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TITLE: Model-Reference Adaptive Control Applied to Load-Following of a Space-Nuclear Power System

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MODEL-REFERENCE ADAPTIVE CONTROL APPLIED TO LOAD-FOLLOWING OF A SPACE-NUCLEAR POWER SYSTEM

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INTRODUCTION

Nuclear power systems are presently being investigated as an alternative for both commercial and military space power systems because of their projected longevity of 7 to 10 years, their mass advantage over other space power sources at powers above approximately 25 kW_e, and their ability to operate without direct illumination from the sun. These space-nuclear power systems are being designed to supply from tens of kilowatts to multimegawatts of power for continuous operation of seven years and more. Space-nuclear power system designs that meet these requirements will not be available for refueling or maintenance during their lifetime. To ensure that the space-nuclear power system will operate safely and will respond in a predictable and desired manner, the design of the system's controller must account for changes in the system parameters over its lifetime. This paper applies model-reference adaptive control to an increase in the power demand by the load. A model-reference adaptive controller will force the actual space-nuclear power system to follow the predictable and desired response of a reference model, despite changes in the actual system's operating parameters. Included in this paper are the model-reference adaptive control algorithm, the description of the computer simulation of a space-nuclear power system and the reference model, and results that demonstrate the application of model-reference adaptive control to a change in the load power demand. The results demonstrate that model-reference adaptive control can ensure the transient response of the system despite differences between the design of the system and the as-built system as well as for variations in the system parameters.

ADAPTIVE CONTROL ALGORITHM

Figure 1 presents a schematic diagram of a model-reference adaptive control system. The adaptation algorithm receives the state vector from the plant, x_p, and the state vector from the reference model, x_m, the input signal vector, u, and the error vector, $e = x_m - x_p$. It uses these inputs at each adaptive time step to adjust the input signal to the plant by adapting the adaptive variable gain vectors, Q and F. The adaptation algorithm for model-reference adaptive control is based upon the second method of Lyapunov and is given (Banks, 1986) as

$$\frac{dF}{dt} = \Gamma_1 B_m^T Pex_p^T ,$$

$$\frac{dQ}{dt} = Q\Gamma_2 B_m^T Pe(u + Fx_p)^T Q^T Q ,$$

(1)
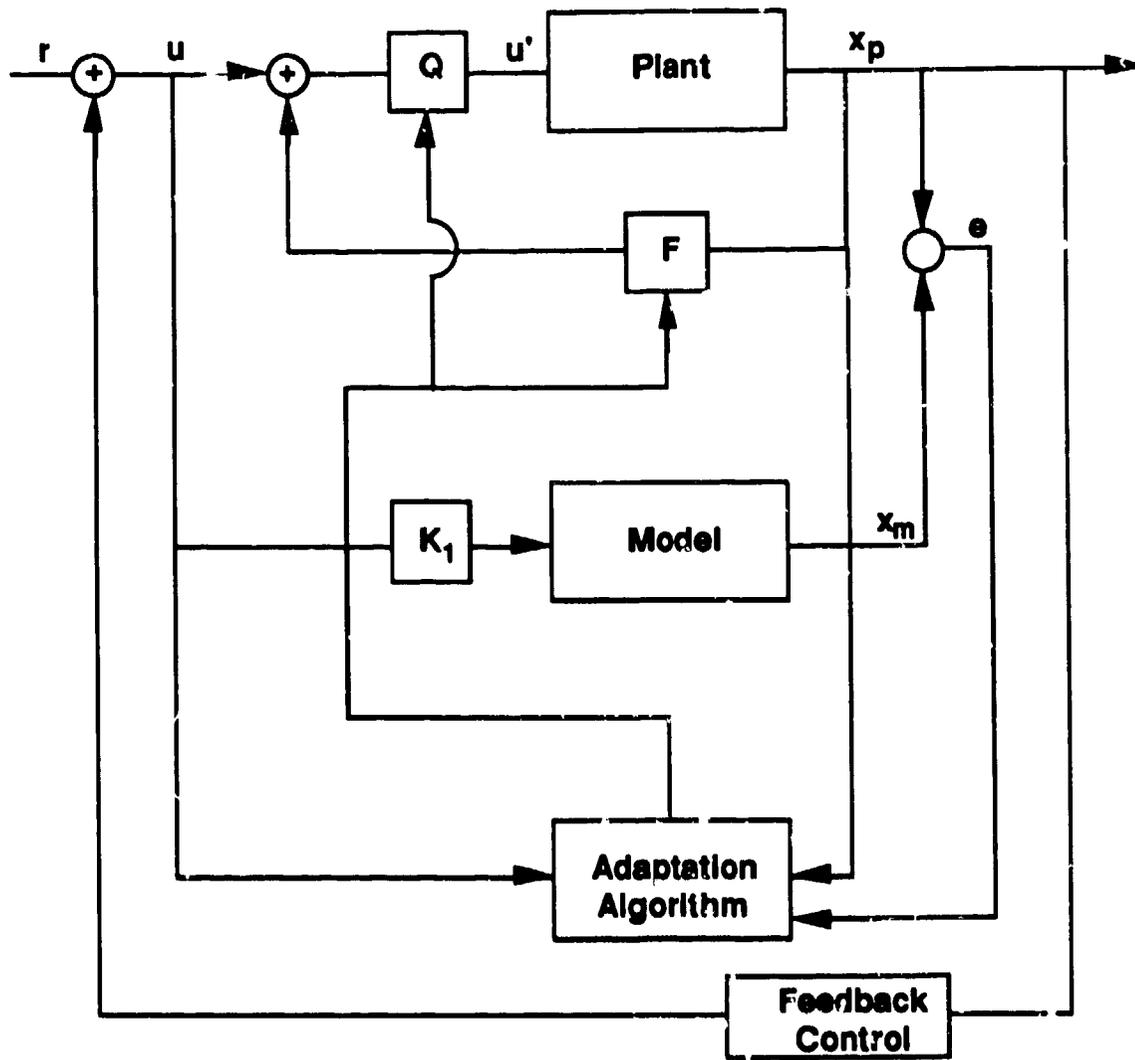
Figure 1. A model-reference adaptive control system for a multiple-input, multiple-output system.

