ADAPTIVE ROBUST CONTROL OF THE EBR-II REACTOR

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ABSTRACT

Simulation results are presented for an adaptive H_∞ controller, a fixed H_∞ controller, and a classical controller. The controllers are applied to a simulation of the Experimental Breeder Reactor II (EBR-II) primary system. The controllers are tested for the best robustness and performance by step-changing the demanded reactor power and by varying the combined uncertainty in initial reactor power and control rod worth. The adaptive H_∞ controller shows the fastest settling time, the fastest rise time and the smallest peak overshoot when compared to the fixed H_∞ and classical controllers. This makes for a superior and more robust controller.

I. INTRODUCTION

The EBR-II reactor is a sodium-cooled, fast-neutron reactor capable of producing a continuous thermal power of 62.5 MW. The EBR-II primary reactor system requires a controller which can accommodate for real-world uncertainty and provide acceptable performance. The controller must accommodate for uncertainty arising from the nonlinear neutron kinetics and from time-varying control rod worth in the plant The controller must provide acceptable performance in the form of quick rise-time, quick settling time, and minimal peak overshoot.

The adaptive robust controller in this work incorporates robustness and performance constraints by using an on-line uncertainty specification $\hat{W}_{dela}$ to bound the uncertainty in the plant and by using a fixed performance specification W_p to incorporate the desired performance in the plant. The controller examines the difference between the actual plant output y and the output of parallel simulation of the plant $\hat{y}$. The difference between y and $\hat{y}$ is indicative of uncertainty between the actual plant G the assumed plant G_0. This uncertainty is approximated by a Fourier-Laguerre expansion on-line. The on-line approximation of the uncertainty between the G and G_0 is expressed in terms of additive uncertainty $\hat{W}_{dela}$. The additive uncertainty is converted into multiplicative uncertainty $\hat{W}_{delm}$. The multiplicative uncertainty along with the assumed plant model G_0 and the performance specification are used to synthesize the H_∞ controller on-line.

II. ESTIMATING UNCERTAINTY ON-LINE

The on-line estimate of the additive uncertainty $\hat{W}_{dela}$ that is obtained using a deterministic Fourier-Laguerre expansion must be greater than the actual uncertainty W_{dela} so that $\hat{W}_{dela}$ includes all of the uncertainty between G and G_0.[1]

The Fourier-Laguerre expansion

$$\hat{W}_{dela} = \sum_{i=0}^{n} E_i \phi_i(s) + \zeta_n \qquad (1)$$

approximates the additive uncertainty between G and G_0

$$W_{dela} = G(s) - G_0(s) \qquad (2)$$

where

h_i = coefficients for the uncertainty W_{dela}

$$\phi_i(s) = \left(\frac{s-\lambda}{s+\lambda}\right)^i \qquad (3)$$

ζ_n = a priori uncertainty

λ = low-pass filter coefficient.

The coefficients h_i from Equation (2) are determined on-line using the deterministic Exponential Forgetting and Resetting (EFRA) identifier. The EFRA is selected since it is internally stable. A least squares identifier is not necessarily internally stable and is therefore not used in this work.[1] The values of the coefficients h_i are entered on-line into the Equation (2) to yield the on-line estimated uncertainty $\hat{W}_{dela}$.

The on-line estimates for h_i, $\hat{\theta}$, are calculated on-line using the equations for the EFRA identifier,

$$\frac{d}{dt}\hat{\theta} = \frac{1}{\Gamma}\sigma P \phi\left[\tilde{y} - \phi^T \hat{\theta}\right] \qquad (4)$$

$$\frac{d}{dt}P = -\frac{1}{\Gamma}\sigma P \phi \phi^T P + \Omega \qquad (5)$$

where

$$\Gamma = 1 + \beta\phi\phi^{T} \qquad (6)$$

σ = variance of the coefficients $\hat{\theta}$

P = covariance of the coefficients $\hat{\theta}$

$$\phi = [\tilde{y}(t-1),\ \tilde{y}(t-2),\ \ldots,\ \tilde{y}(t-n);\ u(t-1), u(t-2),\ \ldots,\ u(t-n)] \qquad (7)$$

$$\tilde{y} = \frac{\sqrt{2\lambda}}{s+\lambda}(y - \hat{y}) \qquad (8)$$

$$\Omega = \sigma P - \varepsilon\sigma P^2 \qquad (9)$$

and

ε = "free" design parameter

β = "free" design parameter.[2]

The additive uncertainty $\hat{W}_{dela}$ is converted to the multiplicative form for use in the adaptive H_∞ controller , such that

$$\hat{W}_{delm} = \hat{W}_{dela} G_0^{-1} \frac{\lambda_1}{s+\lambda_1} \tag{10}$$

where

λ_1 = low-pass filter coefficient.

