Transient Design Optimization of Hybrid Thermal Management Systems

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Problem Statement

The performance requirements of Thermal Management Systems (TMSs) are growing increasingly stringent as a result of advanced electrification

- The increased electrically-driven heat loads are often highly transient
- Traditional steady-state design strategies may result in over-sized systems

Thermal Energy Storage (TES) in the form of phase change materials may be integrated into the TMS design to absorb and store transient heat loads until a period of reduced loading

- System components must be designed to guarantee safe operation of the TMS for uncertain loading

Research Objective:
Develop a framework for the transient design of hybrid thermal management systems with robustness to uncertain heat loads

Robust Analysis of Thermal Management System

(1) Lumped Parameter Model

- 7 dynamic temperature states $\boldsymbol{T}$
- 3 mass flow rates $\dot{\boldsymbol{m}}$
- 1 uncertain heat load $\dot{\boldsymbol{Q}}_{cp}$

(2) Control Logic

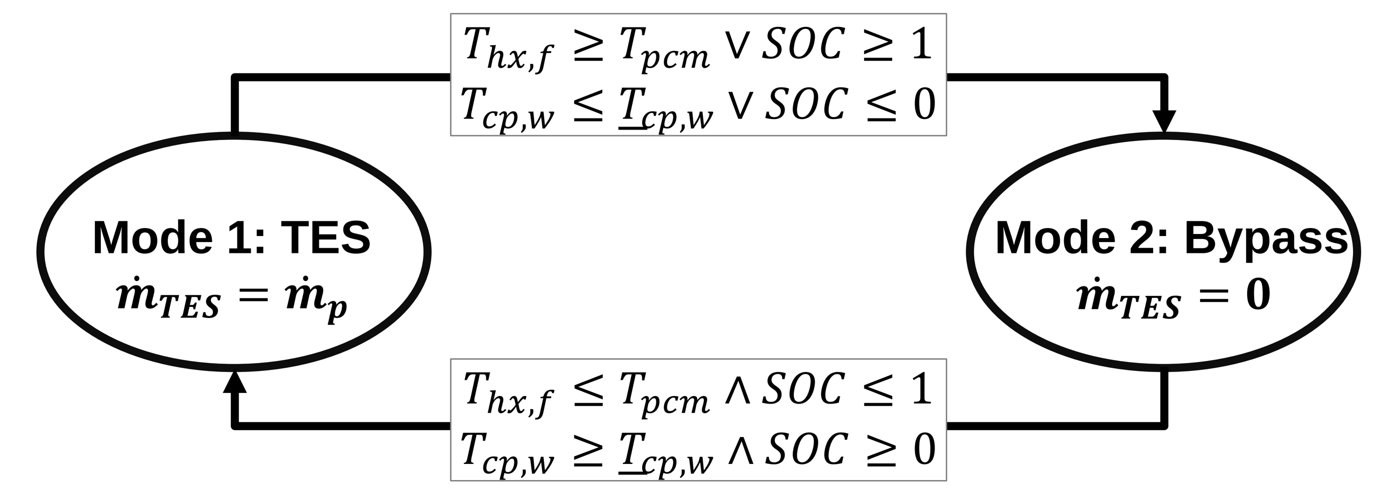
- Switch between full flow rate through TES or full bypass