where B_m is the control matrix of the linearized reference model. The matrix P is a positive definite, symmetric matrix and is defined by the Lyapunov stability equation (Ogata, 1970):

$$-R = A_m^T P + P A_m \quad ,$$

(2)

where the R is also a positive definite, symmetric matrix and A_m is the companion matrix of the linearized reference model. The matrix R is determined according to the method presented in Metzger (1989). The adaptive algorithm constant gain matrices are Γ_1 and Γ_2. The matrices Γ_1 and Γ_2 are diagonal and the elements of the matrices are given (Metzger, 1989) as

$$\Gamma_{1\ ii} = \frac{f_1}{\Delta t} \frac{u_{\cdot j}}{Z_{ij}} \quad ,$$

(3)

and

$$\Gamma_{2\,ii} = \frac{f_2}{\Delta t}\frac{1}{Y_{ij}} \quad , \tag{4}$$

where f_1 and f_2 are constants, the elements Z_{ij} are defined by the matrix

$$Z = B_m^T Pex_p^T x_p \quad , \tag{5}$$

and the elements Y_{ij} are defined by the matrix

$$Y = B_m^T Pe\,(u + Fx_p)^T \quad . \tag{6}$$

Equations (1) through (7) define the adaptation algorithm. By definition the adaptive algorithm results in the error vector being asymptotically stable in the large if both the plant and reference model are linear systems.

SPACE-NUCLEAR POWER PLANT MODELLING

In the application of the adaptation algorithm to a space-nuclear power system neither the plant or the reference model used is linear. However, the results show that model-reference adaptive control is still very useful and applicable if the constant gain matrices, Γ_1 and Γ_2, are chosen correctly. The space-nuclear power system is modelled by a set of nonlinear, time-dependant differential equations with variable coefficients (Metzger, 1989) consisting of (1) the six-group reactor kinetics equations, (2) an energy equation for the nuclear fuel, (3) an energy equation for the primary coolant in the reactor, (3) an energy equation for the primary coolant in each of the heat transport branches, (4) an energy equation for each of the PCA thermoelectrics, (5) an energy equation for each of the TEM pump thermoelectrics, (6) an energy equation for the secondary coolant in each of the branches, (7) an energy equation for each of the branch radiator panels, (8) a momentum equation for the primary coolant in each branch, and (9) a momentum equation for the secondary coolant in each of the branches.

The reference-model is also modelled by a set of nonlinear, time-dependant differential equations with constant coefficients (Metzger, 1989) that consists of (1) the two-group reactor kinetics equations, (2) an energy equation for the nuclear fuel, (3) an energy equation for the reactor coolant, (4) a single energy equation for the primary coolant, (5) a single energy equation for the PCA thermoelectrics, and (6) a single energy equation for the secondary coolant.

