

**ROBUST CONTROL DESIGN VERIFICATION USING
THE MODULAR MODELING SYSTEM**

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ABSTRACT

The Modular Modeling System (B&W MMS) is being used as a design tool to verify robust controller designs for improving power plant performance while also providing fault-accommodating capabilities. These controllers are designed based on optimal control theory and are thus model based controllers which are targeted for implementation in a computer based digital control environment. The MMS is being successfully used to verify that the controllers are tolerant of uncertainties between the plant model employed in the controller and the actual plant; i.e., that they are robust. The two areas in which the MMS is being used for this purpose is in the design of 1) a reactor power controller with improved reactor temperature response, and 2) the design of a multiple input multiple output (MIMO) robust fault-accommodating controller for a deaerator level and pressure control problem.

INTRODUCTION

A definition of a robust controller given by Lunze (1) is "A robust multivariable controller is a linear time invariant feedback controller which satisfies the design requirements in connection with all plants of a given set". With this definition, even a conventional Proportional Integral (PI) output feedback controller can be robust as long as the system design requirements are met. For systems with critical performance requirements, modern optimal control is more likely to be needed. A major concern for implementation of control (optimal or conventional) is that the model used to formulate the control law can never be detailed enough to exactly match the dynamics of the actual process; i.e., there is a set of possible plants that the controller must be capable of controlling while meeting design requirements. Robust control theory and design address this concern by explicitly considering discrepancy between the model used in the control law and the actual process. In robust control terminology (1), discrepancy between the actual process and its model is referred to as uncertainty and can arise from 3 major sources: 1)

the plant model is invariably of lower order than the actual plant (e.g., a lumped parameter model of a distributed parameter process), 2) the plant model (on which the controller is based) is linear whereas the actual plant is non-linear, and 3) the parameters of the low order model may not be correct due to variations in normal plant operation, plant degradations, and faults.

The major emphasis of our work is the pursuit of robust optimal controllers that achieve improved system performance in a robust fault-accommodating manner. System faults are viewed as large uncertainties as part of the robust fault-accommodating controller design requirements. An initial low order linear time-invariant model based controller based on optimal regulator theory is formulated while considering the expected uncertainties due to normal operation of the closed-loop controlled system. The performance of the controller is verified via simulation for the normal operation uncertainties and then evaluated during postulated system faults. The B&W MMS (2) provides a convenient simulation capability to perform initial design verification.

ROBUST REACTOR POWER CONTROLLER

For the robust reactor power controller design, an alternate control configuration (3,4) was considered in an effort to improve reactor temperature performance via application of modern optimal state feedback control methodology. Figure 1 shows the State Feedback Assisted Classical Control (SFAC) configuration as a model based controller (MBC) in the feedback loop for regulating reactor power at an external demand signal. With the switch at position A, reactor power n_r is regulated at the external demand signal n_d by a conventional output feedback control loop using control rod speed z_r as the manipulated variable. With the switch at position B, reactor power demand signal to the embedded conventional controller is augmented to n_{dm} by the model based controller to achieve an optimal control performance objective. Thus far, the optimal control objective has been to speed up reactor temperature response (fuel and coolant) with minimal overshoots beyond the new equilibrium power level. In the SFAC configuration, the augmented demand signal is initially advanced beyond the external demand signal at the beginning of a transient and is then automatically backed off to the level to be maintained.

The original motive for embedding a classical controller in a state feedback system was to provide an intuitive interpretation of the more complicated modern control theory in terms of the more familiar and

