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

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Purpose of Project

Coal-Fired Power Generation Outlook

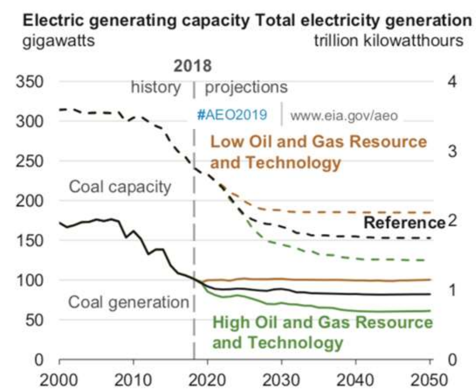
Coal-fired power plants (CFPPs) are critical to US power generation infrastructure

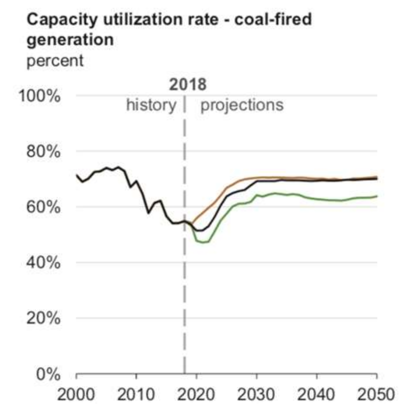
- providing diversity at low cost
- hardening the grid against increased penetration of intermittent generation sources

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

Remaining CFPPs will have to:

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





Program to build a platform for building Digital Twins (UKF + transient model) and Real-Time Optimizers (MPC)

estimates then *optimizes* heat rate at all conditions (target: 5% reduction in feed coal)
optimizes part-load to base-load transitions (target: 30% faster 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

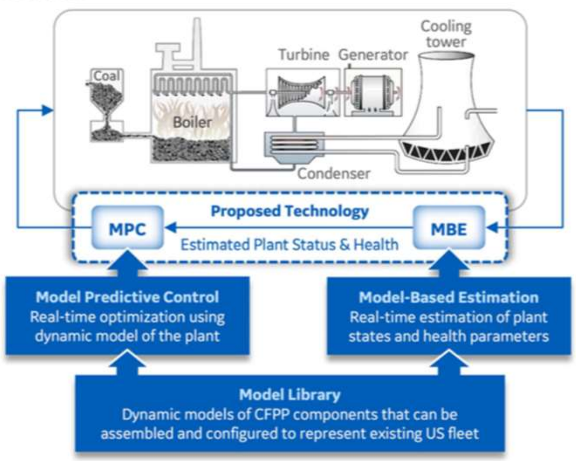
Coal-fired power plant modelling

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

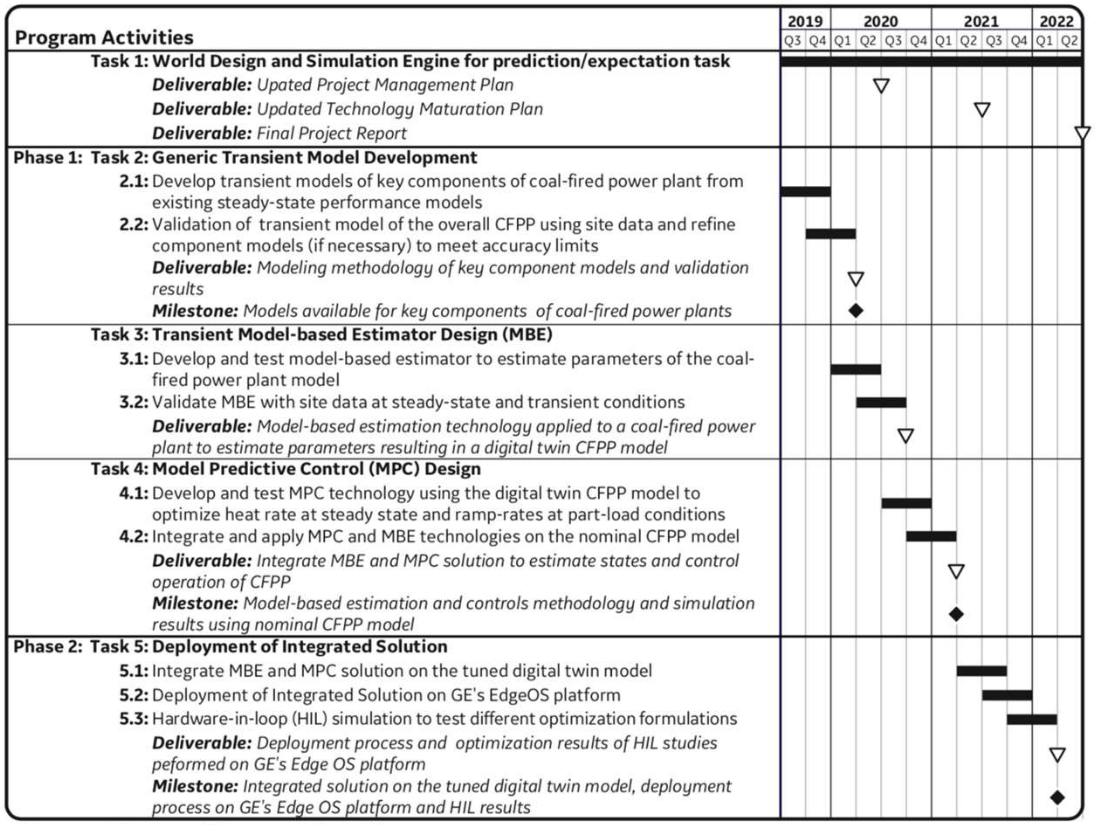
Anticipated Benefits of the Proposed Technology

- 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 coal reduction/year

Current Status

Project started in 2019 Q4 instead of 2019 Q3



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

Task 1: Project Management

Task 2: Reduced Order Model Library Generation
- Completed

Task 3: Unscented Kalman Filter (UKF) development
- Completed

Task 4: Model Predictive Control (MPC) platform development
- Library developed
- Reduced-order model embedded
- *being tested*

Task 5: Integrated HIL-like environment
- UKF is ready for real-time environment
- Communication bridge developed
- MPC is being transferred real-time environment

Current Status

- Completed—Reduced-order-model component library development,
  - This model will be used in the model-based-estimation and model-predictive-controller for the transient optimization of the coal-fired power plant.
- Completed—Model-based-estimation (MBE) algorithm library development,
  - Tested with example generic dynamic system models,
  - MBE tested with the reduced order model of the representative plant,
  - *Ongoing—test MBE with high-fidelity model of the representative plant.*
    - *Communication with high-fidelity model is established robustly*
    - *Decision: test a subsystem (HP Superheaters first)*
- Completed—Model predictive control (MPC) algorithm library development,
  - Tested with example generic dynamic system model,
  - *Ongoing—test MPC with reduced order model of the representative plant.*
    - *Reduced order model is now embedded*
    - *Decision: 2x1 MPC will be tested first*
    - *Ongoing: MPC I/O selection*

