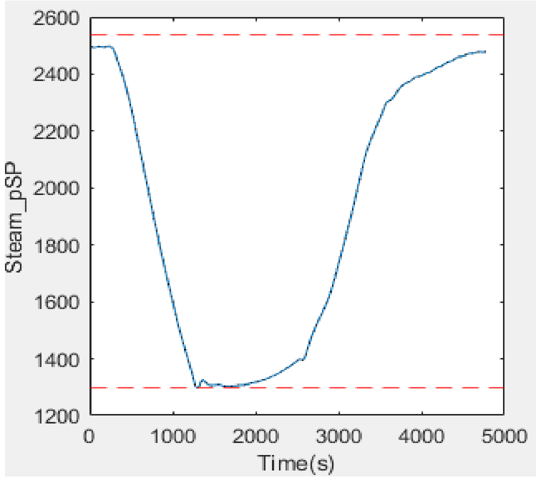
- Apros high-fidelity plant model

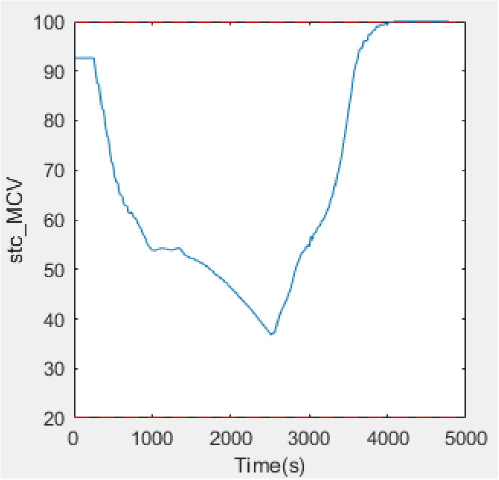
- Add hooks to provide optimal MPC control (steam P SP, MCV, feeder tilt) and bypass built-in baseline controls/schedules
- Keep underlying unit controls (boiler coal/air/water feed, drum level, …) as is

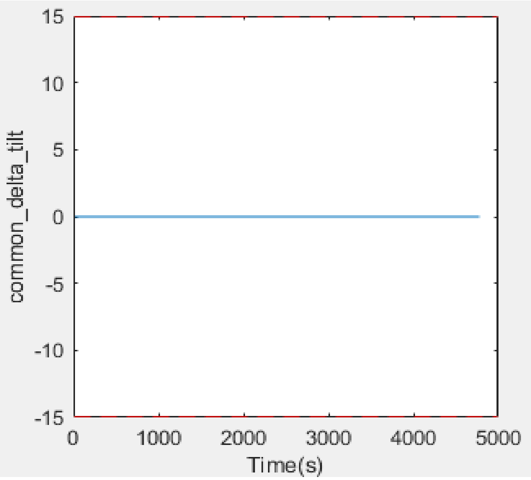
Desktop Simulation - load tracking, NO performance weight, 2 control inputs







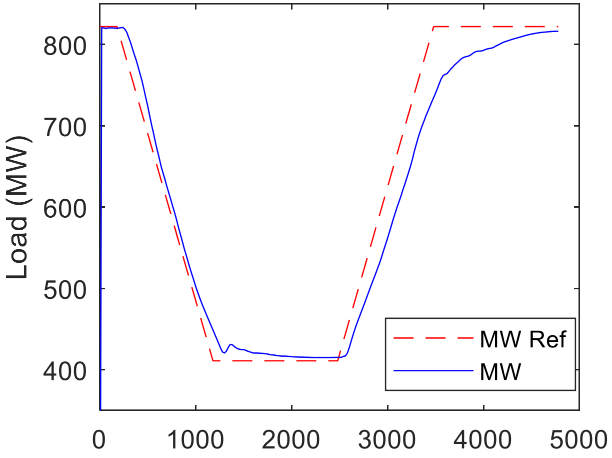


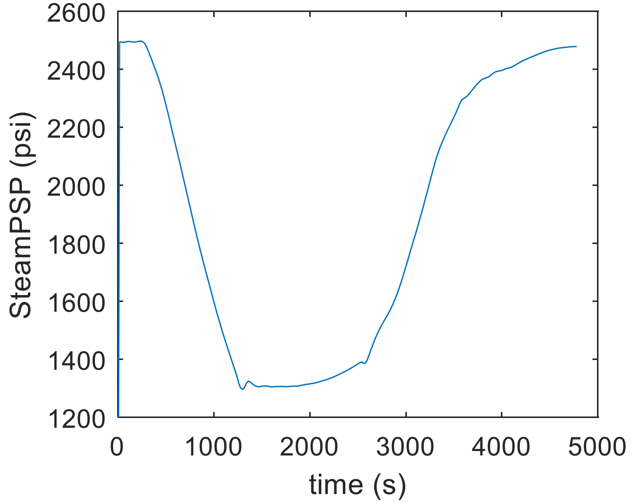


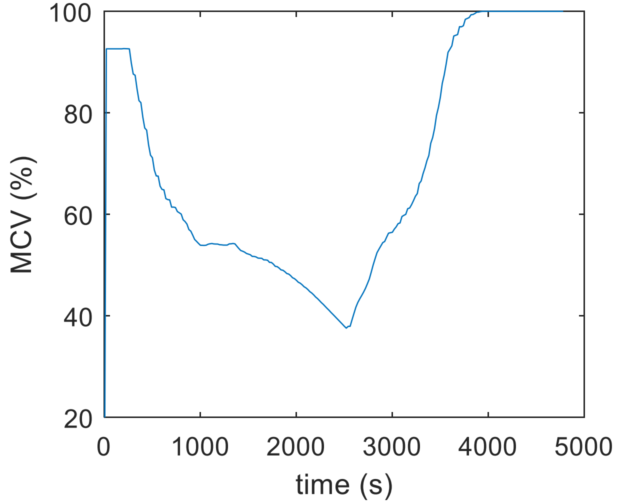
Tilt angle use disabled with high control input weight

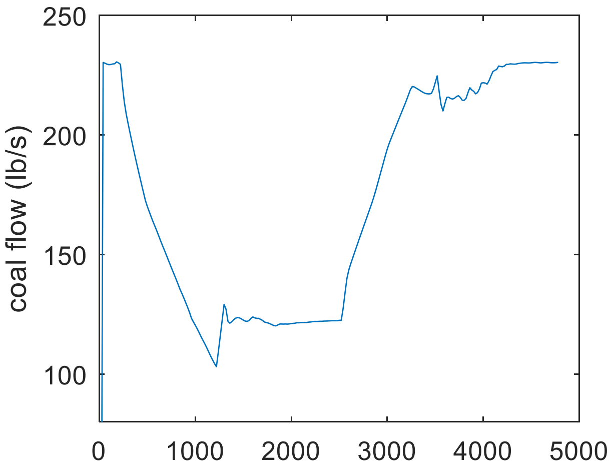
- 100% → 50% → 100% at 3%/min ramp rate - good tracking
  - abrupt change in coal feed at end of load ramp in baseline controller to avoid overshoot (disturbance)