The filter $\frac{\lambda_1}{s+\lambda_1}$ ensures that the on-line estimate of the uncertainty $\hat{W}_{delm}$ is a proper transfer function. A proper transfer function is required in the synthesis of the adaptive H_∞ controller.

III. SYNTHESIS OF THE H_∞ CONTROLLER

The H_∞ controller is designed by incorporating the on-line estimated uncertainty $\hat{W}_{delm}$ into the H_∞ synthesis technique.[3,4] The H_∞ synthesis technique minimizes the normed equation

$$\| T_{yu} \|_\infty = \left\| \begin{matrix} W_p S \\ \hat{W}_{delm} T \end{matrix} \right\|_\infty \tag{11}$$

where

W_p = desired performance specification
$\hat{W}_{delm}$ = on-line uncertainty estimate
T = plant transfer function
S = plant sensitivity function.
u = plant input.

to produce the H_∞ controller K. When Equation (11) is less that $\frac{1}{\sqrt{2}}$ then the controller achieves robust performance.[4] Robust performance is attained when both the plant is stable and the desired performance is upheld over the plant operating range.

IV. PROPOSED ADAPTIVE H_∞ CONTROLLER

For systems such as nuclear reactors which have nonlinear and time-varying effects in the system model, an adaptive robust controller can stabilize the system, guarantee performance over a wide band of operating conditions, and adapt to the current needs of the plant.

The adaptive robust controller in this work uses a fixed nominal plant G_0, a fixed performance specification W_p, and on-line uncertainty $\hat{W}_{delm}$. The plant G_0 is fixed since the nominal plant is generally known well. The performance specification W_p is fixed since the performance specification is known. The uncertainty between G and G_0, W_{del}, is quantified on-line since the uncertainty varies with time due to nonlinear perturbations and time-varying parameters.

The proposed adaptive H_∞ controller is presented in Figure 1. The controller is designed so that the plant output y tracks the reference input r. The plant model of the system G is time-varying and nonlinear. The adaptive H_∞ controller consists of a nominal plant model G_0, an adaptive uncertainty identifier, a controller design stage, a model validation stage and a supervisor stage. The nominal plant model, driven by the same plant input as the nominal plant, produces the real-time estimate of the plant output $\hat{y}$. Discrepancies between y and $\hat{y}$ are indicative of the non-idealness of the actual plant G. The error signal e can be used to drive the uncertainty description $\hat{W}_{delm}$ from the theory in Section II. With a current uncertainty description $\hat{W}_{delm}$, a fixed G_0, and fixed W_p as inputs to the controller design stage, a new controller K_{j+1} is created to replace the old K_j. The new controller K_{j+1} in better suited to control the plant G.

Since the uncertainty is estimated on-line using the actual plant data, the uncertainty estimate is more suited to the actual plant conditions. A robust controller re-designed with this more appropriate uncertainty has improved robustness and performance characteristics over the fixed H_∞ controller. The improved robustness and performance is demonstrated using simulations in Section VI.

