Multi-Model Predictive Control for Enhanced Load Following of a sCO_2 Recompression Brayton Cycle

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Disclaimer

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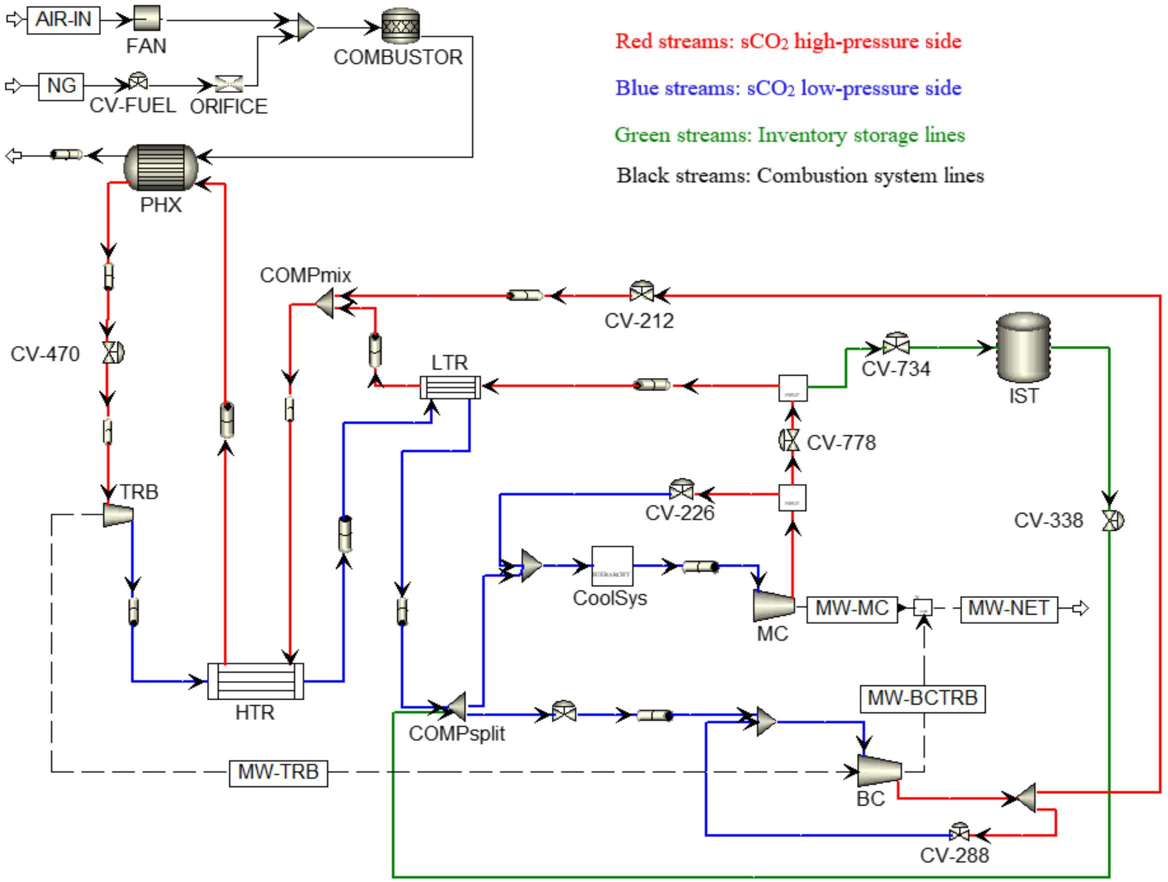
Introduction

- The process being examined is the recompression closed Brayton cycle (RCBC) based on the Supercritical Transformational Electric Power (STEP) pilot plant
- The system is an indirect heat, highly-recuperated, supercritical CO_2 (sCO_2) driven power cycle
- Operation and controls are examined in Liese et al. [1] and Albright et al. [2]
- Sufficient control of the process is possible, but advanced controls are not yet considered
- Model predictive control (MPC) is used here to enhance load following and demonstrate capabilities of the STEP facility