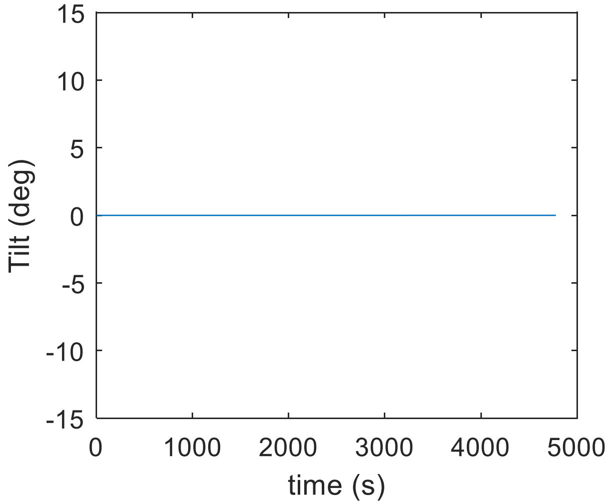
HIL Simulation - load tracking, NO performance weight, 2 control inputs







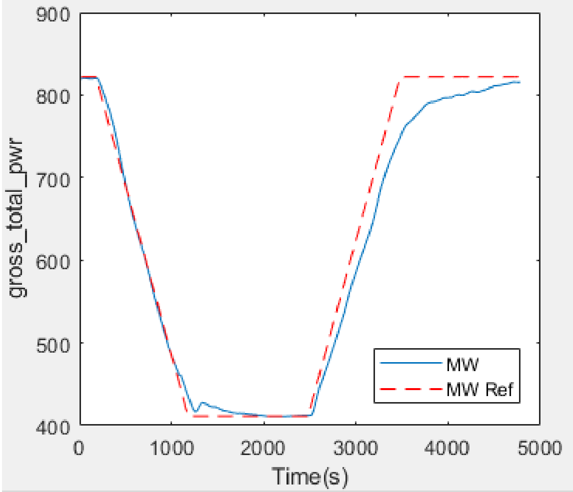


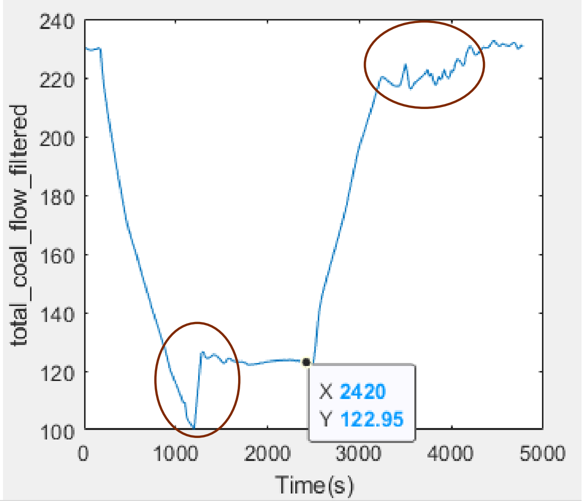


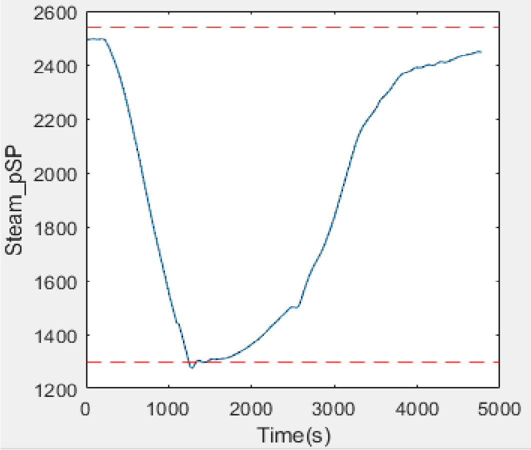
Tilt angle disabled with high weight (R=1000)

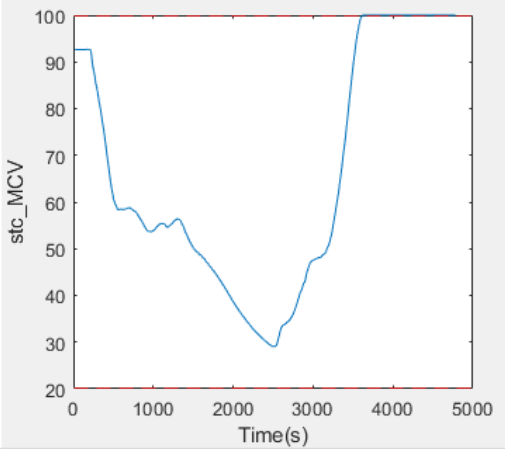
- Reproduce same result as Desktop simulation
- Core computation ~3x faster than real-time even on a Linux VM (would be faster on native Linux PC)

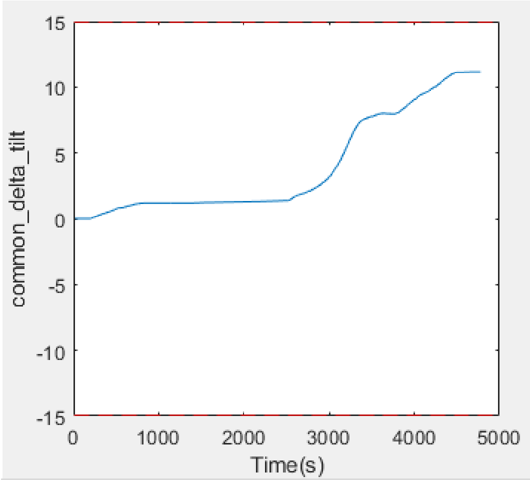
Desktop Simulation - load tracking, NO performance weight