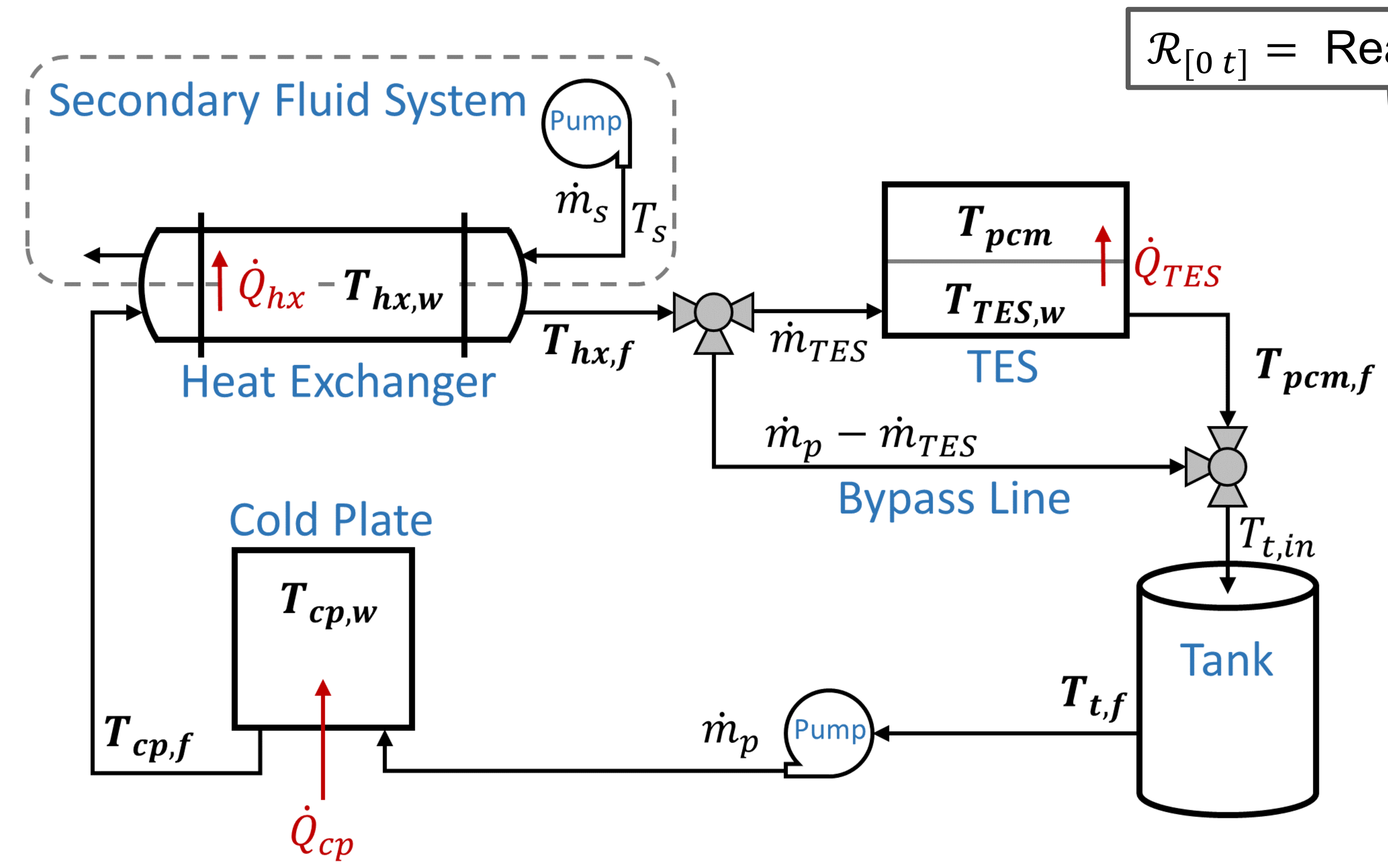
(3) Reachability Analysis

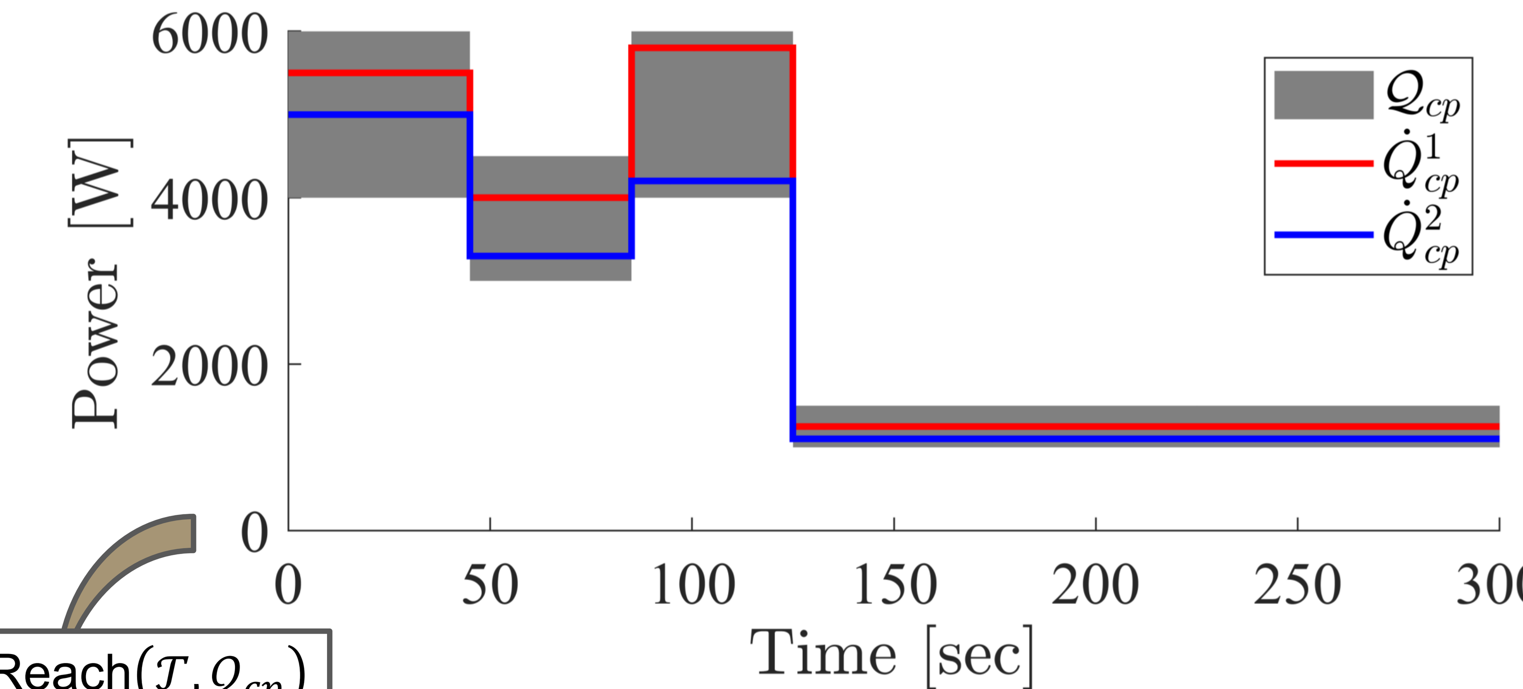
- Reachable set $\mathcal{R}_{[0\ t]}$ captures all possible dynamic responses of the system for an uncertain heat load $\dot{\boldsymbol{Q}}_{cp} \in \mathcal{Q}_{cp}$ from a set of initial temperatures $\boldsymbol{T} \in \mathcal{T}$
- Reachable sets of the closed-loop switched system may be found quickly and exactly using closed-form expressions [1]

(4) Robust Design Criteria

- System satisfies temperature constraints for all time and all possible sequences of heat loads

