THE 4TH INTERNATIONAL TOPICAL MEETING ON
NUCLEAR THERMAL HYDRAULICS, OPERATIONS AND SAFETY
April 6-8, 1994, Taipei, Taiwan

XA04N0551

PWR CONTROL SYSTEM DESIGN USING ADVANCED LINEAR AND NON-LINEAR METHODOLOGIES

N Rabindran and M J Whitmarsh-Everiss
Nuclear Electric plc
Berkeley Technology Centre, Berkeley
Gloucestershire, GL13 9PB, UK
Fax: (44) 453 810451

ABSTRACT

Consideration is here given to the methodology deployed for non-linear heuristic analysis in the time domain supported by multi-variable linear control system design methods for the pruposes of operational dynamics and control system analysis. This methodology is illustrated by the application of structural singular value μ analysis to Pressurised Water Reactor control system design.

INTRODUCTION

This paper is concerned to define the advanced control system design methodologies deployed by Nuclear Electric plc, UK, in support of a strategy to maximise power output and plant availability. In order to illustrate the methodology, a particular operational problem has been chosen which is concerned with reactor/load control interaction.

The methodology deployed recognises that nuclear plant is inherently non-linear in its behaviour and, hence, all design decisions must be underwritten by heuristic non-linear analysis. For this reason, elaborate plant models are written using macro-structure modelling in the simulation language PMSP.

The purpose of this language is to decouple the engineer from computing science and numerical methods and allow concentration on the solution of engineering problems. The language requires the plant to be defined in terms of ordinary differential equations and algebraic equations. It provides a sort algorithm and Fortran translator. Three steady state and thirteen fixed and variable step length integration algorithms are available. The plant model can be linearised about any steady state yielding the state space matrix for the purposes of linear analyses.

A macro is defined as an equation statement representing a given engineering entity. This may be a complex representation of an advanced gas cooled reactor to more simple representations of pipes or relief valves. Macro structure modelling is supported by PMSP. The macros are held in a library and used to configure particular plants which are characterised by plant specific data held in a Data Macro library. Best estimate data is deployed.

The PMSP model is run in a UNIX environment on a single or parallel processor. The information available in the translator has been used to develop automatic mapping algorithms. The engineer communicates with the model through touch screens in a multi-workstation environment. An advanced graphics package enables formats to be built up from 'alpha-numeric information, trend charts and animated displays. Formats are held in libraries and are selected to the six available screens from a master library of formats. When selected they are pre-attached to PMSP variables. Model control, data and structure change can be effected through suitably designed formats. Output hardcopy is available from laser and colour printers.

Given the state-space matrices, as a linear definition of the model, multi-variable linear control theory can be deployed. This is made available through the use of Matlab 4 and its associated tool boxes, namely control system, multi-variable frequency domain, robust control, μ-synthesis and neural network. PMSP models are large, 600-4500 integrators, with heavy numerical overheads and hence SIMULAB, with its powerful block edit facility, is used for the analysis of small plant items e.g. control power amplifiers.

The state space and system identification tool boxes are available. They enable plant data to be analysed and the latter enables the open loop transfer matrix to be calculated as input to Matlab4. Modern plant data processing systems capture large volumes of data. This may involve some 5000 analogue variables being sampled at intervals appropriate to their time constants. This data has to be filtered before being used for model validation and curve fitted if the time history is to be used as a dynamic boundary condition. Such facilities are held in the signal processing tool box. A number of analyses require optimal solutions and, for this purpose, the *optimisation* tool box is available. Special facilities are available for the generation of the thermodynamic and transport properties of fluids and their mixtures and for electrical systems modelling.

Model documentation is a time consuming activity. For this reason, an automatic route has been developed which yields constants and variable dictionaries from macro headers and algebraic equations from the Fortran source. Individual User Manuals are written on the back of a generic structure.

The complete calculational environment is known as the Plant Design Analyser. It is here illustrated by four figures, 1 and 2 which illustrate the computing environment and the Plant Design Analyser desk, while Figures 3 and 4 illustrate the supporting software environment. Various aspects of this facility are here illustrated by an application of Structured Singular Value μ-analysis techniques from the Robust Control Tool Box (see Figure 3) to the study of PWR low load robustness and, in particular, the problem of reactor/load control interaction. The validity of this linear analysis is subsequently proven by the application of heuristic non-linear analysis in the Plant Design Analyser.