Current Status

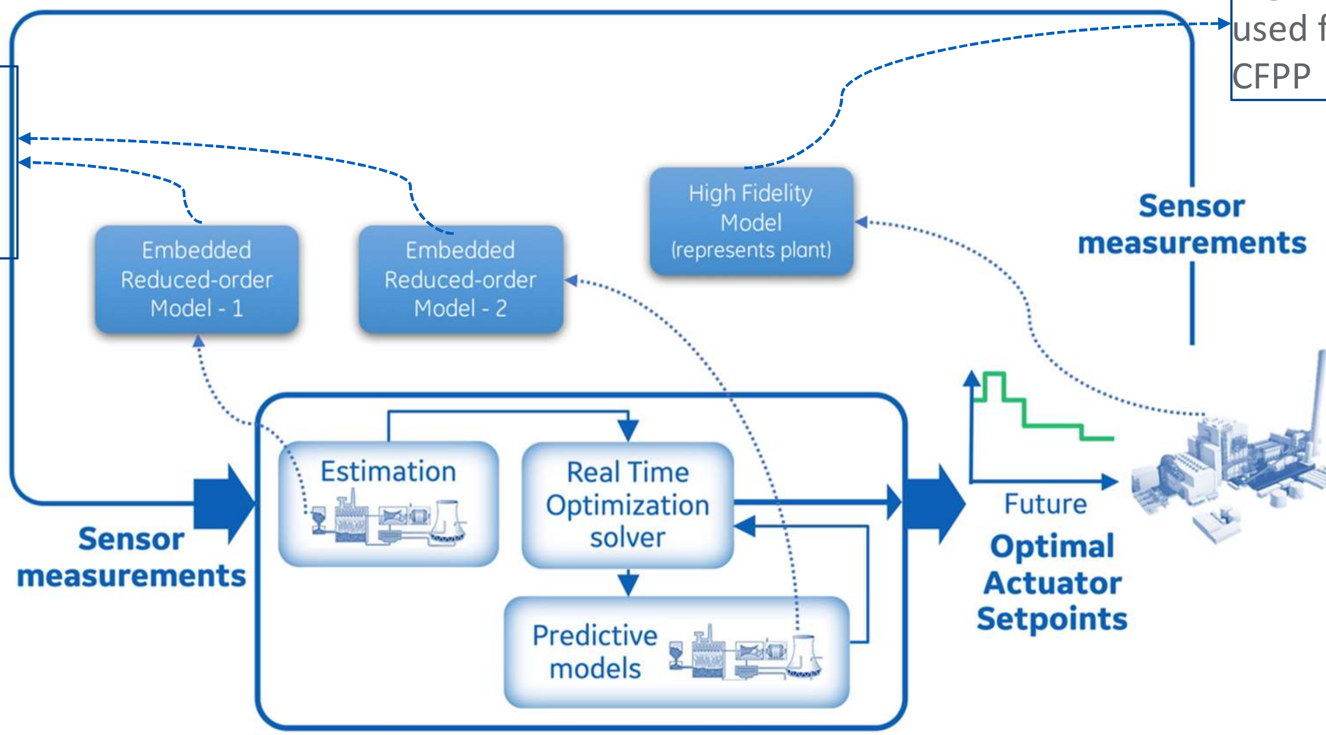
- Completed—High-fidelity model development (model for a representative plant) at base load,
  - This model will represent the coal-fired power plant,
  - Model calibrated for base-load levels,
  - Calibrated high-fidelity model for 100%->47% load levels,
  - *Next step— align reduced order models and the APROS model*
    - *Air-preheaters are added*
    - *Ongoing: add multiple injection zones to the boiler*
- Industry validation—Reduced-order-model component library reviewed with GE Steam Power domain experts,
  - *Next step–Productization options around the use of reduced-order-model component library.*

Project Update

Reduced-order-model component library development

Reduced-order-model will be used in estimation and real-time optimization

High-fidelity model will be used for representing the CFPP

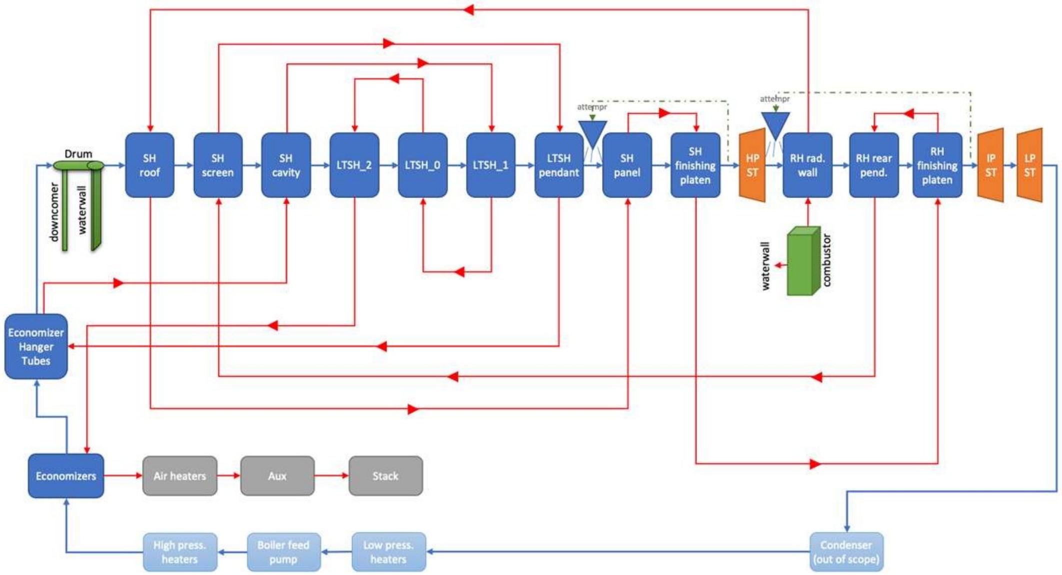


Model-based Estimator and Model Predictive Controller

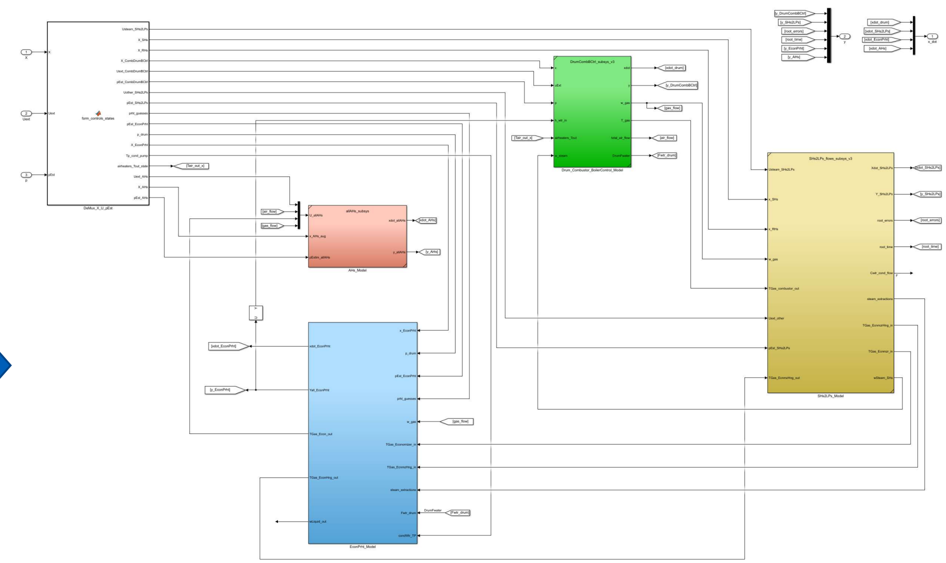
For faster ramps (flexibility), Better heat-rate (efficiency), and Diagnosis

