HNPS 2026 , University of Thessaly , Lamia

Comparative Analysis of Turbine Leading and Reactor Leading Operating Modes in an iPWR Simulator under Load-Following Conditions

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Abstract

The urgent need for carbon-free energy production has established Small Modular Reactors (SMRs) as a vital component of the clean energy transition. Characterized by an electrical output of 10 to 300 MWe, SMRs offer significant versatility, operating in base-load mode for grid stability or in load-following mode to compensate for intermittent Renewable Energy Sources (RES). A key advantage over conventional reactors is their enhanced safety, relying on passive systems that operate without external power or human intervention. To ensure safe deployment, high-fidelity simulation tools are essential for educational purposes and for studying reactor behavior during normal and malfunction scenarios. This study investigates the operational behavior of an integral Pressurized Water Reactor (iPWR) using the IAEA-TECNATOM simulator. The tool models a generic 150 MWth (45 MWe) iPWR with a 4.95% enriched UO2 fuel core, integrating comprehensive primary, secondary, safety, and control systems. Specifically, we examine the dynamic response of the iPWR under a 10% load maneuvering scenario (100% to 90% power reduction and subsequent restoration), comparing two distinct plant operating modes: Turbine Leading and Reactor Leading. In the Turbine Leading mode, electrical output is regulated directly by the turbine control valve, with the control rods modulating core thermal power to match secondary side demand. Conversely, the Reactor Leading mode drives electrical output indirectly via core thermal power regulation using control rods and boron concentration modifications. The results demonstrate that the Turbine Leading mode provides superior precision and faster dynamics. The Turbine Leading mode completes the power decrease in 11 minutes and recovery in 19 minutes. In contrast, the Reactor Leading mode requires 25 minutes for power reduction and 33 minutes for recovery due to indirect neutronic and reactivity feedback. Consequently, the Turbine Leading strategy proves more effective for the high-RES penetration grids and flexible nuclear operations characterizing modern and future power systems.

I. Introduction

The iPWR-SMR simulator provides two distinct plant operating modes selected by the operator: Turbine Leading and Reactor Leading mode. In the Turbine Leading mode, normal operation of a typical PWR, the turbine admission valves are modulated to satisfy the electrical power demand. Consequently, the PCS automatically adjusts core reactivity via control rod positioning to maintain the coolant average temperature (Tavg) at its reference setpoint. Conversely, in the Reactor Leading mode, normal operation of a typical BWR, the thermal power is directly regulated through reactivity control. In this mode, the electrical output tracks the reactor's thermal generation, while the turbine control valves adjust the steam flow to maintain a constant steam header pressure.

