INVESTIGATIONS ON THE PERFORMANCE OF INTELLIGENT TECHNIQUES FOR CONTROL AND FAULT DIAGNOSIS IN PRESSURIZED WATER REACTOR

A THESIS

Submitted by

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ABSTRACT

Nuclear reactors serve approximately 10% of the world's energy usage, and over 430 Nuclear Power Plants (NPP) are currently built globally. They are safety-critical systems as neutron flux density in the nuclear reactor core has to be critically controlled within limits. If neutron flux becomes uncontrolled due to an actuator failure, it leads to explosion and radiation hazards as witnessed in Chernobyl and Fukushima events. It is desirable that the parameters of a reactor core are monitored and optimally regulated to increase the performance of the system. Also, any fault in an NPP system may potentially compromise plant safety. Thus, implementing early Fault Detection and Diagnosis (FDD) techniques becomes crucial.

With considerable advancements in computational speed and electronics becoming cost-effective, Artificial Intelligence (AI) has made implausible growth in recent times. This research utilizes a few AI techniques to optimally control the neutron flux density and design an effective fault diagnosis algorithm to detect sensor faults in the nuclear reactor core.

The Swarm Intelligence (SI) optimization algorithms of AI are iterative stochastic search procedures that can be used to optimally tune the controller parameters to achieve efficient control. Optimization is the procedure of finding the best inputs u* in obtaining the optimal output y* with minimum cost J*. Regarding PID controller tuning, the optimization algorithm will find the controller parameters Kp*, Ki* and Kd* that minimize the error and control effort. The performance of two popular SI techniques namely Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) for PID controller tuning is compared. This optimally tuned PID controller regulates the neutron flux density of the Pressurized Water Reactor (PWR) core.

Ant colony optimization is a probability-based technique in which the optimal route is sought by observing the behaviour of ants looking to find a path

between their colony and a food source. Particle swarm optimization simulates the behavioural pattern of swarming birds or schooling fish. Both the PSO and ACO algorithms are data clustering algorithms that show swarm behaviour. However, the ACO is more suitable for problems where the origin and destination are predefined and precise.

Conventionally, PID controllers are tuned using Ziegler-Nichols (ZN) relay feedback method, process reaction curve or continuous cycling methods. A conventional PID-ZN controller’s performance is compared with the proposed PID-PSO and PID-ACO controllers under load following conditions of PWR via various quantitative performance measures like Integral Square Error (ISE), Integral Absolute Error (IAE), Integral Absolute Control (IAC). Moreover, the optimally tuned PID controller is combined with a Linear Quadratic Regulator (LQR) which is a full-state feedback controller and constructed with the prime motive of regulation of all state variables. This hybrid PID-LQR controller has enhanced regulation in the presence of disturbances. When there are disturbances affecting state variables, the hybrid-ACO control structure designed performs better than the PID-ACO control structure. Excellent tracking with optimal control efforts for ACO-tuned controllers is demonstrated by the simulation results.

Upon successful implementation of SI algorithms for controller tuning, the next phase of this research work is on designing a Neural Network based state estimator for the PWR core. The PWR is a multi-rate nonlinear system in which the state variables progress with widely varying dynamics. It has state variables such as reactivity and delayed neutron precursor densities which are difficult to measure via sensors. Reactivity signifies the criticality of the reactor core. Delayed neutron precursors are the source of delayed neutrons which plays a vital role in the change of neutron densities. Besides, the other states which are measured are also corrupted by measurement noise and are susceptible to sensor faults. Thus, the estimation of these state variables becomes critical.

The traditional nonlinear state estimators like the Ensemble Kalman Filter (EKF), Unscented Kalman Filter (UKF), and Particle Filter (PF) are long established. They do, however, require prior knowledge of the system's nonlinearities. Neural network estimators, on the other hand, are data-driven and rely solely on the input-output measurement of the process. This research compares three neural network topologies namely Feed-Forward Neural Networks (FFNN), Dynamic NARX Neural Networks, and Recurrent Neural Networks (RNN) for estimating the reactor core states. Based on the Mean Square Error (MSE) values for trained and test reference signals, the performance of the NN models is analysed. The performance of the selected neural estimator is also compared with the Unscented Kalman estimator. Upon observing three different test scenarios, it is found that a RNN model with 10 hidden neurons gives better estimate of PWR states.

The selected NN state estimator which outperforms other estimators can be used as an analytical redundant component for early fault detection. Analytical redundancy is a model-based fault detection method wherein states are estimated analytically from other correlated measurements using the model or plant data. Residuals are generated by comparing analytically estimated. When the residual signal crosses the threshold, a fault is indicated. Upon assessing the residual trend, faults can be classified as additive or multiplicative. Instant fault isolation can be achieved via structured or directional residuals. Structured residuals are obtained in this work.

To perform Fault Detection and Isolation (FDI), a bank of residuals of state variables is obtained such that each residual is responsive to a subsection of faults and unresponsive to others. Consequently, an exclusive fault signature is attained for each fault case. One of the merits of the proposed procedure is that it does not necessitate the fault history of the process or first principle models.

The effectiveness of the designed recurrent neural network model for fault detection and isolation of PWR is studied under five different sensor faults scenarios namely drift, erratic, hard-over, spike and stuck. By analyzing the residuals, a structure matrix is formed based on the fault signature. It is noted that the sensor fault in the state variables of PWR leaves a fault signature ‘1’ in its respective residual only, whereas the sensor fault in the input and output variable of PWR leaves a fault signature ‘1’ in all other state residuals except it’s respective residual. The formation of this structure matrix will aid in identifying the location of the faults.