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Abstract

Present digital control system hardware allows the implementation of advanced computerized control algorithms with a high degree of sophistication. In addition to improving disturbance rejection and demand following capabilities, computerized algorithms can provide robustness for abnormal operating conditions while providing diagnostic information on either the plant or the controller itself.

This paper describes the development and implementation of a digital model-based reactivity control system that incorporates a knowledge of the plant physics into the control algorithm to improve system performance. This controller is composed of a model-based module and a modified proportional-integral-derivative (PID) module. The model-based module has an estimation component to synthesize unmeasurable process variables that are necessary for the control action computation. These estimated variables, besides being used within the control algorithm, will be used for diagnostic purposes by a supervisory control system under development.

The PID module compensates for inaccuracies in model coefficients by supplementing the model-based module output with a correction term that eliminates any demand tracking or steady state errors. This control algorithm has been applied to develop controllers for a simulation of liquid metal reactors in a multimodular plant. It has shown its capability to track demands in neutron power much more accurately than conventional controllers, reducing overshoots to almost negligible values while providing a good degree of robustness to unmodeled dynamics.

Introduction

The latest trends in nuclear reactor research and development activities are based on the concepts of modular, inherently safe plant designs with passive safety characteristics. Many of these desirable features are based on relatively low power densities, large thermal inertia, and

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strong inherent negative reactivity feedback. While these features will improve the safety margin of future reactors, they will also impact some issues regarding the controllability of the overall power plant. Large thermal inertias and long transport delays render the system more difficult to control during transients, favoring conditions for large parameter fluctuations before attaining new steady state conditions.

It is likely that future nuclear reactors will have a larger share of grid frequency regulation responsibility than today's reactors, implying that they will be subject to daily load cycling. In order to minimize reactor fuel and component thermal and mechanical stresses, unnecessary power fluctuations should be avoided whenever possible. Conventional controllers present the designer with the challenge of tuning the system for fast response while maintaining relatively small over- or undershoots. These two often conflicting objectives could be achieved through the use of a more suitable type of controller.

Control systems for nuclear reactors have, so far, been implemented mainly with combinations of conventional analog controllers such as the proportional-integral-derivative (PID). In those operating plants being retrofitted, conventional analog controllers are replaced with their equivalent digital versions (Ref. 1) to minimize downtime. While this retrofitting provides some advantages from the reliability and maintainability points of view, it fails to provide improvement on the plant transient performance.

Only in a few cases, like in CANDU reactors, do digital control systems make use of more elaborate algorithms. These include such features as gain scheduling techniques and actuator speed selection (Ref. 2).

Knowledge of the physical behavior of a process can be exploited to design new controllers to significantly improve the closed loop performance of that process. These so called "model-based" controllers (Ref. 3) take into account the functional relationships between plant variables and controls.

All model-based controllers require a mathematical description of the plant or the subsystem to be controlled. This mathematical description involves a functional relationship among the variables representing the process as well as an appropriate set of numerical values for the equation coefficients. The models required for process control system design do not need to be too detailed in general. Spatial effects can be neglected most of the time and typically a few nodes with lumped parameter representation will suffice.

In the case of power generation control in nuclear reactors the neutron flux dynamics is a nonlinear function of the control rod position and the past and present power levels. Upon achieving a new level following a power maneuver, the control rods must still be manipulated to compensate for the effect of delayed neutron precursor concentration and reactor feedback effects from changing fuel and coolant temperatures.

Although much theoretical development has been applied to the flux control problem, there have been only a few put into actual practice, with most of them occurring in experimental research units. One of the most interesting examples is the Nonlinear Digital Controller (NLDC) developed by Bernard et al. (Ref. 4) at MIT-CSDL.

In this work, an original approach is taken to compensate for modelling inaccuracies present in real-life situations. The result is a reactivity controller that has the advantage of using a mathematical plant description to generate the bulk of the required control action and an error correcting, plant-independent, general-purpose conventional controller that compensates for any effects unaccounted for by the model.