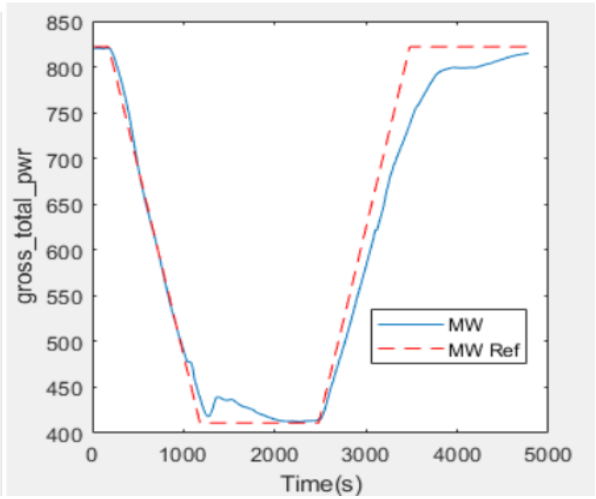


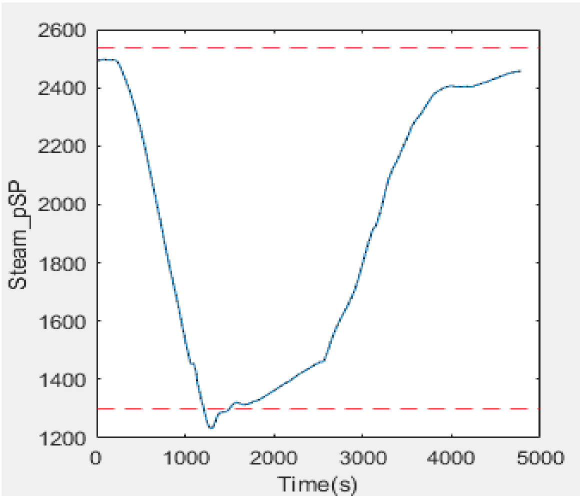


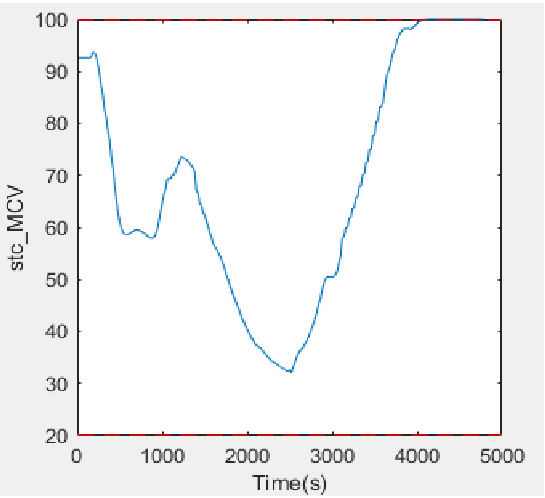


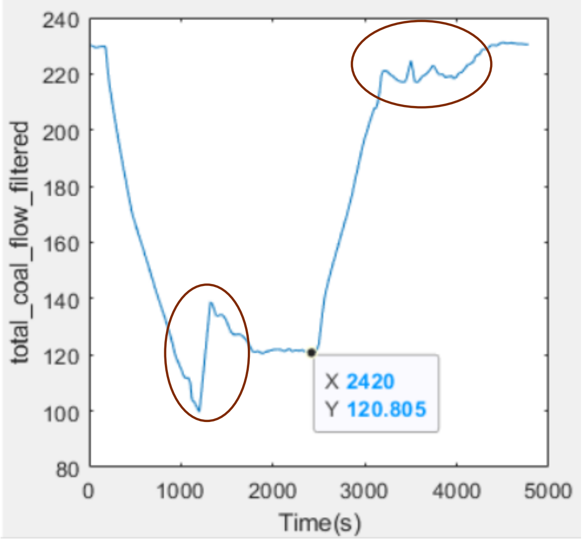
- 100% → 50% → 100% at 3%/min ramp rate - good tracking
  - abrupt change in coal feed at end of load ramp in baseline controller to avoid overshoot (disturbance)
- Tilt increasing – no performance weight, i.e., focus only on tracking
- Baseline run with 122.95 lb/s coal feed at 50% load

Desktop Simulation - load tracking, LOW performance weight

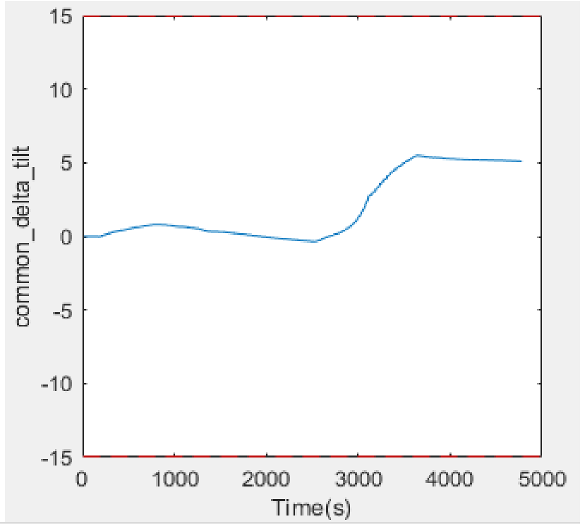






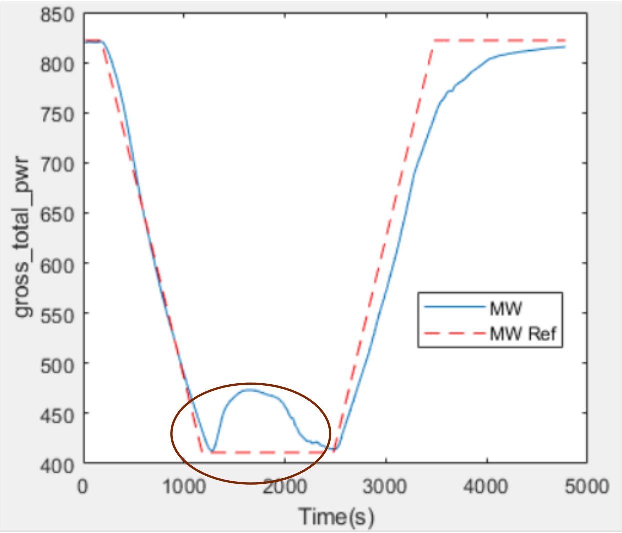


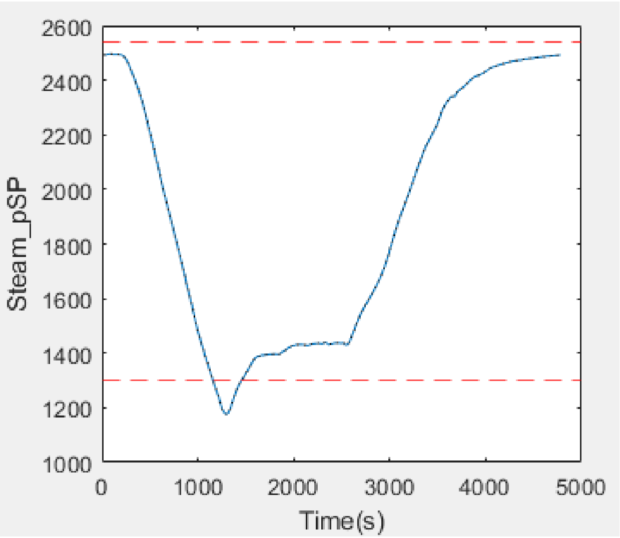
~1.7% reduction in coal (relative)