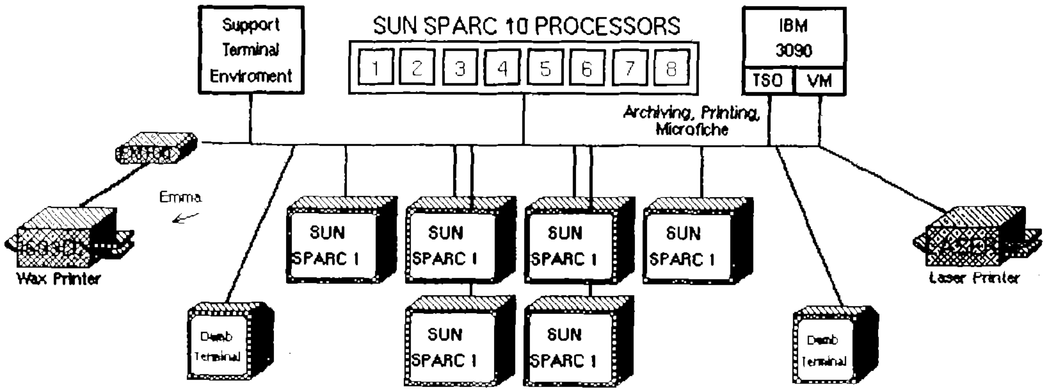


Figure 1: Computing Hardware Environment

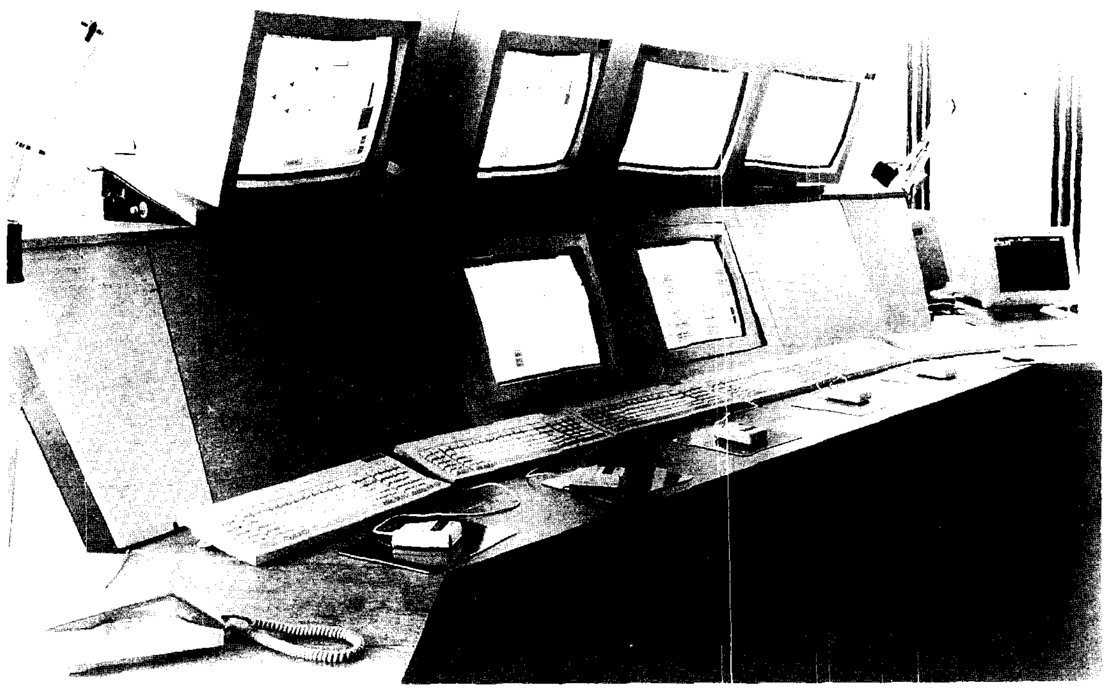
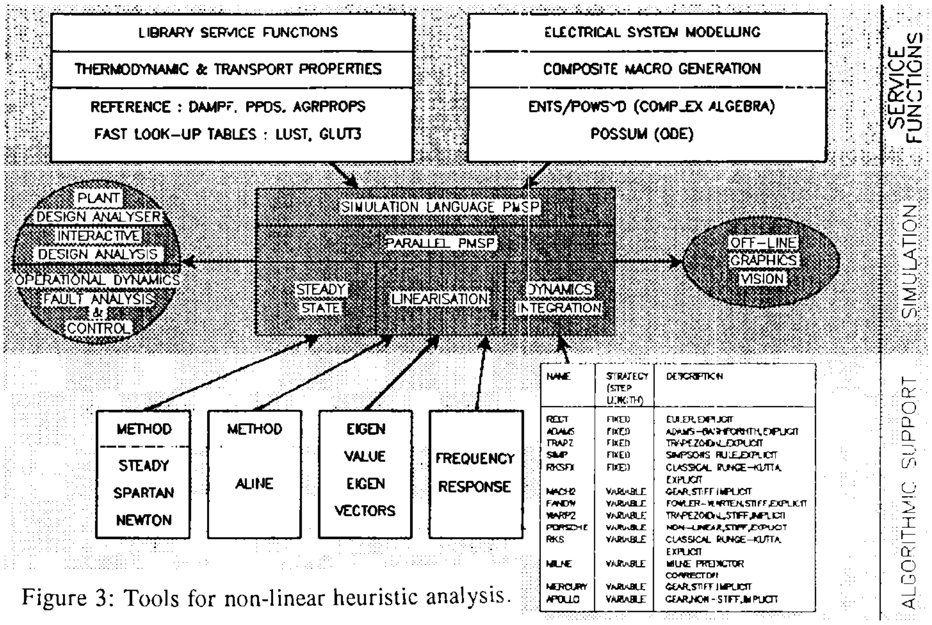


Figure 2: Plant Design Analyser Desk

NON-LINEAR ANALYSIS

The analysis starts by writing a non-linear PWR total plant model in the simulation language PMSP. Such a program has been written in macro structure form and is known as SIBDYM. The model configuration is that of the simplified flow diagram of Figure 5. Here will be found an axially distributed model representing the reactor, a pressuriser, four primary pumps, four boilers, dump system, two turbines, condenser, feed heaters, reheaters, deaerator, feed pump system and drives. Also modelled are the protection and control systems. The steady state of this plant over the load range is determined using method SPARTAN (see Figure 3). This uses sparse matrix techniques, Schuberts update to preserve the sparseness of the Jacobean and L/U decomposition instead of matrix inversion. Given the steady state, the code can be linearised in one job step - SPARTAN ALINE - to yield the state space matrix as input to MATLAB4 (see Figures 3 and 4), which supports the Robust Control Tool Box. When using SIBDYM for dynamic heuristic analysis, it deploys the variable step length trapezoidal, stiff, implicit integration algorithm known as WARP2 (Figure 3).