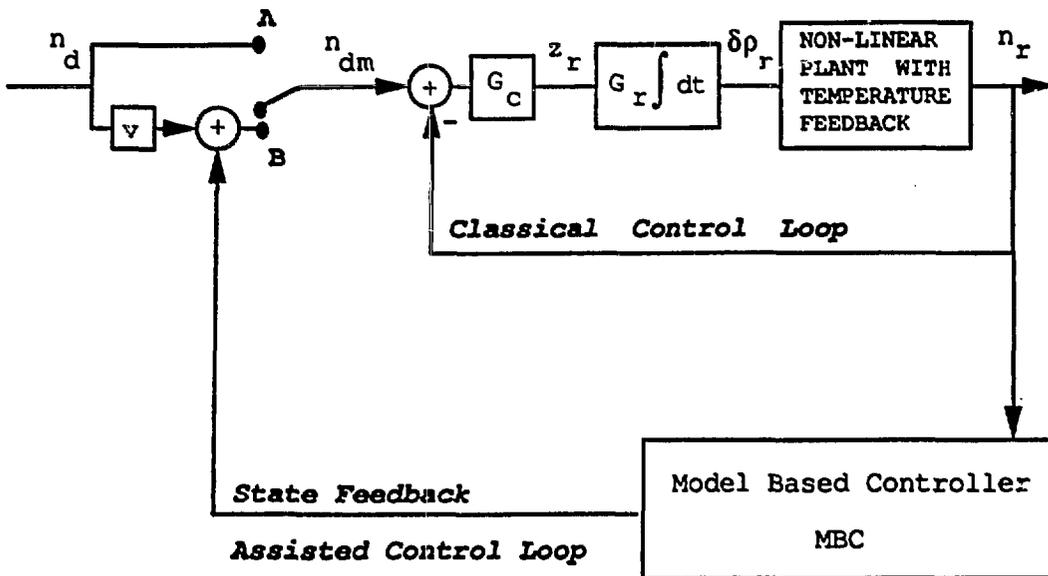


Figure 1. A Model Based Controller (MBC) in the Feedback Loop for Improving Reactor Temperature Response by Augmenting the Demand Signal to an Embedded Conventional Output Feedback Controller, State Feedback Assisted Classical Control (SFAC).

well established output feedback controllers currently deployed in commercial nuclear power plants. A seemingly equivalent model based control law can be formulated without the embedded conventional controller; however, current research (5) has identified a robustness advantage for implementing MBCs with embedded classical control loops. In essence, the embedded classical output feedback controller "cleans-up" some of the system uncertainty before it is processed by an outer layer of model-based compensators. Through a series of linear sensitivity analysis of the dominant eigenvalue of a combined model of simulated plant and controller it was shown that the robust controller implemented in the SFAC configuration could accommodate expected plant parameter variations over the full one year fuel cycle, power level changes in the 10 to 100 percent range, and control rod differential reactivity worth variations of a factor of 10 and still provide good reactor temperature response with good stability margin. (6)

All of the linear analysis predictions were confirmed via non-linear simulation using the Babcock and Wilcox Modular Modeling System (MMS B&W). The MMS representation of a PWR core, used in this analysis, is

a 23rd order non-linear kinetics and non-linear thermal hydraulic model. The reactor core is represented with 3 axial nodes with dynamic fuel and coolant temperature calculations at each node and 3 delayed neutron group point kinetics at each node coupled with leakage currents. As a first level analysis, the reactor was modeled as an isolated component with appropriate inlet and outlet boundary conditions held constant.

A robust 5th order power controller was designed for the full power middle of cycle conditions as an optimal regulator for improving reactor temperature response. (3,4,6) The 5th order controller dynamically estimates a single average fuel temperature, reactor coolant exit temperature, control rod reactivity, and uses non-linear point kinetics with one delayed neutron group. With the parameters (control rod differential worth, heat transfer coefficients, etc.) and state feedback gains of the controller fixed at constant values, the controller is tested by controlling the non-linear time-varying MMS simulation of the reactor at the extremes in parameter ranges. Figure 2 presents the results of a typical analysis which compares the conventional controller and optimal SFAC configuration performance for a step change in demand transient from full power ($n_p=1.0$) to 80% power ($n_p=0.8$) at time 2.5 seconds. In this case, the plant control rod worth is a factor of 3 greater than that used in the model based controller. Other parameters such as temperature reactivity coefficients and heat transfer coefficients also had somewhat smaller variations due to fuel burnup and power level at the end of the fuel cycle. As can be seen in Figure 2, this MBC achieves improved temperature performance (faster response with no overshoot) even with significant modeling uncertainties. The MBC in the SFAC configuration advances the demand signal to the embedded conventional output feedback controller beyond the 0.8 external demand signal to as low as 0.52 fraction of full power at the beginning of the transient. The control element (control rod speed) saturates at a maximum insertion rate for the first 5 seconds of the transient after which reactor power closely follows the modified demand signal to achieve a faster temperature response without overshoot.

The MMS utilizes the ACSL (7) simulation language for solving first order non-linear time-varying differential equations. The MMS itself consists of a large library of fossil and nuclear power plant components which are selected, parameterized, and interconnected to study a problem of interest. The particular structure of the reactor MBC was taken to be that of a Luenberger Observer which is basically a simulation of the process operated in parallel with the plant. A complete ACSL model and command file for this application is available in reference 6.

