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3. Multilayer Robust Control for Safety Enhancement of Reactor Operations, *R. M. Edwards, K. Y. Lee, Asok Ray (Penn State)*

INTRODUCTION

A novel concept of reactor power and temperature control has been recently reported[1-3] in which a conventional output feedback controller is embedded within a state feedback setting. The embedded output feedback controller at the inner layer largely compensates for plant modeling uncertainties and external disturbances, and the outer layer generates an optimal control signal via feedback of the estimated plant states. A major advantage of this embedded architecture is the *robustness* of the control system relative to parametric and nonparametric uncertainties[4] and thus the opportunity for designing fault-accommodating control algorithms to improve reactor operations and plant safety.

DISCUSSION

Figure 1 illustrates the architecture of the state-feedback-assisted classical (SFAC) control,[1-3] which utilizes an embedded output feedback controller designed via classical techniques.[5] Switch position A in Fig. 1 corresponds to operation of the output feedback controller for reactor power regulation. The error signal (i.e., the difference between the desired power and the measured power) is an input to the classical controller (of gain G_c), and the resulting manipulated variable is the control rod speed z_r. Switch position B in Fig. 1 determines the SFAC configuration, which creates a modified power demand signal P_m to accomplish an optimal control objective. The optimal control law improves reactor temperature response by estimating and feeding back the internal states of the reactor, e.g., average reactor fuel temperature and precursor density, based on an approximate (uncertain) dynamic model of the reactor. A major feature of this embedded control architecture is that the model-based state estimator is subjected to reduced modeling uncertainty due to the inherent uncertainty compensation performed by the output feedback at the inner layer. In contrast, a conventional state feedback control (CSFC) configuration, i.e., without the embedded controller and using an equivalent control law, would manipulate the rod speed directly and be subject to uncompensated uncertainties. Sources of uncertainties between a real-world reactor and its mathematical model incorporated in a state estimator are (a) physical parameters, e.g., the actual plant control rod worth G_r is different than that used in the controller; (b) unmodeled dynamics, e.g., the controller may model only one or two delayed neutron groups, whereas the actual plant is of higher order; and (c) unmodeled nonlinearities, e.g., the controller may use a linearized model of the actual nonlinear process.

RESULTS

Figure 2 demonstrates the difference between the performance of CSFC and SFAC by examining the sensitivity of the dominant eigenvalues of the individual closed-loop systems.[3] The specific case of modeling error considered is a low-order model-based controller, formulated on the basis of one delayed neutron group applied to the control of a reactor represented by six delayed neutron groups. For either configuration, the position of the dominant eigenvalue is a function of the equilibrium power level due to the nonlinear characteristic of the reactor. Because of the embedded classical controller, the SFAC configuration can be designed to be more robust by tuning the gain of the embedded controller that provides additional damping for plant transients. As this gain is adjusted toward zero, the benefit of the embedded classical output feedback controller is reduced, and the sensitivity of the SFAC to

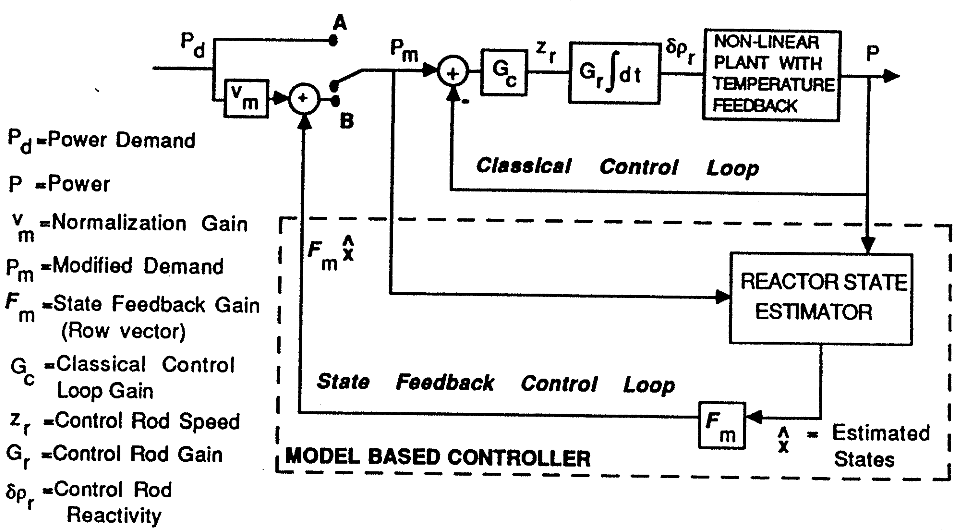

Fig. 1. State-feedback-assisted classical control.

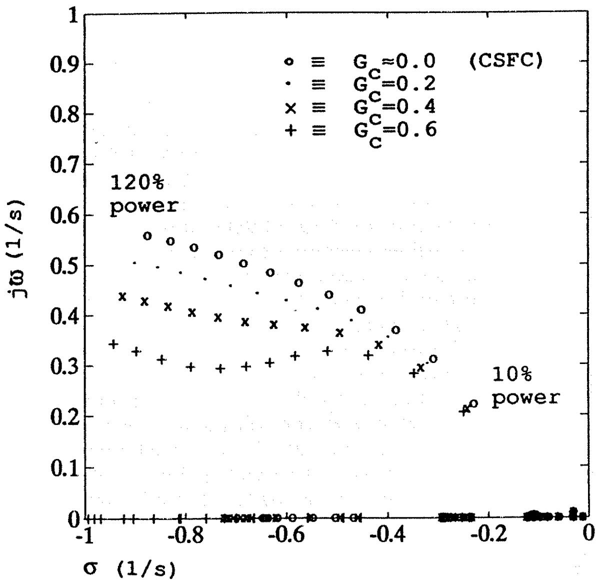

Fig. 2. Robustness characteristic of an embedded classical controller with gain G_c: dominant eigenvalue as a function of power (120 → 10%).

uncertainties approaches that of the less capable CSFC configuration.

CONCLUSION

The proposed multilayer SFAC concept is more robust than conventional single-layer state feedback systems because the detrimental effects of modeling uncertainties and disturbances are largely mitigated by an embedded output feedback controller. This robustness advantage has also been verified[3] via simulation of high-order nonlinear plants using the modular modeling system[6] and is important for accommodating component malfunctions and other parametric uncertainties. Current and future research is being directed toward exploitation of multilayer control configurations as a new dimension of robust fault-accommodating control of power plants for enhanced operational safety.

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