NAME	STRATEGY (STEP LENGTH)	DESCRIPTION
RECT	FIXED	EULER, EXPLICIT
ADAMS	FIXED	ADAMS-BASHFORTH, EXPLICIT
TRAPZ	FIXED	TRAPEZOIDAL, EXPLICIT
SIMP	FIXED	SIMPSONS RULE, EXPLICIT
RKSFX	FIXED	CLASSICAL RUNGE-KUTTA EXPLICIT
MACH2	VARIABLE	GEAR, STIFF IMPLICIT
FANDW	VARIABLE	FOWLER-WARTEN, STIFF, EXPLICIT
WARP2	VARIABLE	TRAPEZOIDAL, STIFF, IMPLICIT
PORSCHE	VARIABLE	NON-LINEAR, STIFF, EXPLICIT
RKS	VARIABLE	CLASSICAL RUNGE-KUTTA EXPLICIT
MILNE	VARIABLE	MILNE PREDICTOR CORRECTOR
MERCURY	VARIABLE	GEAR, STIFF IMPLICIT
APOLLO	VARIABLE	GEAR, NON-STIFF, IMPLICIT

Figure 3: Tools for non-linear heuristic analysis.

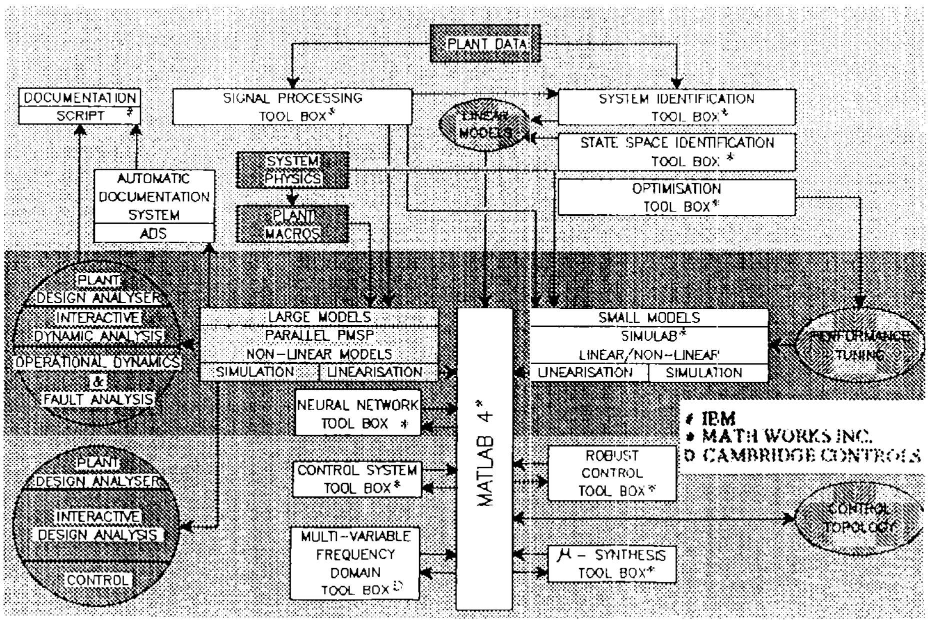


Figure 4: Tools for linear control system synthesis and analysis.