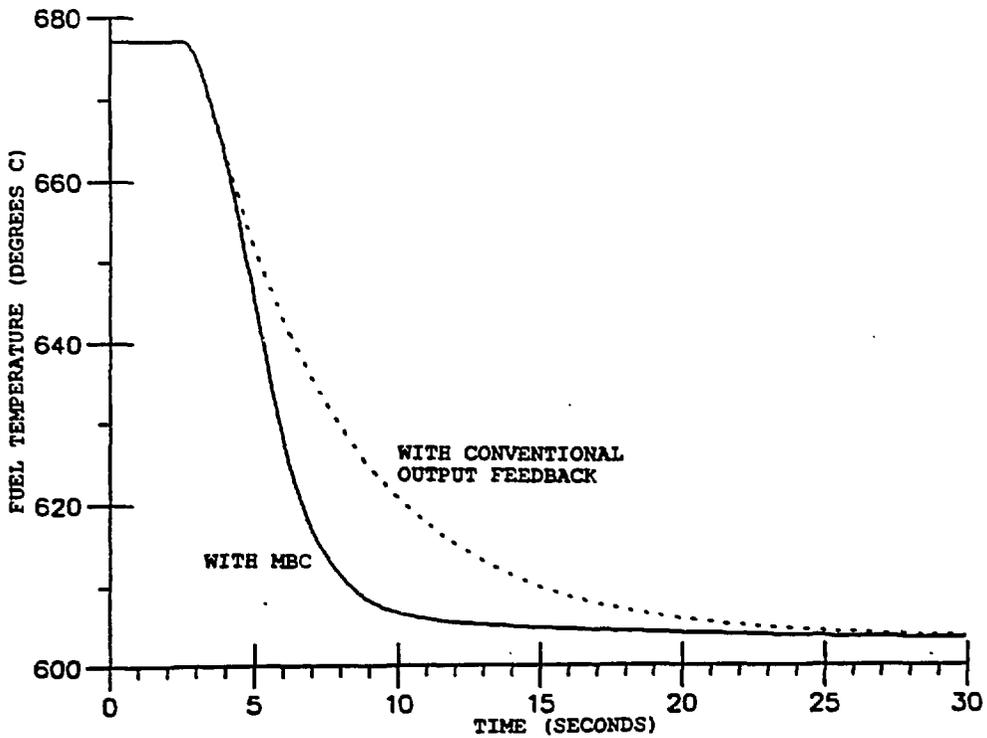
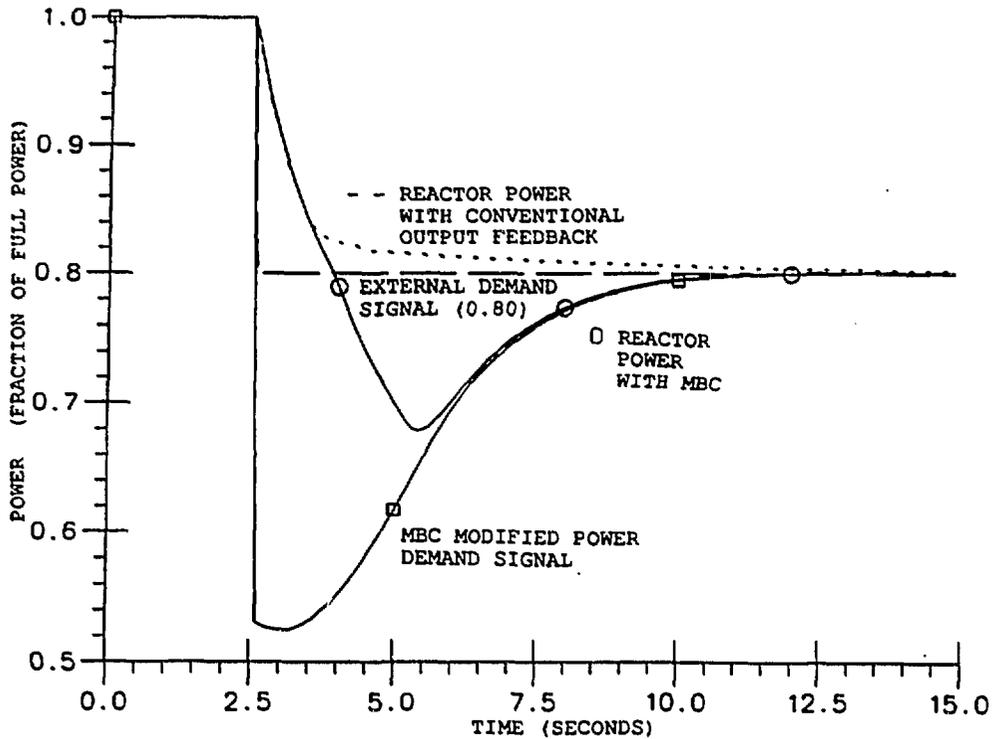