Project Update

Reduced-order-model component library development



Simplified configuration of the representative CFPP



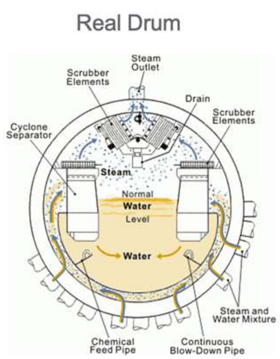
Representative CFPP model in MATLAB/Simulink

- Created by connecting individual component models from the library

Project Update

Example of Simplification to Obtain Reduced-Order Representations

A reduced-order drum model enables the model to be used in model-based estimation and controls/optimization



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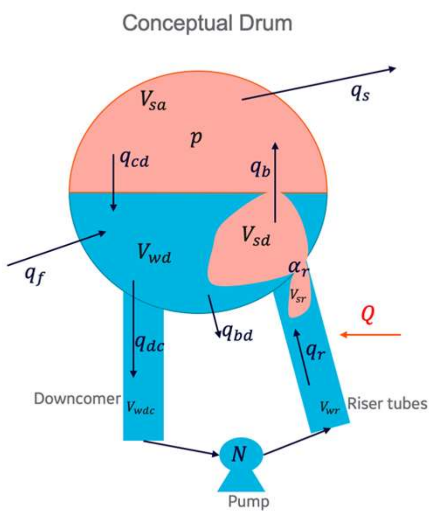
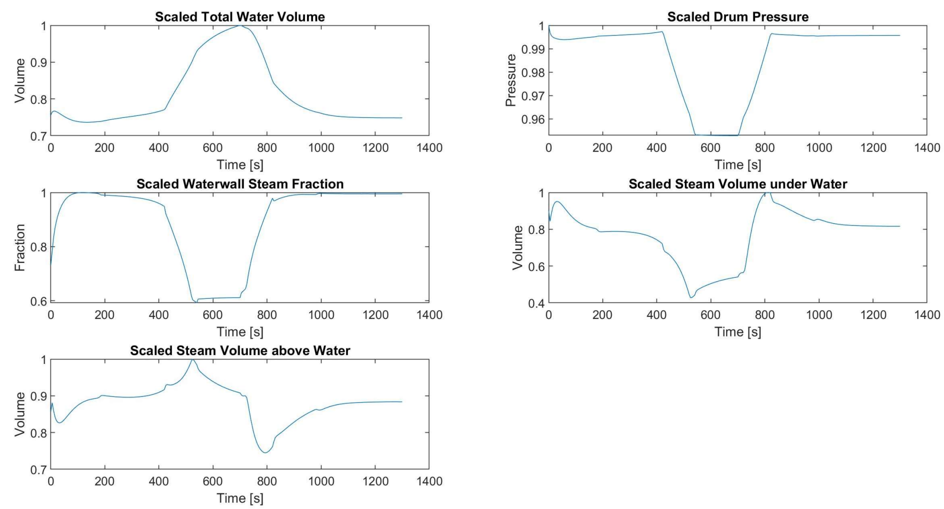


Representative results from the drum model

- Captures the main dynamics
- Computationally efficient

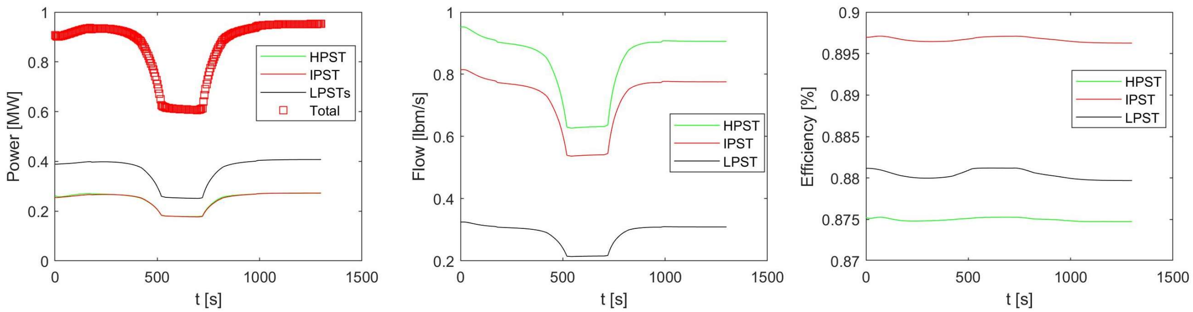


Overall model is collection of reduced-order component models

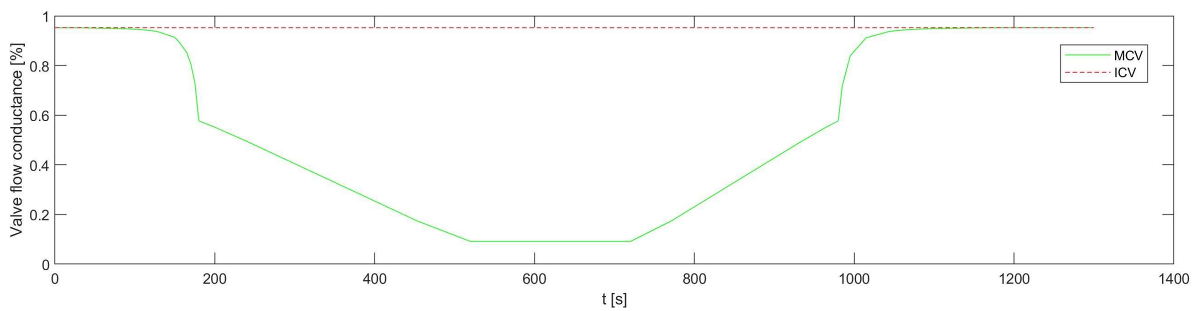
Project Update

Reduced-Order-Model of the Representative Plant

A reduced-order overall model enables the model to be used in model-based estimation and controls/optimization



