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基于 LightGBM 的核电站失水事故关键参数预测与相关性分析

摘要

全范围模拟机在核电厂应急演练、人员培训及事故分析环节具有关键作用。传统系统程序在反应堆系统处于复杂事故工况时计算性能无法满足实时性需求。本研究以核电厂小破口失水事故 (SBLOCA) 为对象，通过数字试验生成大规模数据集，经过数据预处理与标准化处理，利用机器学习人工智能算法建立了轻量梯度提升决策树（LightGBM）回归模型，并通过 SHAP 可解释性分析识别出特征贡献因素，该模型可用于预测燃料包壳峰值温度、反应堆一回路冷却剂压力及稳压器水位等关键参数。该模型均方误差（MSE）低于 0.002，决定系数（R^2）超过 0.98，预测速度较系统程序提升约 32500 倍，单个数据点计算耗时不足 0.0004 秒。本研究为核电站全范围模拟机复杂工况计算提供了一种新的解决方法。

关键词

核电厂仿真; 轻量梯度提升决策树; 参数预测; 相关性分析

Abstract

The full-scope simulator plays a critical role in nuclear power plant emergency drills, personnel training, and accident analysis. Traditional system programs lack sufficient computational performance to meet real-time requirements when simulating complex accident scenarios in reactor systems. This study focuses on the Small Break Loss of Coolant Accident (SBLOCA) in nuclear power plants, generating large-scale datasets through digital simulations. After data preprocessing and standardization, a lightweight Gradient Boosting Decision Tree (LightGBM) regression model was developed using machine learning algorithms. SHAP (Shapiro's Hypothesis Testing and Interpretation) analysis identified the contributing factors, enabling the model to predict key parameters such as fuel peak cladding temperature, primary reactor coolant pressure, and pressurizer water level. The model achieved a mean square error (MSE) below 0.002 and a coefficient of determination (R^2) exceeding 0.98, with a prediction speed approximately 32,500 times faster than traditional system programs—requiring less than 0.0004 seconds per data point. This study provides a novel solution for complex condition simulations in nuclear power plant full-scope simulators.

Keywords

Nuclear Power Plant Simulator; LightGBM; Parameter Prediction; SHAP

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