Figure 2. Comparison of Optimal MBC SFAC Reactor Response with a Conventional Output Feedback Control Response to a Step Change in External Demand Signal from 1.0 to 0.8 at Time 2.5 Seconds.

The MBC differential equation model for estimating the five internal states of the reactor are simply included within the dynamic section of the ACSL model file and interconnected with the appropriate output variables by the MMS simulation as shown in Figure 3. By implementing the controller in differential equation form within an ACSL dynamic section the implicit assumption is made that the controller is an analog controller. As stated in the abstract, the eventual implementation of the more complicated model based controllers is expected to be a digital control environment. The ACSL simulation language provides a convenient facility to simulate sampled-data control algorithms interfaced to a real world continuous process. Prior to real world experimentation with a sampled-data version of a MBC, its robustness to the additional uncertainties between the continuous process and sampled-data controller must be verified.

MIMO MULTIPLE LAYER (MIMOML) ROBUST FAULT-ACCOMMODATING CONTROL

The goal of the Single Input - Single Output (SISO) robust reactor power controller was to demonstrate that improved performance could be achieved while accommodating large uncertainties between the model based controller and the actual plant. Since existing power plants

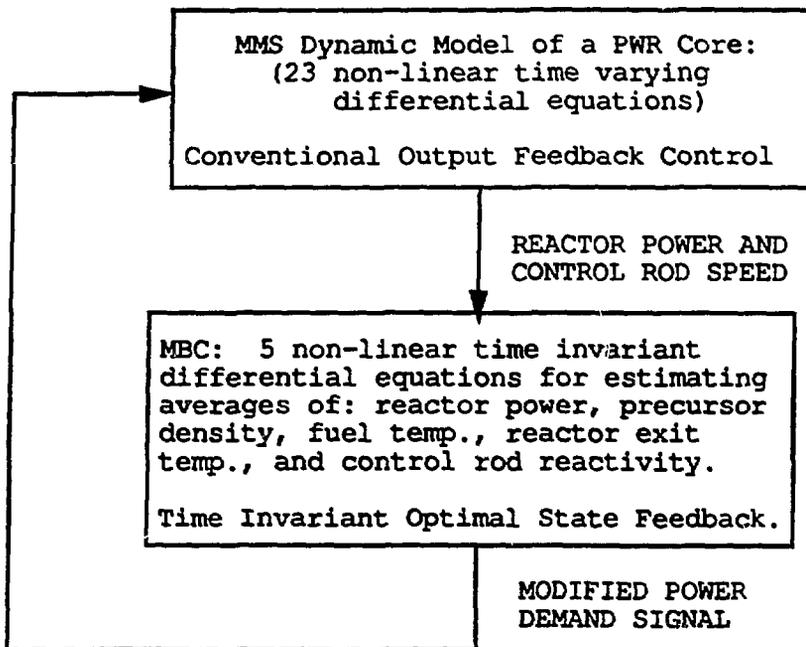


Figure 3. Block Diagram of the Contents of an ACSL Simulation Model File for Verifying a Robust Reactor Power Controller using the MMS B&W.

already have controllers which achieve the required level of performance, it has been difficult to promote the robust optimal controller for serious consideration as an addition to existing plants. Improved temperature performance could be important for plants with serious load following requirements. A stronger case for considering the additional complexity of model based controllers in existing plants is in the more realistic Multiple Input - Multiple Output (MIMO) environment of power plants. In an MIMO application, the main robust control goal is to cause operational control loops to cooperate in mitigating the consequences of component and controller failures, fault-accommodating control; the secondary goal is to also achieve some performance improvement during normal operation.