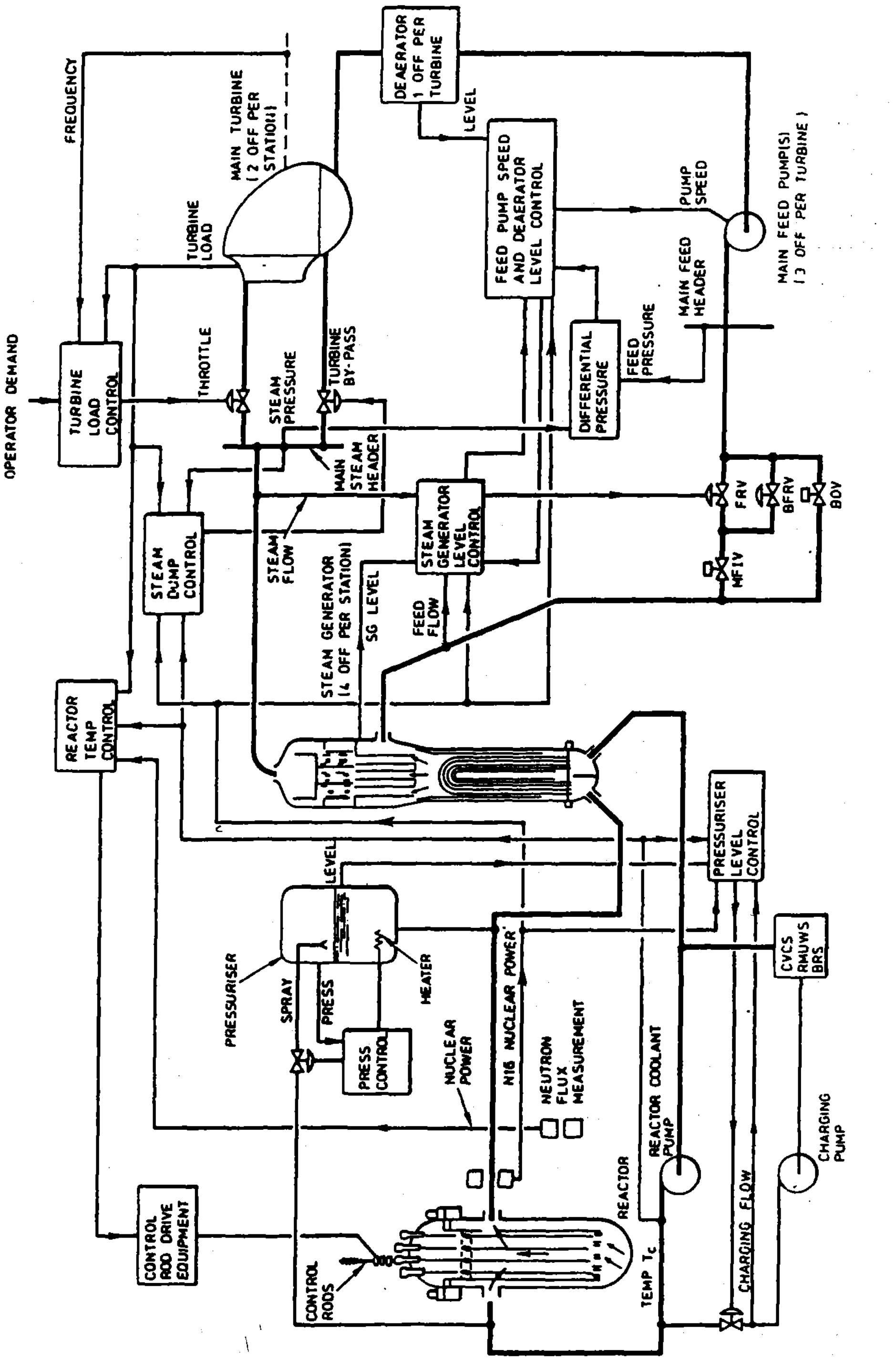


Figure 5: Schematic flow diagram of the total plant steady state and dynamic model SIBDYM (NB only one boiler and turbine feed train is shown)

SIZEWELL B LOW LOAD CONTROL SYSTEM STUDIES

Introduction

The Sizewell B control system topology is essentially a DDC (Direct Digital Control) implementation of the Bechtel's Standardised Nuclear Unit Power Plant Systems (SNUPPS) design with significant enhancements[1] to the steam generator level control system. These enhancements were the result of comprehensive design investigations utilising the well known linear multivariable frequency control system design methods, namely, the Inverse Nyquist Array[2] and Characteristic Loci[3] techniques. The operating strategy adopted for the Sizewell B power station is such that considerable reliance will be placed on the automatic controllers for the regulation and load manoeuvres of the plant throughout the load range. It is, therefore, paramount that the automatic control system exhibits robust regulation, tracking and disturbance rejection properties. Thus, a clear need exists for the assessment of the robustness of the automatic control system in a rigorous systematic manner. It is the purpose of the work presented in this section to illustrate, by way of example, the analysis procedure deployed at Nuclear Electric to meet this need.

The selected design example is concerned with an instability identified in the reactor temperature control system at low powers during the design substantiation studies. The control system design studies are effected in three distinct stages. The first stage involves the formulation of the generalised total plant linear model from the non-linear model, SIBDYM. The infra-structure of the linear model is such that a wide range of controller configurations and problems can be readily addressed in the multi-input multi-output manner. The linear model is used to synthesise an improved feedback control law for the stabilisation of the reactor temperature control system. In the second stage, the total plant linear model is conveniently reformulated, and the Structured Singular Value Technique[4,5] deployed for the analysis of the robustness properties of the overall control system in the multivariable sense. In the final stage, the control laws which emerge from the linear studies are incorporated in the total plant non-linear model, and the plant subjected to a wide range of forcing functions to confirm the viability of the improved design.

The Structured Singular Value μ Framework

Uncertainty in mathematical models used to represent the process being controlled, and uncertainty in the disturbance inputs poses major difficulties in control system design. Robust control refers to the maintenance of design specifications in the face of uncertainty. The structured singular value (μ) is a means of assessing not only the robust stability but also the robust performance of a system. In this section a brief description of the structured singular value technique is presented.

The structured singular value technique for investigating the performance and robustness characteristics of control systems utilises the general framework shown in Fig 6. Any linear interconnections of inputs, outputs, commands, disturbances, and controllers can be readily rearranged to produce this structure, where P is the system interconnection structure, Δ is the plant uncertainty, K is the control law, v is the vector of external inputs and disturbances, e is the vector of errors, y is the vector of measurements, u is the vector of inputs to the plant from the controller, z is the input vector to the uncertainty block, and w is the output vector from the uncertainty block.

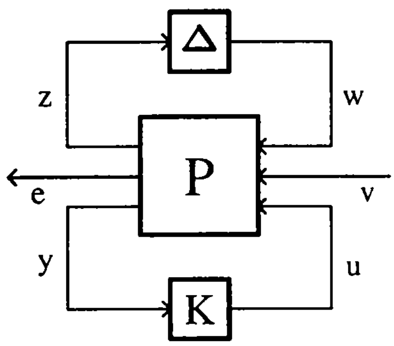


Figure 6: General Interconnection Structure

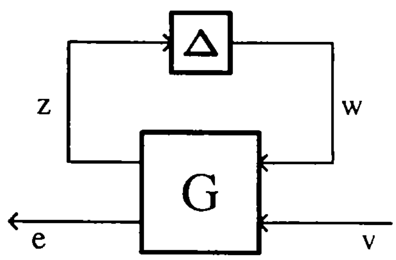


Figure 7: Structure for Analysis.

In the robust control system design context, the following terminology is extensively used:

Nominal Stability: To achieve nominal stability, the nominal plant model has to be stabilised by the controller design.

Nominal Performance: In addition to nominal stability, the nominal closed-loop response should satisfy some prescribed performance criteria.

Robust Stability: The closed-loop system must remain stable for all possible plants as defined by the uncertainty description.

Robust Performance: The closed-loop system must satisfy the performance requirement for all possible plants defined by the uncertainty description.