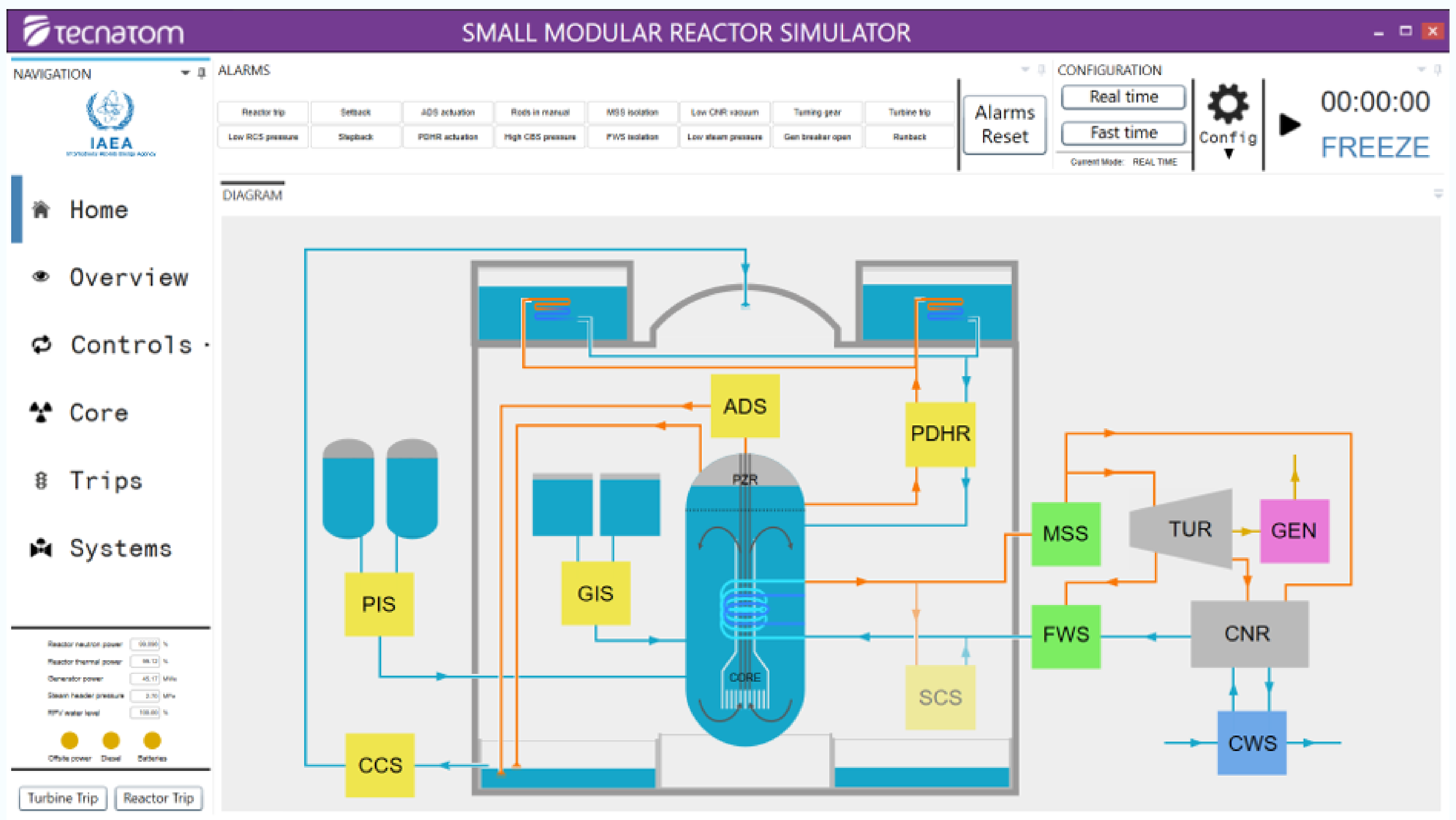

Figure 1: A correlation matrix with the characteristic intrinsic, element-wise noise. The SNR is defined as the ratio of the peak height to the standard deviation of the noise.

II. Simulation

iPWR simulator, developed by the IAEA in collaboration with TECNATOM [1]. This simulation tool models a generic iPWR [Fig. 1] designed with a thermal power output of 150 MWth and electrical output of 45 MWe. The core configuration implemented in the model utilizes uranium dioxide UO2 fuel with an enrichment of 4.95%, reflecting typical design parameters aimed at extending the fuel cycle length.

We investigate the dynamic response of the iPWR under a load maneuvering scenario, comparing two distinct plant operating modes: Turbine Leading and Reactor Leading. Specifically, the study analyzes a 10% load maneuver, defined by a power reduction from 100% to 90% of nominal load, followed by a subsequent restoration to full power (100%).

