

Development of a Flexible Operation Evaluation Program for Establishing Reactor Core Control Strategy and Preliminary PCI Analysis

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I. Introduction

- In the field of Small Modular Reactors (SMRs), research on Low Enriched Uranium Plus (LEU+) and Accident Tolerant Fuel (ATF) has been actively conducted to reduce the generation of spent nuclear fuel. Accordingly, there is a growing need to quantitatively evaluate the load-following performance of SMR cores utilizing LEU+/ATF. To perform such evaluations, it is essential to establish detailed core loading models, control rod control strategies, and specific evaluation scenarios in advance.
- While a basic program for this purpose was developed in a previous study, this research extends it by newly implementing features to compare various control strategies and to monitor the primary indicators associated with Pellet-Cladding Interaction (PCI), which directly affects fuel integrity, thereby establishing a foundation to perform practical PCI assessments through integration with a specialized fuel design code.

II. Program Features

Local Data Derivation & Preliminary PCI Analysis

- Tracks rapid local power changes, a primary indicator of Pellet-Cladding Interaction (PCI) risk, at the fuel rod level.
- Visualizes real-time power fluctuations and time-dependent trends to preemptively assess cladding integrity during load-following operations (Fig. 1).

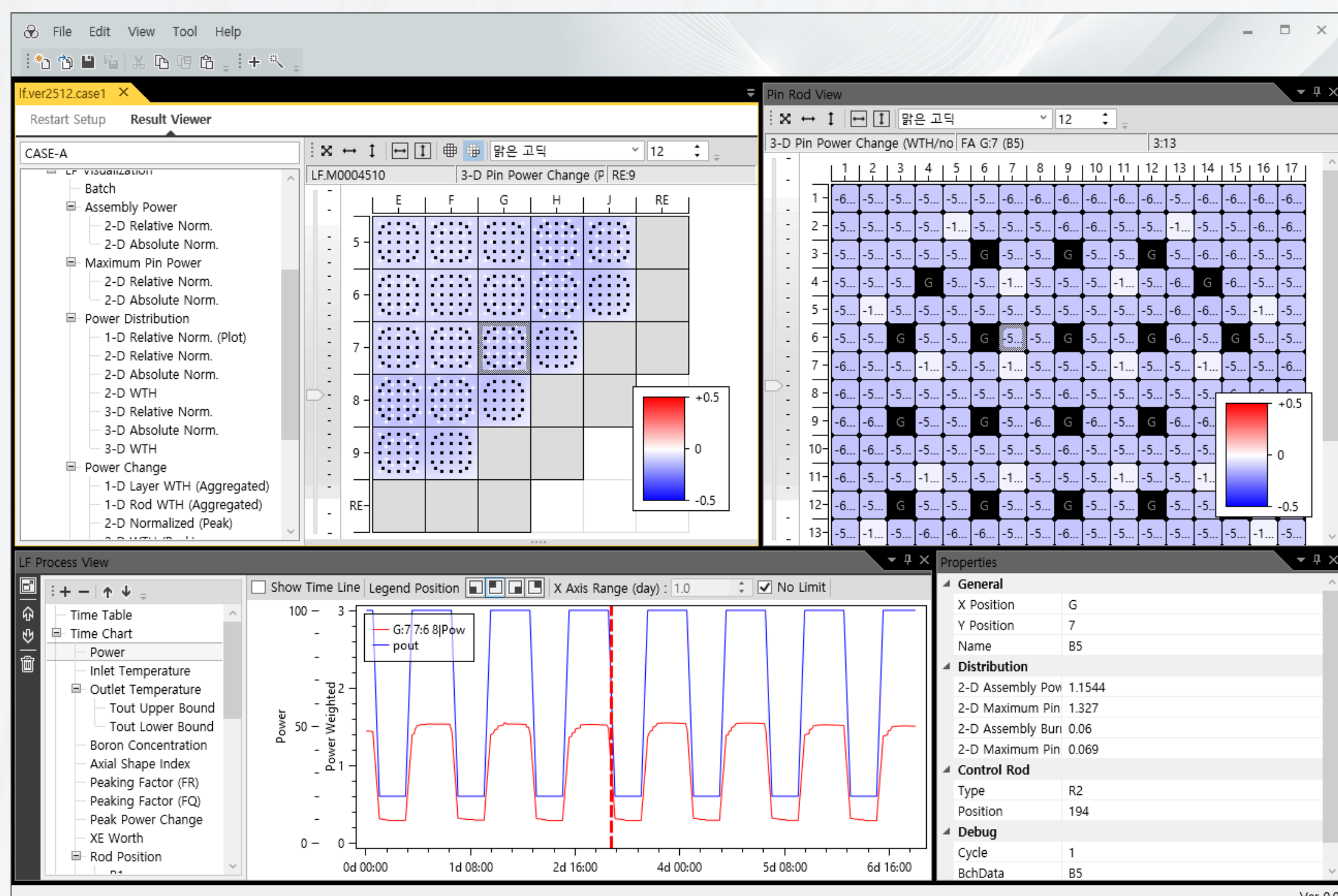


Fig. 1. Program interface visualizing the local power changes and the trend graphs of power changes for fuel rod nodes at a specific axial position within the fuel assembly.