The SFAC configuration is a multi-layer (ML) control system approach which demonstrates improved robustness characteristics. Extension of the ML approach to the MIMO case has also been examined for the pressure and level control requirements of the deaerator at the experimental breeder reactor, EBR-II. (8) The EBR-II deaerator is a vertical direct contact open feedwater heater elevated 25 feet above the main feedwater pump in order to provide a reliable net positive suction head during normal steady operation. If pressure is suddenly decreased in the deaerator, there is a concern that cavitation may occur at the pump due to the transport delay for the arrival of cooler condensate at the pump inlet. A valve in the condensate flow line is used to regulate deaerator level and a valve in a steam supply line is used to regulate pressure in the control strategy of the actual plant.

Robust LQG/LTR Design

Figure 4 shows the structure of a multivariable unity feedback gain model based compensator for regulating pressure and level in an MMS simulation of the EBR-II deaerator. Similar to the robust reactor power controller, the deaerator MBC achieves an optimal control objective by modifying the demand signals to the embedded conventional controllers, State Feedback Assisted Control (SFAC). In a reconfigurable robust control strategy, controllers predesigned for specific operating conditions (MBC a, MBC b, etc) could be made available for selection as necessary to achieve better system performance over a wide range.

The strictly linear SFAC MBC was designed using the LQG/LTR Technique (9) as solved in the Robust Control Toolbox of the MATLAB (10) software package. The robust controller is based on a MMS model of a deaerator with embedded conventional PI controllers for deaerator level and pressure regulation. To design the controller the 4th order

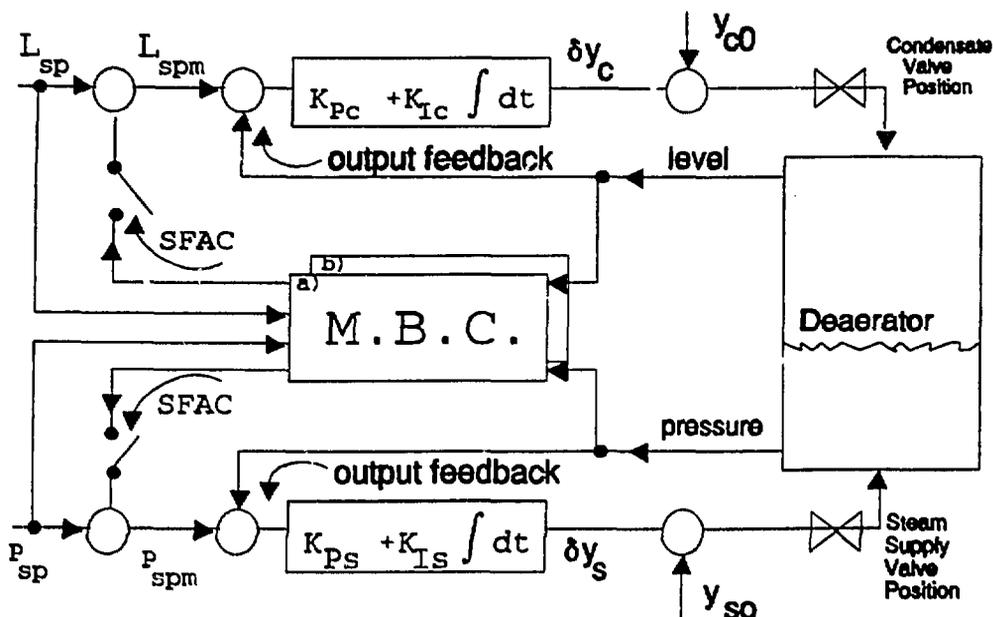


Figure 4. A Multivariable Robust Fault-Accommodating Model Based Controller (MBC) for Deaerator Pressure and Level by Augmenting the Demand Signals to Embedded PI Controllers (SFAC).

non-linear time varying model is linearized about the nominal operating point (165 psia and 144 inches)

$$\dot{x} = Ax + Bu + Gw$$

$$z = Hx + \mu Iv \quad (1)$$

$$y = Cx$$

where w and v are zero mean Gaussian white-noise processes, z are the available measurements, y are the controlled plant outputs, I is the identity matrix, and μ and G are the design parameters that are used in the LQG/LTR procedure to synthesize a compensator to meet desired specifications (11); $C=H$ has been used in this application. The robust controller design has two steps: an LQG step consisting of a target feedback loop design via Kalman Filter and an LTR step consisting of Loop Transfer recovery via LQR.