Process Model & Controls

Cycle Diagram

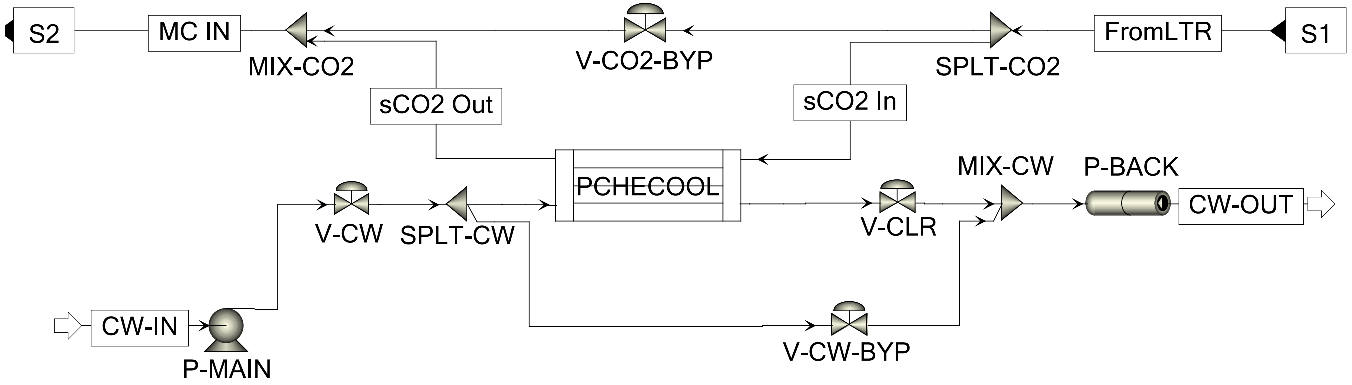
- Gas fired
  - Combustor effluent temp. maintained with air/gas ratio controller
- Turbine inlet temperature controlled by adjusting natural gas (NG) flow
- High temperature/low temperature recuperator (HTR/LTR) are 1D printed circuit heat exchangers (PCHE)
  - Specs provided by GTI/Heatric
- Inventory storage tank (IST) used to manipulate total sCO_2 cycle flowrate
  - Inventory management control maintains net load of cycle
- Main compressor (MC)/Bypass Compressor (BC) flow split maintained with MC inlet guide vane (IGV)adjustments
- Main compressor inlet temperature (MCIT) controlled by cooler control system



Process Model & Controls

Cooler Section

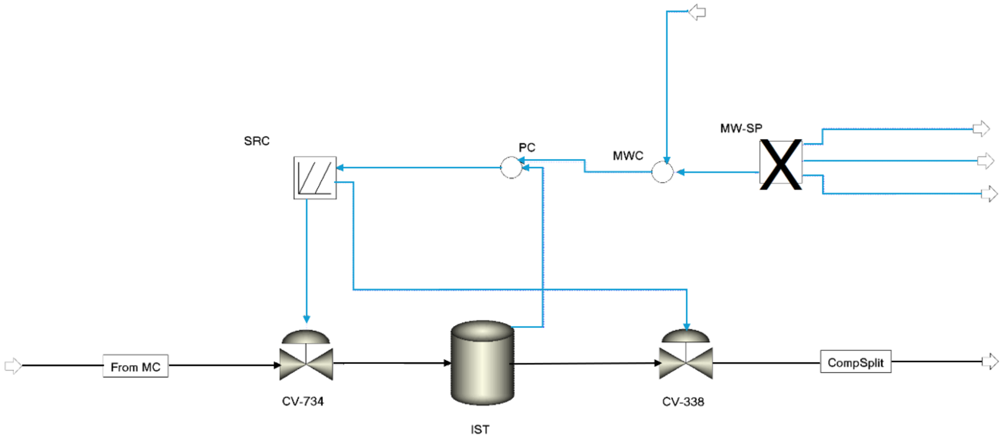
- Main cooler is also 1D PCHE
- Cooling water (CW) flow is manipulated to maintain temp. at sCO_2 outlet
- sCO_2 cooler bypass is adjusted to control MCIT
- Use of both temperature controls detailed is in Albright et al. [2]
  - Helps maintain cycle stability for aggressive load following