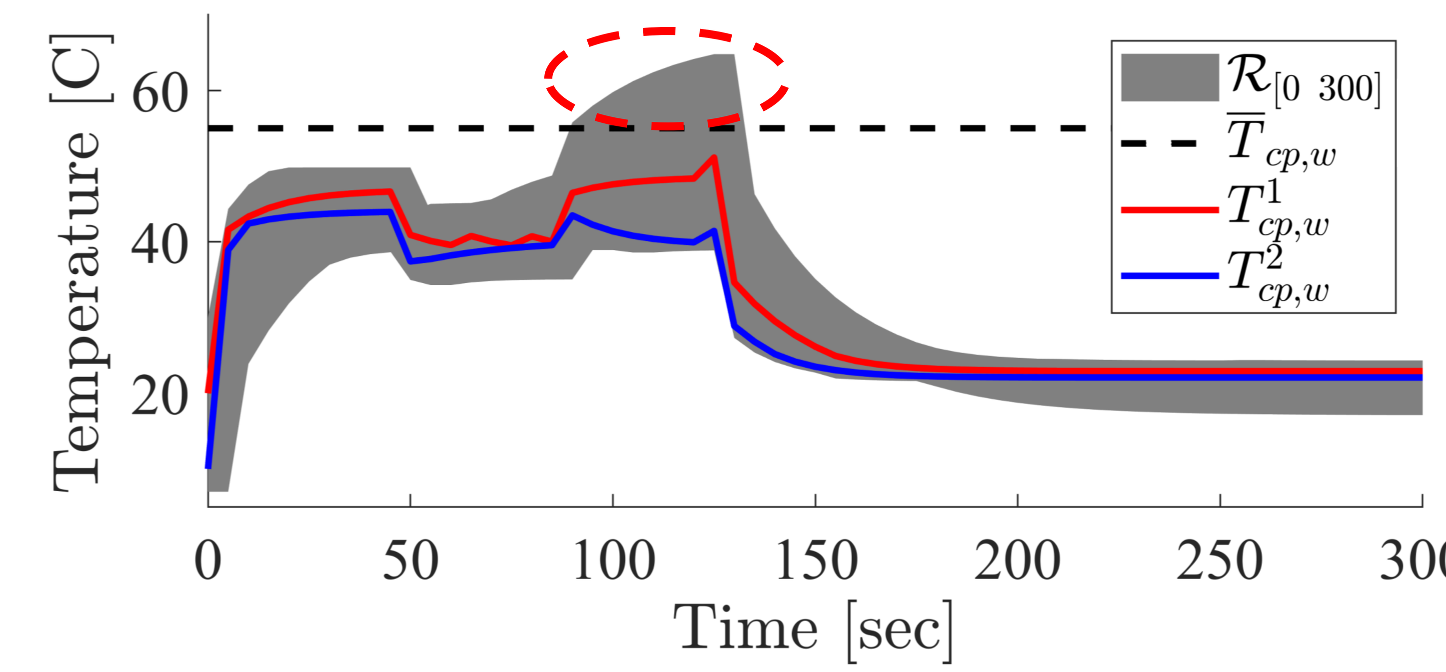






$\mathcal{R}_{[0\ t]} =$ Reach$(\mathcal{T}, \mathcal{Q}_{cp})$

It is possible that the above heat loads will cause the system to violate constraints