Inclusion of the controller, K, with the plant, P, transforms the structure in Fig 6 to that in Fig 7. In the analysis problem, the aim is to determine whether the error, e, meets the specified criteria for a given set of inputs, v, and perturbation, Δ. The uncertainty in v, Δ, and the performance specification, e, are normalised to 1, which requires that all weighting functions and scalings must be incorporated in the interconnection matrix, G. The relationship between v and e is governed by the linear fractional transformation:

$$e = F_u(G,\Delta)v \,, \tag{1}$$

where

$$Fu(G,\Delta) = G_{22} + G_{21}\,\Delta(I - G_{11}\,\Delta)^{-1}G_{12} \,, \tag{2}$$

and

$$G = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \tag{3}$$

Nominal performance is achieved if

$$sup\ \sigma_{max}(G_{22}(j\omega)) \le 1 \quad \forall\omega, \tag{4}$$

where $\sigma_{max}(G_{22}(j\omega))$ is the maximum singular value of G_{22} (jω).

If Δ is structured and belongs to the set

$\underline{\Delta} = diag(\Delta_1, \Delta_2, \ldots, \Delta_n)$,

$B\,\underline{\Delta} = \{\Delta \in \underline{\Delta}:$

$$\sigma_{max}(\Delta) \le 1\}, \tag{5}$$

then, for a complex matrix, $M \in C^{n \times n}$, the structured singular value, $\mu_\Delta(M)$, is defined as

$$\mu_\Delta(M) := \min \frac{1}{(\sigma_{max}[\Delta : \Delta\epsilon\Delta, det(I+M\Delta) = 0])} \tag{6}$$

unless no $\Delta \in \underline{\Delta}$ makes I+M Δ singular, in which case

$\mu_\Delta(M) := 0$.

In the presence of structured uncertainty, stability is robust if

$$sup\ \mu(G_{11}(j\omega)) \le 1\ \forall\ \omega, \tag{7}$$

and, performance is robust if

$$sup\ \mu(G(j\omega)) \le 1\ \forall\ \omega, \tag{8}$$

where μ(G (jω)) is computed in relation to the structure,

$$\underline{\Delta} = \{diag(\Delta, \Delta_{n+1})\},\ \Delta \in \underline{\Delta} \tag{9}$$

CONTROL SYSTEM DESIGN

Formulation of Reduced-order Linear and Non-linear Models

The total plant non-linear PMSP model, SIBDYM, was linearised with all automatic loops closed with the exception of the loops related to load and reactor temperature. This results in a state space realisation of 248 states 3 inputs and 4 outputs. In order to reduce the computational burden on MATLAB, and to keep the analysis numerically tractable, the state space realisation was reduced to 29 states using the balanced realisation technique[6]. The reduced-order linearised model was then used in the construction of the load/reactor temperature control system in the MATLAB/SIMULINK environment. Fig 8 shows the resulting control system structure which is used for the multivariable analysis.

The power generated by each of the twin turbines are individually controlled by manipulation of the turbine governor valves. The load controller implements proportional plus integral feedback control action.

The reactor temperature controller regulates the reactor cold leg coolant temperature (tcold) by manipulating the control rods. Additionally the rate of change of the mismatch between nuclear power and measured turbine power is suitably shaped and fed forward to the control rods as shown. The steady state characteristics of the control system are governed by the integral action on tcold error, and the transient response of the control system is shaped by the derivative action on tcold and the mismatch between nuclear and turbine power.

A subset of the state space realisation used in the formulation of the structure in Fig 8 has been extracted to construct a stand alone reactor temperature control system (Fig 9) for single-input, single-output control system analysis purposes.

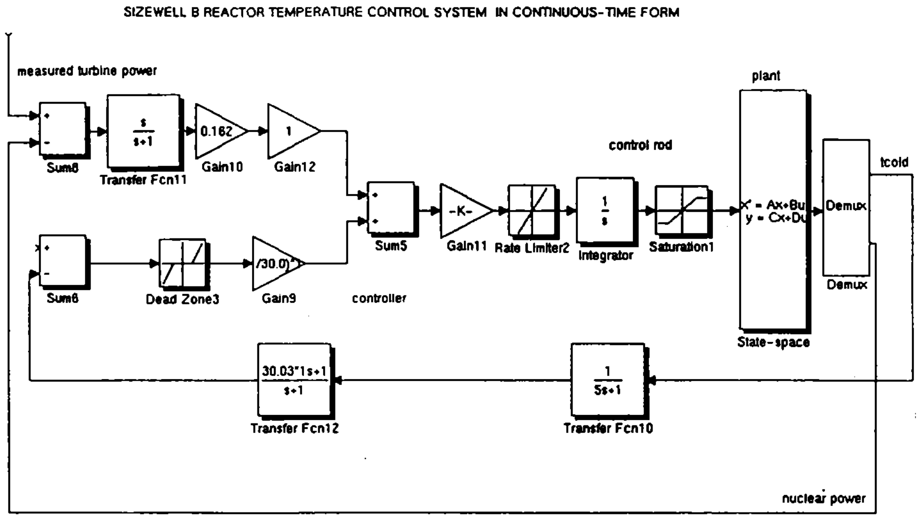


Figure 8: Load/Reactor Temperature Control System - SIMULINK Representation.