Steam turbine dynamics

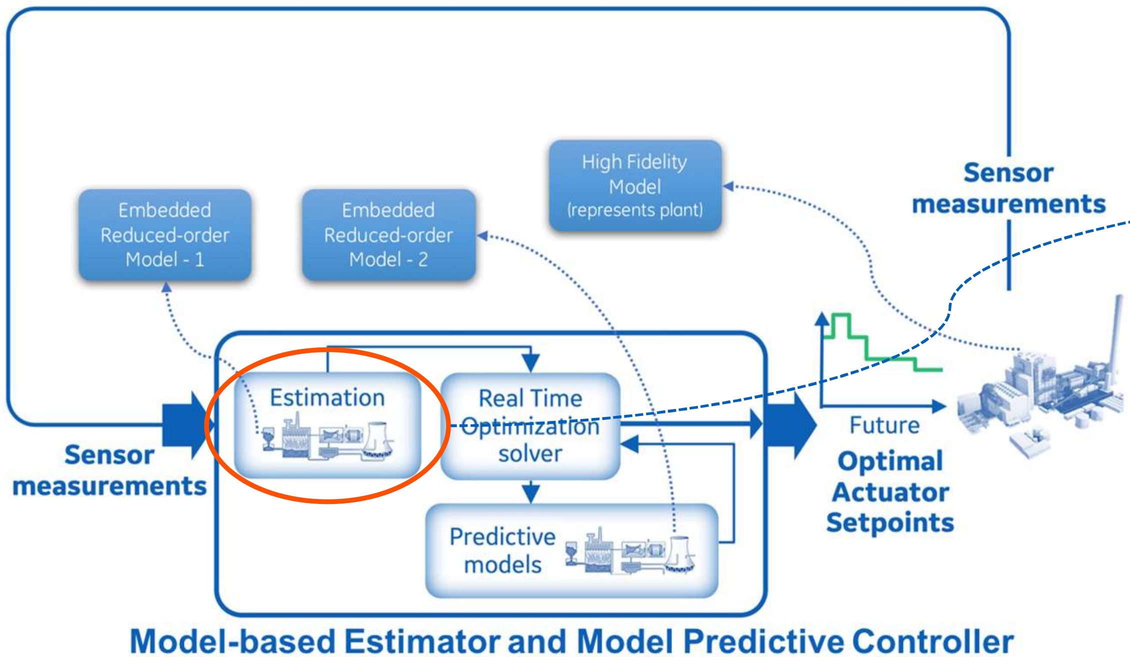


Control Valve dynamics

Overall model runs >50x faster than real-time

Project Update

Model-based Estimation (MBE) Library Development

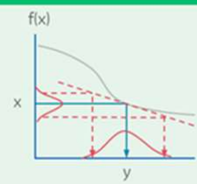
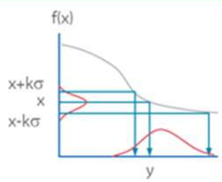
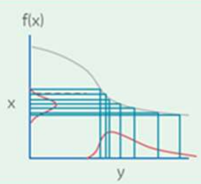


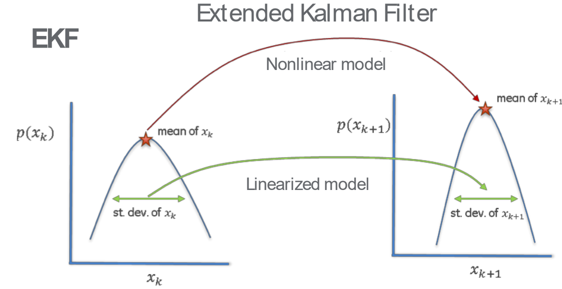
Model based estimator is developed to work with any embedded model

Integrated the reduced-order-model of the representative plant into MBE library

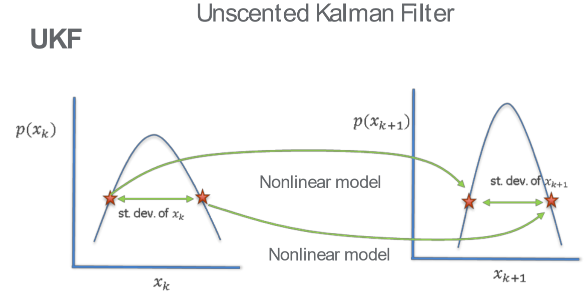
Project Update

Model-based Estimation (MBE) Library Development

Technique	System Model	Computation
Extended Kalman Filter (EKF) • Non-linear propagation of mean • Linear propagation of covariance – **needs online linearization of model** • First order approximation		Low n+1 or 2n+1 model evaluations for numerical linearization n x n matrix algebra
Unscented Kalman Filter (UKF) • Non-linear propagation of sigma points • **No linearization required** – lends itself to generic software implementation • Fit Gaussian to propagated points • Captures higher order moments		Moderate n+2 or 2n+1 function evaluations n x n matrix algebra
Particle Filter (PF) • Non-linear propagation of random points • Monte Carlo approximation of distribution • Non-linear and/or non-Gaussian		High Many function evaluations ↑ particles = ↑ accuracy = ↑ computation



• Mean computed by the nonlinear model



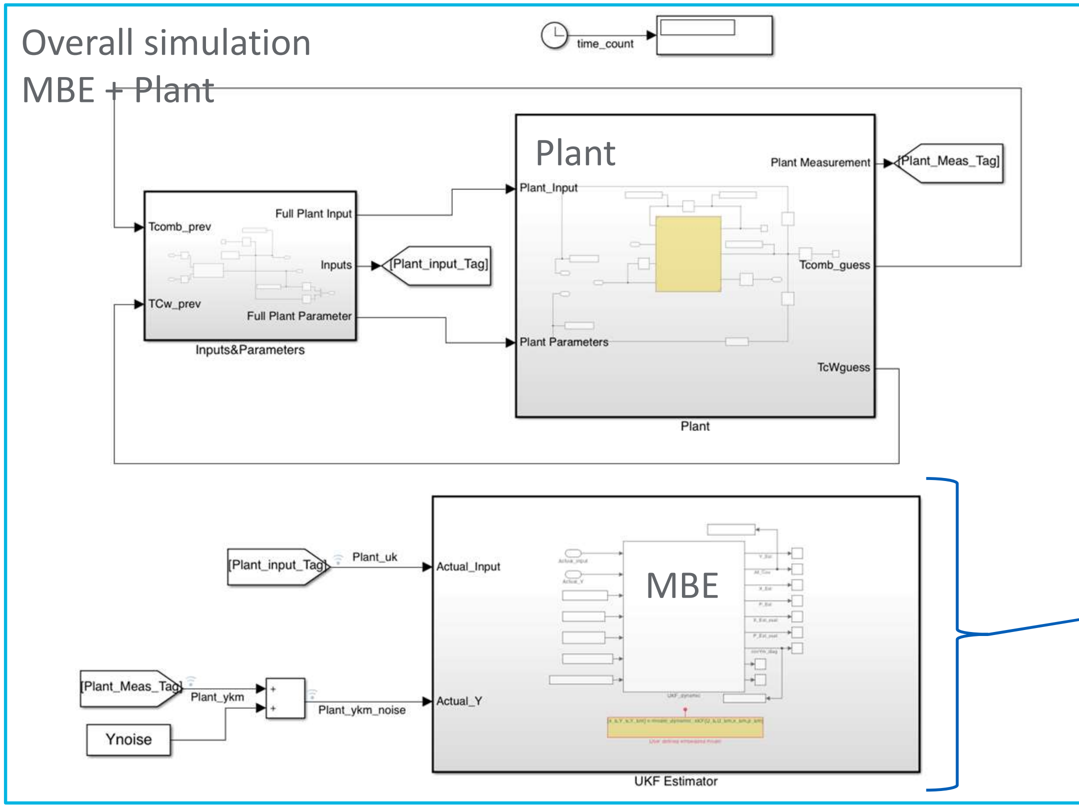
Both mean and st. dev. computed from sigma points