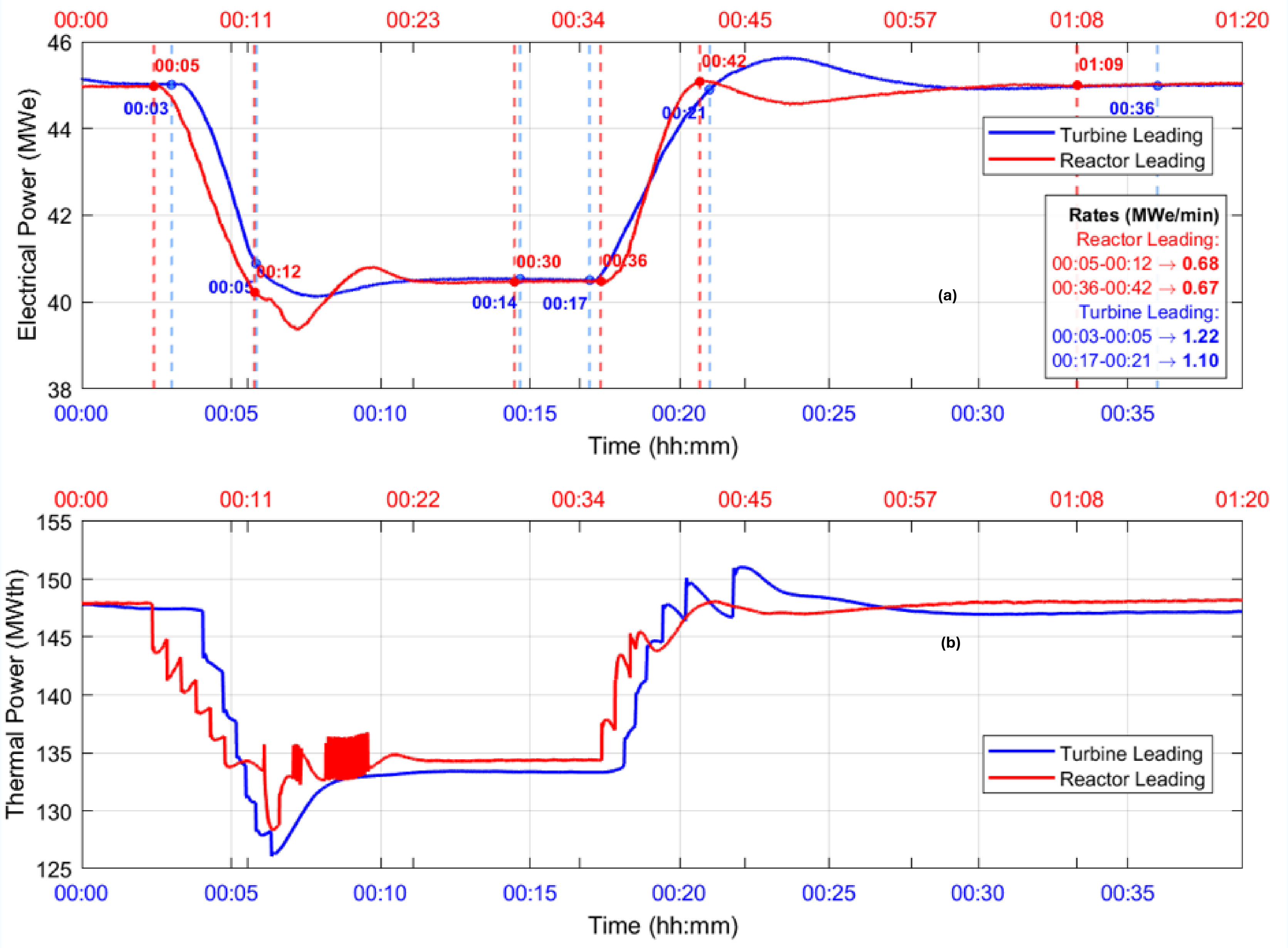

Figure 2: Reactors response at Turbine Leading and Reactor Leading

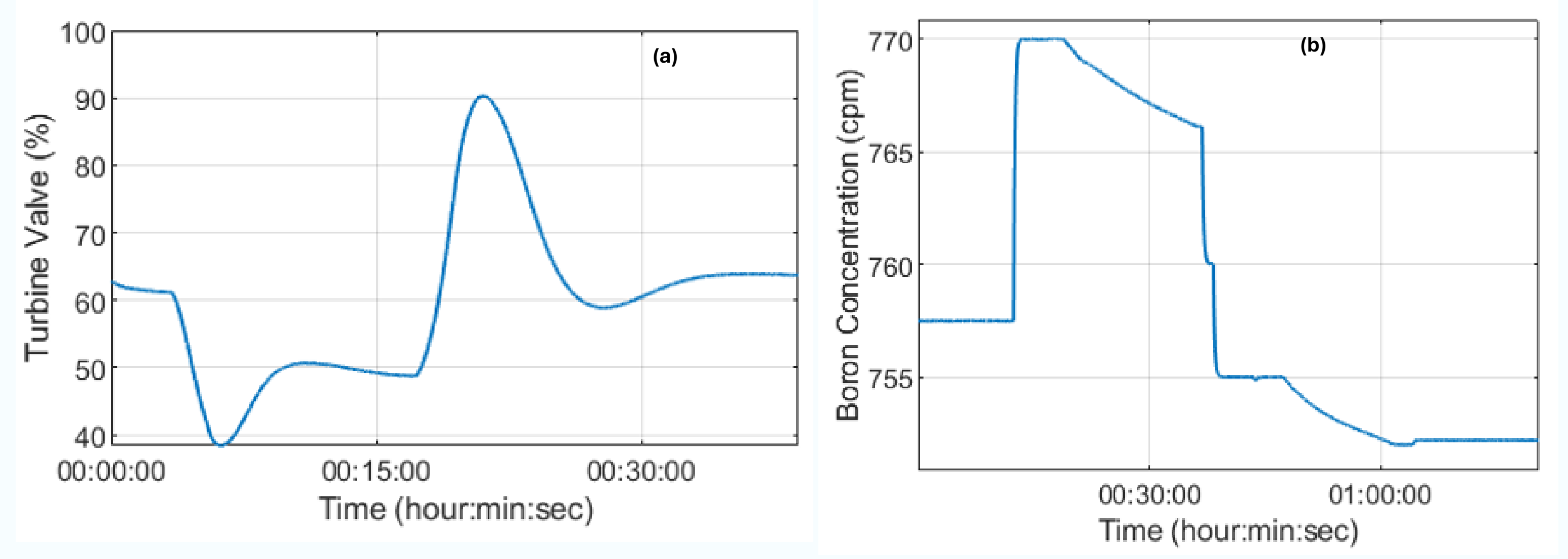

Figure 3: Turbine control valve at Turbine Leading and Boron concentration modification at Reactor Leading

III. Results

Figure 2 illustrates the reactor's dynamic response under the Turbine Leading operating mode. In this mode, the generator's electrical output [Fig. 2(a)] is strictly regulated by turbine control valve position [Fig. 3(a)]. Modulating the steam flow to the turbine directly dictates the electrical power level. To maintain the energy balance, the PCS subsequently actuates the control rods —inserting or withdrawing them— to align the core's thermal power [Fig. 2(b)] with the secondary side demand. Consequently, the electrical output precisely tracks the grid load variations.

In parallel, Figure 2 depicts the reactor's response under the Reactor Leading operating mode. In this mode, the electrical output [Fig. 2(a)] is driven exclusively by the reactor's thermal power generation [Fig. 2(b)]. Through the coordinated actuation of control rods and boron concentration modification [Fig. 3(b)], the core thermal power is regulated to reach the desired target level. Consequently, the electrical output is modulated to track grid load variations, achieving load following.

Comparing the two operating modes, the Turbine Leading mode demonstrates superior precision and faster dynamics in electrical power regulation. This accuracy is attributed to the fact that the electrical output is directly modulated by the turbine control valve position. Consequently, the system exhibits a smooth and rapid response to load variations. Specifically, as