Preliminary Assessment of Control Strategy for a MSR Coupled with TES and OTSG

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1. Introduction

As renewable energy penetration increases, nuclear power plants are increasingly required to provide load-following capabilities to support grid stability. While Molten Salt Reactors (MSRs) offer inherent safety features and high-temperature operation advantages, frequent power maneuvering can induce thermal fatigue in high-temperature structural components. To address this, hybrid systems integrating MSRs with Thermal Energy Storage (TES) have been proposed so that the reactor can operate at stable baseload conditions while the power conversion system follows grid demand[1].

This paper proposes an integrated control strategy for a Generation IV MSR coupled with a two-tank molten salt TES and a Once-Through Superheated Steam Generator (OTSG). The primary objective is to maintain a constant reactor outlet temperature T_{hot} while satisfying strict steam quality requirements (e.g., nominal main steam pressure and superheat conditions) under varying load conditions. Building upon the Babcock & Wilcox Integrated Control System (ICS) concept, a novel "3-way cross-limiting" logic is introduced to coordinate the energy balance among the reactor, TES, and feedwater systems, and its performance is preliminarily assessed using a simplified dynamic model.

2. System Description and Simplified Dynamic Model

The proposed plant configuration consists of three main coupled loops: the primary fuel salt loop, the secondary salt loop with TES, and the tertiary steam cycle.

2.1 Primary System: Constant T_{hot} Control

Unlike conventional Pressurized Water Reactors (PWRs), which often utilize a sliding T_{avg} program, this MSR adopts a constant reactor outlet temperature T_{hot} program to minimize thermal stress on high-temperature components[2]. The primary system utilizes constant speed pumps, fixing the mass flow rate $\dot{m}_1$. so the reactor power Q_{Rx} is approximately proportional to the core temperature rise $\Delta T = T_{hot} - T_{cold}$.

For the purpose of this simplified model, the reactor power is approximated by

$$Q_{Rx} \approx \dot{m}_1 c_{p,salt}(T_{hot} - T_{cold})$$

where $\dot{m}_1$ is fixed by the pump design and $c_{p,salt}$ is the specific heat of the primary salt.

Reactor power is adjusted by control drums, which change core reactivity and compensate for temperature feedback effects associated with variations in the inlet temperature T_{cold}. The control loop maintains T_{hot} at a constant setpoint.

A lumped energy balance for the primary loop is written as below.

$$C_{p,1}\frac{dT_{cold}}{dt} = Q_{Rx} - Q_{IHX}$$

where $C_{p,1}$ is the effective thermal capacitance of the primary loop and Q_{PHX} is the heat transferred to the secondary side.

2.2 Secondary System: TES Configuration

The secondary system serves as a thermal buffer decoupling the heat source from the heat sink. It employs a 2-tanks molten salt TES configuration consisting of a hot tank and a cold tank, with variable-speed pumps controlling the salt flow through the intermediate heat exchanger (IHX) and OTSG[3].

The hot and cold tank energy balances are represented as below.

$$\frac{dE_{hot}}{dt} = Q_{IHX} - Q_{OTSG} - Q_{loss,hot}$$
$$\frac{dE_{cold}}{dt} = Q_{OTSG,ret} - Q_{IHX} - Q_{loss,cold}$$

where Q_{OTSG} is the heat transferred to the OTSG and $Q_{OTSG,ret}$ is the return heat from the OTSG outlet.

The TES State of Charge (SOC) is defined as a normalized function of tank enthalpy, and the system is operated in three modes:

$$SOC = \frac{E_{hot} - E_{hot,min}}{E_{hot,max} - E_{hot,min}}$$

- Charging: Excess heat from the reactor is stored in the Hot Tank when grid demand is low.
- Discharging: Stored heat is supplied to the OTSG to meet peak demand.
- Normal: Heat is transferred directly or in a balanced manner for baseload operation.

2.3 OTSG Constraints and Reduced-Order Model

The OTSG is a once-through unit with low thermal inertia and no recirculation drum, which makes it sensitive to rapid changes in flow and heat input.

To prevent turbine damage and ensure cycle efficiency, the control system is designed, for the purpose of this conceptual assessment, to maintain representative steam conditions [4].

Following reduced-order approaches used for molten salt OTSG analyses, the steam side is modeled by a lumped pressure:

$$C_{p,s}\frac{dT_{steam,out}}{dt} = Q_{OTSG} - \dot{m}_{FW}\left(h_{steam,out} - h_{FW,in}\right)$$

and outlet temperature dynamics:

$$\frac{dP_{steam}}{dt} = f(\dot{m}_{steam,out}, \dot{m}_{FW}, V_{steam})$$

where $\dot{m}_{FW}$ is the feedwater flow rate, $h_{steam,out}$ and $h_{FW,in}$ are outlet steam and inlet feedwater enthalpies(kJ/kg), and V_{steam} is the effective steam volume(m^3). The steam superheat used for control purposes is computed as

$$T_{Superheat} = T_{steam,out} - T_{sat}(P_{steam})$$

These simplified equations are used to design and assess the proposed ICS response to load changes.