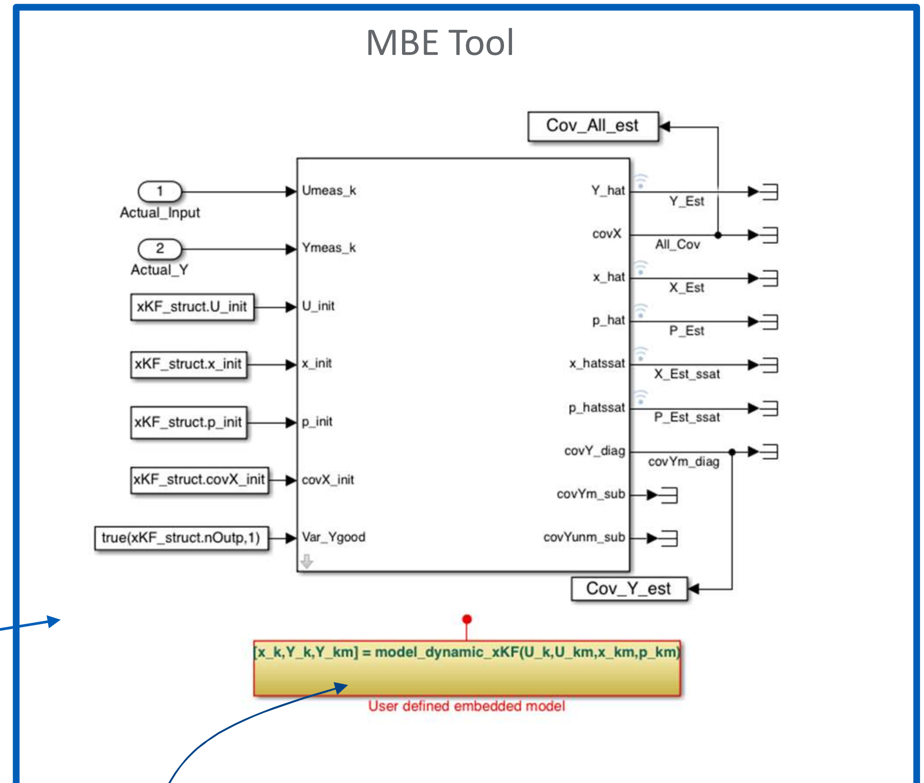
Model-drop-in library for Unscented/Extended Kalman Filtering is ready in Matlab/Simulink

Integrated the reduced-order-model of the representative plant into MBE library

Project Update

Model-based Estimation (MBE) Library Development



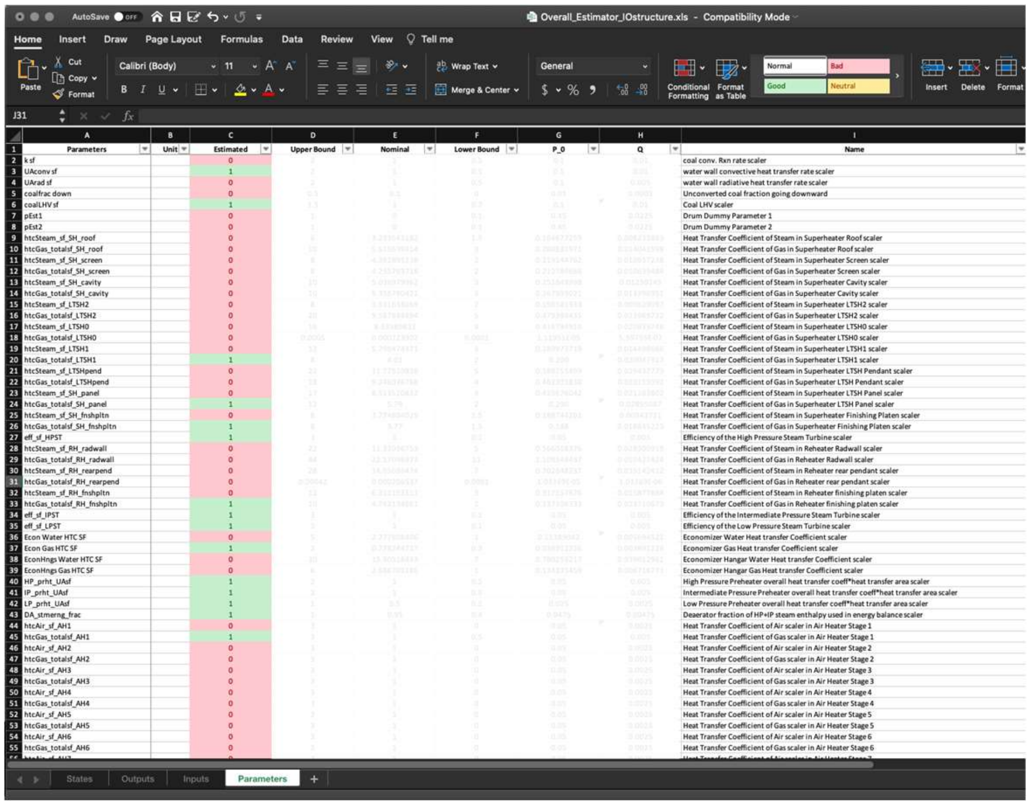


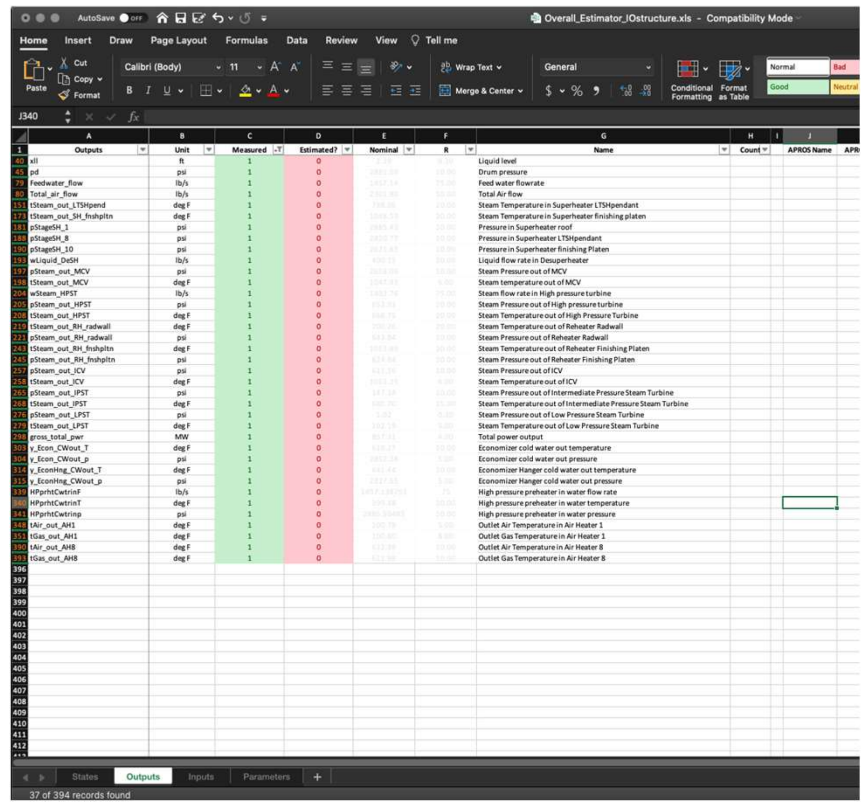
Library will easily work with reduced-order models of different plants