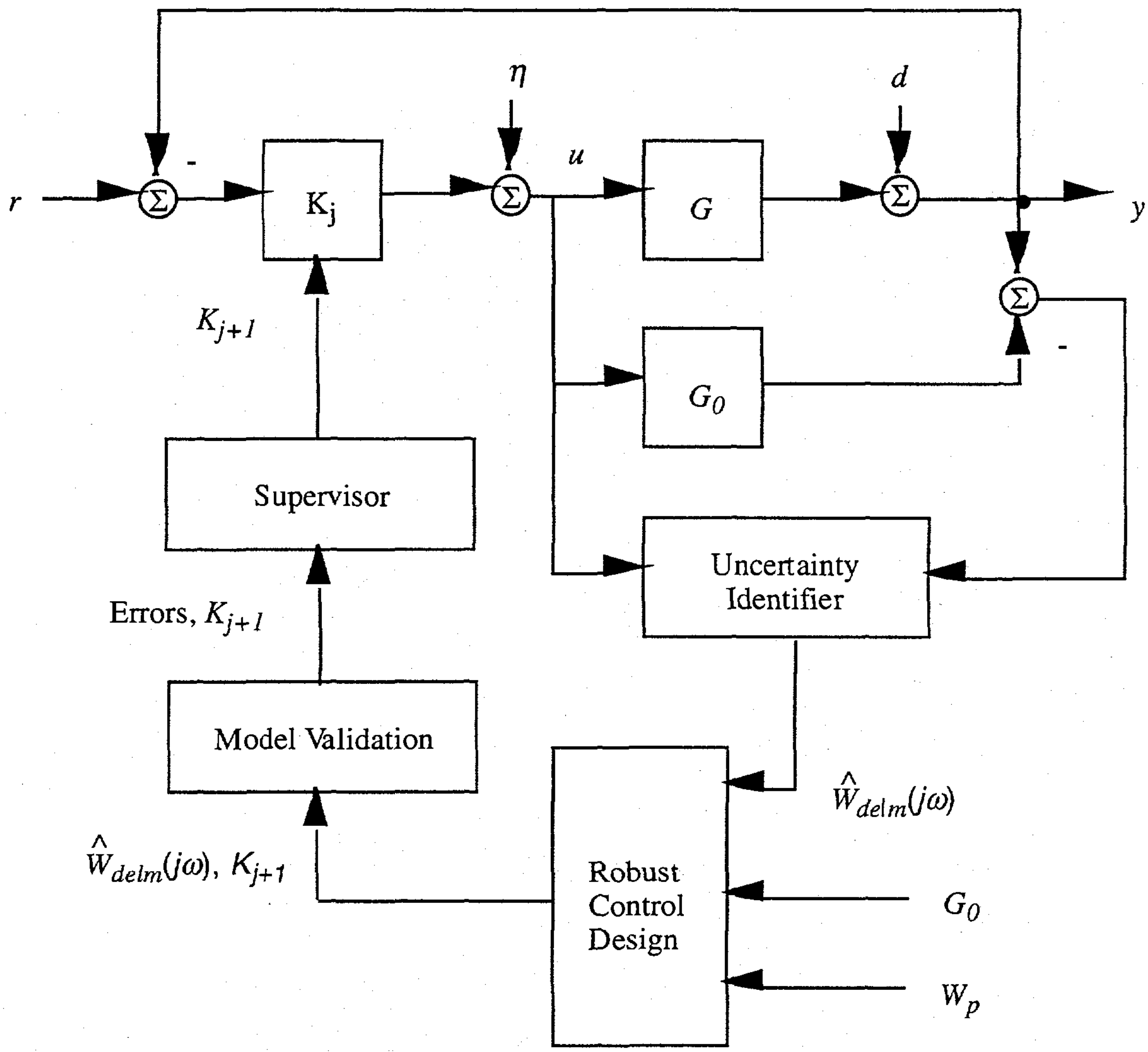
The model validation stage uses a priori thresholds to ascertain whether or not the plant is operating normally. If the plant is operating normally then errors are not generated. If the plant is operating abnormally, then errors are generated. In this work, the errors do not automatically shut down the system. The errors are logged so that a plant operator (supervisor) can manually shut down the plant.

V. COMBINED DSNP AND MATLAB SIMULATION

The high-order EBR-II model which includes an embedded proportional controller is simulated using the Dynamic Simulator for Nuclear Power Plants (DSNP) language.[5,6] The fixed and adaptive H_∞ controller are designed and simulated in MATLAB.[3]

The benchmarked EBR-II simulation provides an excellent testbed for the adaptive robust control algorithm as well as previously tested algorithms. The high-order DSNP code for the EBR-II plant contains a model of the prompt neutron dynamics, the nodalized thermo-hydraulics, and the control rod actuator dynamics.

The fixed H_∞ controller is designed off-line and simulated using MATLAB subroutines from the μ-Analysis and Synthesis toolbox whereas the adaptive H_∞ controller is designed on-line and simulated using MATLAB subroutines from the μ-Analysis and Synthesis toolbox. The adaptive H_∞ controller uses the low-order EBR-II model, a fixed performance description, and an on-line calculation of the plant uncertainty $\hat{W}_{del}$ to generate a new controller. The new controller is updated every 20 seconds and is then implemented for control. The embedded proportional classical controller is simulated using DSNP. The feedback command from MATLAB is set to zero in order to obtain classical controller results.