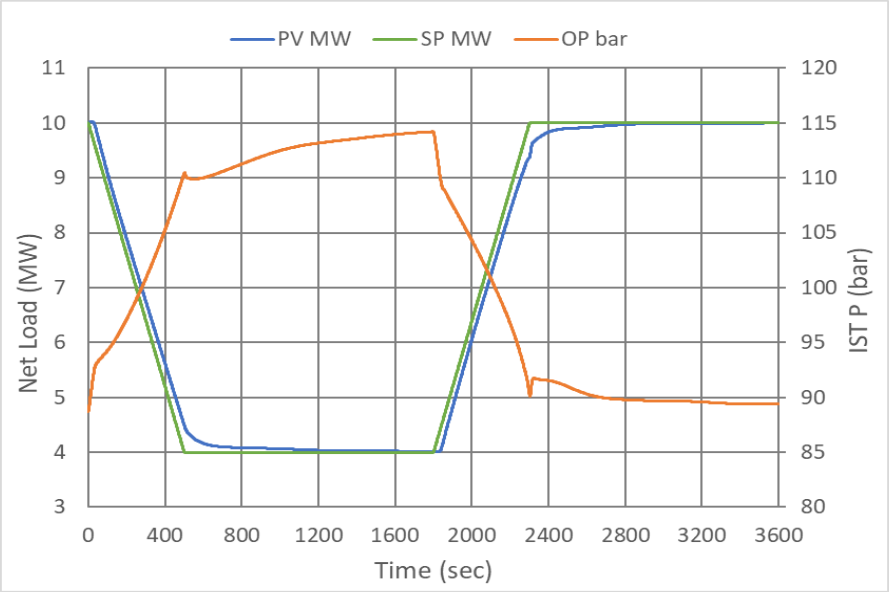


Process Model & Controls

Inventory Management Control (IMC)

- IMC improvement will be the focus of this work
- Load setpoint (SP) is provided to load controller (MWC)
  - Maintains the net load process variable (PV)
- MWC output (OP) sets pressure SP for pressure controller (PC) of IST
  - MWC is typically PI controller, de-tuned to maintain cycle stability
  - Replaced with MPC
- Split range control (SRC) determines operation of inlet/outlet valves
- Load SP is sent to several controllers across the cycle
  - Gain scheduling





Predictive Controller

- Set of linear state-space models used to represent areas of operation:
  - 10 to 8MW, MPC_1
  - 8 to 6MW, MPC_2
  - 6 to 4MW, MPC_3
- Cost function is used by MPC to determine optimal control move
  - Weights, w, and scaling factors, s, for each function is used to tune MPC response
- Additionally, prediction and control horizons (PH/CH) have significant effect on MPC response
  - CH is number of control moves, *k*, is used to determine optimal sequence
  - PH is the projected response, up to time *p*