Project Update

Model-based Estimation (MBE) Library Development

Inputs to the tool: Spreadsheet to configure the MBE



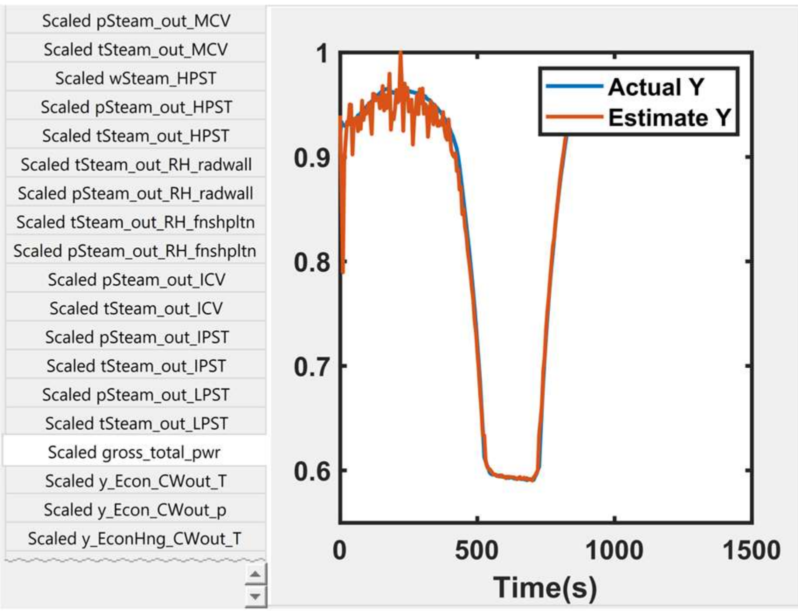


Project Update

Model-based Estimation (MBE) Library Development

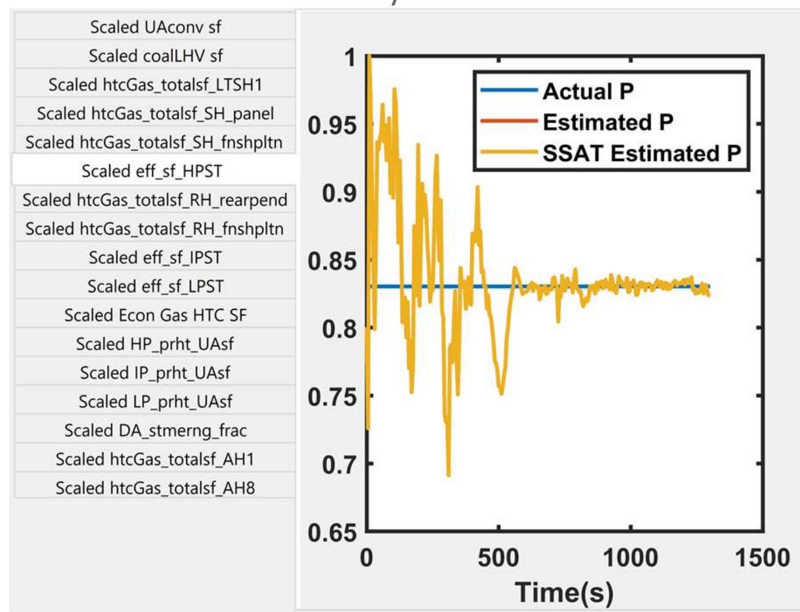
Outcome of tool: All signals of reduced-order model can be analyzed

Output: total gross power



Virtual outputs can be monitored (e. g. heat rate)

Parameter: HP ST efficiency



Component health can be monitored

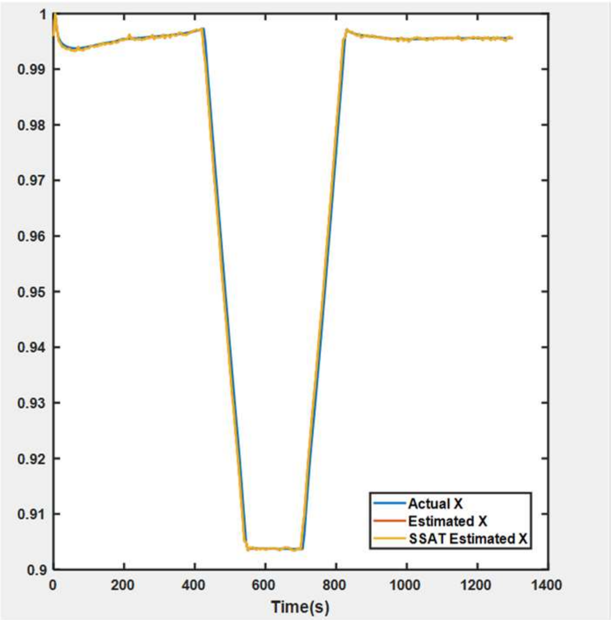
MBE + Reduced Order Model → Digital Twin

Project Update

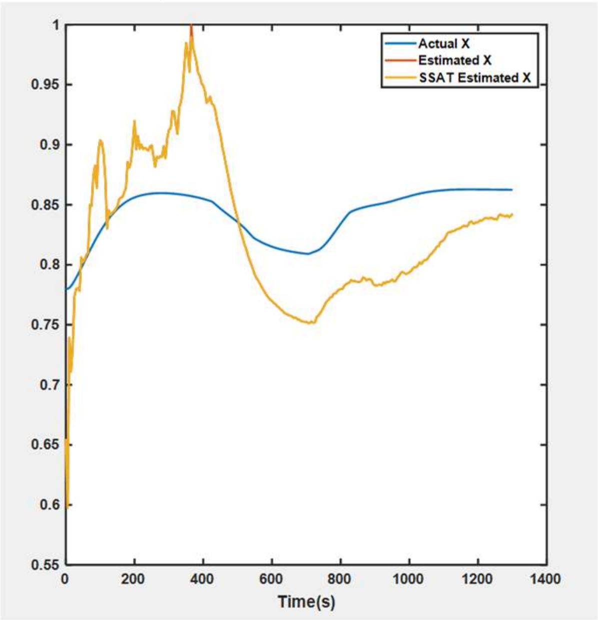
Model-based Estimation (MBE) Library *Performance*

Initial Conditions perturbed by 5%, noisy measurements

Scaled Drum Pressure



Scaled Temperature LTSH Pendant

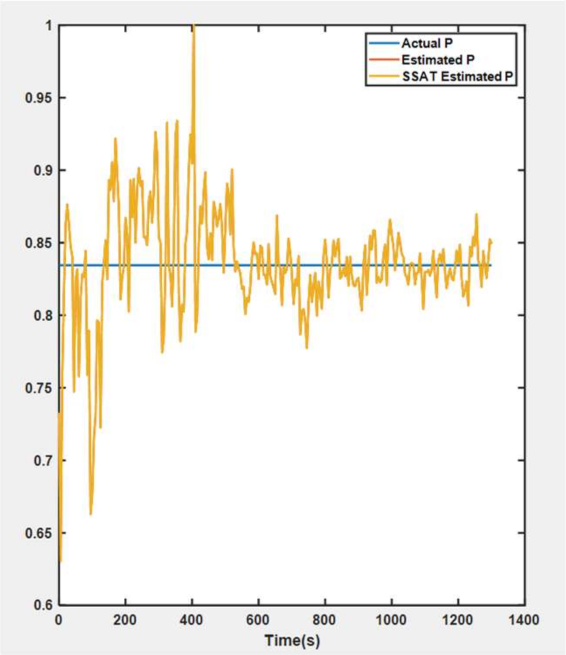


Project Update

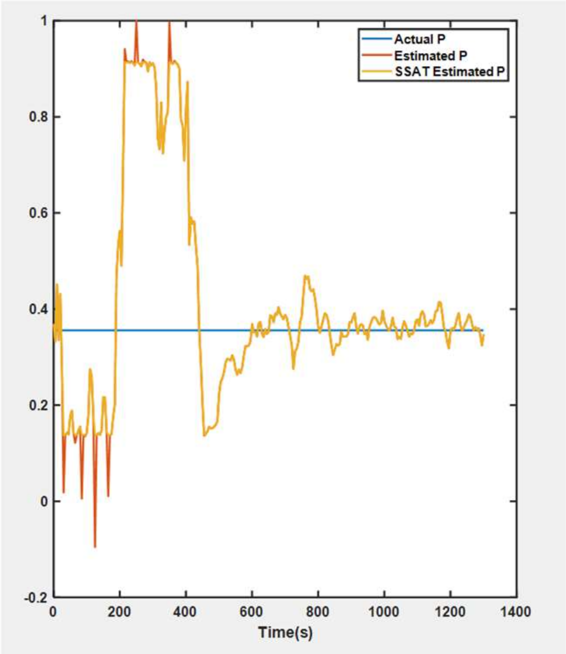
Model-based Estimation (MBE) Library *Performance*