G	=	actual plant,	G_0	=	assumed nominal plant
$\hat{W}_{delm}$	=	on-line uncertainty	W_p	=	performance specification
K_j	=	current controller	u	=	control signal driving both G and G_0
d	=	external disturbance	η	=	noise added for persistent excitation
y	=	actual reactor power	r	=	demanded reactor power

Figure 1 - Proposed Integrated Adaptive H_∞ Controller and Model Validation

VI. SIMULATION RESULTS

The classical controller, the fixed H_∞ controller, and the adaptive H_∞ controller are tested for the best robustness and performance by step-changing the demanded reactor power and by varying the combined uncertainty in initial reactor power and control rod worth. The three controllers are step-changed from a relative reactor power of 1.0 at 1.0 second and then at 50 seconds. The initial step-change trains the adaptive robust controller to the new level of plant uncertainty. The adaptive robust controller is updated every 20 seconds and is therefore redesigned twice before the 50 second step-change. The initial reactor power is varied over the range from $n_{r0} = 0.25$ to $n_{r0} = 1.0$ and the control rod worth is varied over the range from $G_r = 0.5$ to $G_r = 2.0$.

The simulations in Figure 2 are for operating point 1 where $G_r = 2.0$ and $n_{r0} = 0.25$. All of the controllers perform robustly. The classical controller is slightly less-damped than the other controllers. The fixed H_∞ and adaptive H_∞ controllers are identical until the adaptive H_∞ controller is redesigned at 20 seconds. The states of the fixed H_∞ and adaptive H_∞ controllers are zeroed at 20 seconds, yielding bumpless transfer.

The second transient in Figure 2 is expanded in Figure 3. The adaptive robust controller demonstrates the best robustness and performance. The adaptive robust controller demonstrates the fastest rise-time, the fastest settling-time, and the smallest peak overshoot, followed by the fixed H_∞ controller and then by the classical controller.

The simulations in Figure 4 use operating point 2 where $G_r = 1.0$ and $n_{r0} = 0.8$. These values represent the nominal plant. The adaptive robust controller demonstrates the best robustness and performance. The adaptive robust controller demonstrates the fastest rise-time, the fastest settling-time, and the smallest peak overshoot, followed by the classical controller and then by the fixed H_∞ controller.

The simulations in Figure 5 use operating point 3 where $G_r = 0.5$ and $n_{r0} = 1.0$. The adaptive robust controller has the best overall response. The adaptive robust controller demonstrates the fastest rise-time, the fastest settling-time, and the smallest peak overshoot, followed by the fixed H_∞ controller and then by the classical controller. The fixed H_∞ controller demonstrates a slightly smaller peak overshoot than the classical controller; however, the classical controller demonstrates a shorter settling time than the fixed H_∞ controller.

VII. CONCLUSION

Three controllers are compared for robustness and performance. The adaptive H_∞ controller demonstrates the best over all performance and robustness. Owing to the excellent robustness and performance characteristics, the adaptive robust controller is recommended for further experimental validation using a research reactor.