3. Integrated Control Strategy

3.1 Integrated Master and Mode Selection

The Integrated Master (IM) receives the Unit Load Demand (ULD) signal from the grid operator and computes the required gross electrical output. It compares the ULD with the reactor's available power range [$P_{Rx,min}$, $P_{Rx,max}$] and the TES SOC to determine the operating mode as follows:

- Discharge Mode($P_{demand} > P_{Rx,max}$ & SOC > SOC_{min}): If the requested power exceeds $P_{Rx,max}$, the TES is commanded to discharge up to its maximum discharge rate while the reactor is held near $P_{Rx,max}$.
- Charge Mode($P_{demand} < P_{Rx,min}$ & SOC < SOC_{max}): If the requested power falls below $P_{Rx,min}$, the TES is charged by diverting excess reactor power to the hot tank.
- Normal Mode: For intermediate demands, the reactor and TES share the load so that Thot is maintained and TES SOC remains within a target band.

The IM outputs demand signals for reactor power, TES charge/discharge rate, secondary salt flow, and feedwater flow, which are then constrained by the cross-limiting logic described below.

3.2 3-Way Cross-Limiting Logic

To ensure thermal stability and prevent component damage during transients, a "3-way cross-limiting" logic is implemented by extending the conventional reactor-feedwater cross-limits to include TES capacity.

1) Feedwater Flow Limits (Sink Constraints)

The demanded feedwater flow($\dot{m}_{FW,dem}$) is constrained by the total available heat source, defined as the sum of the actual reactor power and the maximum TES discharge power:

$$\dot{m}_{FW} \leq \frac{Q_{Rx,act} + Q_{TES,dis,max}}{h_{steam,ref} - h_{FW,in}}$$

$Q_{TES,dis,max}$ is the maximum discharge power from the hot tank (MW) and $h_{steam,ref}$ is the reference specific enthalpy at the assumed steam conditions.

This limitation prevents overcooling of the salt loops in cases where the TES is depleted or TES pumps fail by ensuring that the steam cycle does not extract more heat than the reactor–TES combination can supply. If this limit is violated, the primary T_{cold} would drop excessively, requiring the control drums to insert large amounts of positive reactivity and potentially destabilizing the core power.

2) Reactor Power Limits (Source Constraints)

The reactor power demand $Q_{Rx,dem}$ is constrained by the system's capacity to absorb heat, defined by the actual feedwater flow and maximum TES charge capability:

$$Q_{Rx,dem} \leq \dot{m}_{FW,act}\left(h_{steam,ref} - h_{FW,in}\right) + Q_{TES,chg,max}$$

$Q_{TES,chg,max}$ is the maximum charge power into the hot tank (MW). This term represents the additional heat that can be safely absorbed by the TES when the steam cycle demand is low.

This constraint ensures that the reactor does not overheat during turbine trips (sudden loss of feedwater flow), rapid load rejections, or when TES approaches its maximum SOC and can no longer absorb additional heat.

Without this limit, T_{cold} would rise sharply, pushing the core into a highly negative temperature feedback regime with delayed neutron precursor poisoning and potential fuel temperature violations.

3) TES Power Limits (Storage Constraints)

The TES charge and discharge powers are further limited by tank levels and salt temperature margins, introducing a third linkage in the cross-limiting network. In the simplified formulation, the allowable TES powers are expressed as

$$Q_{TES,chg} \leq Q_{TES,chg,max} \times f_{SOC}(SOC)$$
$$Q_{TES,dis} \leq Q_{TES,dis,max} \times f_{SOC}(SOC)$$

where f_{SOC} is a derating function that reduces charge capability near SOC = 1 and discharge capability near SOC = 0, preventing pump cavitation and tank overflow.

Overall, the 3 cross-limiting constraints form a feasible region for (Q_{Rx}, $\dot{m}_{FW}$, Q_{TES}) that tightens near TES operational limits, preventing controller fighting and ensuring safe transitions between charging, normal, and discharging modes.

This structure is expected to reduce steam pressure overshoot and primary temperature excursions during load changes compared with a conventional 2-way reactor–feedwater cross-limit, particularly when TES SOC is low.

3.3 OTSG Control Logic

The OTSG utilizes a "feedforward + feedback" control scheme similar to those deployed in previous molten salt–OTSG studies[5].