Initial Conditions perturbed by 5%, noisy measurements

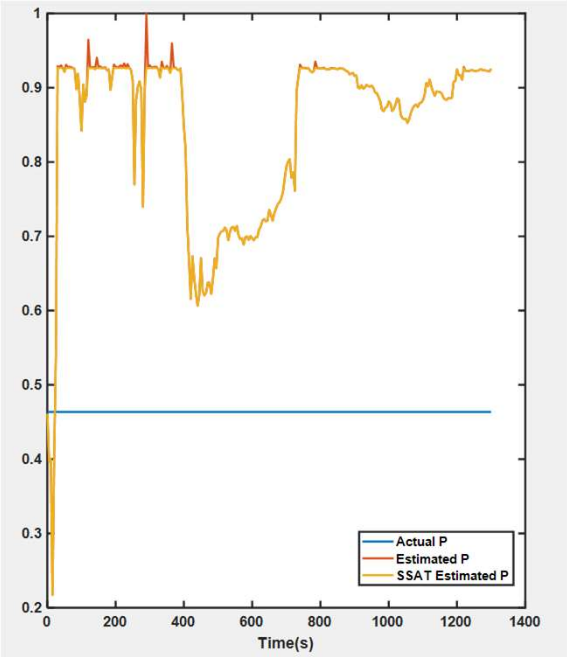
IP ST efficiency scaler



Economizer HTC scaler



LP preheater HTC scaler

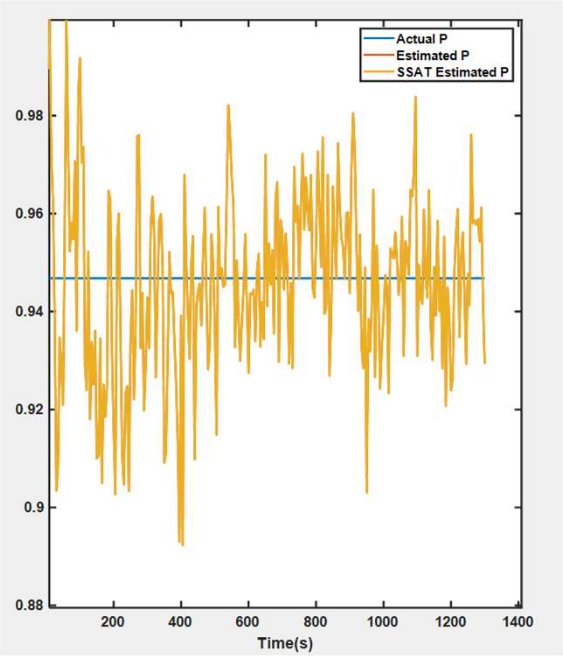


Project Update

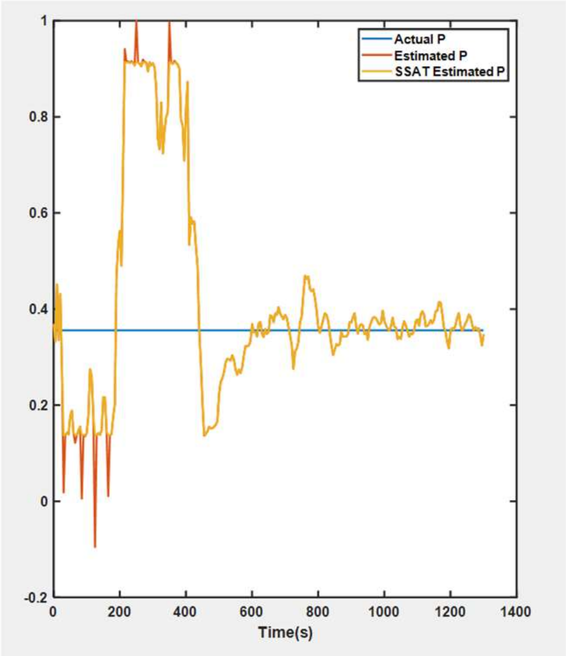
Model-based Estimation (MBE) Library *Performance*