Data Sorting & Integration with Fuel Design Codes

- Systematically screens and sorts vulnerable fuel rods experiencing significant power variations among the core (Fig. 2).
- Establishes a technical foundation for rigorous thermo-mechanical PCI assessments by automatically generating input files for specialized fuel design codes.

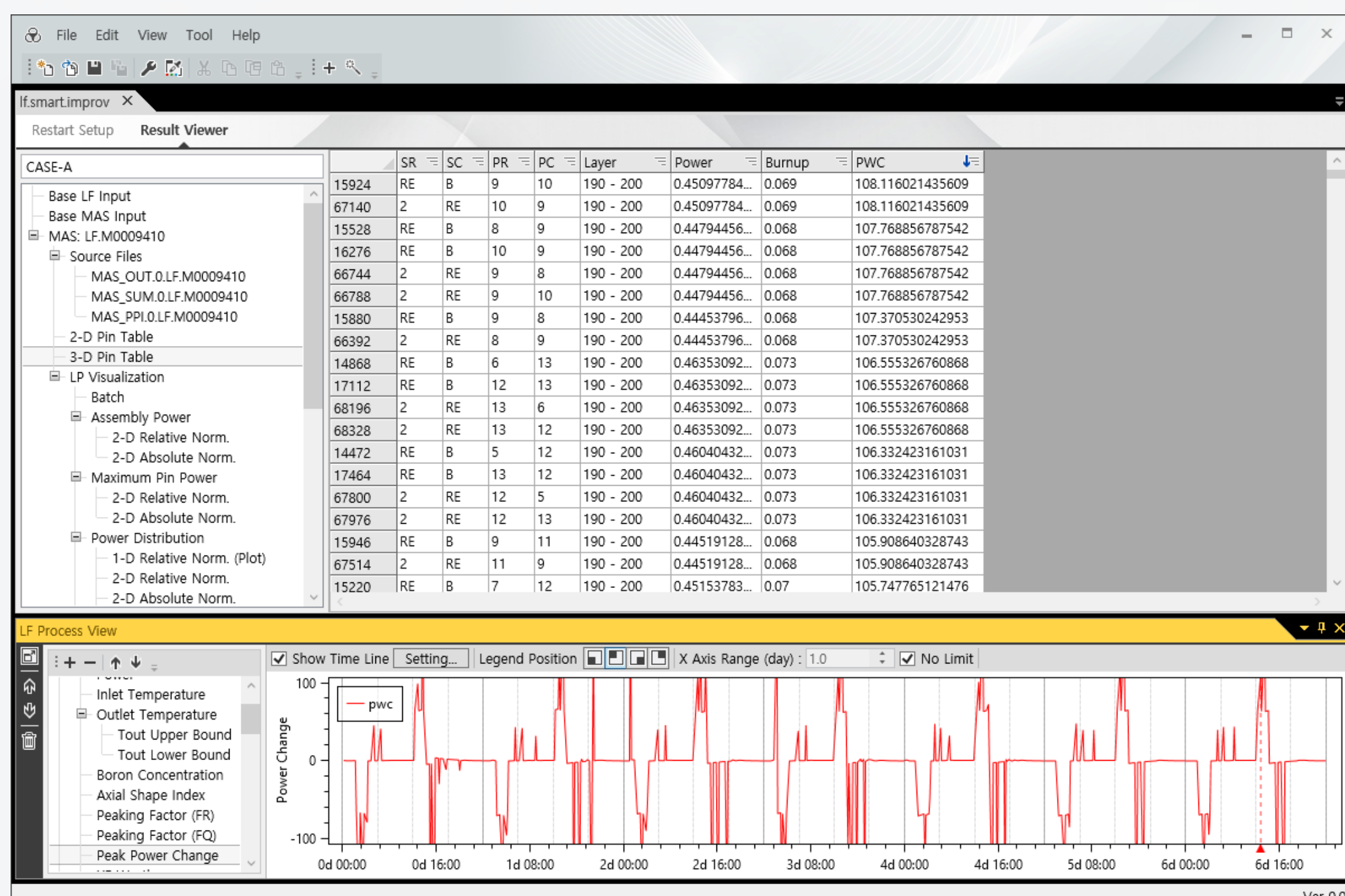


Fig. 2. Example of a data list for all fuel rod nodes sorted by local power change.