- Pressure Control: A turbine-leading strategy is employed in which turbine valves track the ULD signal, while the secondary salt flow through the OTSG is modulated to maintain an assumed nominal main steam pressure. In the simplified formulation, the salt flow setpoint is given by

$$\dot{m}_{2,OTSG,ref} = \frac{\dot{m}_{steam,cmd}\left(h_{steam} - h_{FW,in}\right)}{\left(T_{2,in} - T_{2,out}\right) \times c_{p,salt}} + \Delta\dot{m}(P_{error})$$

where the first term provides a feedforward estimate based on the commanded steam flow and enthalpy balance, and $\Delta\dot{m}(P_{error})$ is the feedback trim generated by the steam pressure error controller to drive the pressure deviation to zero.

- Superheat Control: A ratio controller sets the nominal feedwater flow proportional to the measured secondary salt flow, establishing a basic enthalpy balance. In the simplified formulation, the nominal feedwater flow is given by

$$\dot{m}_{FW,base} = \frac{Q_{OTSG}}{c_{p,steam}\left(T_{steam,out} - T_{FW,in}\right)} + k_{ratio}$$

A PID trim based on the outlet superheat error then adjusts the feedwater flow to maintain the assumed superheat setpoint at the turbine inlet:

$$\dot{m}_{FW,final} = \dot{m}_{FW,base} + K_p e + K_I \int e\,dt + K_D \frac{de}{dt}$$

where $e = \text{Superheat}_{meas} - \text{Superheat}_{ref}$.

4. Safety Interlocks

Critical safety interlocks are implemented to protect the plant from abnormal conditions and complement the ICS response.

- Low Superheat Runback: If the measured superheat margin falls below a specific setpoint, an automatic runback is triggered to rapidly close feedwater valves and reduce steam generation, thereby protecting the turbine from wet steam.
- Freeze Protection: If any salt temperature approaches the freezing point of the salt mixture, pre-programmed drain sequences and/or auxiliary electric heating are activated to keep salt lines and tanks above the freezing threshold.
- TES Level Interlocks: High- and low-level setpoints on the hot and cold tanks inhibit charging or discharging modes to prevent pump cavitation, overflow, and loss of NPSH, enforcing safe operating windows for TES processes.

5. Preliminary Dynamic Assessment

The dynamic behavior of the proposed control strategy is examined at a conceptual level by considering representative load-following scenarios based on the lumped-parameter model in Section 2 and the control logic in Section 3.

2 typical ULD changes are discussed to illustrate the expected behavior of the three-way cross-limiting structure in comparison with a conventional 2-way reactor–feedwater cross-limit.

- Case 1: ULD Step Decrease (Normal Mode):
  The reactor operates near baseload, and a decrease in ULD causes the turbine valves to throttle, reducing the steam and feedwater flow demand.
  The proposed 3-way cross-limiting logic is expected to limit the rapid reduction in reactor power demand so that the deviation of the reactor outlet temperature Thot remains relatively small, while excess reactor heat is directed to TES charging.
  Under this behavior, the main steam pressure and superheat are anticipated to stay close to their nominal targets with moderate transient deviations.

- Case 2: ULD Step Increase (Discharge Mode):

When the ULD increases such that the required power exceeds the reactor capacity, the IM commands TES discharge so that stored heat from the hot tank supplements the reactor.

By constraining the feedwater flow according to the combined reactor–TES capacity, the 3-way cross-limiting logic is expected to mitigate excessive cooling of the primary and secondary loops and to suppress large steam pressure spikes during the mode transition.

Although the deviation of Thot may increase somewhat due to the change of mode, it is anticipated to remain smaller than in the case with a conventional 2-way cross-limiting structure.

From a qualitative standpoint, these scenario-based considerations suggest that incorporating TES into the cross-limiting network can help reduce steam pressure overshoot and primary temperature excursions during load steps and maintain a more stable superheat margin, compared with a 2-way reactor–feedwater cross-limit.

More detailed and quantitative performance comparisons will require future high-fidelity dynamic simulations and optimization of controller parameters.

6. Conclusions

An integrated control strategy for an MSR–TES–OTSG hybrid system has been developed and preliminarily assessed using a simplified dynamic model. By adopting constant T_{hot} operation for the primary loop and implementing a 3-way cross-limiting logic that incorporates TES capacity, the design can mitigate reactor and steam-cycle transients during load-following operation while maintaining steam pressure and superheat targets.

Future work will focus on high-fidelity coupled neutronics–thermal–hydraulics analysis to verify control drum stability and assess delayed neutron precursor drift under dynamic flow conditions, as well as detailed analysis of OTSG low-load instabilities and bumpless transfer algorithms during mode switching.

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