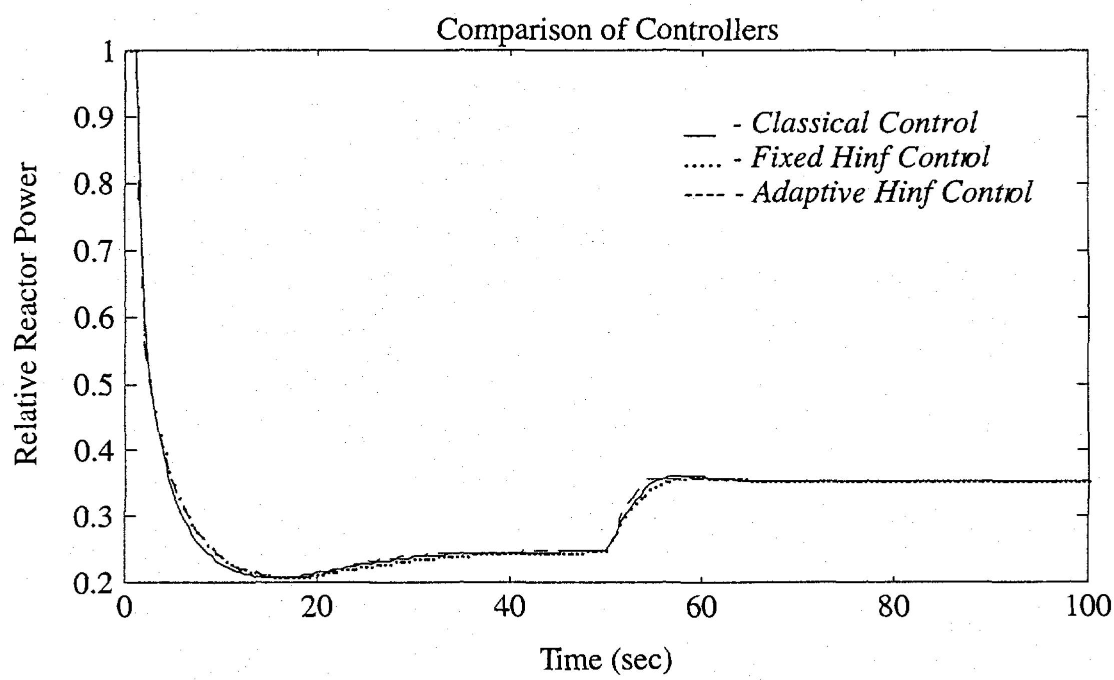


Figure 2 - Normal Plant Operating at $G_r = 2.0$, $n_{r0} = 0.25$

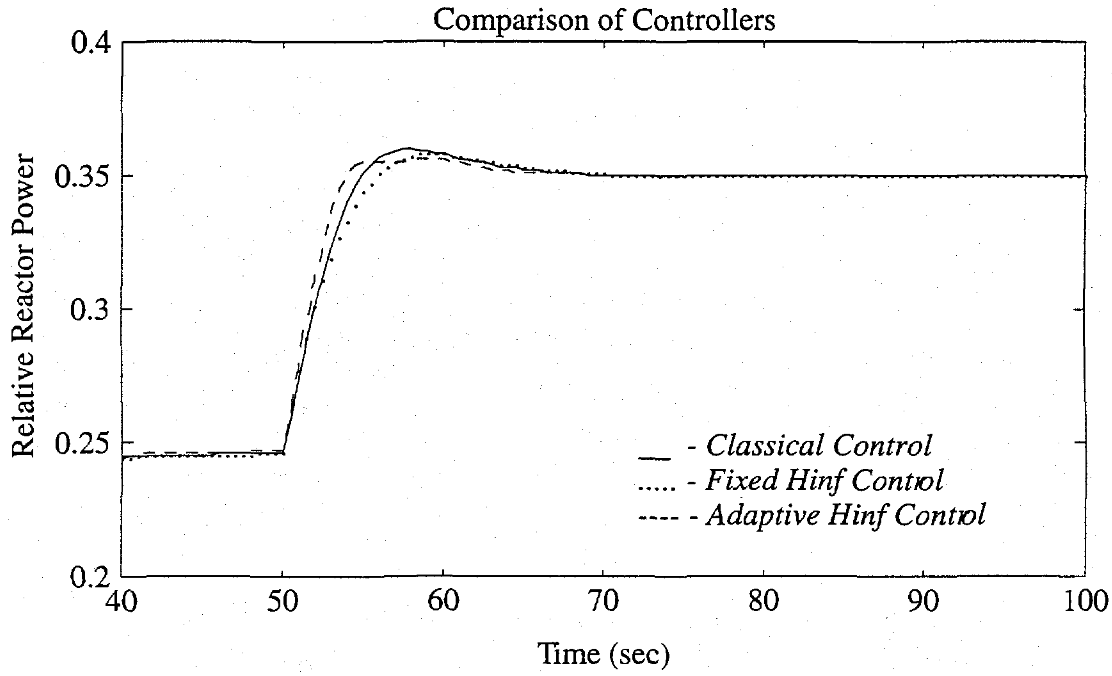


Figure 3 - Normal Plant Operating at $G_r = 2.0$, $n_{r0} = 0.25$

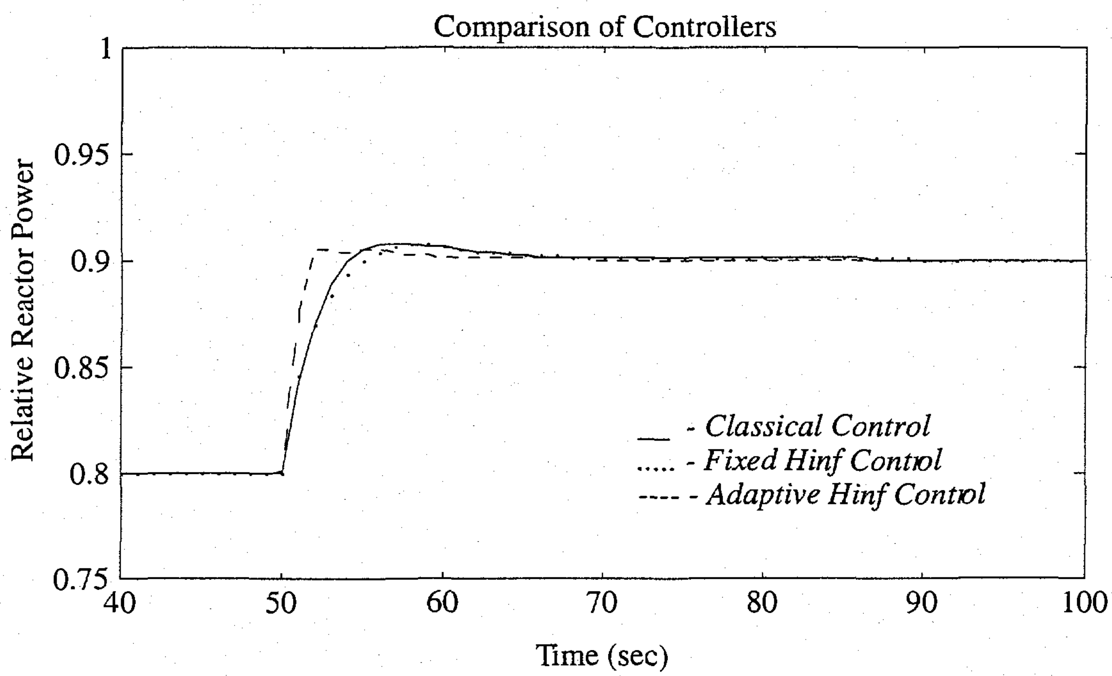


