POWER PEAKING WITH SMALL MODULAR REACTORS TO SUPPORT DEEP PENETRATION OF RENEWABLE ENERGY SOURCES

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ABSTRACT

As inherently intermittent sources of renewable energy more fully penetrate the US grid, peaking power is largely being supplied by carbon-emitting natural gas turbines. Significant greenhouse gas emissions can be avoided if these plants are replaced with carbon-neutral nuclear facilities to provide peaking power to complement renewable generation and meet overall power demand. There is a great deal of previous work regarding reactor power shaping with control rod movement for both currently operating nuclear power plants and proposed plants, but the literature on load-following to meet less predictable, more rapidly varying power demand is less comprehensive. We have chosen the Westinghouse IRIS integral PWR as our candidate for modeling, simulation, and control studies. A nodal model of the IRIS integral PWR, partially adapted from a MATLAB/Simulink model constructed by prior students at the University of Tennessee in Knoxville, has been constructed in Modelica. Currently the model includes the reactor vessel and steam generator system and simple assumptions for the balance of plant. The control scheme for the load-following operation of an IRIS integral PWR model would ultimately lead to the development of real operational mechanisms and principles in a grid with significant renewables capacity. In the future the model will be integrated with sophisticated grid and hybrid energy systems.

Key Words: IRIS, SMR, renewable, load follow, Modelica

1 INTRODUCTION

1.1 IRIS

The International Reactor Innovative and Secure (IRIS) integral PWR, laid out in Figure 1, is a fully integral small modular reactor with proposed rated power of 1000 MWth or 335 MWe [1]. We have chosen it as our candidate model because of the extensive literature and engineering data available for it. As one of the higher rated power SMRs, it may be more economically viable than the smaller SMRs and easier to operate in tandem with small but highly variable renewable power sources such as small and medium-sized wind or solar farms on the order of 10-100 MWe nameplate capacity. In such cases the IRIS plant may be able to operate close to full power most of the time and be able to ramp up or downcoast slowly enough to be well within EPRI guidelines.

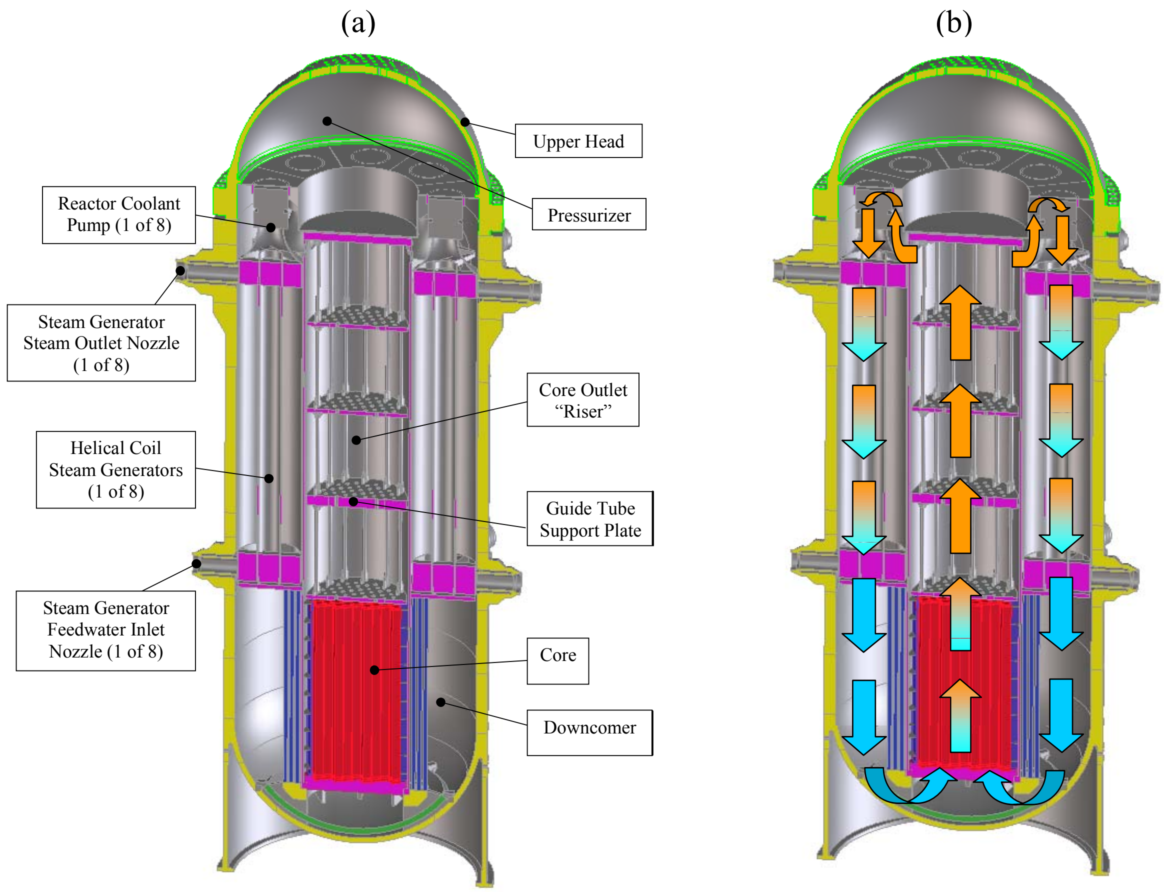

Figure 1. IRIS integral layout: (a) main components; (b) main flow path [1]