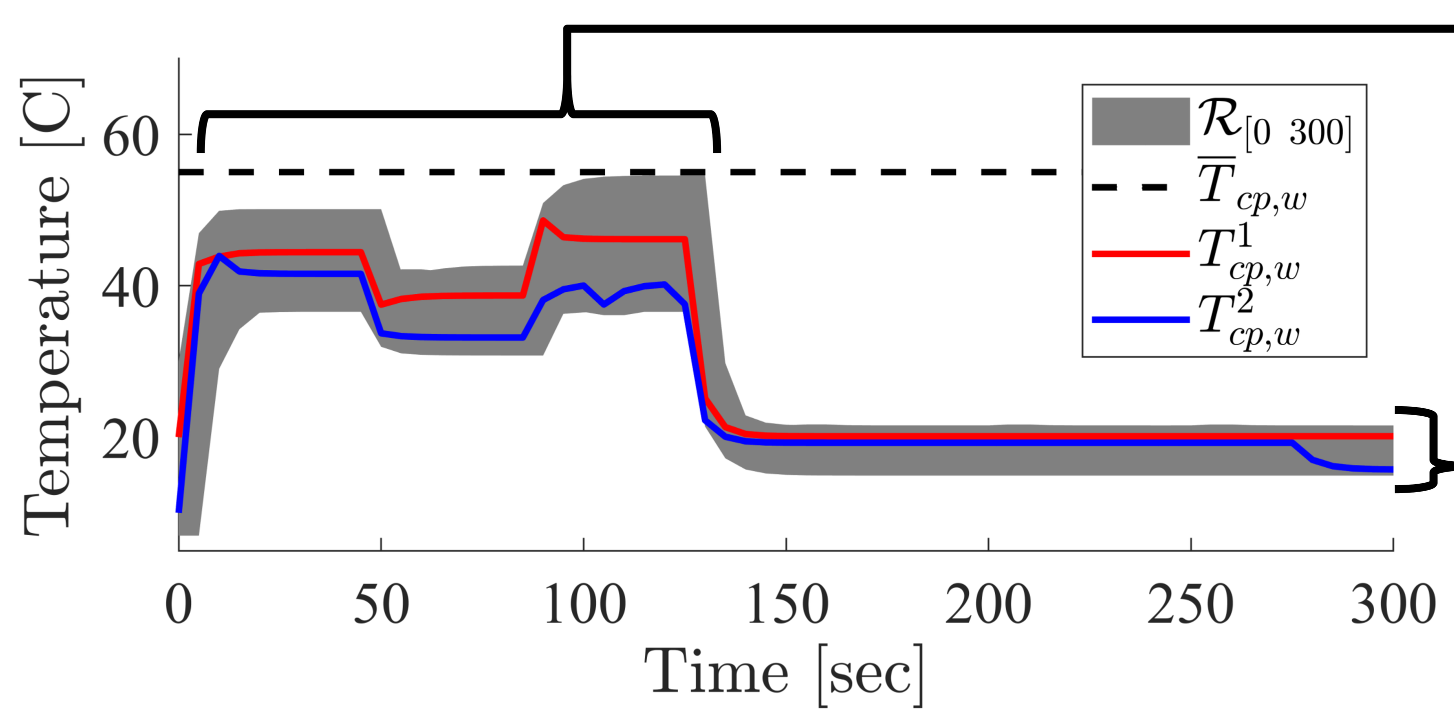
Design Optimization

Optimization problem formulated to choose the mass of the TES and Heat Exchanger, the mass of fluid within the Tank, and the primary and secondary mass flow rates