Figure 4 - Normal Plant Operating at $G_r = 1.0$, $n_{r0} = 0.8$

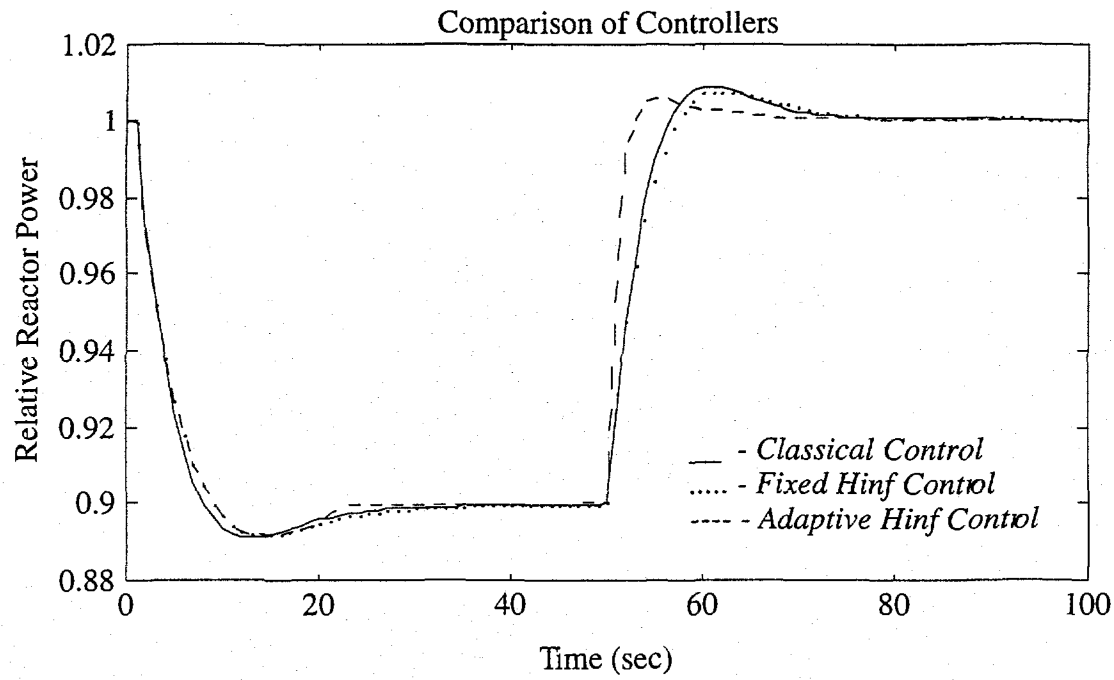


Figure 5 - Normal Plant Operating at $G_r = 0.5$, $n_{r0} = 1.0$

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