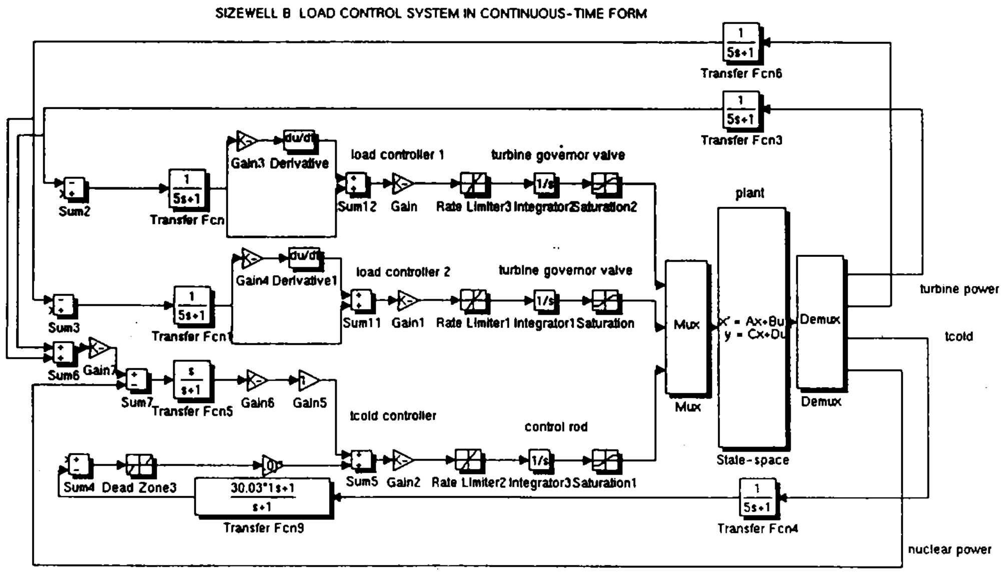


Figure 9: Reactor Temperature Control System - SIMULINK Representation.

Synthesis of an Improved Reactor Temperature Controller

Simulations performed at 10% load using the total plant model, SIBDYM in the plant design analyser are presented in Fig 10. Case A exemplifies the existence of a divergent instability. The reactor and load control system responses to a -3% step change in the load controller set point are shown. Exploratory simulations with various controller configurations indicated that the instability is associated with the reactor temperature control system. The root locus of the reactor temperature control system is shown in Fig 11. Clearly, the pole-zero placement in the feed back control law synthesis is not commensurate with the open-loop plant dynamic characteristics. Case B shows the root locus of the improved control system with appropriate modifications to the proportional plus integral feedback control law. It can be inferred that the improved pole zero placement enables the use of relatively high gains yielding tight, stable, closed- loop control system dynamic characteristics. The corresponding Nyquist contours for the nominal and improved control systems are shown in Fig 12. Case B in Fig 10 shows the plant non-linear responses due to implementation of the stabilised reactor temperature control systems. It is evident that the overall control system exhibits excellent transient and settling characteristics.

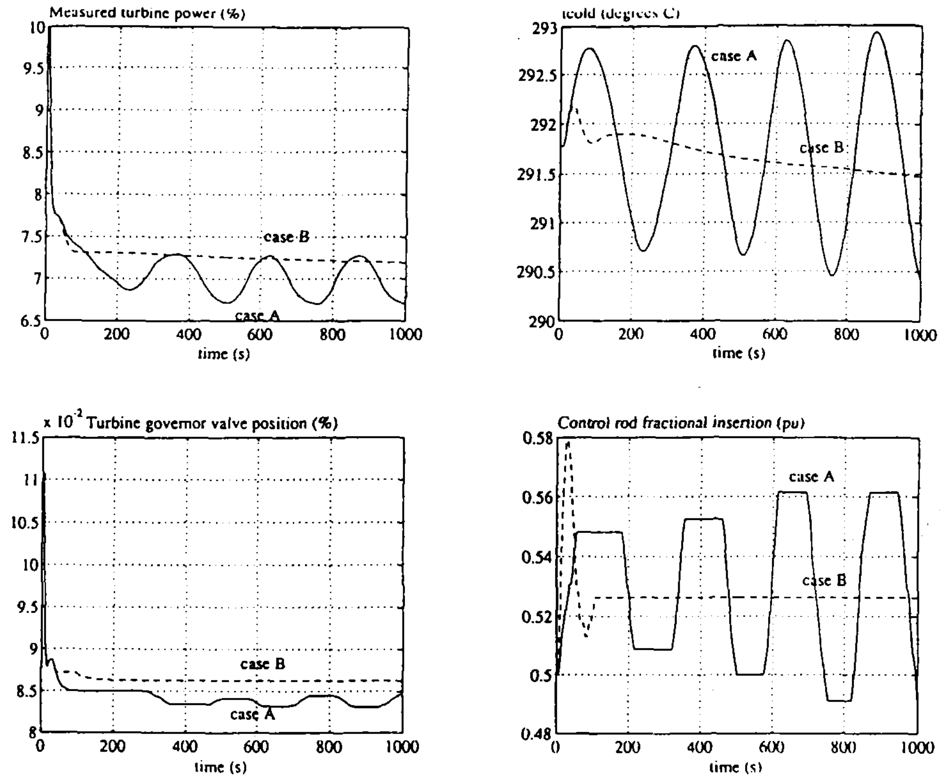


Figure 10: Load/Reactor Temperature Control System Response to a -3% Step on Load Set Point.

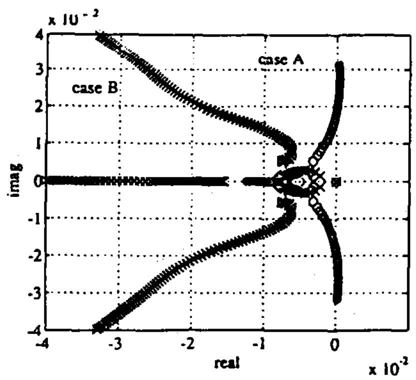


Figure 11: Root Loci of the Reactor Temperature Control System.

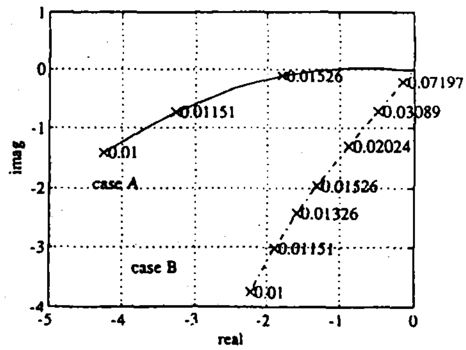


Figure 12: Nyquist Contours of the Reactor Temperature Control System.