- **Linear Time-Invariant (LTI) Model:**

$$x(k+1) = Ax(k) + Bu(k) + Ke(k)$$

$$y(k+1) = Cx(k) + Du(k) + e(k)$$

$$x(k), y(k), u(k), e(k) \in R^n$$

$$U_{LB} \leq u_n \leq U_{UB}$$

- **Cost Function:**

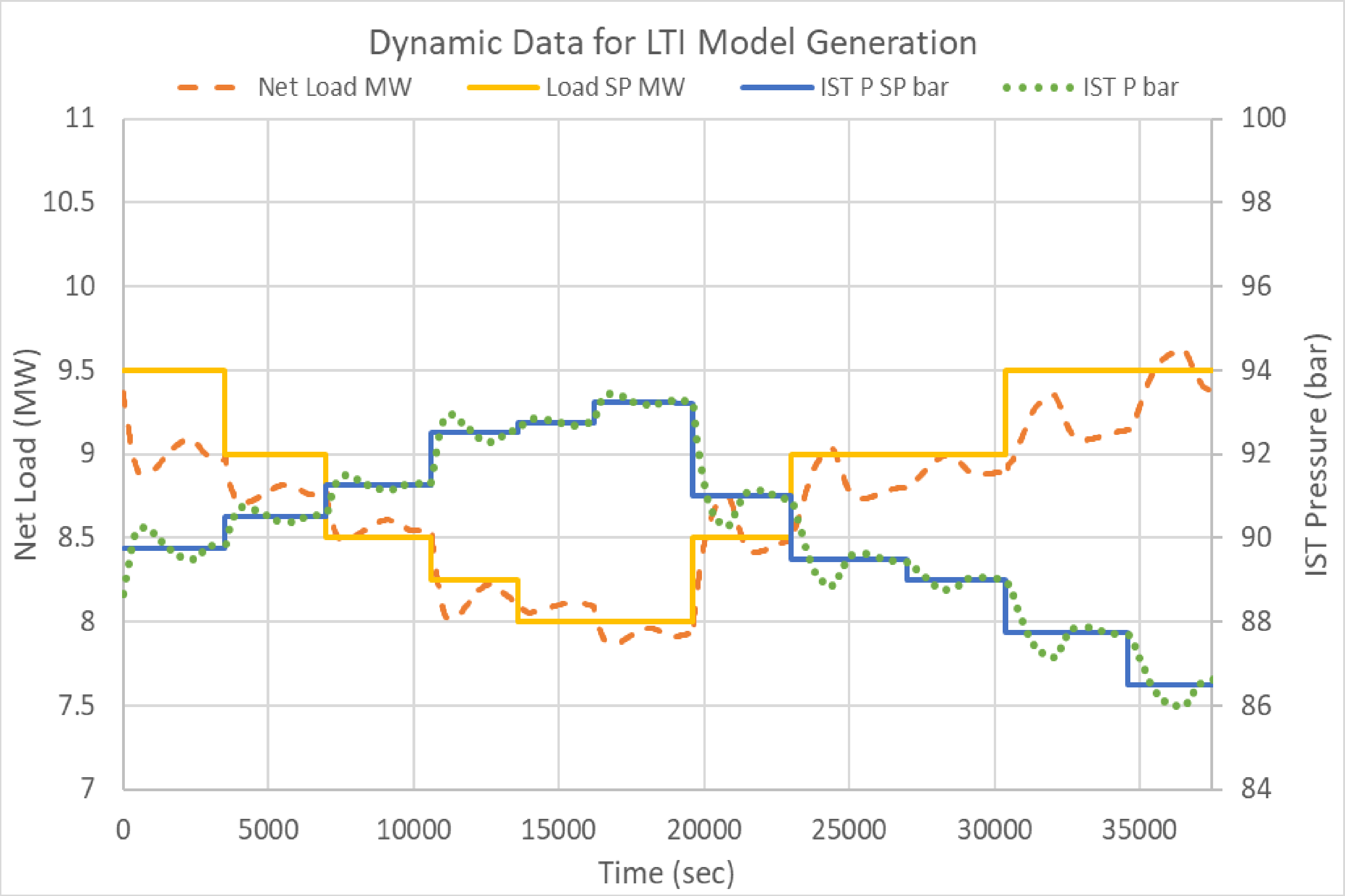
$$J(z_k) = J_y(z_k) + J_u(z_k) + J_{\Delta u}(z_k) + J_\varepsilon(z_k)$$

$$J_y(z_k) = \sum_{i=1}^{p} \left(\frac{w_{1,i}}{s_{1,i}} [r_1(k+i|k) - y_1(k+i|k)] \right)^2$$