LQG Step. The Kalman filter equations for the state estimates, the error and gain are:

$$\begin{aligned}\dot{\hat{x}} &= A\hat{x} + K_f [z - H\hat{x}] \\ \dot{e} &= [A - K_f H] e + Gw - K_f v \\ K_f &= PH^T R^{-1}\end{aligned}\quad (2)$$

where P is the solution of the algebraic Ricatti Equation, K_f is the Kalman filter gain, R is the measurement noise covariance matrix, and e is error. The parameters G and μ are selected in such a way that the minimum singular value $\underline{\sigma}$ and maximum singular value $\bar{\sigma}$ of the target feedback loop are within prescribed bounds that establish the performance and stability robustness characteristics of the system.

LTR Step. The loop transfer recovery is accomplished using the linear quadratic regulator (LQR) method. The regulator performance measure is chosen as

$$J(u) = \int_0^{\infty} \left[q y^T Q_o y + \rho u^T R_o u \right] dt \quad (3)$$

where Q_o is the positive semidefinite symmetric matrix penalizing the outputs y , R_o is the positive definite symmetric matrix penalizing the controls and q and ρ are positive design parameters. The optimal control law is given by

$$u = -K_o \hat{x} \quad (4)$$

where K_o is the optimal feedback matrix; $\rho=1$ has been used in this work. If q is chosen large, the loop transfer recovery is obtained pointwise as long as the plant is MINIMUM PHASE and the number of inputs is greater or equal to the number of outputs. Thus, if q is chosen large enough such that the filter loop meets the desired specifications, then asymptotically, the LQG/LTR procedure will result in a compensator that will also meet the specifications.

Robustness Verification Using the MMS

The optimal control objective for the deaerator ($Q_o R_o$) was chosen to penalize the pressure variable relative to the level variable in order

to achieve tighter control of pressure which was assumed to be more important for overall condensate system performance. The resulting robust controller was then evaluated by controlling the non-linear time varying MMS model of the deaerator. Figure 5 shows the result of an external pressure setpoint change from 165 to 180 psia. The MBC achieves a modest improvement in pressure performance by temporarily lowering the level in the deaerator. Reduction of the flow of relatively cool condensate into the deaerator causes pressure to increase more quickly.

The true efficacy of the model based controller for the deaerator is demonstrated by considering a fault in the steam supply system to the deaerator. Loss of the steam supply causes the deaerator pressure to decrease and consequently cause concern for cavitation at the feedwater pump. The normal control strategy without the MBC results in the operational level control loop exacerbating the loss of steam supply problem by admitting more relatively cool condensate in a misguided effort to maintain level. Accommodation of this loss of steam supply fault using a reconfigurable control strategy based on learning theory showed that by switching to a conventional PI pressure control law on the condensate valve that the rapid pressure decrease could be arrested. (12) Pressure regulation using the condensate valve results in valve positioning completely opposite to that required for level regulation. To increase pressure with the condensate valve, the valve must be closed in order to reduce the flow of relatively cool condensate. The reduction in flow to maintain pressure causes level in the deaerator to be lowered.

The MMS was used to study the performance of the competing control strategies for the deaerator steam supply failure scenario. Figure 6 compares the response of the conventional single loop control strategy, the learning systems reconfiguration to pressure regulation using the condensate valve, and the MBC modification of the level setpoint to the regular level controller. The failure of the steam supply is simulated by closing the steam supply valve to the 10% open position at time 50 seconds. The conventional single loop control strategy results in the worst pressure response as it continues to maintain level regardless of pressure. The learning systems reconfiguration to pressure control using the condensate valve arrests the pressure decrease once it has been decided that a reconfiguration is to be tried (60 seconds after the onset of the simulated failure, time 110 seconds in Figure 6). The MBC has an advantage in that it is continuously working and begins to sacrifice level immediately at the beginning of the fault, time 50 seconds on Figure 6, which results in a noticeably slower rate of decrease in pressure.