The reference design used in the study is based upon the General Electric 300 kW$_e$ thermoelectric SP-100 design (General Electric Co., 1986).

RESULTS

El-Genk, Seo, and Buska (1987) determined that the SP-100 design is inherently load-following as long as the load's equivalent electrical resistance matches the internal resistance of the PCA's. When additional load is added in parallel to the in-place load and the new equivalent resistance of the load is less than the internal resistance of the PCA's, the system is not inherently load-following and the thermal energy of the system needs to be increased prior to adding the new load. The system thermal energy is increased by inserting reactivity into the nuclear core.

The reference case is the response of the space-nuclear power system to a 20% increase in power demand, assuming that the load resistance and the PCA's internal resistance are initially equal. To

offset the increase in the power demand 23.34¢ worth of reactivity must be added to the core to ensure that the power demand is met while maintaining a steady-state 100-volt drop across the load. To inject an error between the plant and reference-model response the fuel temperature reactivity feedback coefficient of the plant is assumed to be 25% of the fuel temperature reactivity feedback coefficient of the reference model. Figures 2 and 3 compare the response of the system's neutron power, the fuel temperature, and the voltage drop across the load, as well as showing the difference in the input signal, the reactivity. Figure 2 represents the system response when adaptive control is not applied. Figure 3 represents the system response when the plant's neutron power is adapted to follow the reference-model's neutron power.

When the fuel temperature reactivity feedback coefficient is reduced by 75% and a step of 23.34¢ of reactivity is inserted into the core, Figure 2 shows that the system neutron power peaks at a power 11 MW above the original power of 6.8 MW and achieves a steady-state power 7.5 MW above the original power. This is in contrast to the reference model response that achieves a peak power of 5.8 MW above the original power level and a new steady-state power 0.75 MW above the original power. The plant fuel temperature reaches a steady-state temperature that is approaching 70% of the melting point of UN fuel, which may encroach on the system operating safety limits. The final voltage drop across the load, once the additional load is added at 400 seconds into the transient, is 83 volts instead of the desired 100 volts, but the peak voltage prior to the addition of the new load is close to 170 volts. The plot of the power dissipated by the load is not shown, but the results are that instead of achieving a new steady state 20% above the original power level, the power level reaches a steady state at 21% below the original power.

Figure 3 represents the same case as Figure 2, but with adaptive control. As the plot of the neutron power shows, with adaptive control the plant neutron power follows the reference model neutron power. Even though the plant fuel temperature is not adapted to the fuel temperature of the reference model, the adaptation of the neutron power prevents the plant fuel temperature from reaching the very high temperature exhibited in Figure 2. Also, once the load is added at 400 seconds into the transient, the steady-state voltage drop across the load is the desired 100 volts with a peak prior to the addition of the new load at 140 volts. The final electrical power meets the 20% increase in the demand. Comparing the reactivity plots of Figures 2 and 3 shows how the input reactivity is adjusted by the adaptation algorithm to force the plant neutron power to track the reference-model neutron power.