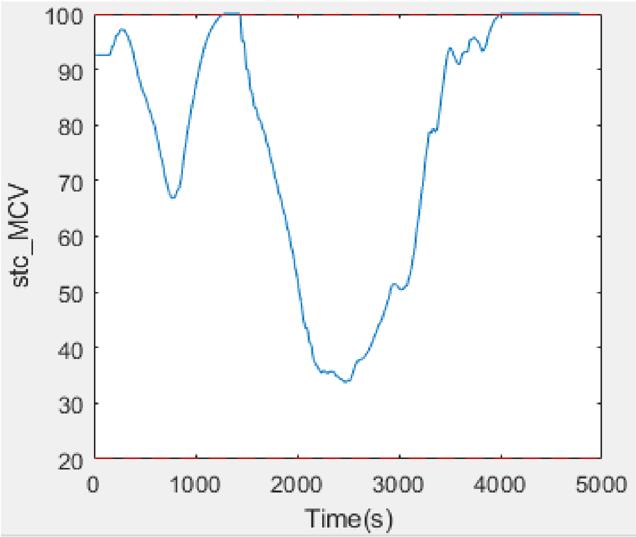


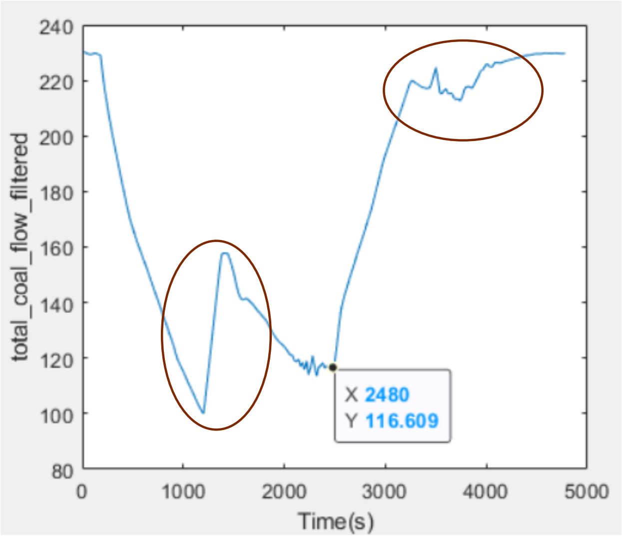
- 100% → 50% → 100% at 3%/min ramp rate - good tracking
  - abrupt change in coal feed at end of load ramp in baseline controller to avoid overshoot (disturbance)
  - increased impact on tracking at end of ramp down with sudden increase in coal feed (non-zero emphasis on coal minimization)
- Tilt increasing less – low performance weight for efficiency
- Reduce coal use by ~1.7% (relative) at 50% load

Desktop Simulation - load tracking, HIGH performance weight

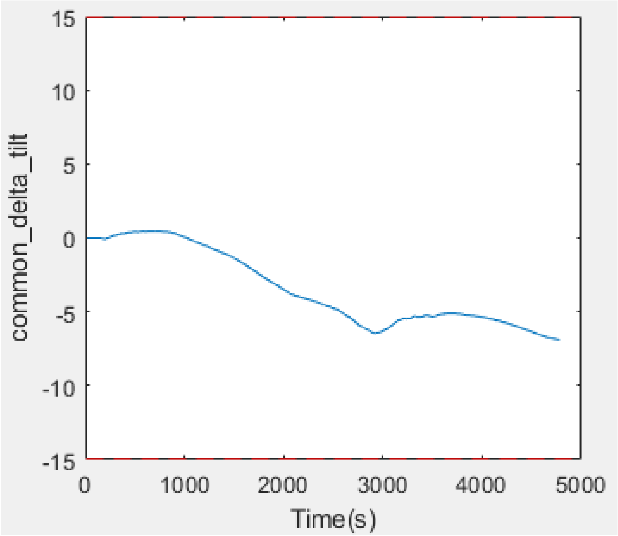






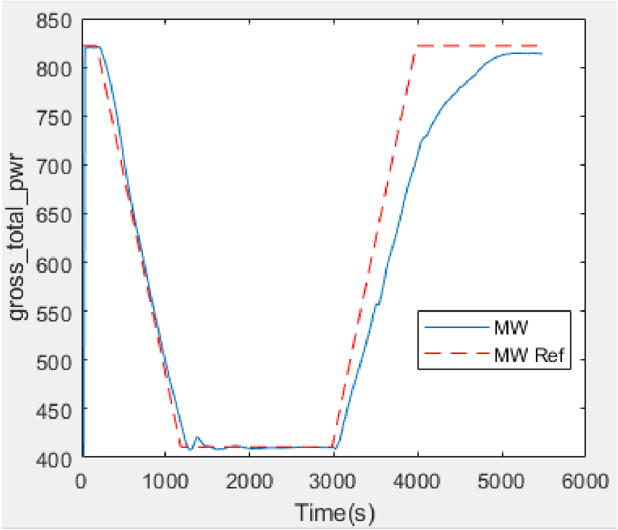


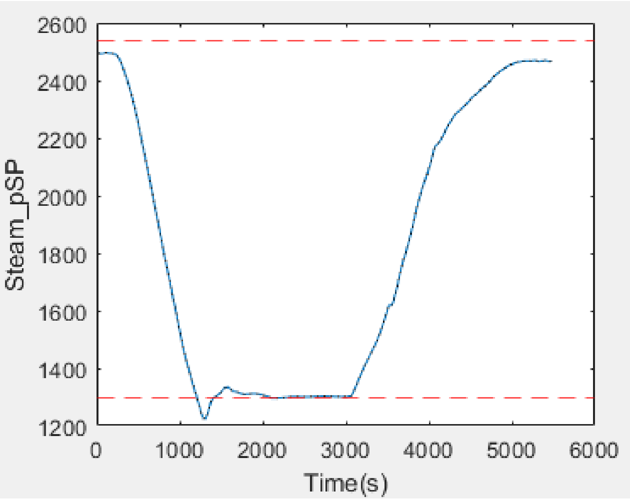
~5.1% reduction in coal (relative)