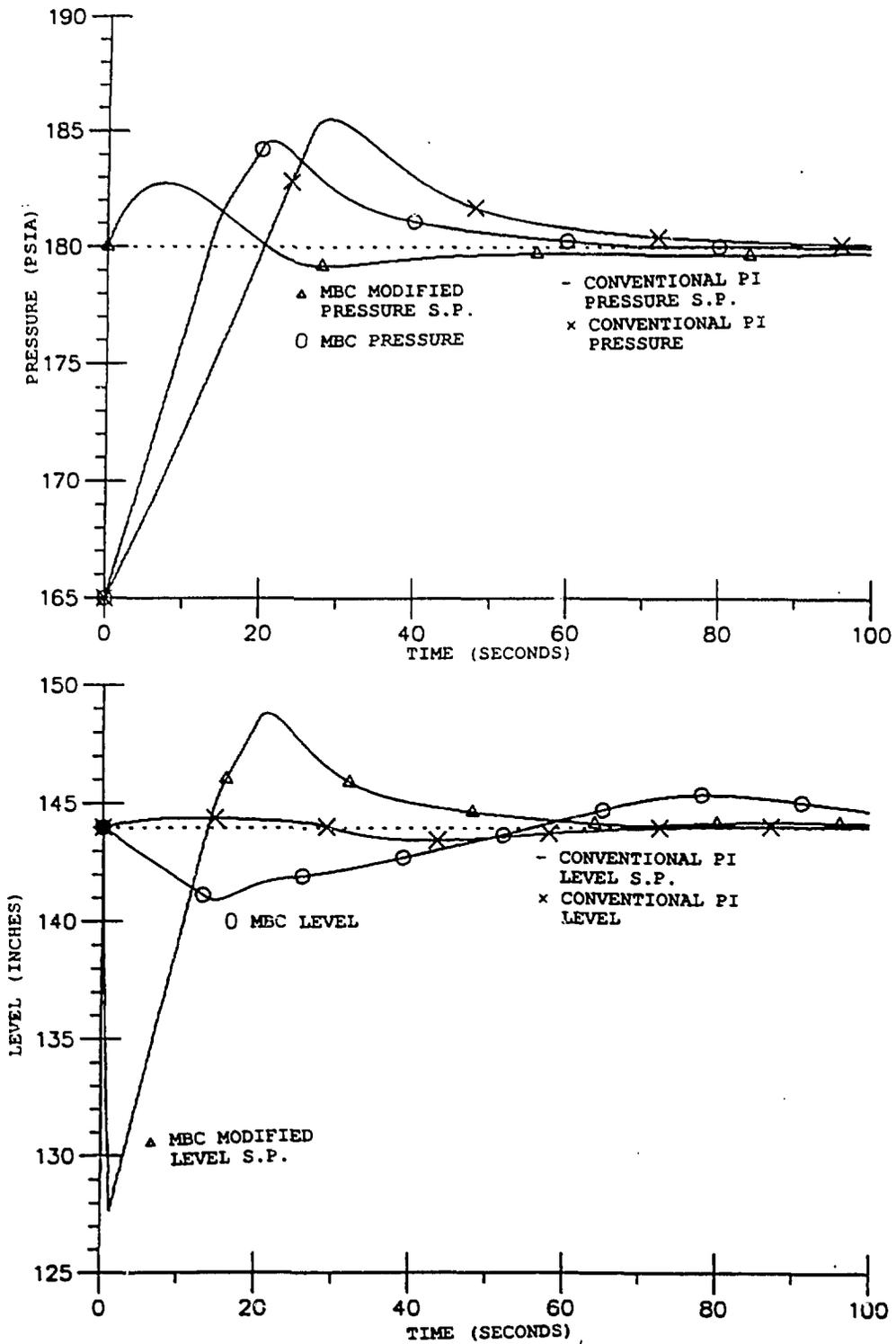


Figure 5. Normal Operation of a Deaerator Multivariable Robust Controller for an External Setpoint Change in Deaerator Pressure from 165 to 180 psia at Time 0 (External Level Setpoint Unchanged).