Controller Philosophy

Most physical systems can be represented by a set of mathematical relationships describing as accurately as necessary the dynamics of the process through an appropriate set of state variables. The process dynamics can be represented as a set of ordinary differential equations, either linear or nonlinear, of the form (see Appendix for nomenclature):

$$\dot{X} = f\,(X, U, t\,). \qquad (1)$$

This set of differential equations contains information about the relationship between state variables, their derivatives and the control actions. If this mathematical model represented the real process exactly, a control action U could be generated by formal inversion of eq. (1) so that the plant variables could follow a specified set of trajectories D. This inversion could be formally represented by:

$$U = g\,(D, X, \dot{X}, t\,). \qquad (2)$$

Unfortunately, this ideal situation of perfect plant knowledge seldom occurs so that feedforward control alone is seldom practical. Nevertheless, this idea has served as the basis for the implementation of several control systems in the area of robotics where this technique has received the name of "Inverse Dynamics" (Ref. 5).

Due to certain process modelling errors, a compensating mechanism should be provided to correct any errors in the control action computation. In this work, a PID module was chosen to compensate for inaccuracies in modelling by supplementing the model-based module output with a correction term that eliminates any demand tracking or steady state errors.

State Estimation

The variables chosen for mathematical representation of a real plant may not all be readily accessible for measurement, so that an observer or estimator should be used to synthesize these otherwise unknown variables from available measurements. There are basically two approaches to state estimation, through the use of full observers and reduced order observers, as schematized in Fig. 1.

The use of reduced order observers has the advantage of requiring less computational effort to perform the estimation every time step. In this work, all available plant measurements were used directly in the control algorithm, only unmeasured variables are estimated. If plant measurements are too noisy, then it is generally preferred to construct a full order observer to filter out the perturbations (Ref. 6).

The estimation process requires the partitioning of the set of state variables into two subsets, according to the availability of measurements for each the state variable. The partitioned system can be represented by:

$$X = \begin{bmatrix} M \\ Z \end{bmatrix} \tag{3}$$

with :

$$Z = h(M, U) . \tag{4}$$

The conditions for the existence of the reduced order estimator is subject to the observability conditions for the subsystem described by Z, i.e., the function h(M,U) should be defined for all possible values of M and U.

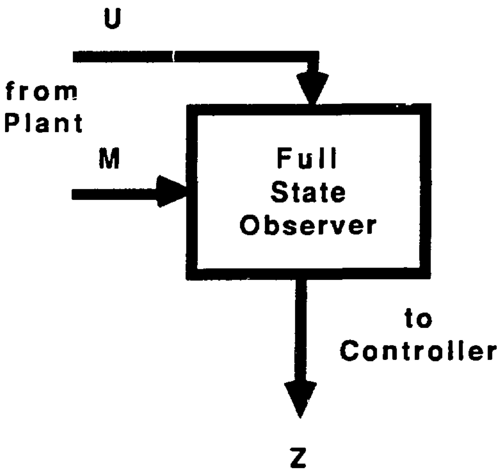

Fig. 1-a Full state estimation

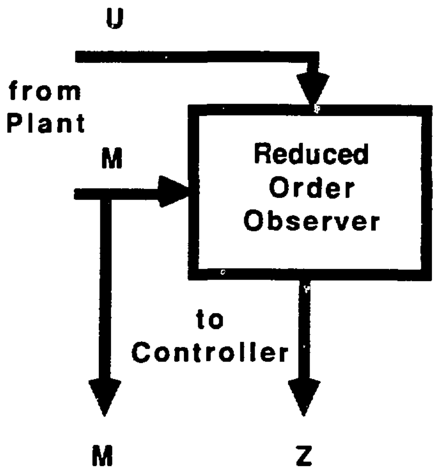

Fig.1-b Reduced order observer

Application to Reactivity Control

The objective of this controller is to determine the control rod reactivity necessary to achieve the desired rate of change and power level. For control purposes, an appropriate mathematical description of the core power generated in a nuclear reactor is given by the point kinetics equation using one delayed neutron group (Ref. 7)as follows:

$$\dot{n} = \frac{[\rho(u_{rod}, T_f, T_c) - \beta]}{\Lambda} n + \lambda c \tag{5}$$

$$\dot{c} = \frac{\beta}{\Lambda} n - \lambda c . \tag{6}$$

Using a lumped parameter approximation and a simple node discretization, the fuel temperature time derivative is given by:

$$\dot{T}_f = \alpha n + \frac{h_{fc}(w)\, A_{fc}}{m_f c_f} (T_c - T_f) \qquad (7)$$

Measured magnitudes are the neutron flux, primary flowrate, inlet and outlet core temperatures. Variables that must be estimated to complete the required inputs for the controller are: the neutron precursor concentration and fuel temperature.