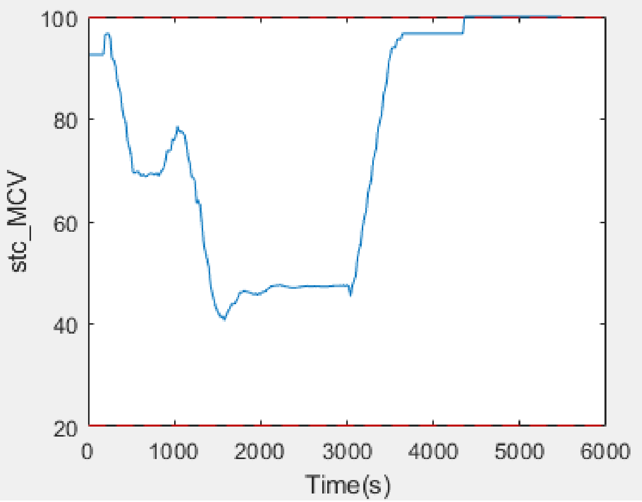


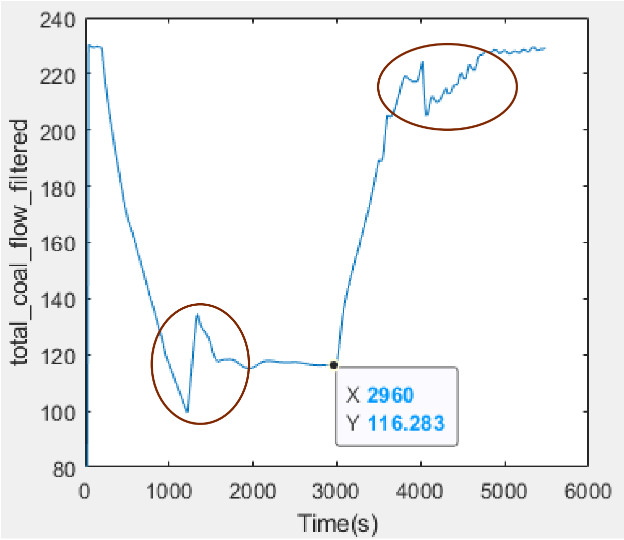
- 100% → 50% → 100% at 3%/min ramp rate - good tracking
  - abrupt change in coal feed at end of load ramp in baseline controller to avoid overshoot (disturbance)
  - high impact on tracking at end of ramp down with sudden increase in coal feed (high emphasis on coal minimization)
- Tilt decreasing – high performance weight for efficiency
- Reduce coal use by ~5.1% (relative) at 50% load
- Improve tracking by re-tuning MBE to respond quicker to jump in coal feed

Desktop Simulation - load tracking, HIGH performance weight, retuned MBE

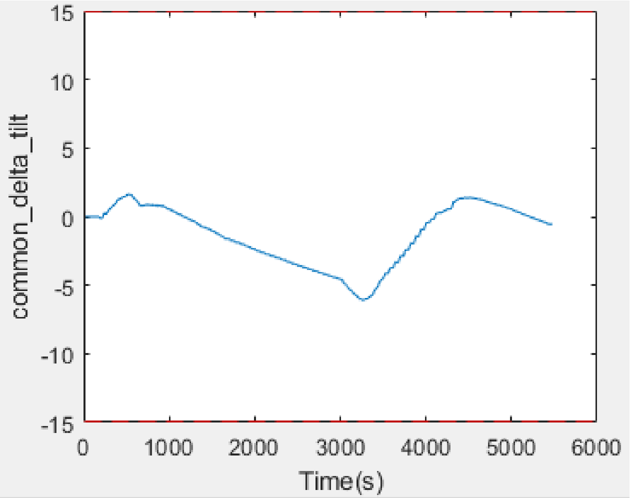








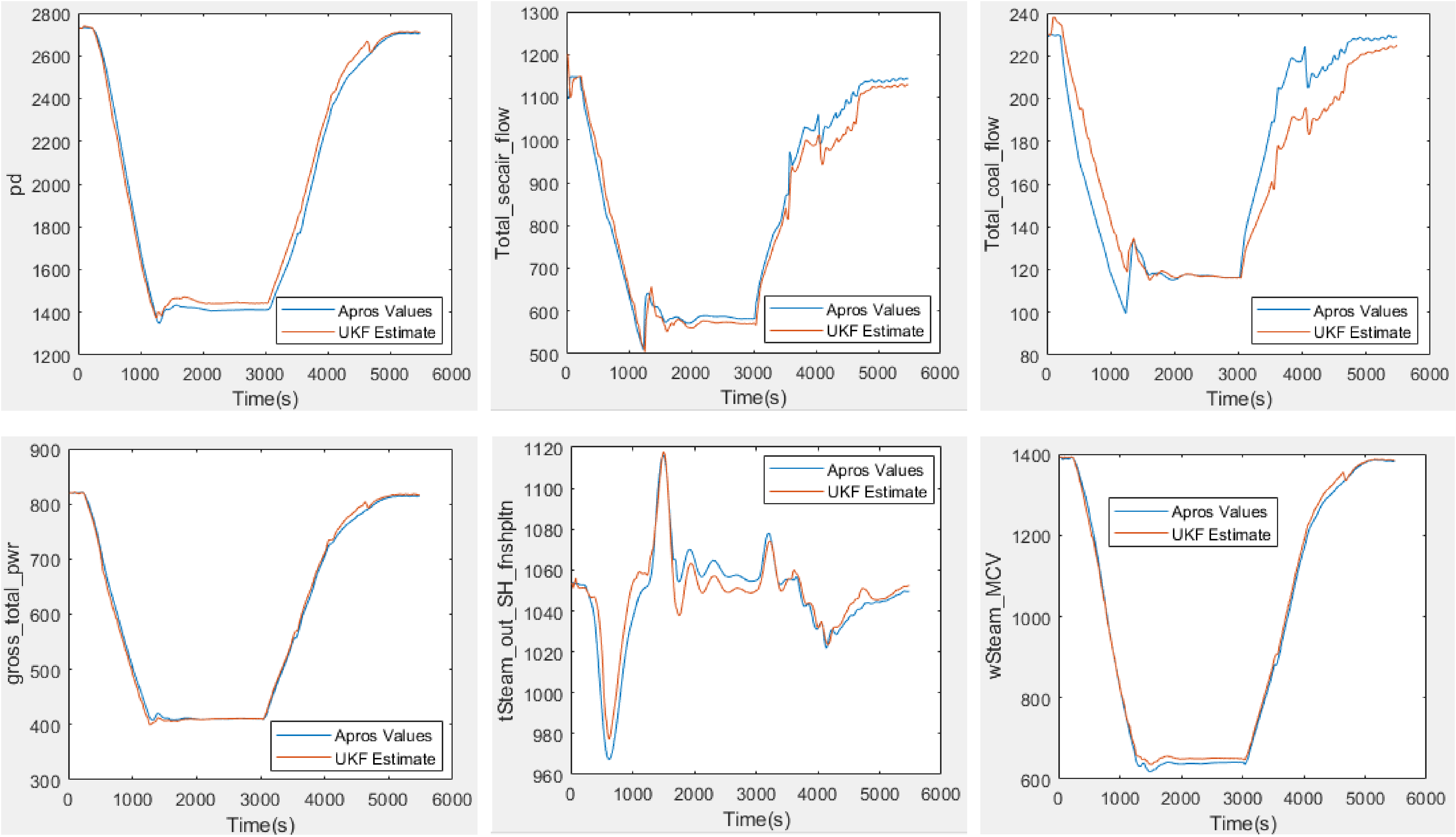
~5.4% reduction in coal (relative)



