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A Robust Smith-like Predictor-Enhanced Passivity-Based Control Method for the HTR-PM Reactor Module Subject to Large Hot Helium Temperature Response Delay

摘要

全球首座商业化球床模块式高温气冷堆核电站——高温气冷堆核电站示范工程（HTR-PM）于 2023 年 12 月 6 日投入商业运行。为验证反应堆协调控制策略的可行性，开展了功率斜坡升降、汽轮机跳闸、反应堆跳闸等多项全厂试验，获取了关键过程变量的宝贵现场数据。数据分析表明，热氦温度存在显著响应滞后，显著影响了单模块协调控制性能。

针对该工程问题，本文面向热氦温度响应滞后工况下的 HTR-PM 反应堆模块，提出一种鲁棒型类史密斯预估器增强无源控制方法。设计时域类史密斯预估器，用于估计无滞后热氦温度，并将其融入无源控制框架。该方法可补偿热响应滞后的不利影响，同时保留无源控制的稳定性优势。与传统无源控制（PBC）相比，该方法提升了系统瞬态调节性能，增大了闭环稳定的允许滞后裕度，能够在传统无源控制失稳的大滞后工况下维持系统稳定运行。本文对闭环系统的渐近稳定性进行了理论分析，并基于 HTR-PM 单模块协调控制场景开展仿真，验证了所提方法的有效性与鲁棒性。

关键词

HTR-PM；协调控制；大时延系统；类史密斯预估器；无源性控制

Abstract

The HTR-PM demonstration project, the world's first commercial high-temperature gas-cooled reactor pebble-bed module nuclear power plant, entered commercial operation on December 6, 2023. Several plant-wide tests, including power ramping, turbine trip, and reactor trip tests, were conducted to verify the feasibility of the reactor coordinated control strategy and provided valuable field data on key process variables. Analysis of these data reveals a pronounced response delay in the hot helium temperature, which significantly degrades the performance of single-module coor-dinated control.

Motivated by this engineering issue, this paper proposes a robust Smith-like predictor-enhanced passivity-based control method for the HTR-PM reactor module with large hot helium temperature response delays. A time-domain Smith-like predictor is developed to estimate the delay-free hot helium temperature and incorporated into the passivity-based control framework. The proposed method compensates for delayed thermal response while preserving the stability advantages of passivity-based control. Compared with conventional PBC, it improves transient regulation performance and increases the allowable delay margin for closed-loop stability, maintaining stable operation under large-delay conditions where conventional PBC becomes unstable. Closed-loop asymptotic stability is theoretically analyzed, and simulations based on the HTR-PM single-module coordinated control scenario verify the effectiveness and robustness of the proposed method.

Keywords

HTR-PM; coordinated control; large time-delay system; Smith-like predictor; passivity-based control

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