Control Strategy Comparison

- Simultaneously simulates multiple operational scenarios applying different control algorithms.
- Quantitatively compares cumulative control rod movements, local power changes, and core stability parameters (e.g., ASI) across various strategies.

III. Application and Verification

- Simulated a 7-day, 100-20-100 daily load-following operation for the SMART reactor, monitoring ASI compliance and local power changes.
- Compared two control strategies based on coolant outlet temperature (T_{out}) dead-bands: $\pm 3^\circ\text{C}$ (Case A) vs. $\pm 2^\circ\text{C}$ (Case B).
- Applied practical control logic: prioritizing control rod driving (R-banks) for reactivity and ASI control, supplemented by boration/dilution when margins are insufficient.
- Strategy Trade-off: Visualized results confirmed that Case A reduces cumulative control rod movement, whereas Case B significantly minimizes local power fluctuations.
- Irreversible Power Change: Identified a specific vulnerable fuel node (max change: -237 WTH) that failed to fully recover its initial local power after the daily cycle ended.
- Root Cause & PCI Risk: This irreversible shift is primarily attributed to asymmetric localized Xenon transients. It continuously affects the conditioning and deconditioning of the fuel, acting as a major factor that increases PCI likelihood.

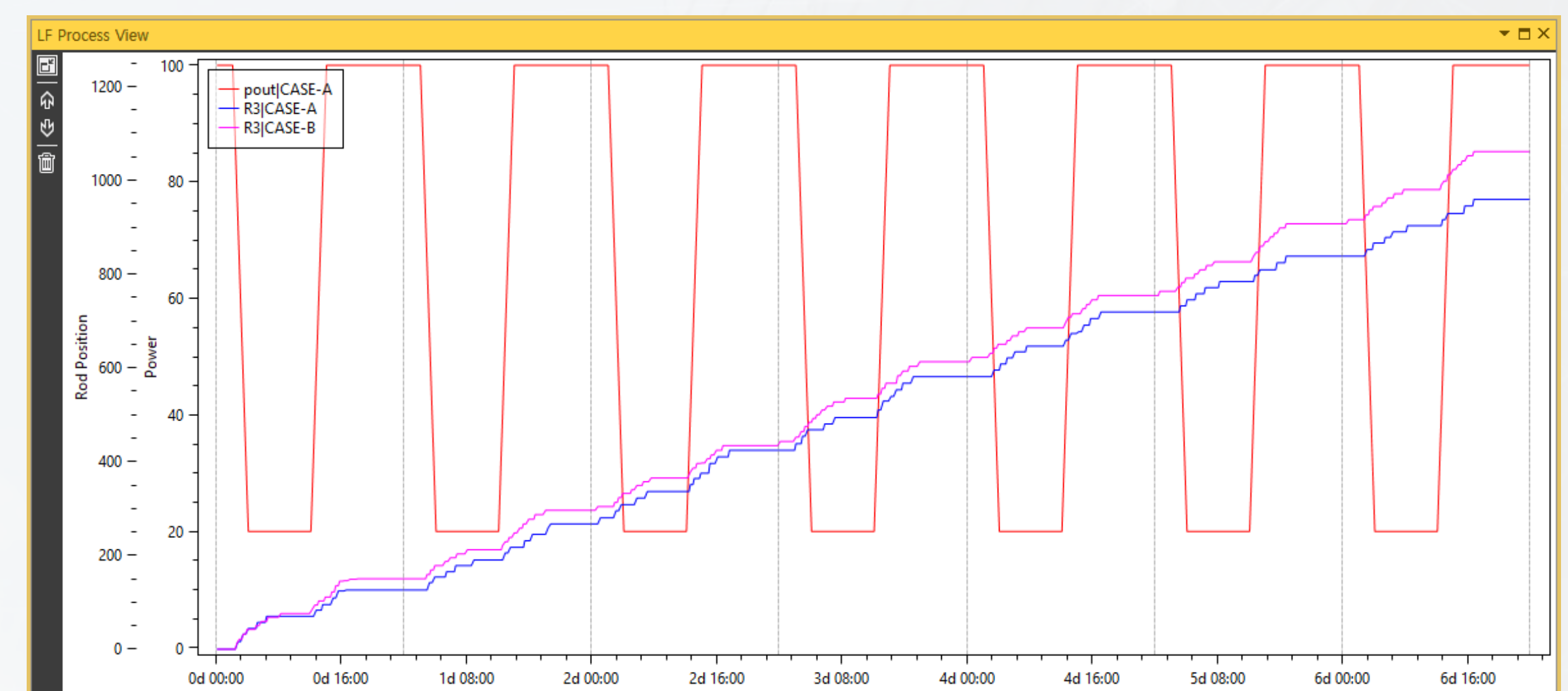


Fig. 3. Comparison results of control strategies over a one-week period, showing the graphs of cumulative control rod driving distance.