1.2 Contemporary load following operation

It is generally most economical to operate nuclear power plants in baseload generation mode at full rated power. However, grids with high nuclear penetration or high renewables penetration require reactors that are able to load follow [2] [3] [4]. Much work has focused on power maneuvering that is more properly categorized as load shaping or power shaping, such as that done at Columbia Generating Station in Richland, WA [4]. Greater attention is being given to true load following wherein reactor power and systems must be able to adapt to more rapidly varying and unpredictable grid power demand. In France and Germany nuclear power plants operate in load following mode,i.e., they participate in primary and secondary frequency control [2]. European Utilities Requirements (EUR) require nuclear power plants be capable of daily load cycling operation between 50% and 100% rated reactor power with change of electric output between 3-5% per minute [2]. This kind of power maneuvering achieved primarily by control rod movement [2] [3].

1.3 Load following with SMRs

Utah Associated Municipal Power Systems (UAMPS) and NuScale Power, LLC., have explored the possibility of very aggressive load following operation with SMR power plants [4]. In the model a 50 MWe NuScale reactor is operated in tandem with Horse Butte wind farm. The model power profile of the wind farm is a typical 24-hour real power profile. Operation schemes include taking SMR modules offline for extended periods of low grid demand/sustained wind output, reactor power maneuvering for intermediate power changes, and bypassing the turbine to dump steam directly into the condenser for rapid power changes [4]. It is not currently an economical mode of operation. This has motivated interest in hybrid energy systems that allow for efficient use of fuel and avoiding revenue loss.

1.4 Collaboration at CURENT

Under this collaboration at the Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (CURENT) between the Department of Nuclear Engineering and the Department of Electrical and Computer Engineering, we are exploring load following with on-line grid demand forecasting every two, five, or ten minutes. In addition to developing control for load following operation, we also plan to integrate the power plant model into a larger grid model to perform studies with realistic power demand profiles and examine the economic viability of load following with SMRs in many scenarios.

2 MODELING

The model developed and explored here is a zero dimensional lumped parameter nodal model. Previous modeling at the University of Tennessee used iterative techniques to initialize the nonlinear system in MATLAB/Simulink [5]. To avoid duplication of effort, these initial conditions are fed into the present Modelica model. In the future it should be possible to have all steps fully contained within the Modelica model.

There exists other physically motivated modeling of the IRIS reactor in Modelica [6] [7]. This paper is restricted to a nodal approach that was validated against a high fidelity FORTRAN model developed at North Carolina State University. We have retained the nodal model for this reason instead of fully leveraging Modelica standard libraries for fluids and heat transfer at this time.

2.1 Reactor Core

The Modelica model of the reactor core is adapted from the MATLAB/Simulink model in the NERI-C report. A nodalized, lumped parameter model of a one reactor system was constructed. The reactor core nodalization was constructed in accordance with Mann's model of heat transfer for one fuel node and two coolant nodes, diagrammed in Figure 2. The power level of the core is calculated using the point reactor kinetic equations (PRKE).

$$\frac{\mathrm{d}P/P_0}{\mathrm{d}t} = \frac{\rho(t) - \beta}{\Lambda}\frac{P}{P_0} + \sum_{i=1}^{6} \lambda_i C_i \tag{1a}$$

$$\frac{\mathrm{d}C_i}{\mathrm{d}t} = \frac{\beta_i}{\Lambda}\frac{P}{P_0} - \lambda_i C_i \tag{1b}$$

Here $\rho = \rho(t)$ is the total reactivity of the system including thermal feedback with proportional dependence on deviation from the steady-state conditions of the system.

$$\rho = \rho_{ex} + \alpha_f(T_f - T_{f_0}) + \frac{1}{2}\alpha_c[(\theta_1 - \theta_{1_0}) + (\theta_2 - \theta_{2_0})] \tag{2}$$

The external reactivity ρ_{ex} term represents the feed-forward control associated with control rod insertion/withdrawal. Other forms of control affected the total system reactivity through feedback caused by changes in the coolant node temperatures θ_1 and θ_2.