Since coolant temperature and neutron flux are measured values, the measurements can replace state variables in the observer. Eliminating their corresponding differential equations from the original system, the remaining set of equations for the observer is given by:

$$\dot{c}' = \frac{\beta}{\Lambda} n_m - \lambda c' \qquad (8)$$

$$\dot{T}'_f = \alpha n_m + \frac{h_{fc}(w_m)\, A_{fc}}{m_f c_f} (T_{c_m} - T'_f) \qquad (9)$$

It should be noted that the above observer set of equations results in a non-singular system for any physically feasible set of reactor parameters.

The desired trajectory for this system is expressed in terms of the neutron power and its rate of change. Solving the neutron power differential equation (5) for the control rod reactivity, and substituting neutron power by its demanded value and its derivative by the demanded rate of change, the expression for the required control rod reactivity insertion is given by:

$$\rho_{cr} = (\dot{D}_n - \lambda c') \frac{\Lambda}{D_n} - \rho_f (T'_f , T_{c_m}) + \beta - \rho_0 \qquad (10)$$

The control rod position is computed from its integral reactivity worth curve through an iterative process:

$$u_{mb} = \xi(\rho_{cr}) \qquad (11)$$

To compensate for inaccuracies in the model, this model-based control is complemented with a contribution of a PID module for feedback compensation. The objective of this module is to eliminate the error between neutron power demand and neutron power measurement. The basic algorithm for a PID controller is given by:

$$\varepsilon = D - n_m \qquad (12)$$

$$u_{pid} = K_p \varepsilon + K_i \int \varepsilon \, dt + K_d \frac{d\varepsilon}{dt} \qquad (13)$$

Variable gains are used in order to achieve a good steady state error correction capability and reducing over- or undershoots due to integral error buildup during power transients. The integral gain is reduced for large errors thus reducing buildup. It is adjusted according to the following strategy:

$$K_i = \begin{cases} K_i^0 \quad \text{if} \quad \left| D - D_{target} \right| \leq \delta \\ K_i^0 \cdot \mu \quad ; \quad \mu \leq 1 \; ; \; \text{if} \quad \left| D - D_{target} \right| > \delta \end{cases} \qquad (14)$$

The PID controller developed includes an antiwindup mechanism to avoid saturation effects when operating close to actuator limits or when operating in open loop mode (plant in manual control).

The total control action is computed as the sum of the model-based and PID contributions:

$$u_{rod} = u_{mb} + u_{pid} . \qquad (15)$$

It should be noted that during normal operation, the control rod position is largely determined by u_{mb}, u_{pid} only contributes with a small correcting term. Should some of the plant parameters change, the correction term u_{pid} will increase accordingly to compensate for any mismatches.

Simulation Studies

The described control algorithm has been implemented in a simulation environment for liquid metal reactors of the multimodular plant PRISM (Ref 8). This environment consists of a plant simulation running on an Encore/Multimax parallel computer, and a set of 5 SUN workstations to implement the local level controllers and the supervisory controllers. All computers run under the UNIX operating system and communicate through an Ethernet connection using remote procedure calls (RPCs) (Ref. 9).

The implemented controller also provides for an external mode operation selector to allow the controller to be frozen, restarted, etc. It also has a switching logic to initialize all variables when such a mode change occurs. Gains for the proportional, integral and derivative components of the PID controller can be modified by external commands allowing for gain scheduling operation. These external commands are given through a set of shared memory areas created throughout the different computers running the overall simulation. Figure 2 shows a schematic of its implementation in this distributed computing environment (Ref. 10).

This control system generates a set of magnitudes that are posted to shared memory awaiting further processing by the supervisory control system diagnostic module. These magnitudes involves: controller status indicator, state estimations, tracking errors, mismatches between requested and real control rod positions, and saturation conditions. Work on the diagnostic module is presently underway.

In all simulated transients, measurements and controls were updated every 0.5 sec. There also exists a delay in communication between the plant and the controller due to the computer finite processing and communication speeds. The time required to pass a plant measurement to be passed as input to the control algorithm, compute the control action, transmit it to the plant, and observe the corresponding changes is approximately 1 sec. This is the cause of the visible time delay between demand and plant response in the following transients.

