Transactions of the American Nuclear Society, Volume 70 (June 1994)

2. Automation for Efficient and Safe Large Power Changes in Nuclear Power Plants, *Chen-Kuo Weng, Robert M. Edwards, Asok Ray (Penn State)*

This paper presents a robust control structure for wide-range operations of nuclear power plants, which is built upon the feedforward and feedback concepts and provides guaranteed robust stability and performance. Nonlinear programming and the μ approach are applied to synthesize the optimized feedforward and robust feedback control policies, respectively. The results of simulation experiments are presented to demonstrate efficacy of the proposed control structure for a large rapid power reduction or scheduled shutdown.

Operational safety and high performance are the impetus for automation and control of nuclear power plants.[1] The proposed automatic control strategy is conceptually similar to the sequence of actions taken by an experienced human operator and would significantly reduce the risk of human errors.

From the perspectives of automatic control, the prescriptive operator-based approach can be viewed as a combination of both the feedforward control (FFC) and the feedback control (FBC). The procedures followed by the human operator are analogous to the FFC, which steers the plant from the initial operating point to the final desired operating point under nominal conditions. In addition to the prescribed inputs, the corrective actions taken by the human operator based on the sensor data are analogous to the FBC.

Since the FFC (whether automatic or manual) is based on off-line design, on-line FBC actions are necessary to fine-tune the control system to compensate for any possible deviations of the plant response from the desired trajectory. Figure 1 summarizes the combination of these two control policies, where the main function of the FFC is to provide good nominal performance, and the objective of the FBC is to achieve both stability and performance robustness. The FFC is synthesized by nonlinear programming[2] to achieve optimized performance under specified constraints. The H_∞-based structured singular value (μ) approach is adopted to synthesize the FBC. The specific advantage of this μ approach is that it allows a systematic evaluation of the robust performance measure of the synthesized control system.[3]

To examine its efficacy, the FF/FB controller was designed to regulate the reactor power in the 100 to 25% range with a good temperature response.[4] Furthermore, in response to the

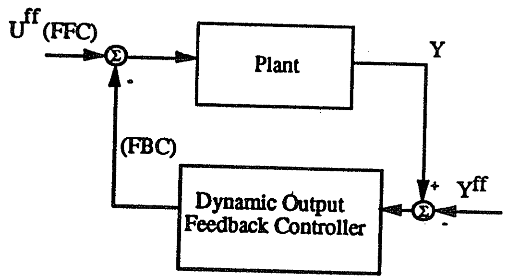

Fig. 1. The proposed feedforward/feedback control system.

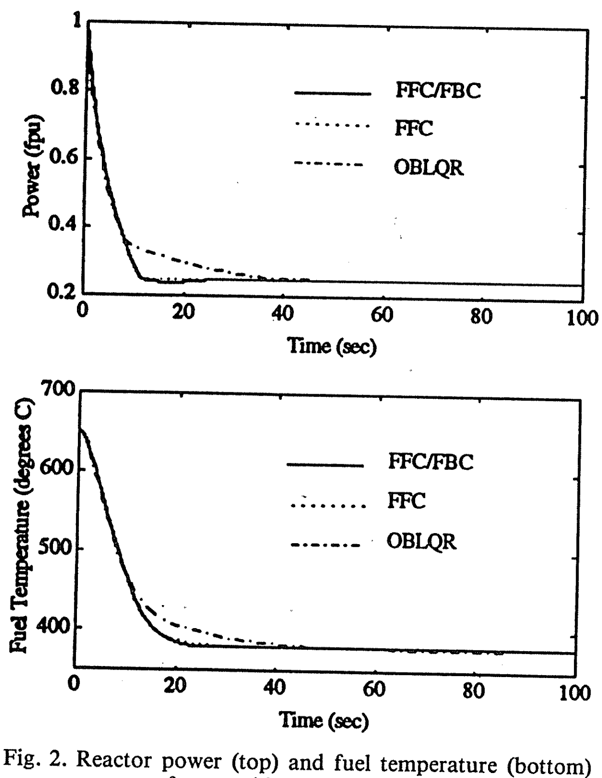

Fig. 2. Reactor power (top) and fuel temperature (bottom) response for a rapid cutback from 100 to 25% power using a proposed FFC/FBC, feedforward control alone (FFC), and an OBLQR.

operational and safety requirements, the reactor power was rapidly reduced to lower the core temperature. Safety systems, independent of automatic control, are incorporated in nuclear plants to shut down the power generation; however, the stress resulting from their activation may significantly reduce plant service life[5] and require a prolonged outage to restart the reactor from the hot-standby condition. An efficient automated system to rapidly maneuver the plant to a safe intermediate power level in a controlled manner is thus desirable.

CONCLUSIONS

Extensive simulation experiments have been conducted to compare the performance of the proposed FF/FBC with that of the previous work using an observer-based linear quadratic regulator[1,4] (OBLQR). The plant under consideration is a pressurized water reactor (PWR) and is modeled with six delayed neutron groups and temperature feedback based on the lumped fuel and coolant temperature.[1] As compared in the simulation results of Fig. 2, the FF/FBC system reaches the desired equilibrium power level much faster than the OBLQR system. The two major advantages of FF/FBC are summarized as follows:

1. significantly superior performance in contrast to that solely based on feedback
2. guaranteed robust stability and performance under specified uncertainty bounds are guaranteed.

1. R. M. EDWARDS, K. Y. LEE, A. RAY, "Robust Optimal Control of Nuclear Reactors and Power Plants," *Nucl. Technol.*, **98**, 137 (1992).
2. D. G. LUENBERGER, *Linear and Nonlinear Programming*, Addison-Wesley (1973).
3. A. PACKARD, J. C. DOYLE, "The Complex Structured Singular Value," *Automatica*, **29**, *1*, 71 (1993).
4. C.-K. WENG, R. M. EDWARDS, A. RAY, "Robust Wide Range Control of Nuclear Reactors Using the Feedforward-Feedback Concept," to appear in *Nucl. Sci. Eng.*
5. A. RAY, X. DAI, M. CARPINO, C. F. LORENZO, "Damage-Mitigating Control—An Interdisciplinary Thrust Between Controls and Material Science," *Preprints Proc. American Control Conf.*, Baltimore, Maryland, June–July 1994.