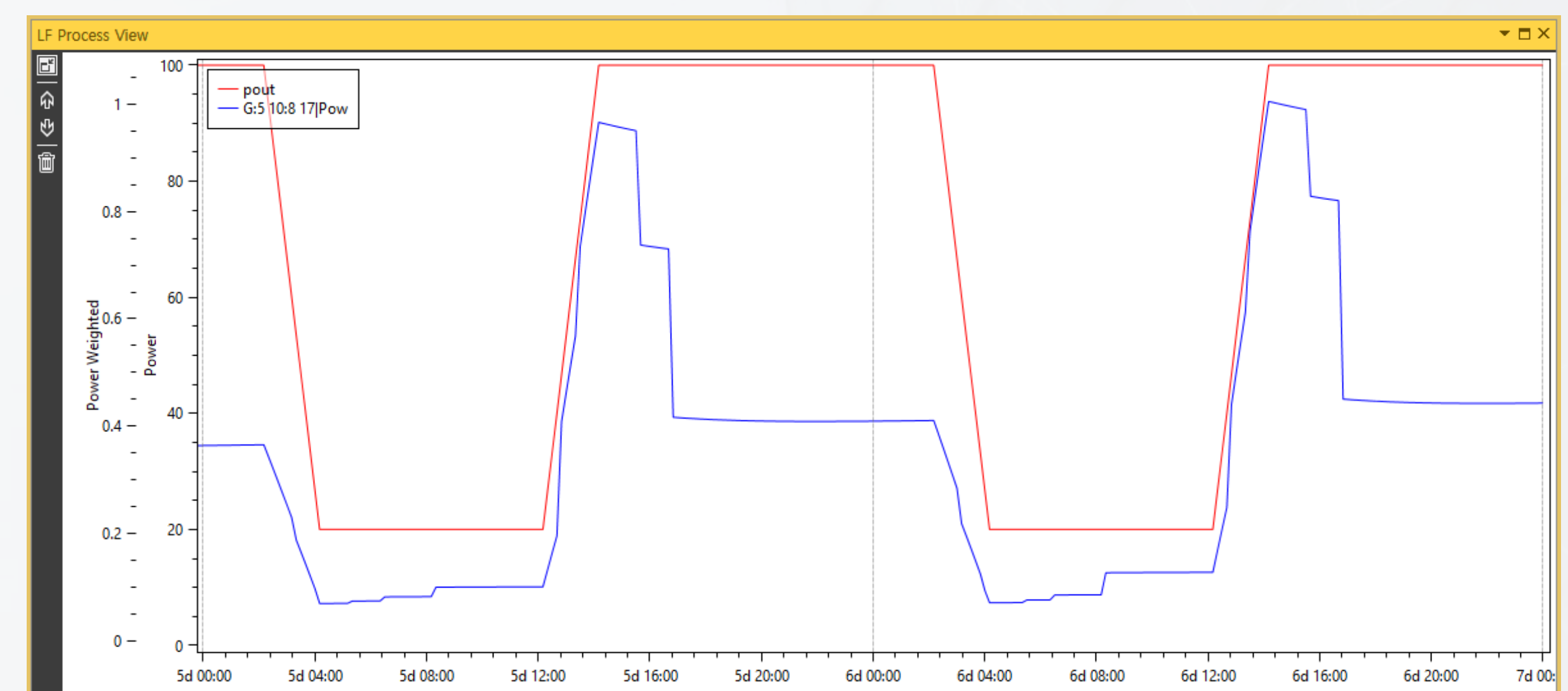


Fig. 4. Reactor Power (Red) and Local power graphs of a specific fuel rod node (Blue) exhibiting irreversible power changes.

IV. Conclusions

- As a result of simulating different control strategies, it was confirmed that significant behavioral differences occur in terms of control rod driving distance and local power changes depending on the established criteria of the strategy.
- In particular, the irreversible change trend of local power observed during load-following operations was identified as a key characteristic that increases the likelihood of future PCI occurrence. Through the feature that classifies and sorts fuel rod characteristics based on this trend, it is anticipated to be highly useful in performing actual PCI assessments by integrating with fuel design codes in the future.

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