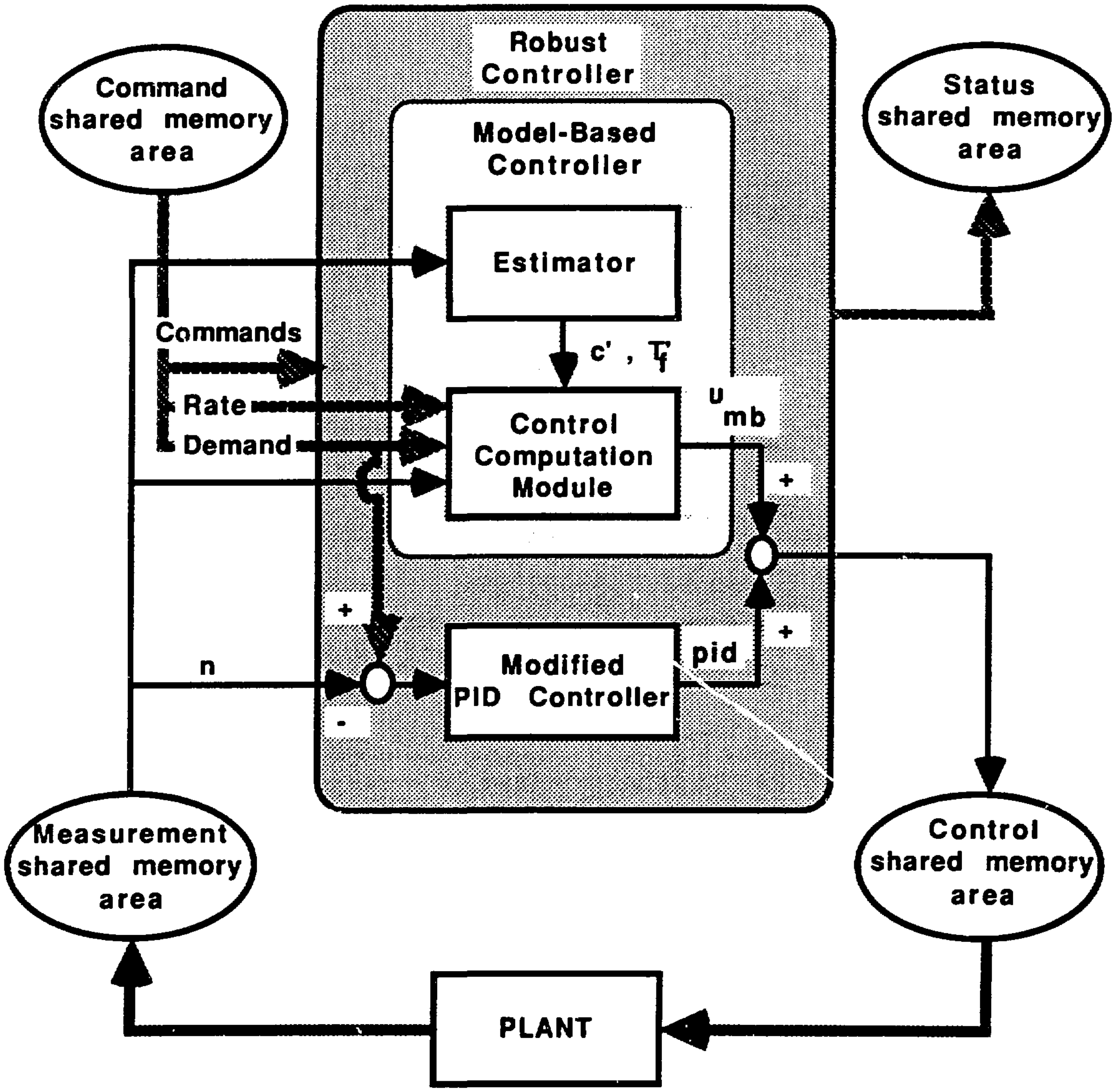

Fig 2 Control system implementation

The communication scheme was implemented with the prime objective of emulating real-life conditions as far as practicable with the available combination of hardware/software. The 0.5 sec. communication interval was selected to achieve a reasonable simulation speed, but it can be modified to accommodate different transients or strategies. This communication strategy proved