Results

Model Generation

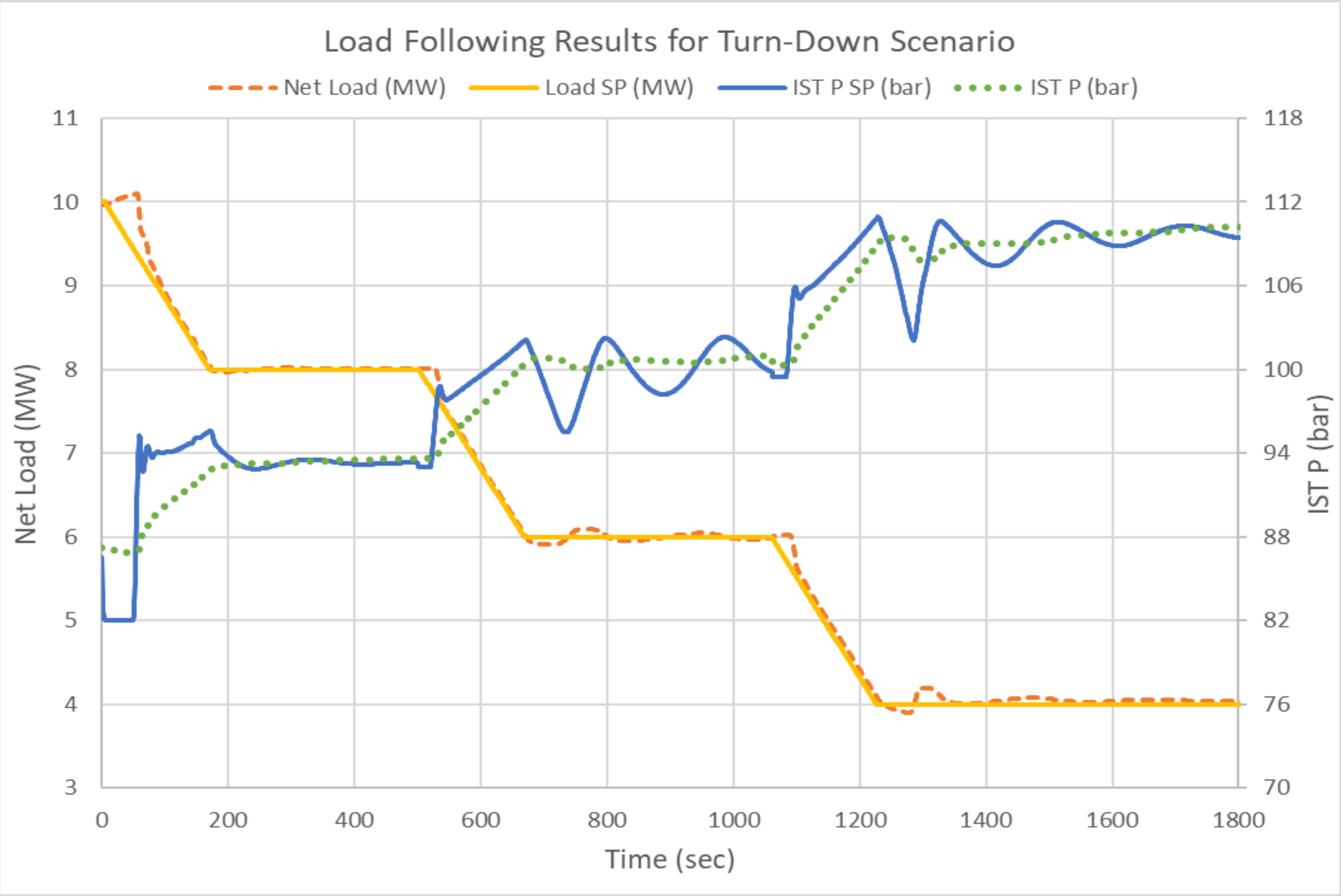
- Randomly generated perturbations are made to the IST pressure SP to produce higher quality data
- MWC is not operational during this
  - Other controllers in cycle are online
- 8 to 10 MW data is shown here
- Load SP adjustments are made here to mimic usual operation
  - Gain scheduling and IGV operation
- Data here is used to generate state space matrices for LTI model