- 100% → 50% → 100% at 3%/min ramp rate - good tracking
  - abrupt change in coal feed at end of load ramp in baseline controller to avoid overshoot (disturbance)
  - Much reduced impact on tracking at ramp end despite jump in coal feed at ramp end
- Tilt decreasing (increases during ramp up) – high performance weight for efficiency
- Reduce coal use by ~5.4% (relative) at 50% load

Desktop Simulation - load tracking, HIGH performance weight, retuned MBE

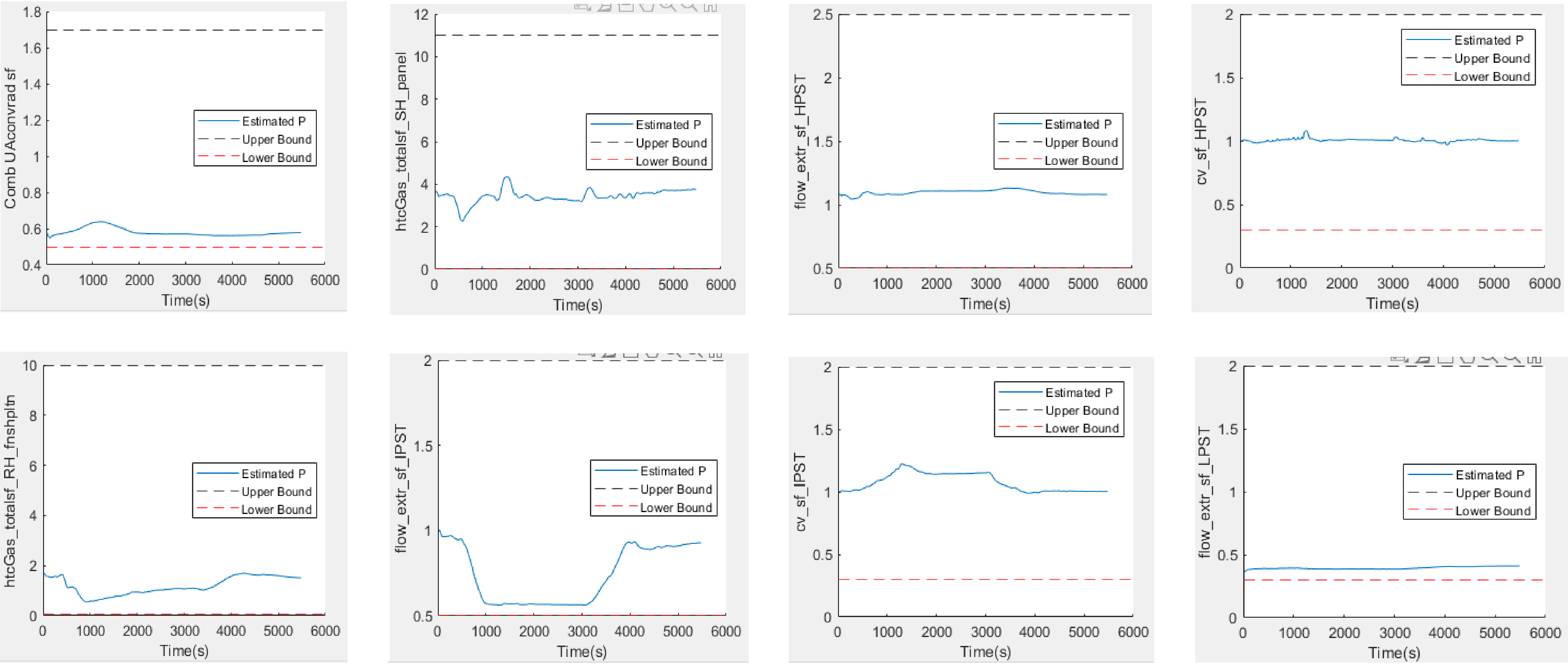
Plant (Apros) output measurement tracking - key outputs



- Overall, very good transient tracking of measured outputs
- Good robustness despite very significant plant-model mismatch (Apros vs. ROM)

Desktop Simulation - load tracking, HIGH performance weight, retuned MBE

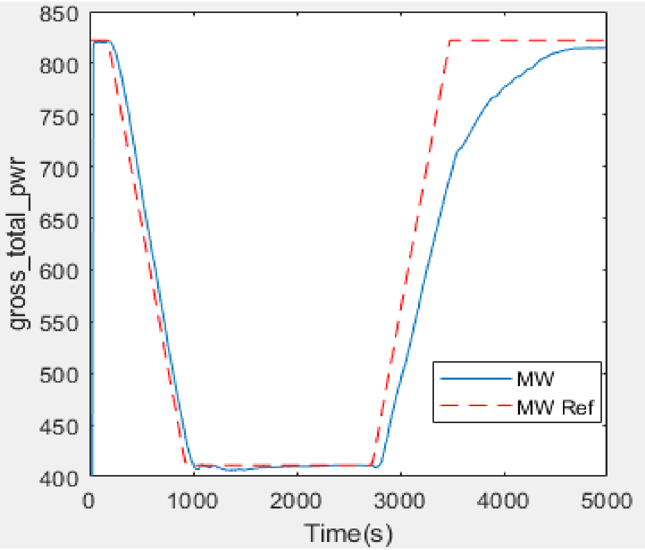
ROM parameter estimates – key adapted parameters

