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MULTIVARIABLE ROBUST CONTROL OF AN INTEGRATED NUCLEAR POWER REACTOR

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Abstract - The design of the main control system of the CAREM nuclear power plant is presented. This plant is an inherently safe low-power nuclear reactor with natural convection on the primary coolant circuit and is self-pressurized with a steam dome on the top of the pressure vessel (PV). It is an integrated reactor as the whole primary coolant circuit is within the PV. The primary circuit transports the heat to the secondary circuit through once-through steam generators (SG). There is a feedwater valve at the inlet of the SG and a turbine valve at the outlet of the SG. The manipulated variables are the aperture of these valves and the reactivity of the control rods. The control target is to regulate the primary and secondary pressures and to monitor steam flow reference ramps on a range of nominal flow from 100% to 40%. The requirements for the control system are robust stability, low-order simple controllers and transient/permanent error bounding. The controller design is based on a detailed RETRAN plant model, from which linear perturbed open-loop dynamic models at different powers are identified. Two low-order nominal models with their associated uncertainties are chosen for two different power ranges. Robust controllers with acceptable performances are designed for each range. Numerical optimization based on the loop-shaping method is used for the controller design. The designed controllers are implemented in the RETRAN model and tested in simulations achieving successful results.

Keywords: multivariable robust control, loop-shaping, identification, nuclear power plants.

INTRODUCTION

CAREM is a nuclear power reactor under development by CNEA (Comisión Nacional de Energía Atómica) and INVAP SE. A schematic plant drawing is shown in Figure 1.

It is an inherently safe low-power nuclear reactor with natural convection on the primary coolant circuit and is self-pressurized with a steam dome on the top of the pressure vessel (PV). It is an integrated reactor as the whole primary coolant circuit is within the PV. The primary circuit transports the heat to the secondary circuit through once-through steam generators (SG). There is a feedwater valve at the inlet of the SG and a turbine valve at the outlet of the SG. The manipulated variables (U) are the aperture of these valves (Afwv and Atv) and the reactivity of the control rods (Rcr).

The control target is to regulate the primary and secondary pressures (Pp and Ps) and to monitor steam flow (Ws) reference ramps on a range of nominal flow from 100% to 40%. The requirements for the control system are robust stability, low-order simple controllers and transient/permanent error bounding.

The robust control design procedure (Sánchez Peña and Sznaier, 1998) requires a nominal model of a plant and a description of the uncertainty between the model and the actual process provided in the frequency domain. There are some previous applications of this technique to nuclear reactor power control. Suzuki et al. (1993) designed an H_{inf} robust power controller for a simple seventh-order

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Boiling Water Reactor model. Weng et al. (1994) and Power and Edwards (1995) designed a robust wide-range power controller for a simple tenth-order Pressurized Water Reactor (PWR) model. All these design approaches result in controllers of orders similar to the order of the nominal plant. As a consequence implementation of the controllers is impractical for complex high-order plants. They are also based on simple nonlinear models of the plant, which are indeed approximations of the real plant, and have their own uncertainties.

The main control systems of traditional PWR designs consist of several SISO control loops. In the primary cooling system the nuclear power is controlled by the reactivity of the control rods, the Pp is controlled by heaters and showers in a pressurizer and the coolant flow is fixed. In the secondary cooling system the pressure is normally controlled by the turbine valve. As opposed to traditional PWR designs, in the CAREM plant the nuclear power is strongly coupled with the Pp and the primary flow. The inlet temperature and flow to the SG on the secondary side are also coupled with the Pp. Therefore multivariable control must be considered in controller design.

In this work the design of the main control loops of the CAREM plant is presented. The plant to be controlled is a RETRAN (EPRI, 1988) nonlinear neutronic and thermohydraulic detailed model developed for engineering calculations with several hundred internal variables. Identification techniques are applied to this model in several power ranges. Analysis of the identified models allows definition of two nominal models with their associated uncertainties for both the high-power range (above 75%) and the low-power range. In section 2 we describe this identification process.