Results

Load Following, Turn-Down

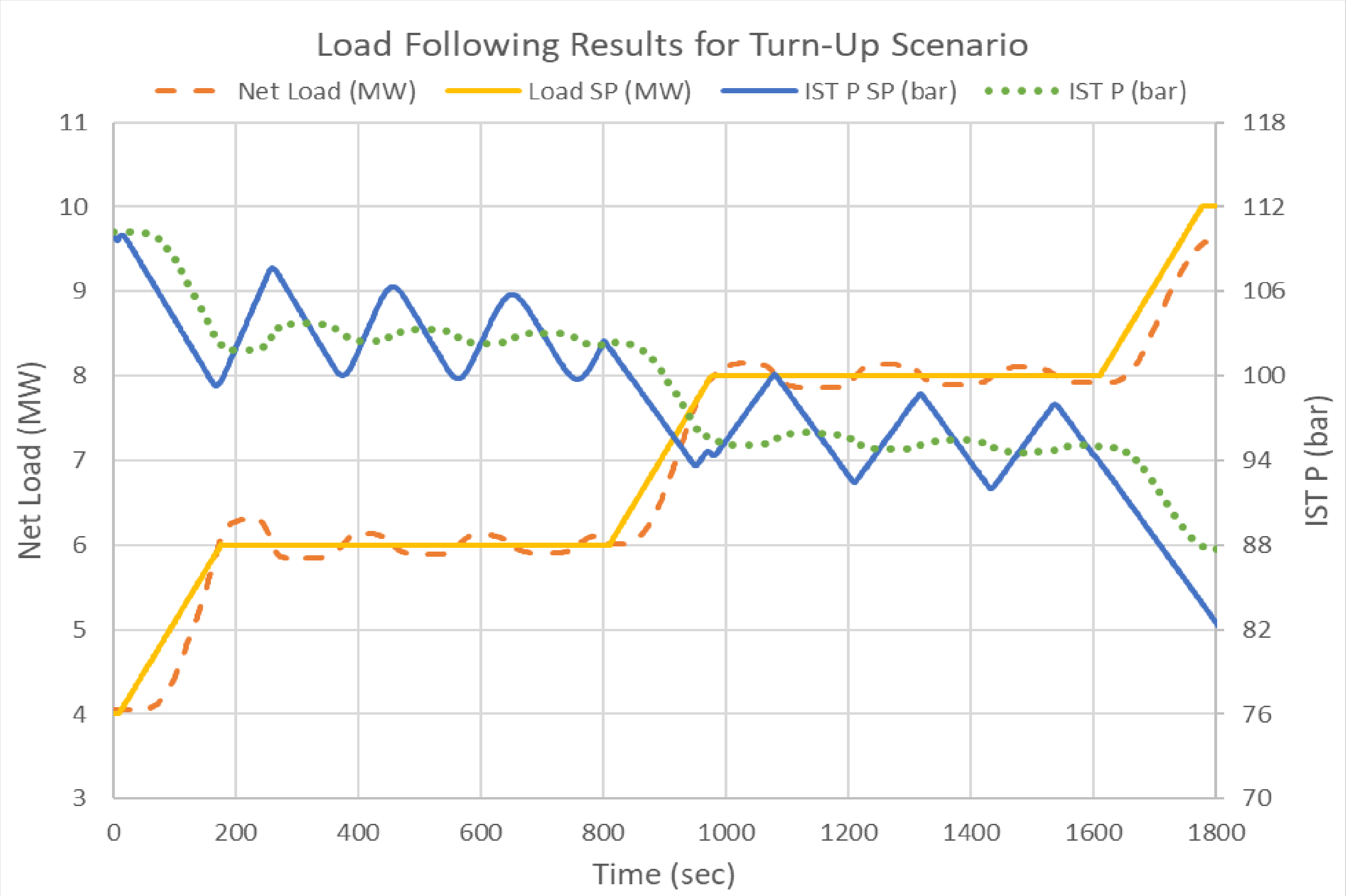
- Load tracks the demand profile closely
- There is an initial delay in the response for each turn-down sequence
  - Possibly due to model switching
- The response from the MWC is somewhat aggressive
  - Forces both IST inlet/outlet valve action
- Increasing penalty on input movement could reduce aggressive behavior
  - Decreases load tracking and settling time



Results

Load Following, Turn-Up

- Load tracking is still fast but error has increased
  - There is a similar delay in the initial response
- Similar MWC response results in small sustained oscillations around final SPs
- Pressure pinch is reached for 8 to 10 MW operation during turn-up
- LTI models do not sufficiently represent the turn-up response
  - MPC optimization cannot settle on final IST pressure SP
- Separate turn-up model could be used



Results

MPC Performance Comparison

- Load tracking error during ramp is comparable to Albright et al. [2] for both turn-up and turn-down
- Settling times are significantly improved for turn-down response
- Overall, this method shows promise for further improvement of cycle response

	Avg. Difference (MW)	Settling Time, 2% of Final SP (sec)
MPC$_1$, TD	0.19	0
MPC$_2$, TD	0.062	0
MPC$_3$, TD	0.12	103
MPC$_1$, TU	0.39	255
MPC$_2$, TU	0.29	0
MPC$_3$, TU	0.43	n/a
MWC [2], TD	0.34	320
MWC [2], TU	0.37	196

Conclusion & Future Works

- Multi-model predictive control was applied to a sCO_2 RCBC
- Improvements to the turn-down response were achieved
- Turn-up response showed that linear model may not be sufficient, but multi-model approach is promising
- Centralized MPC approach could be more effective at efficient control of the cycle
- sCO_2 RCBC has promising performance while operating under a fast ramp schedule

Previous Work

- [1] Liese E., Albright J., Zitney S. “Startup, Shutdown, and Load Following Simulations of a 10 MWe Supercritical CO_2 Recompression Closed Brayton Cycle,” J. of Applied Energy, Volume 277, 1 November 2020, 115628. https://doi.org/10.1016/j.apenergy.2020.115628

- [2] Albright J., Liese E., Zitney S. “Control Methods for Mitigating Flow Oscillations in a Supercritical CO_2 Recompression Closed Brayton Cycle,” J. of Applied Energy, Volume 352, 15 Dec 2023, 121922. https://doi.org/10.1016/j.apenergy.2023.121922

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