The example above demonstrates how model-reference adaptive control can be used to ensure the response of a space-nuclear power system during a transient, even though there has been changes to the system parameters. The example also demonstrates how adaptive control can be used to prevent the system from violating operating limits and can increase the utility of the system. As Figure 2 shows, without adaptive control a 20% increase in the electrical power demand is not posssible. Additional results will be presented that demonstrate the effect of using a ramp in the reactivity insertion for the reference case. A step reactivity is initially used since it is the most stringent input signal. Also, results will be presented to show that model-reference adaptive control can be used to accommodate differences between the desired response of the system and the as-built response of the system.
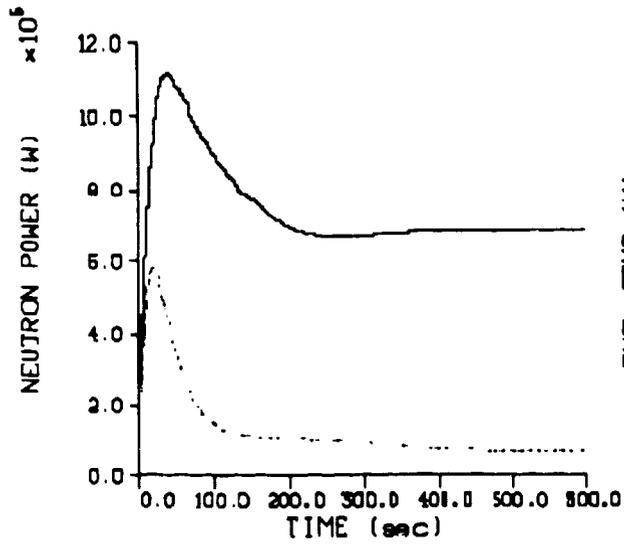
(a) Change in the neutron power (the original power is 6.8 MW)
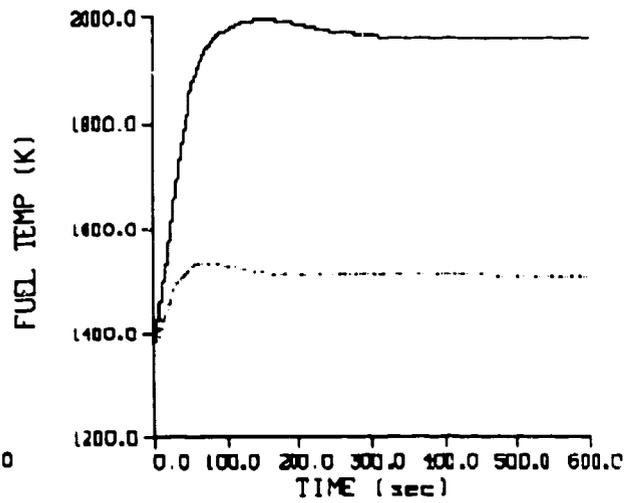
(b) Nuclear fuel temperature
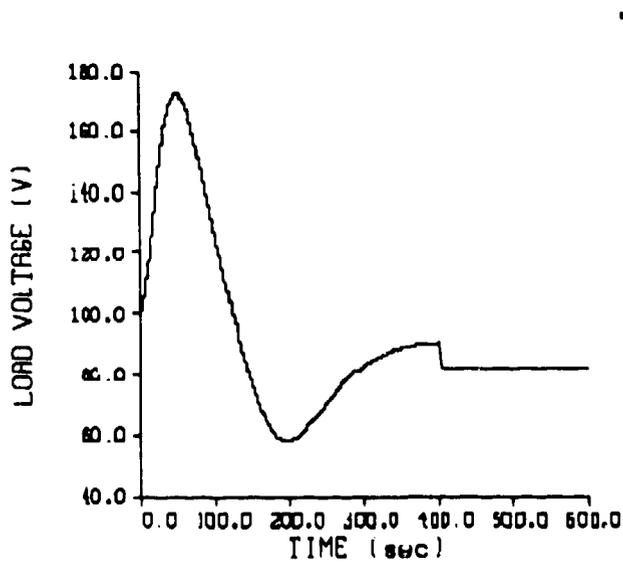
(c) Voltage drop across the load
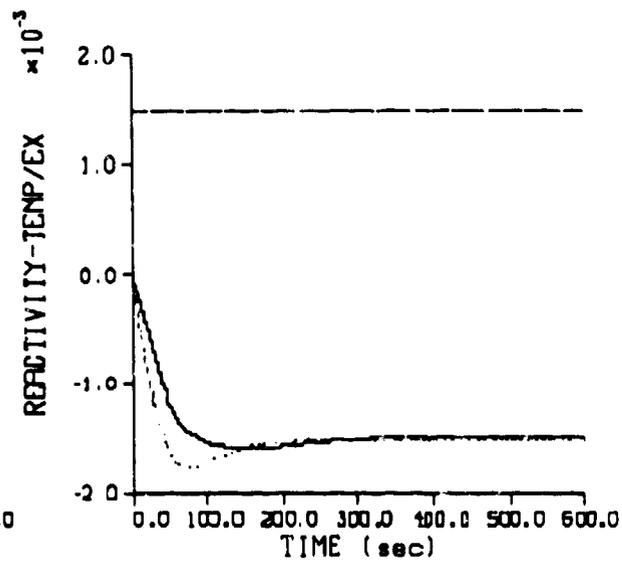
(d) Reactivity, temperature and external