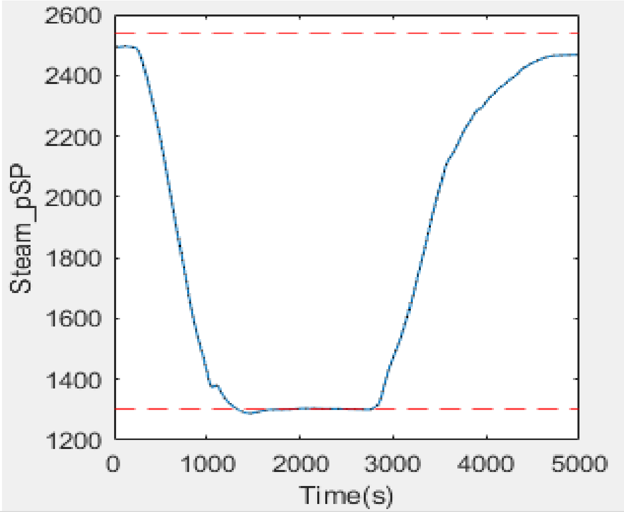


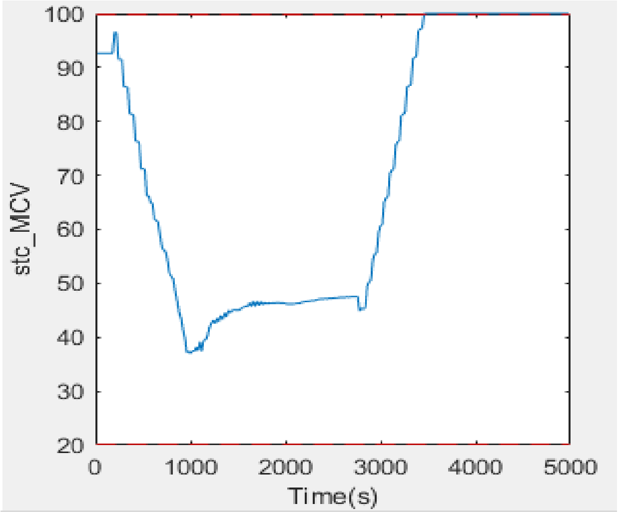
- Fairly constant parameter estimate for HP/LP section
- Variation in parameter estimate with load for IP section – higher structural difference between Apros and ROM
- Use long-term trends in component health parameters, AI/ML for equipment health monitoring/maintenance

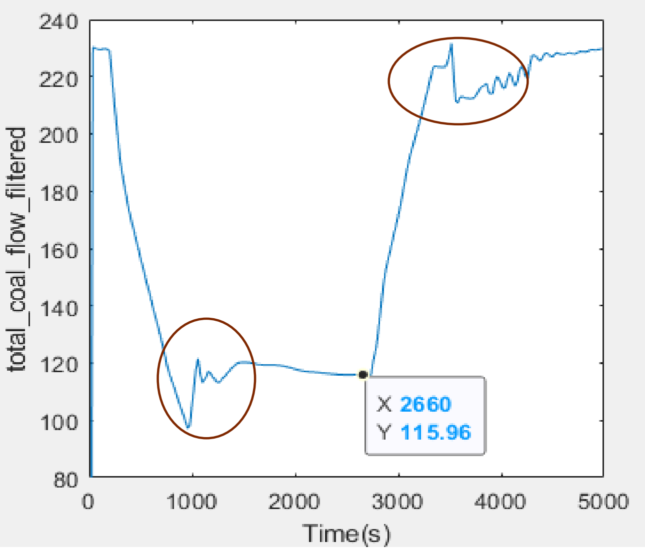
Desktop Simulation - load tracking, HIGH performance weight, retuned MBE

Faster load ramps (4%/min)

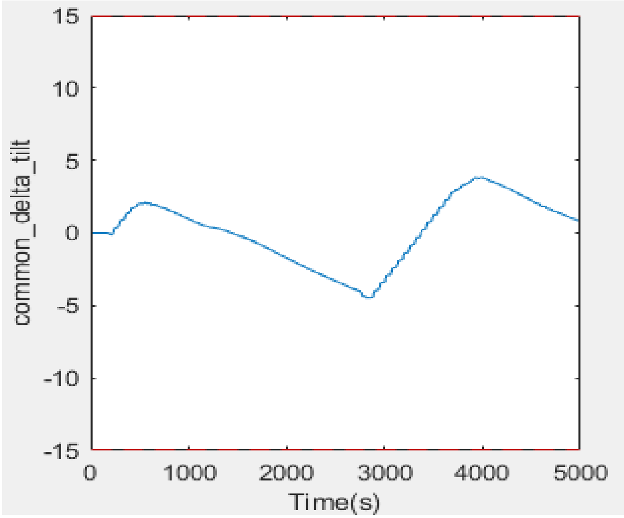








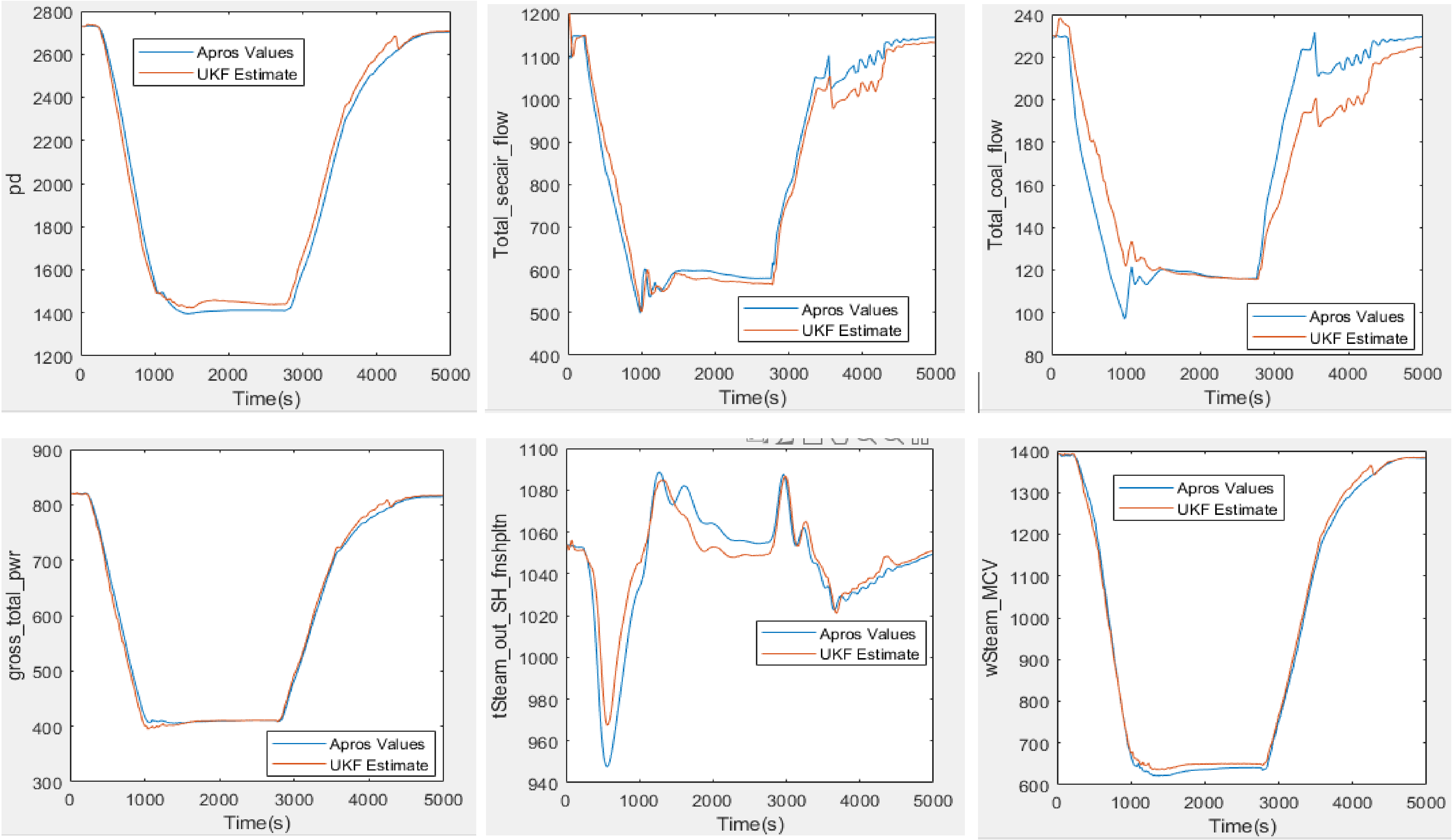
~5.6% reduction in coal (relative)