very useful and flexible for development tasks involving plant simulations, although it may not be fully applicable for practical applications due to real time requirements.
Transient response of this controller is presented in Fig. 3-a for a demanded power reduction from 100% to 90% at a rate of 20%/min. This case corresponds to the situation of almost perfect knowledge of plant coefficients, resulting in a very small tracking error. The plant response for a pure PID controller, with the best set of gains found, is presented in this figure for comparative purposes. Control rod position is presented in Fig. 3-b for both cases and the rate of insertion is shown in Fig. 3-c. It should be noted that its required speed is well below the maximum limit (approx. .3%/s). Fig. 3-d shows that the contribution of the PID term in the hybrid controller is very small compared to the model-based model output.

Sensitivity analyses were performed to determine the impact of parametrization errors on the controller response. Fig. 4 shows the controller response for perturbations, applied one at a time, in fuel-to-coolant heat transfer coefficient, control rod worth, and fuel temperature reactivity feedback. In all cases the parameters were perturbed 10% from their nominal values.

This controller has shown its capability to track demands in neutron power much more accurately than conventional controllers, reducing overshoots to almost negligible values while providing a good degree of robustness to modeling errors.

Summary

A model-based controller has been developed, implemented and successfully tested in a distributed simulation environment. The performance of this controller is considered superior to the typical PID control algorithm used in conventional control systems.

This new controller provides a very good dynamic response even to steeper demands than normally used during reactor power maneuvering (10 %/min.). The model used in the plant simulation makes use of the same point kinetics approximation and a single node representation for both fuel and coolant as the model-based controller does. The specific application of this controller may be best suited for compact cores like those of LMRs or small thermal reactors, where the neutron point kinetics equation represents the reactor dynamics more accurately.

Even when model coefficients present significant deviation from those of the real plant, the system response is satisfactory. It is expected that the performance of this controller could be maintained close to optimal through the use of a parameter identification module to be handled by the supervisory controller. Optimal parameter tracking techniques are being investigated for utilization in this type of controllers.

In addition to improved transient performance as compared to conventional control methods, this controller provides a set of indices that result from comparison of plant measurements, controller model variables, and demands. These indices are being posted in a shared memory area in this application and will be used for diagnostic purposes by a supervisory control system currently under development.

This research work has been performed as part of a major effort in supervisory control being conducted under the Oak Ridge National Laboratory's Advanced Controls Program.

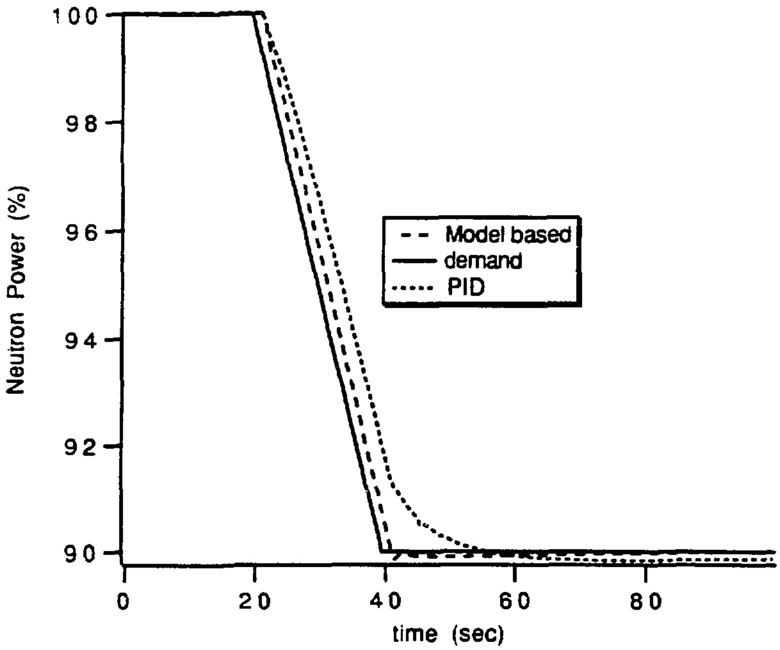

Fig. 3-a Response of model-based and PID controllers.