Figure 2. The response of the space-nuclear power system to a 23.34¢ step insertion of reactivity and a 20% power demand increase without adaptive control. The solid line plots are the plant response and the broken line plots are the reference model response.
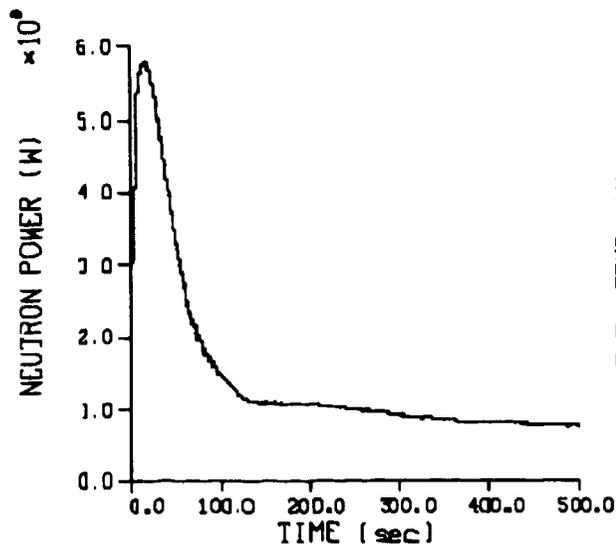
(a) Change in the neutron power (the original power is 6.8 MW)
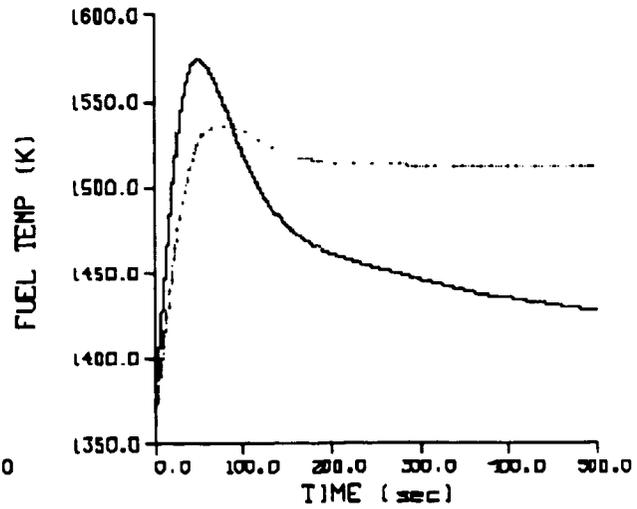
(b) Nuclear fuel temperature
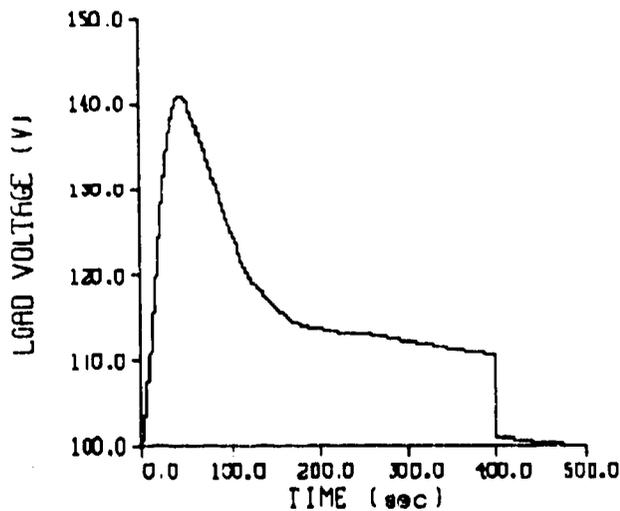
(c) Voltage drop across the load
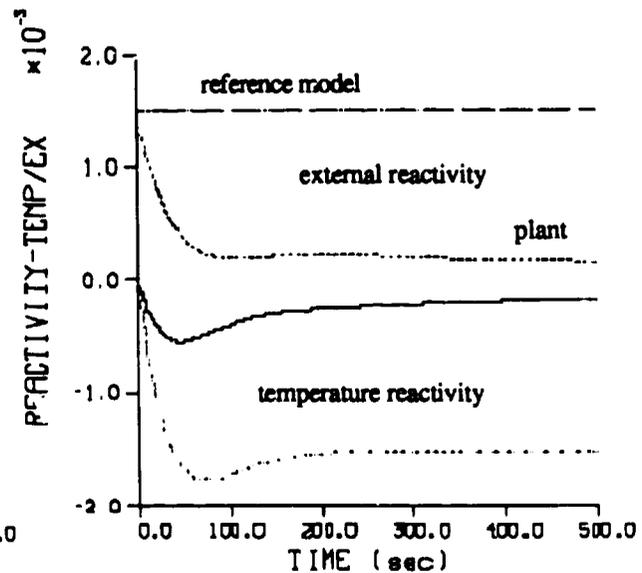
(d) Reactivity, temperature and external

Figure 3. The response of the space-nuclear power system to a 23.34¢ step insertion of reactivity and a 20% power demand increase with adaptive control. The solid line plots are the plant response and the broken line plots are the reference model response.

ACKNOWLEDGEMENT

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