- **100% → 50% → 100% at 4%/min ramp rate - good tracking**
  - abrupt change in coal feed at end of load ramp in baseline controller to avoid overshoot (disturbance)
  - Much reduced impact on tracking at ramp end despite jump in coal feed at ramp end
  - Room for tracking improvement for ramp up – update/retune baseline controller to coordinate with MPC
- Tilt decreasing (increases during ramp up) – high performance weight for efficiency
- **Reduce coal use by ~5.6% (relative) at 50% load**

Desktop Simulation - load tracking, HIGH performance weight, retuned MBE

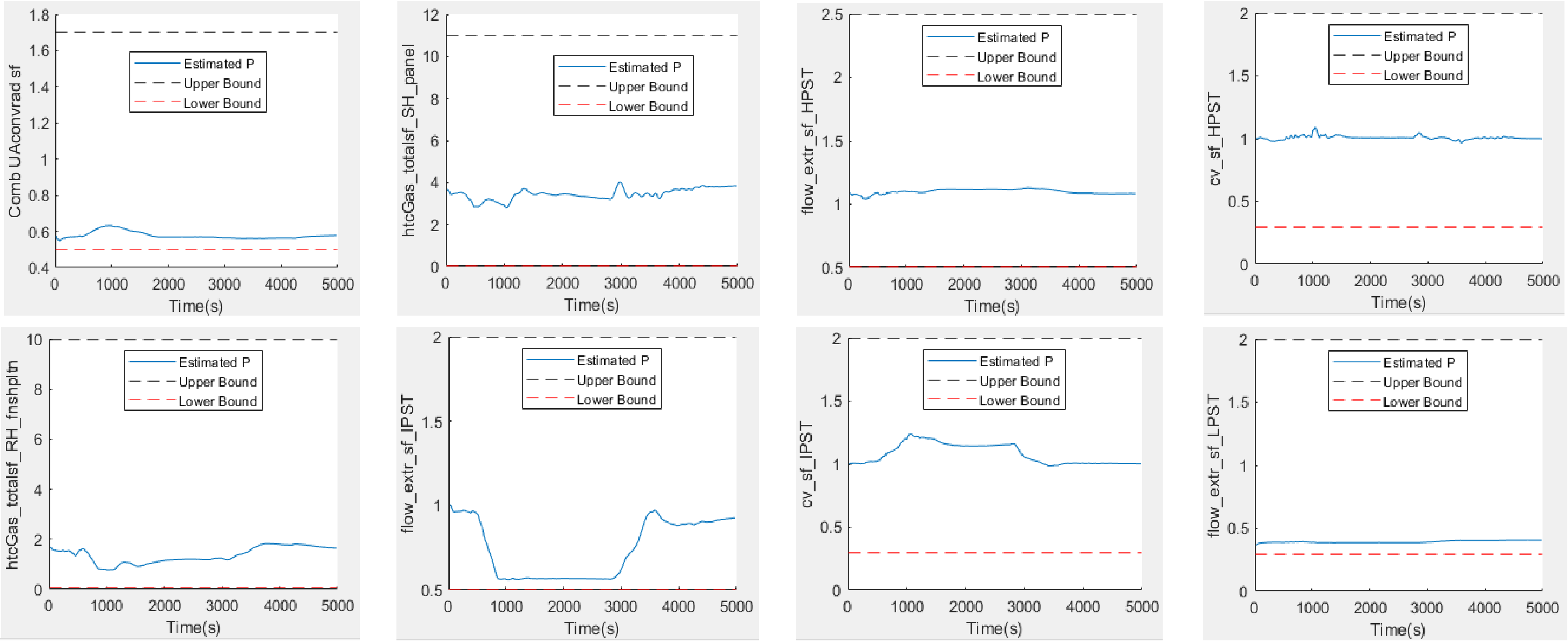
Plant (Apros) output measurement tracking - key outputs



- Overall, very good transient tracking of measured outputs
- Good robustness despite very significant plant-model mismatch (Apros vs. ROM)

Desktop Simulation - load tracking, HIGH performance weight, retuned MBE

ROM parameter estimates – key adapted parameters



- Fairly constant parameter estimate for HP/LP section
- Variation in parameter estimate with load for IP section – higher structural difference between Apros and ROM
- Use long-term trends in component health parameters, AI/ML for equipment health monitoring/maintenance

Conclusions

- Successfully developed all key elements of proposed model-based optimal control technology (matured to TRL 5)
  - Close coordination between GE Research & GE Steam Power
  - ROM (>100x faster than real-time) & Apros high-fidelity model
  - MBE for matching ROM with plant measurements – Digital Twin
  - MPC for optimal control – flexibility, efficiency
- Met key goals for flexibility, efficiency and reliability
  - **Fast load changes – up to 4%/min ramp rates between 100-50% load**
  - **Optimization for efficiency/coal use - up to 5.5% reduction (relative) in coal at 50% load**
  - **Continuous monitoring of equipment health** – trending for degradation in component health parameters (heat transfer fouling, efficiency, …)
  - **Exhaustive testing in desktop simulations**
  - **Deployment and validation in real-time HIL setup**
    - Leverage auto C-code generation, Docker containers in Linux
- Path Forward
  - Follow-up program for TRL 5-7 – beta customer deployment?
    - Deployment of MBE for health monitoring, virtual sensing
    - Deployment of MBE+MPC for improved operation (flexibility, efficiency) – advisory vs. closed-loop implementation
    - Combination of physics & AI-based models & algorithms
    - Use transient model simulations to generate data for AI/ML for fault diagnostics, cyber security, …
  - Commercialization for sub-critical CFPP