Based on these models with their associated uncertainties, a simple robust low-order controller is obtained for each power range with a numerical optimization technique based on the loop-shaping method (Skogestad and Postlethwaite, 1996). This is described in section 3.

The controllers are embedded in the RETRAN model and the design specifications are verified by simulation. These results are presented in section 4.

Finally the conclusions of this work are presented in section 5.

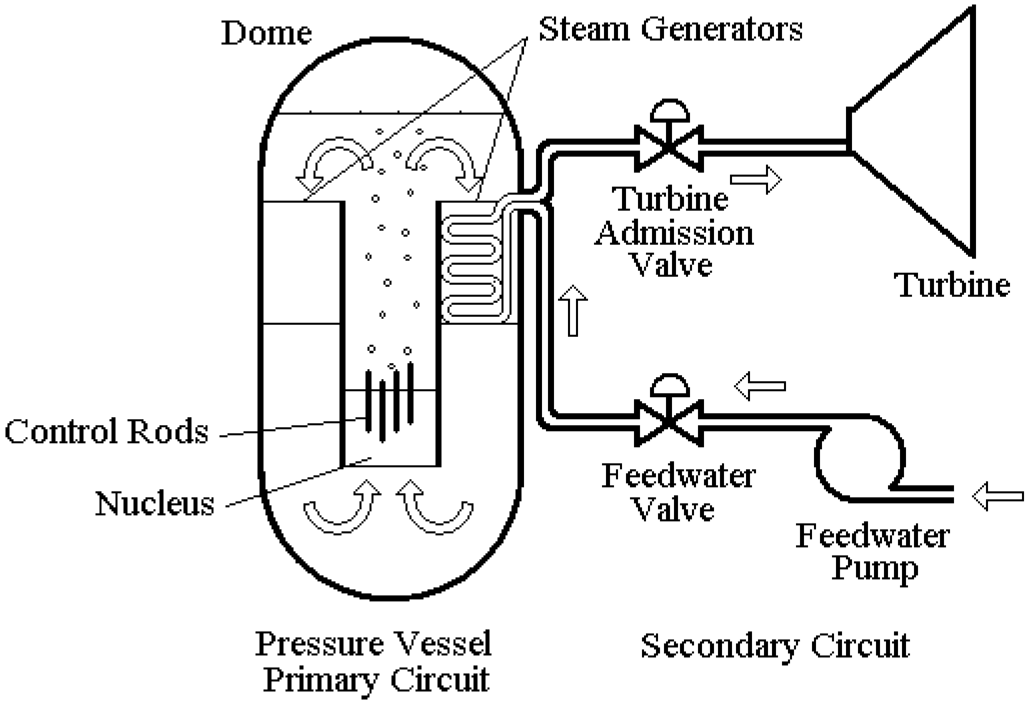

Figure 1: Schematic drawing of the CAREM plant.

IDENTIFICATION

Starting from five different RETRAN model stationary states, each input is successively perturbed through small amplitude test signals, like chirp and pseudorandom binary sequences (PRBS). The amplitude of the test signals selected was small enough to avoid appreciable nonlinear effects on the plant response. With the input-output response to the chirp signals, nine parametric models are identified for each of the input-output combinations, following a least squares error procedure, (Ljung, 1987). The structures and orders of the parametric models were selected using the RETRAN model response to PRBS as validation sets. From these models, nine transfer functions with their associated uncertainties are obtained. These constituted an identified model at each stationary power point. The identified models are reduced by gramian-based balancing and truncation (Sánchez Peña and Sznaier, 1998). Choosing as nominal models a reduced model (of about 20 state variables) for high power (from 75% to 100% full power) and another reduced model for low power (from 40% to 75%), we determine the highest singular value of the uncertainties considering both the appropriate uncertainties of the specific identification process and the differences between the identified models at other powers in the range and the nominal model. The criteria for the selection of the reduced models as nominal models was the minimum highest singular value for the associated uncertainty. The definition of two ranges is because with only one range the magnitudes of the highest singular value for the uncertainties at low frequency rise above the 0 db (see Figure 2), and thus a robust controller for the entire power range (40% to 100%) cannot be obtained.