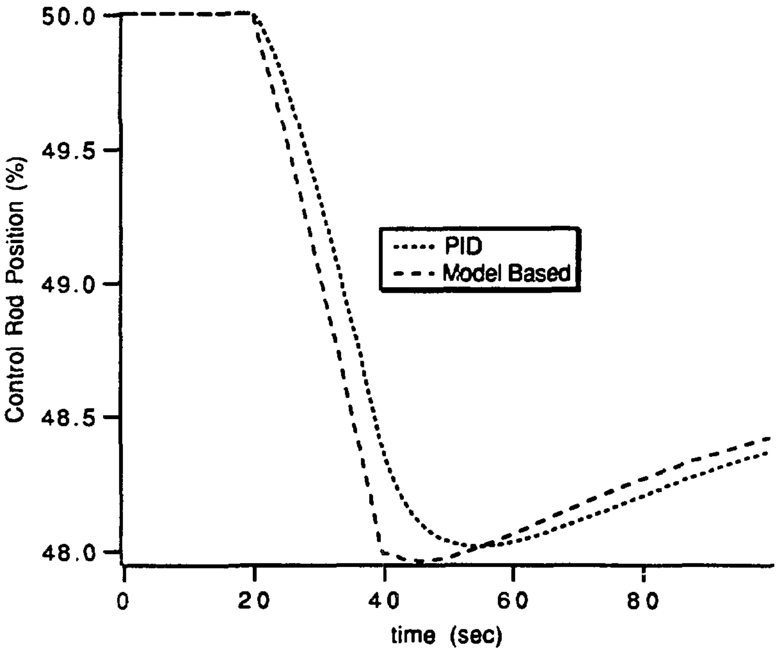

Fig. 3-b Comparison of demanded control rod position for model-based and PID controllers.

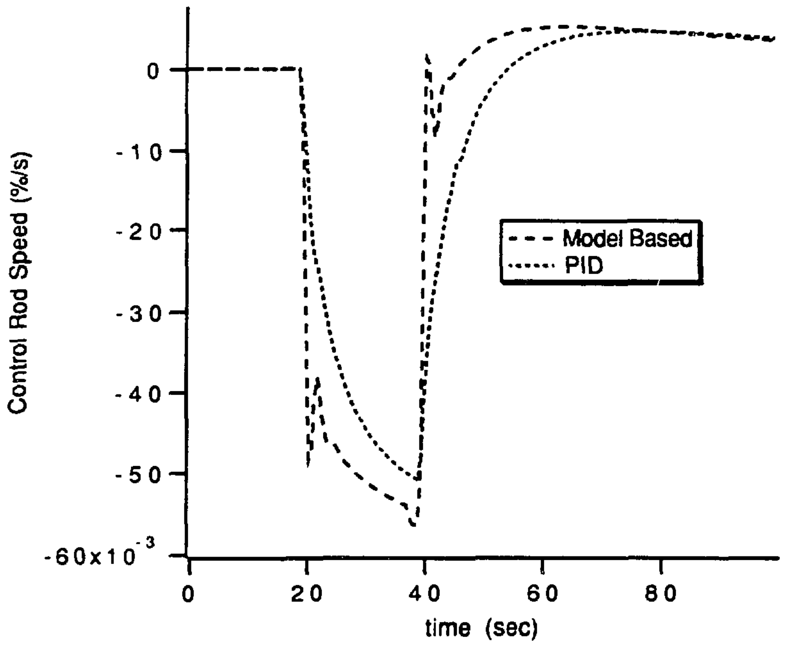

Fig. 3-c Control rod speed for model-based and PID controllers.