detailed in the inset table of Fig. 5(a), the ramp rates for both the reduction and increase of electrical power are higher in the Turbine Leading mode. This rapid response is further evidenced by the shorter time intervals required for the power to stabilize. The power decrease is completed within 11 minutes (00:03 to 00:14), and the subsequent recovery takes 19 minutes (00:17 to 00:36). Conversely, the Reactor Leading mode results in slower and less precise electrical power control. In this mode, the electrical output follows the thermal power generation, making the control mechanism inherently indirect. Because of this indirect control, variations in neutronic balance and core reactivity are reflected in the electrical output. As a result, the transient periods until stabilization are notably longer, requiring 25 minutes (00:05 to 00:30) for the power reduction and 33 minutes (00:36 to 01:09) for the power recovery.

IV. Conclusions:

Considering these findings, the Turbine Leading mode demonstrates a superior response to load variations, particularly regarding the stability and precision of the generated electrical power. Given the increasing demand for load following capabilities in modern grids characterized by high-RES penetration [2], the Turbine Leading strategy appears to be the most suitable operating mode. This conclusion is further supported by the technical and economic requirements for flexible nuclear operation [3], suggesting that Turbine Leading proves to be more effective in handling the dynamic needs of future power systems.

Acknowledgements: We would like to thank IAEA for providing the iPWR simulator

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