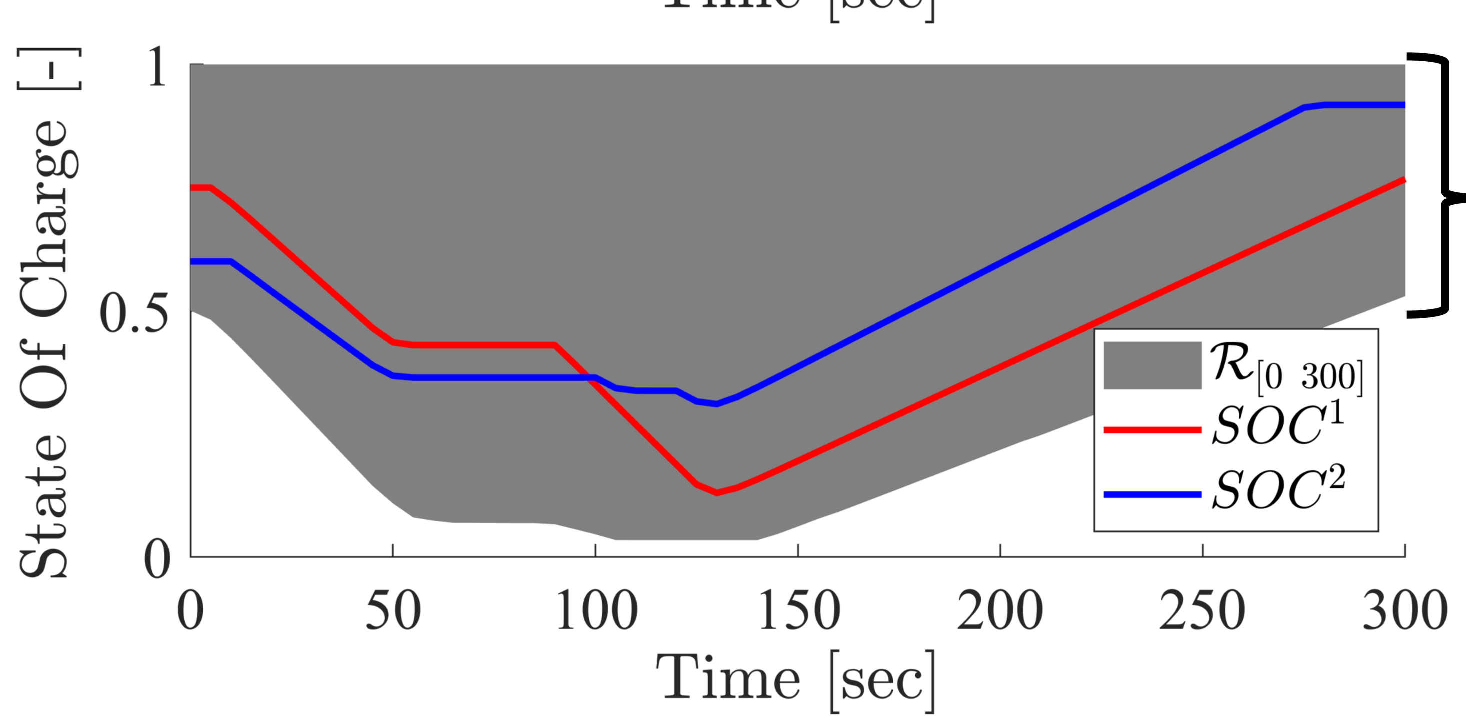
$$p = [M_{TES}, M_{hx}, M_{tank}, \dot{m}_p, \dot{m}_s]$$

- Reachable set $\mathcal{R}$ of the system from a set of initial temperatures $\mathcal{T}$ used to guarantee robustness to set of possible heat loads $\mathcal{Q}_{cp}$
- $\mathcal{R}_{[0\ t]} \subset \overline{\mathcal{T}}$ (robustness constraint) ensures that the system does not violate temperature constraints $\overline{\mathcal{T}}$
- $\mathcal{R}_t \subseteq \mathcal{T}$ (invariance constraint) ensures that the system returns to an initial condition and the design holds for periodic loading

$$\min_{p}\ M_{TES} + M_{hx} + M_{Tank}$$
$$s.t.\ \mathcal{R}_{[0\ t]} = \text{Reach}(p, \mathcal{T}, \mathcal{Q}_{cp})$$
$$\mathcal{R}_{[0\ t]} \subset \overline{\mathcal{T}}$$
$$\mathcal{R}_t \subseteq \mathcal{T}$$



Robustness constraint results in critical temperatures are never violated by the optimal system



Invariance constraint results in a system that can always recharge the TES and return to an initial condition by the end of the simulation time

Future Work

1. Simultaneously design plant parameters p and control strategy c to vary fluid flow rates
2. Introduce an outer loop with design validation against a high-fidelity model

Check feasibility of high-fidelity model with controller and identify new lumped parameters

$$\min_{p,c}\ M_{TES} + M_{hx} + M_{Tank}$$
$$s.t.\ \mathcal{R}_{[0\ t]} = \text{Reach}(p, c, \mathcal{T})$$
$$\mathcal{R}_{[0\ t]} \subset \overline{\mathcal{T}},\ \mathcal{R}_t \subseteq \mathcal{T}$$

Acknowledgements

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[1] **T. J. Bird**, H. C. Pangborn, N. Jain, & J. P. Koeln, “Hybrid Zonotopes: A New Set Representation for Reachability Analysis of Mixed Logical Dynamical Systems,” arXiv.2106.14831, 2021

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