Robustness Analysis

Fig 13 shows the closed-loop interconnection structure for the reactor temperature/load control system. Fig 14 shows the corresponding block diagram structure for checking robust performance. Perturbation matrix Δ_2 leads to the robust performance test using the structured singular value, μ. The nominal plant model, P, consists of 3 inputs and 4 outputs. K is the feedback controller. W_a is multiplicative uncertainty weight at the plant inputs, governor valves and control rods, and W_p is the performance weight on the outputs, turbine power and tcold.

The uncertainty weight, W_a, assumes the form $Wa(s) := w_a(s) I_3$, where

$$w_a(s) = 2\left(\frac{s + 0.2}{s + 2}\right) \tag{10}$$

This uncertainty weight indicates that, at low frequencies, there is potentially 20% modelling error on the actuators increasing up to 200% at high frequencies as shown in Fig 15.

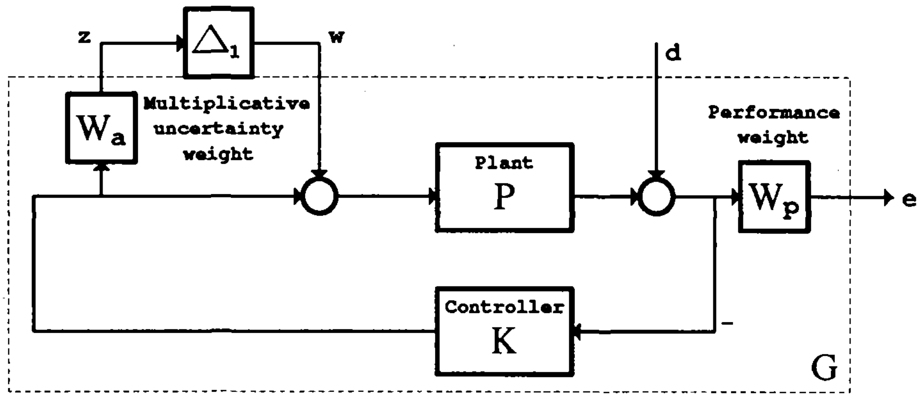


Figure 13: Closed-loop Interconnection for the Load/Reactor Temperature Control System.

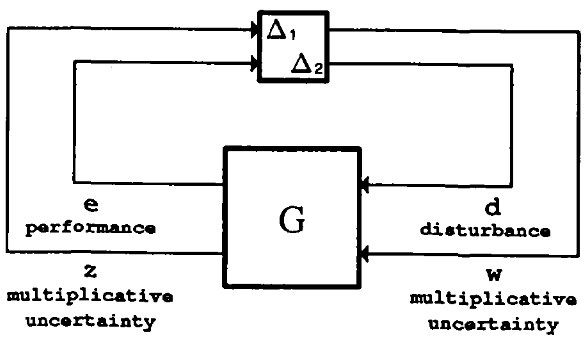


Figure 14: Structure for Checking Robust Performance.

The performance weight, W_p, assumes the form $W_p(s) := w_p(s)I_3$, where

$$w_p(s) = 0.5\left(\frac{s+0.025}{s}\right) \qquad (11)$$

This performance weighting function implies that integral action is required for rejection of disturbances at the outputs. Thus as shown in Fig 16 at zero frequency, 1/wp=0, and at high frequencies disturbance amplification up to a factor of 2 is allowed.

Fig 17 shows $\sigma_{max}(G_{22}(j\omega))$, $\mu(G_{11}(j\omega))$, and $\mu G(j\omega))$ for the closed loop system with the improvements to the reactor temperature control system. It is evident that the stability and performance of the control system is robust for the given uncertainty description and performance criteria. The achievement of robust performance and stability characteristics has been facilitated by the use of the total plant non-linear model, SIBDYM, in the Plant Design Analyser environment. A wide range of forcing functions and disturbances are applied to the control system, and adjustments made to the control-laws which emerge from the linear analysis. Thus, the feed-back control-law synthesis is essentially an iterative process between the linear robust control system design process and non-linear simulations. It is of course possible to adopt a more systemmatic approach such as combining the structured singular value analysis with H_∞ optimisation[7] to design the multivariable controller. While this approach has the advantage of seemingly being able to guarantee levels of robust stability and performance, the control-laws which emerge from this approach are not only complex but of high order. Implementation of such controllers is not a viable proposition at the present time.

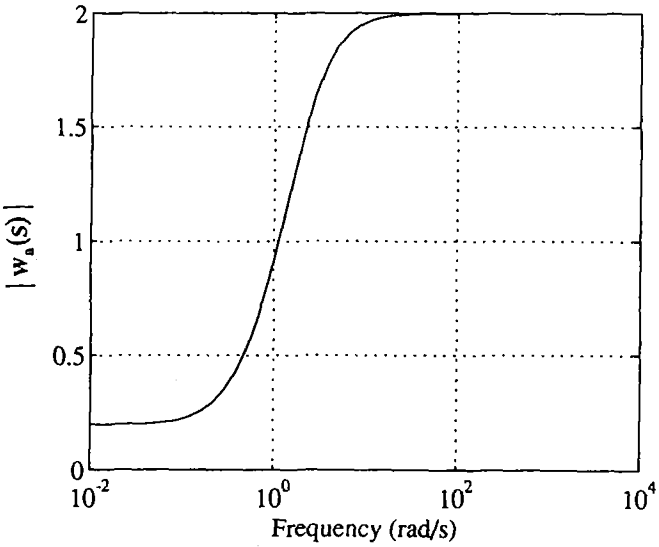


Figure 15: Multiplicative Uncertainty Weighting Function, w_a.