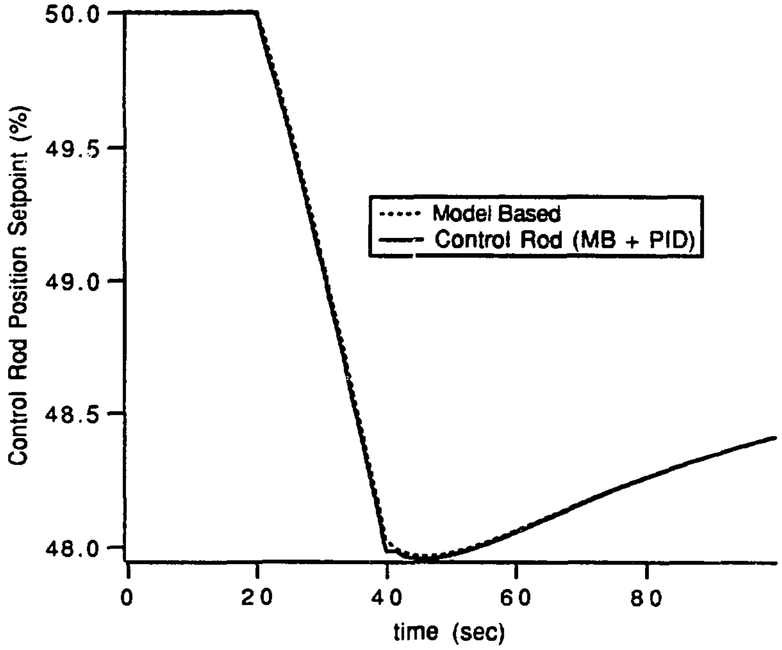

Fig. 3-d Control rod position. Contributions of model-based and PID terms in the hybrid controller.

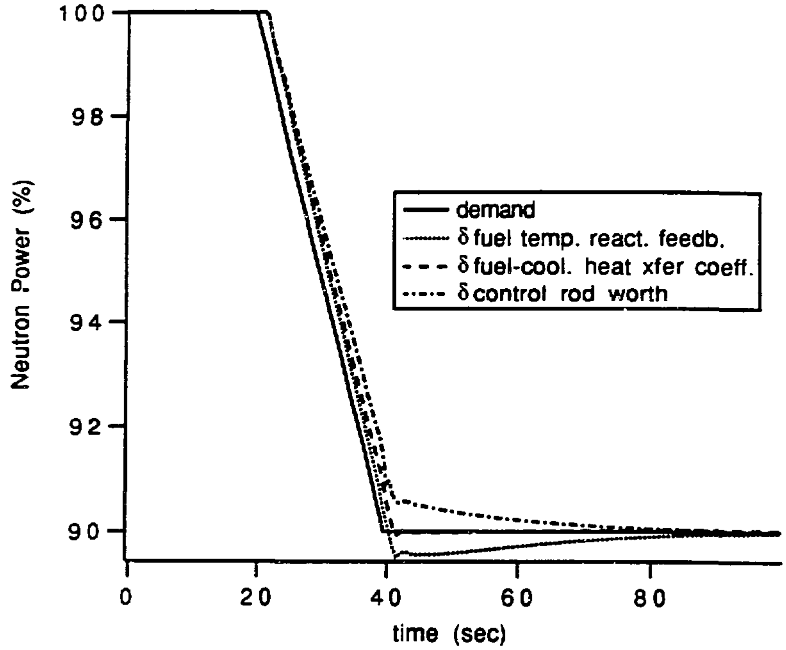

Fig. 4 Neutron flux response to a demand change in the presence of parameter perturbations.

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Appendix: Nomenclature

α: thermal power normalization factor
β: total delayed neutron precursor yield
λ: delayed neutron precursor decay constant
Λ: prompt neutron generation time
ε: tracking error
ρ: net core reactivity
ρ_{cr}: control rod reactivity
ρ_f: temperature feedback reactivity
ρ_0: core excess reactivity
ξ: control rod integral reactivity worth curve
A_{fc}: fuel to coolant heat transfer area
c: neutron precursor concentration
c': estimated neutron precursor concentration
c_f: fuel specific heat
D: demand
$D_n, \dot{D}_n$: neutron flux demand and rate
D_{target}: goal demand
h_{fc}: fuel to coolant heat transfer coefficient
m_f: fuel mass
n, n_m: neutron flux, measured neutron flux
T_c, T_{cm}: coolant temp., measured coolant temp.
T_c^{in}: core inlet temp.
T_f: fuel temp.
T'_f: estimated fuel temp.
T_{cm}: measured coolant temp.
U: control vector
u_{mb}: model based computed control rod position
u_{pid}: pid control output
u_{rod}: control rod position

X: state variable vector
M: measured magnitudes representing a state variable vector
w, w_m: primary flowrate, measured primary flowrate
Z: estimated state variable vector