Initial Conditions perturbed by 5%, noisy measurements

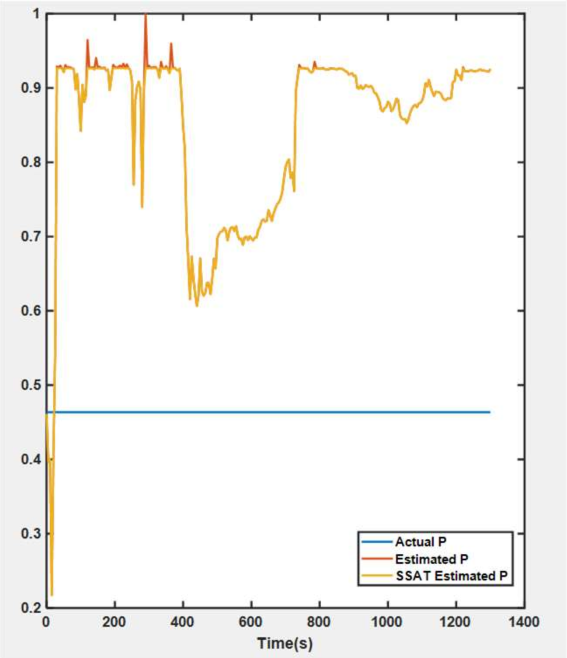
IP ST efficiency scaler



Economizer HTC scaler



LP preheater HTC scaler

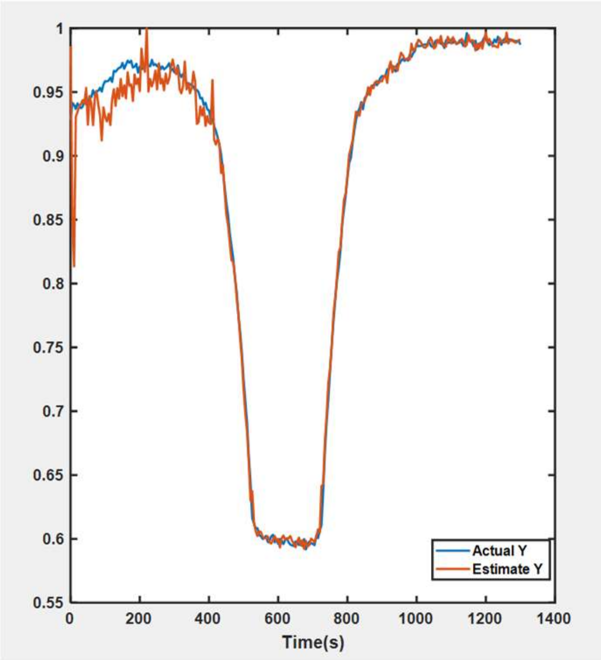


Project Update

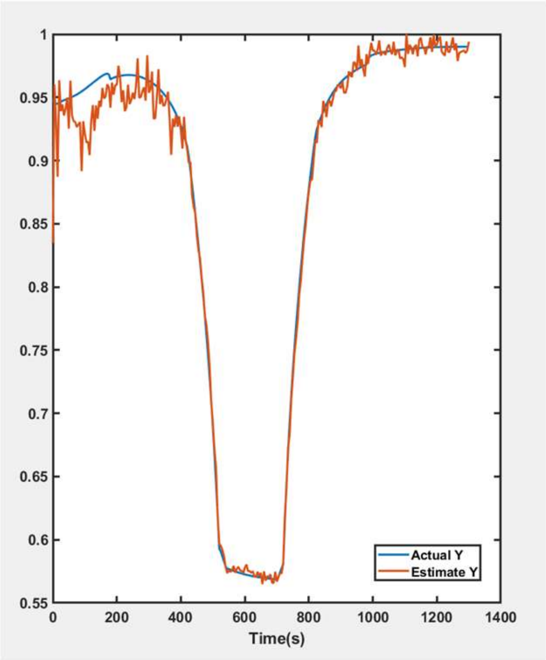
Model-based Estimation (MBE) Library *Performance*

Initial Conditions perturbed by 5%, noisy measurements

Total gross power

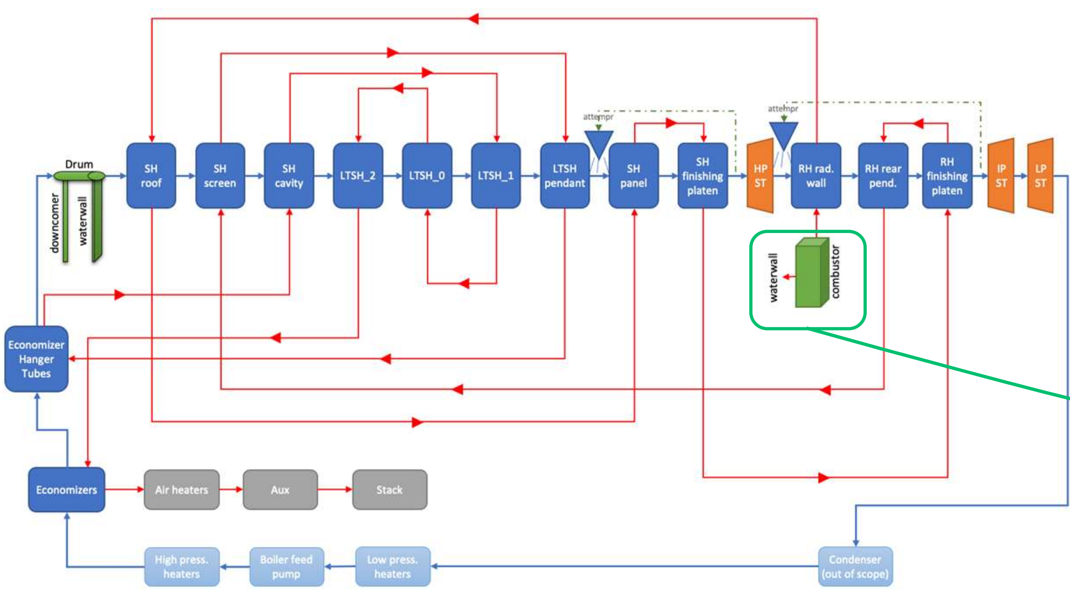


LP ST Torque



Project Update

High-fidelity plant model development in APROS modeling software



This detailed high-fidelity model will represent the real plant in the testing of MPC-MBE algorithms

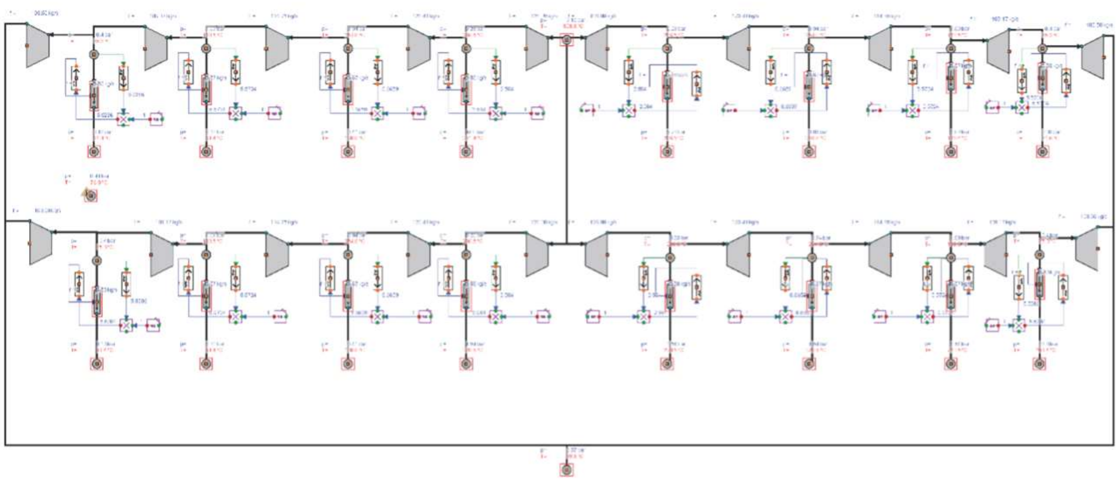
Plant Model in APROS calibrated for TMCR/part load conditions *except* air preheaters being tuned, and multiple combustor injection zones

Model development in APROS is completed for TMCR /part-load conditions

Project Update

High-fidelity plant model development in APROS modeling software

LP ST model in APROS



APROS Model Example: LP Steam Turbines

This detailed high-fidelity plant model will represent the real plant in the testing of MPC-MBE algorithms

Plant Model in APROS calibrated for TMCR/part load conditions *except* air preheaters being tuned, and multiple combustor injection zones

Model development in APROS is completed for TMCR/part load conditions

Next step: Multiple combustor injection zones added to the model and compare baseline with reduced order model

Preparing Project for Next Steps

Project Path:

- Year 1+: Individual modules completed: model library, model-based estimation, model predictive control
- Year 2: Integration of the modules
- Year 3: Hardware-in-the-loop testing

Technology-to-Market Path:

- Follow-on with TRL5-TRL7 program to test at pilot-scale and customer sites – beta deployment
- Follow GE-Steam-Power's procedures to get to approval-to-quote status
- Potential new research: faster requisition of reduced-order models for given sites
- Potential new research: consideration of stochastic market conditions in MBE/MPC technologies

Concluding Remarks

Program focuses on developing:

- *Reduced-order models:* for representing CFPPs
- *Model-based estimation:* for assessing current status of a CFPP
- *Model-predictive-controls:* for efficient/flexible operation of CFPPs
- *High fidelity models:* for representing the actual CFPP

Developed technology will support CFPPs to be :

- more efficient at and getting to part-load
- more flexible
- more efficient

Next Steps/Challenges:

- Integrate MPC and MBE applications
- Integration of overall architecture and demonstration on the representative CFPP high-fidelity plant model

Challenges for productization:

- More rapid reduced-order-model development for a given CFPP

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