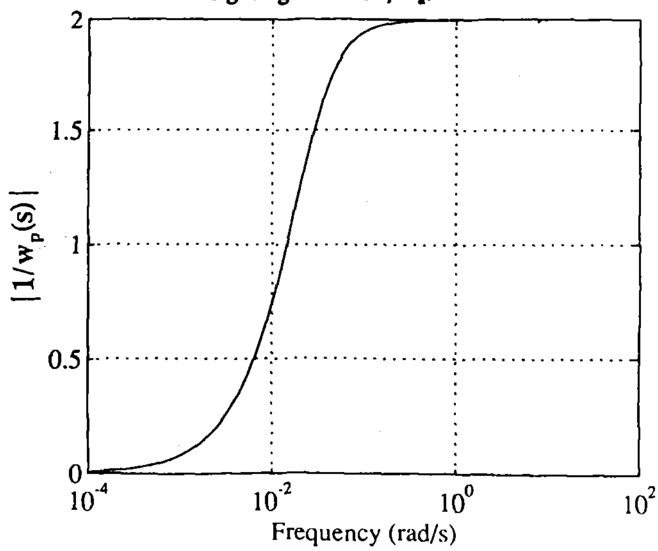


Figure 16: Inverse of Performance Weighting Function, w_p.

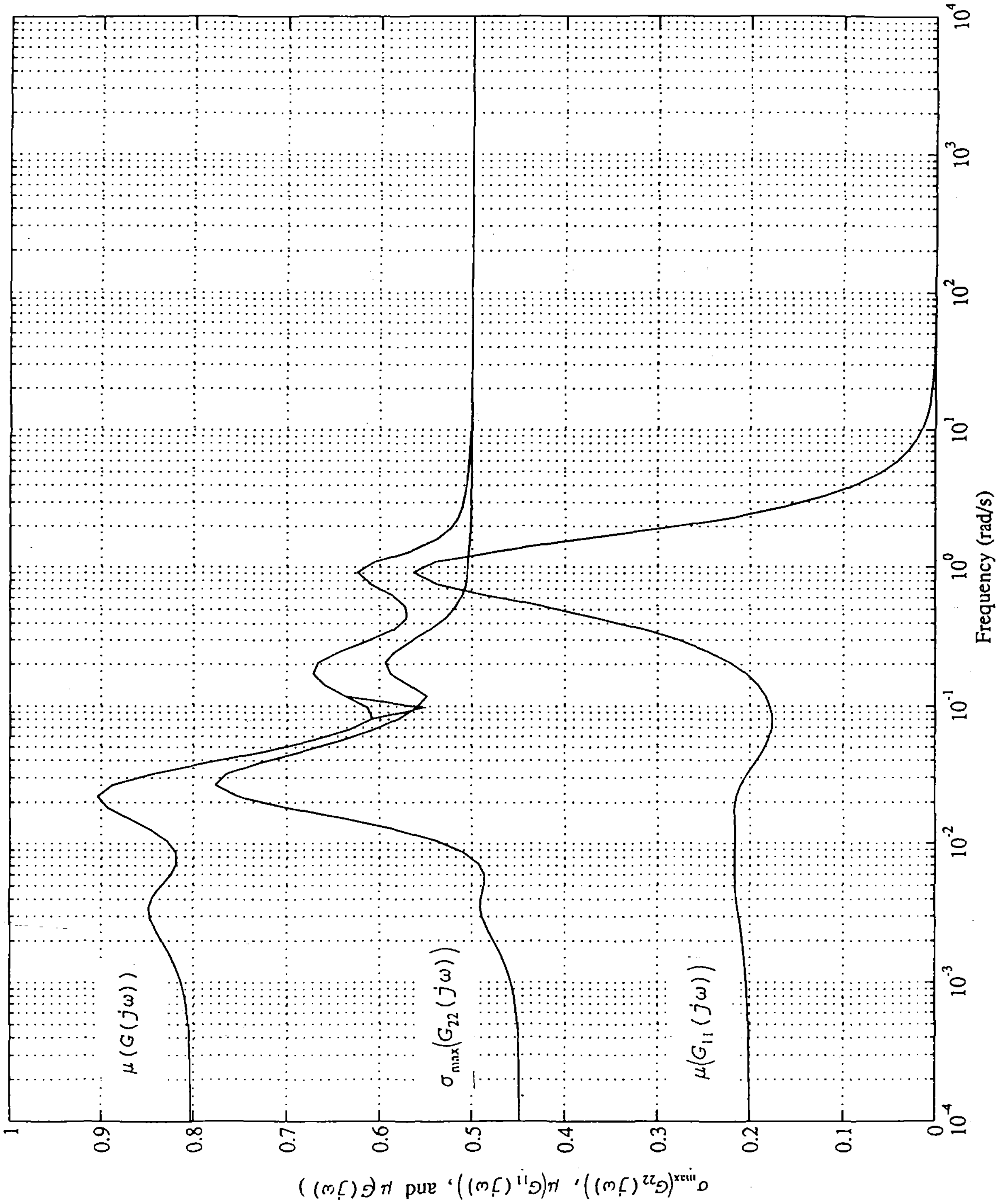


Figure 17: $\sigma_{max}(G_{22}(j\omega))$, $\mu(G_{11}(j\omega))$, and $\mu(G(j\omega))$ for the Closed Loop System.

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ACKNOWLEDGEMENTS

The authors would like to thank Nuclear Electric plc for permission to publish the material in this paper. Where opinions are expressed they are those of the authors and not necessarily those of the Company.

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NUCLEAR THERMAL HYDRAULICS, OPERATIONS AND SAFETY
April 6-8, 1994, Taipei, Taiwan

Diagnosis Function of Safety Status in the Safety Parameter Display System(SPDS)

Yuanfang Zhang (TH U)

Session 13
Plant Simulators, Analyzers, and Workstations-II