

高通量堆系统可靠性与可用性智能建模及动态分析研究

摘要

面向高通量堆安全关键可修复系统在复杂工况下的在线动态可靠性与可用性评估需求, 针对现有方法中环境感知失效率更新与系统级评估脱节、连续时间马尔可夫链 (CTMC) 模型构建依赖人工、状态空间增大后重复瞬态评估代价高等问题, 本文提出一种高通量堆系统可靠性与可用性动态智能建模与分析方法。该方法构建了融合物理信息神经网络 (PINN) 与大语言模型辅助自动建模的 PEARL 框架, 实现了环境感知失效率处理、CTMC 自动生成、状态空间约简以及物理约束瞬态求解的一体化流程。其中, MarkovOps 模块可根据结构化输入或工程文本描述, 自动生成显式带速率标注的马尔可夫状态转移图, 并支持失效、维修、备用切换、启动失效和共因失效等复杂机制建模; PINN 模块用于学习系统状态概率随时间演化的规律, 从而实现可靠性与可用性的快速在线查询。以宽能谱超高通量试验堆 (简称高通量堆) 的反应堆冷却剂系统和设备冷却水系统为案例开展验证, 结果表明, 所提方法在保证评估精度的同时, 能够实现 CTMC 的快速自动生成以及一次训练后的多时刻快速推理, 为研究堆系统在线动态可靠性与可用性评估提供了一种可行方法。

关键词

在线动态可靠性与可用性; 环境感知失效率; 连续时间马尔可夫链自动生成; 物理信息神经网络; 宽能谱超高通量试验堆

Abstract

For the online dynamic assessment of reliability and availability of safety-critical repairable systems in the Tsinghua High Flux Reactor (THFR) under complex operating conditions, existing methods still face several challenges. Environment-aware failure-rate updating is often disconnected from system-level assessment. The construction of Continuous-Time Markov Chain (CTMC) models still relies heavily on manual work. Repeated transient evaluation also becomes increasingly expensive as the state space grows. To address these problems, this study proposes a dynamic intelligent modeling and analysis method for the reliability and availability of THFR systems. A PEARL framework is developed by integrating Physics-Informed Neural Networks (PINNs) with large language model (LLM)-assisted automated modeling. The framework establishes a unified workflow for environment-aware failure-rate processing, automated CTMC generation, state-space reduction, and physics-constrained transient solving. Within this framework, the MarkovOps module can automatically generate explicit, rate-labeled Markov state transition diagrams from structured inputs or engineering textual descriptions. It also supports the modeling of complex mechanisms, including failures, repairs, standby switching, start-up failures, and common-cause failures (CCF). The PINN module is used to learn the temporal evolution of system state probabilities. It further enables rapid online querying of reliability and availability. The proposed method is validated using the Reactor Coolant System (RCS) and the Component Cooling Water System (CCWS) of THFR. The results show that the method can achieve rapid automated CTMC generation while maintaining assessment accuracy. It also supports fast multi-time inference after a single round of training. This study therefore provides a feasible approach for the online dynamic assessment of reliability and availability of research reactor systems.

Keywords

online dynamic reliability and availability; environment-aware failure rate; automated continuous-time Markov chain (CTMC) generation; Physics-Informed Neural Network (PINN); Tsinghua High Flux Reactor (THFR)

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