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基于 **L-D** 对抗神经网络框架的热工系统开放集事故诊断研究

摘要

随着社会经济的高速发展，工业生产对能源的需求日益增长。由于常规化石能源对环境存在着严重的污染，亟需加大新型能源的研发投入。随着核反应堆系统安全性和可靠性的不断提高，核能有望在安全性、经济性和环境友好性上达到新的高度，成为全球能源体系脱碳进程中不可或缺的支柱。为了提升反应堆的安全性，快速且精准的系统级故障诊断技术在核电厂中的应用显得尤为重要。现有的故障诊断研究大多基于封闭空间假设，即依靠有监督的方法学习人工标记好的数据进行故障分析。但上述方法模型参数固定，对于未知故障的识别并不敏感。事实上，反应堆系统的故障诊断是一个开集识别问题，系统无法获取所有信息，可能存在未知的变量或状态。基于上述限制，本文创新性地提出了一种基于对抗生成理论的 L-D 对抗神经网络的核电厂故障诊断新型框架。它通过逐步学习并标记未知故障的特征，实现识别未知故障的同时，可有效提高模型可靠性，并具备自我优化功能。通过高维度、非线性的复杂的 AP1000 核电厂软件 PCTran 的事故数据集和基于"华龙一号"后续核电机型智能化开发做设计搭建的 PHM 系统级热工实验台架故障实验数据集开展上述新型框架的可行性及泛化性验证。结果表明，L-D 对抗神经网络模型可以很好的提高未知故障的识别精度。与传统的 openmax、ocsvm 等开集识别算法相比，其对于未知故障识别的准确率提升了 5%-15%。通过 L 网络与 D 网络的不断对抗训练，不断的分离出未知故障特征，从而大幅提高了 L 网络识别未知故障的能力，为压水堆核电厂热工系统故障诊断及辅助决策提供技术支撑。

关键词

热力系统；系统故障诊断；核反应堆系统；开基识别 L-D 对抗神经网络

Abstract

With the rapid development of the social economy, the demand for energy in industrial production continues to grow. Due to the severe environmental pollution caused by conventional fossil energy, there is an urgent need to increase investment in the research and development of new energy sources. As the safety and reliability of nuclear reactor systems continue to improve, nuclear energy is expected to reach new heights in safety, economic efficiency, and environmental friendliness, becoming an indispensable pillar in the global energy system's decarbonization process. To further enhance reactor safety, fast and accurate system-level fault diagnosis technologies are particularly important for application in nuclear power plants. Most existing fault diagnosis studies are based on a closed-set assumption, relying on supervised methods trained on manually labeled data for fault analysis; however, such models have fixed parameters and are not sensitive to unknown faults. In fact, fault diagnosis in reactor systems is an open-set recognition problem, where the system cannot access all information and unknown variables or states may exist. To address these limitations, this paper innovatively proposes a novel fault diagnosis framework for nuclear power plants based on an L-D adversarial neural network derived from generative adversarial theory. The framework progressively learns and labels features of unknown faults, enabling their identification while effectively improving model reliability and incorporating self-optimization capability. The feasibility and generalization of the proposed framework are validated using the high-dimensional and nonlinear accident dataset generated by the AP1000 nuclear power plant simulation software PCTran, as well as fault experimental data from a PHM system-level thermal-hydraulic test platform designed and constructed for the intelligent development of the "Hualong One"nuclear reactor. The results show that the L-D adversarial neural network model significantly improves the accuracy of unknown fault identification. Compared with traditional open-set recognition algorithms such as OpenMax and OCSVM, the accuracy for unknown fault recognition is improved by 5%–15%. Through continuous adversarial training between the L network and the D network, unknown fault features are progressively separated, greatly enhancing the L network's capability to recognize unknown faults, thereby providing technical support for fault diagnosis and auxiliary decision-making in the thermal-hydraulic systems of pressurized water reactor nuclear power plants.

Keywords

Thermal systems; System-level fault diagnosis; Nuclear reactor systems; Open-set recognition; L-D adversarial neural network

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