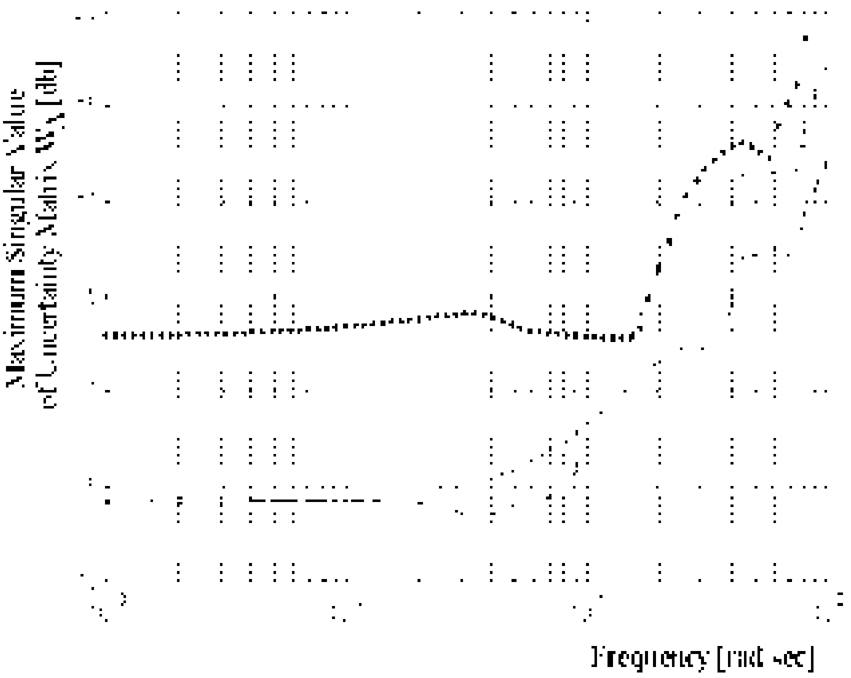

Figure 2: Highest singular values of W_Δ as a function of frequency. Solid line: low-power range with the 43 % reduced model as the nominal model. Dashed line: high-power range with the 88 % reduced model as the nominal model. Dotted line: entire power range (40% to 100%) with the 75% reduced model as the nominal model.

CONTROLLER DESIGN

Relative gain array (RGA) analysis (Skogestad and Postlethwaite, 1996) indicates that Pp can be independently controlled with Rcr alone and that both Ws and Ps must be controlled with Afwv in conjunction with Atv. Based on these results, in Eq. (1) a block diagonal structure is selected for the controller that uncouples the primary and secondary control loops, where the integral terms on the diagonal elements are included to obtain bounded errors for ramp inputs:

$$K(s)=\begin{pmatrix} K_{11}\left(\tau_{z11}s+1\right)/s(\tau_{p11}s+1) & K_{12}\left(\tau_{z12}s+1\right)/\left(\tau_{p12}s+1\right) & 0 \\ K_{21}\left(\tau_{z21}s+1\right)/\left(\tau_{21}s+1\right) & K_{22}(\tau_{22}s+1)/s(\tau_{p22}s+1) & 0 \\ 0 & 0 & K_{33}(\tau_{33}s+1)/s(\tau_{p33}s+1) \end{pmatrix} \quad (1)$$

The block diagram of the controlled system is shown in Figure 3.

The plant is represented by the nominal system transfer matrix, Gu0(s), and the associated uncertainty transfer matrix, W∆s).