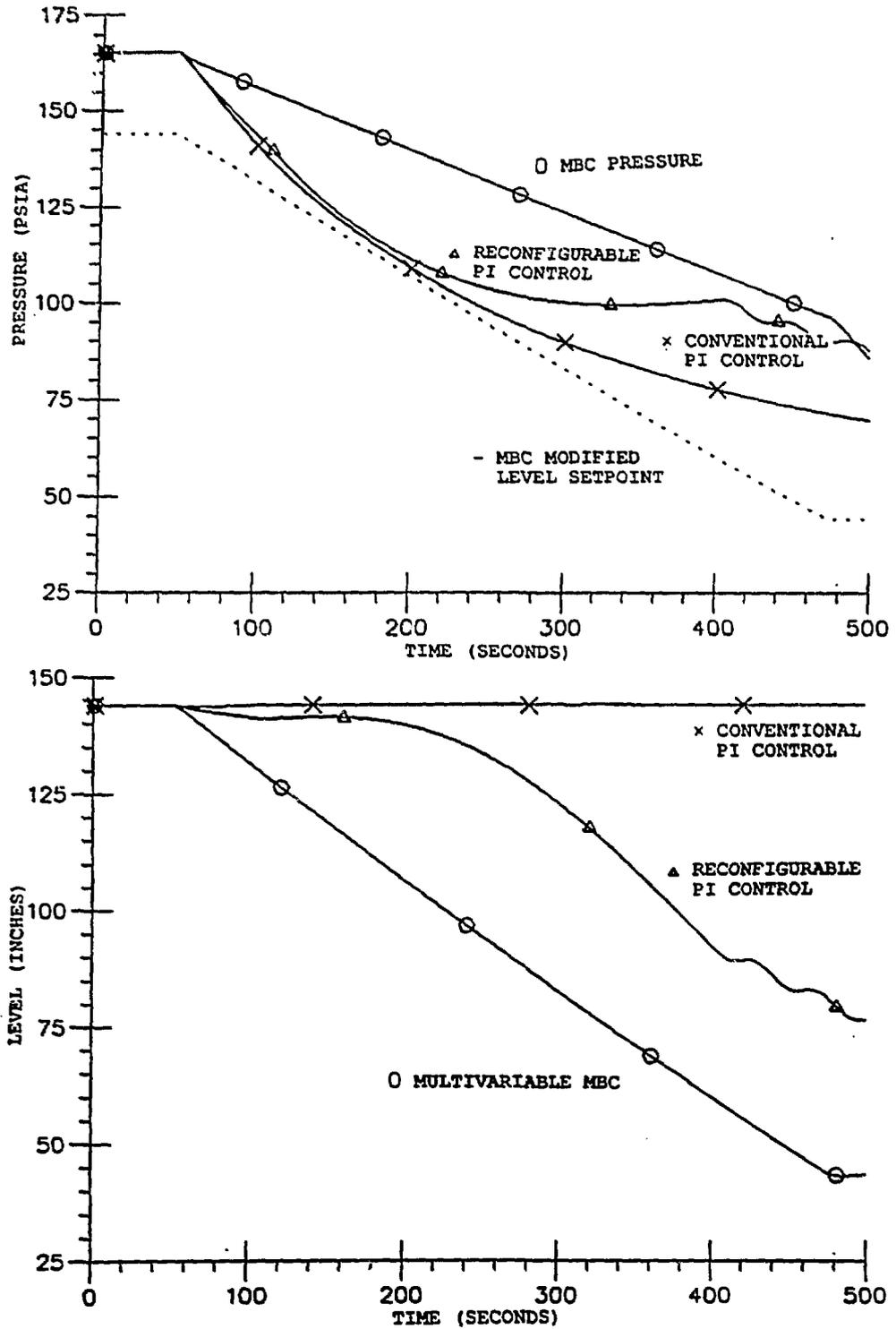


Figure 6. Comparison of Conventional PI, Reconfigurable PI, and Multivariable Robust Control for a Loss of Deaerator Steam Supply Fault at time $T=50$ Seconds.

Similarly to the robust reactor power controller of the previous section, the differential equations of the deaerator MBC are specified in an ACSL DYNAMIC section and interconnected to the MMS model of a deaerator parameterized for the EBR-II steam plant. Again, this initial analysis studies an analog implementation of the MBC which must be shown to have desirable performance and robustness characteristics before it can be considered for implementation in the more uncertain environment of a sampled data controller implemented on a continuous process.

SUMMARY

Current and future research seeks to define, expand, and exploit the properties of the Multiple Layer (ML) approach for improving robustness and fault accommodating capability of model-based power plant control algorithms. The Modular Modeling System plays a key role in this research by providing realistic non-linear time-varying modeling of power plant components and systems for initial design verification.

The combination of a reconfigurable control strategy with a robust controller designs is the foundation of an intelligent control system for dealing with a wide range of operating conditions. The example presented here used a robust LQG/LTR controller design for the nominal plant and demonstrated that its desirable performance characteristics could be extended to the faulted regime. A more elaborate approach would predesign additional controllers for specific operating regimes far away from the nominal conditions (e.g., the deaerator nearly empty or full) and under additional specific faulted conditions. If these additional controllers are designed using robust control methods, fewer controllers would be expected to be needed to cover the same range of conditions than if they were all designed using conventional output feedback approaches. With robust controllers a reconfigurable control strategy would have more intelligent choices to make in order to obtain the best possible system performance.

ACKNOWLEDGEMENTS

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9107-W. However, any findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of DOE.

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