The input to the plant is

$$u=\left(\text{Atv}\ \ \text{Afwv}\ \ \text{Rcr}\right)^{T},$$

the output is

$$y=\left(\text{Ps}\ \ \text{Ws}\ \ \text{Pp}\right)^{T}$$

and the reference input is

$$r=\left(\text{Ps}_{\text{ref}}\ \ \text{Ws}_{\text{ref}}\ \ \text{Pp}_{\text{ref}}\right)^{T},$$

where subscript ref denotes reference signal and ∆ is any transfer matrix such that

$$\|\Delta\|_{\infty}\le 1.$$

The uncertainties in the actuators are represented through an external perturbation, $\underline{\Delta u}$, with G_{wu} its associated dynamic weight matrix. W_r is the reference input weight matrix and W_e is the output error weight matrix, defined in order that transient error bound is allowed to double the ramp following permanent error bound.

To satisfy the criteria of robust stability and nominal performance a loop-shaping design procedure is implemented through a numerical optimization method in order to obtain the parameters of K(s). An F cost function that measures the mean distance from the actual loop transfer matrix, L(s), to a desired transfer matrix, $L_D(s)$, is defined. This desired transfer matrix is of the type K/s, with the gain K defined in order to obtain a 0 db crossover frequency ω_c compatible with the uncertainties associated to the family of models. The F cost function has a term that measures: lower than desired gain at low frequencies (F_{lf}), higher than desired gain at high frequencies (F_{hf}) and higher than desired peak gain on the closed-loop transfer matrix, (F_T). The optimization process obtains the controller parameters, K_{ij}, τ_{zij} and τ_{pij}, that minimizes the cost function F subject to the following set of constraints: stable closed-loop system; stable and minimum phase controller and limitations on the maximum frequency for the poles and zeros of the controller related to a limited sampling frequency (aliasing). The relative weight of the F cost function terms are adjusted, based on the results of the optimization process. A higher weighting of the F_{lf} term implies higher performance; of the F_{hf} term, improved robustness; and of the F_T term, improved transient performance. The singular values for L(s), $L_D(s)$ and the closed-loop transfer matrix T(s), together with the inverse magnitude of the maximum singular value of the uncertainties W_{Δ}^{-1} at high frequencies, are given in Figure 4.

The nominal and robust performance condition is evaluated separately for each external perturbation $\underline{w}$ and for the reference input r in order to analyze the relative sensitivity of the output error with respect to these external signals and to modeling uncertainty. As an example, the maximum slope for the reference input to the nominal plant in the range of 75% to 100%, is reduced a factor of two if uncertainties are considered.

SIMULATION RESULTS

The controllers are implemented in the RETRAN model and the design specifications are verified by simulation. Ramp properties are shown in Figure 5.

A 1%/min and a 3%/min steam flow ramp are simulated for the low- and the high-power range. The control is switched from the low- to the high-power range just before the 3%/min steam flow ramp. The output errors are shown normalized with respect to the admissible steady-state error bounds. These are the steam flow error (Ws_{ref}-Ws), the secondary pressure error (Ps_{ref}-Ps) and the primary pressure error (Pp_{ref}-Pp). Note that the errors are within the transient admissible error bounds, which are twice these admissible steady state bounds.

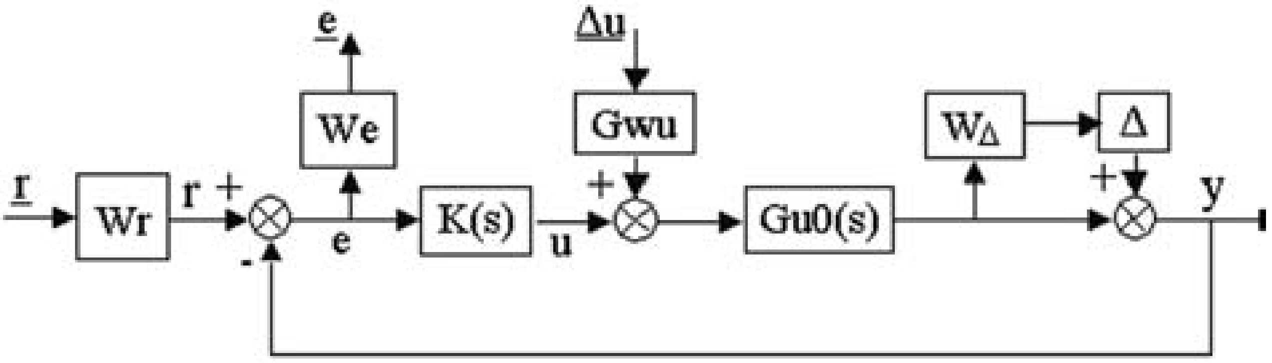

Figure 3: Block diagram of the controlled system.

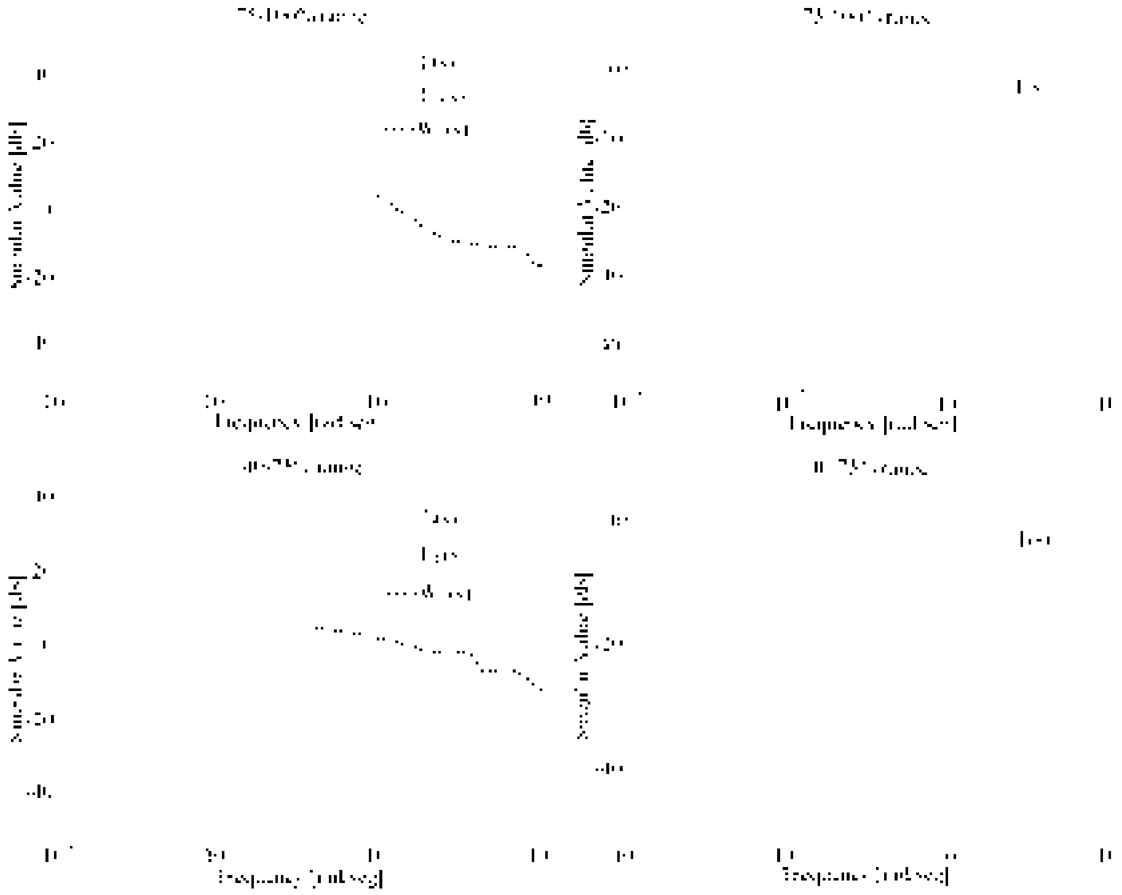

Figure 4: Controller design results: singular values of L(s), L_D(s) and T(s).

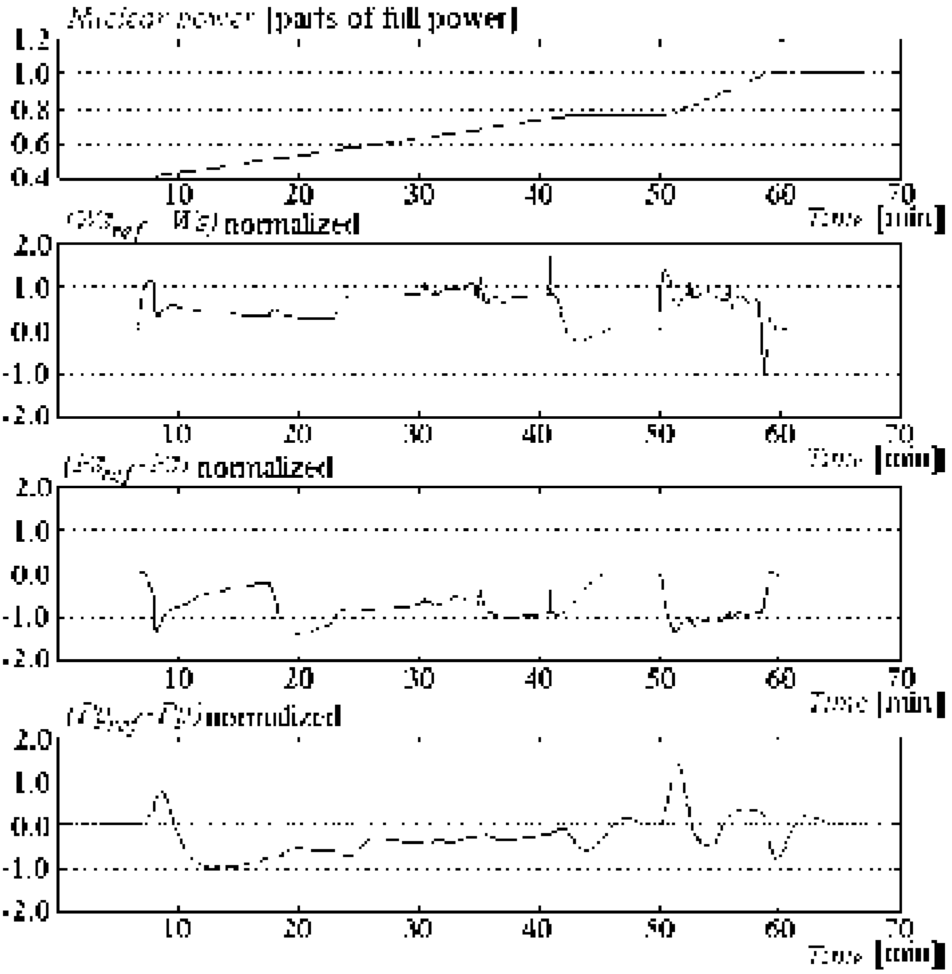

Figure 5: Time evolution of nuclear power and output variable errors.

CONCLUSIONS

Two stable, robust, low-order and simple controllers were designed for both high- and low-power operation of the CAREM reactor. A steam flow ramp capacity of 3 %/min and 1 %/min is observed for the high- and the low-power range, respectively, within a restrictive error bound, showing an acceptable performance of the controllers. Sensitivity to external perturbations is also evaluated as acceptable although the results are not presented in this work.

An accurate determination of the nominal models with the associated uncertainties is successfully obtained by use of model identification techniques for a complex and detailed engineering model of the plant. This fact encourages the later use of this technique in the real plant.

In this case, the numerical optimization used for the synthesis of the controllers was effective in easily balancing robustness, performance and transient behaviour requirements.

The controller will have to be verified when a more detailed model of the feedwater system, the turbine-generator system and the control rod mechanisms are incorporated in the RETRAN model. The life cycle of the nucleus, switching between controllers, and extension to 20% of full power will also have to be considered.

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