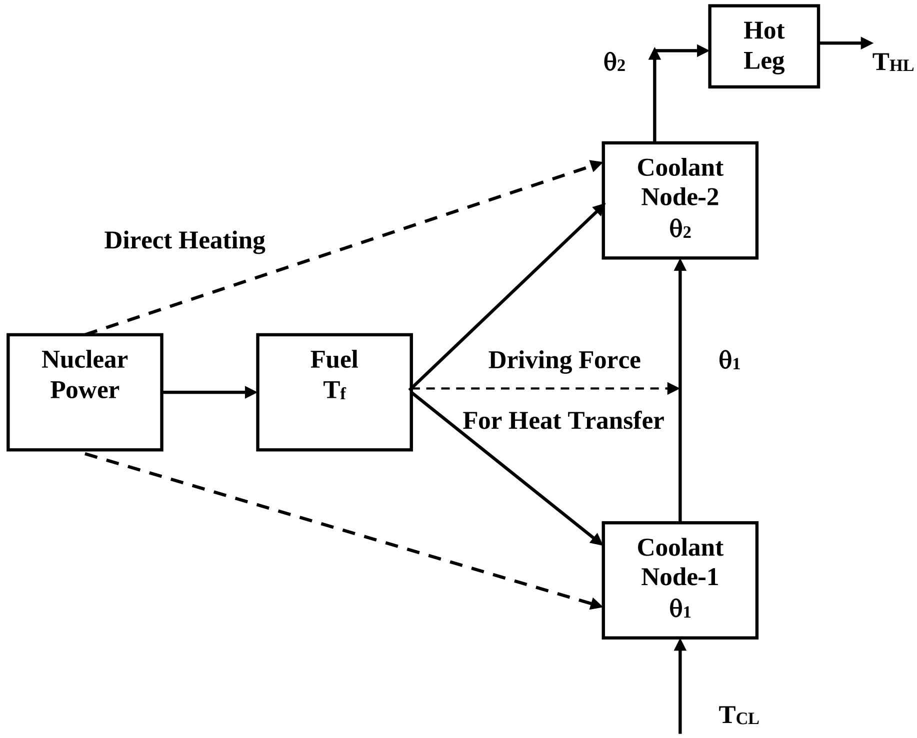

Figure 2. **Mann's model of heat transfer between fuel node and coolant nodes [5]**

2.2 Steam Generator

The nodalized steam generator models the heat transfer between a primary loop and one tube wall and between the tube wall and one secondary loop. The secondary loop is formulated as one of the 656 tubes of a single steam generator and currently is treated as a straight tube with no pressure drop. The heat transfer behavior is affected by the division of the secondary loop into three fluid regions. These regions are the superheated steam region, the saturated region where the liquid water transitions to steam, and the subcooled region of liquid water where the feedwater enters. All this is diagrammed in Figure 3.

3 CONTROL SCHEME

In this nodal model all power maneuvering is achieved through manipulation of the reactivity, directly by reactivity insertions or implicitly by changing steam generator and balance of plant behavior to affect the core inlet and outlet temperatures and thus the coolant node temperatures. Gross power adjustments are achieved through direct external reactivity insertion, typically mechanical shim (MSHIM), while fine power adjustments are achieved through control of the secondary coolant loops and balance of plant components.

3.1 Feed-forward Control

In feed-forward, or open-loop, control, the action of the controller is independent of the process variable. In this work open-loop controllers are programs designed to achieve a desired power output regardless of current process variable behavior. For this model main the feed-forward control is an external reactivity insertion is made at an initial steady-state power to achieve a new steady-state power; it is an abstraction of the control rod drive mechanism that governs the movement of the control rods. In order to comply with the

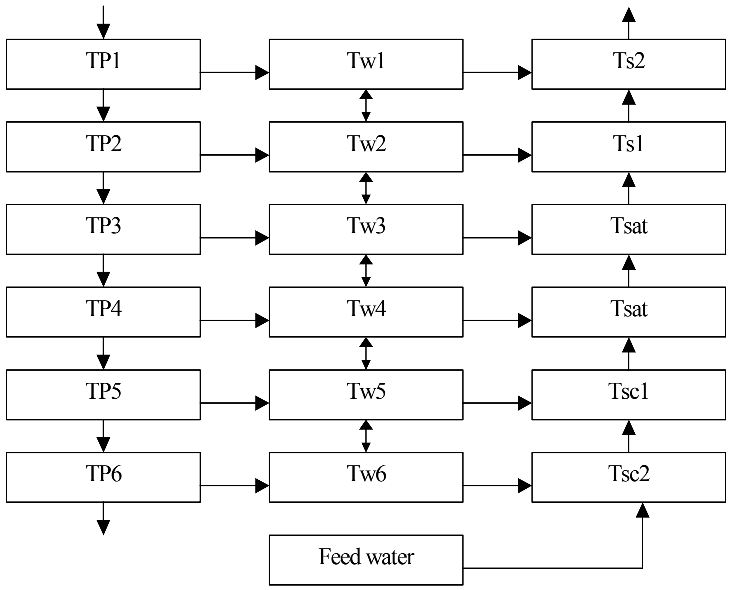

Figure 3. Nodalization of steam generator into primary loop, tube wall, and secondary loop [8]. The inlet temperature TP1 is the hot leg temperature of the reactor core, and the outlet temperature TP6 is the cold leg temperature of the core.

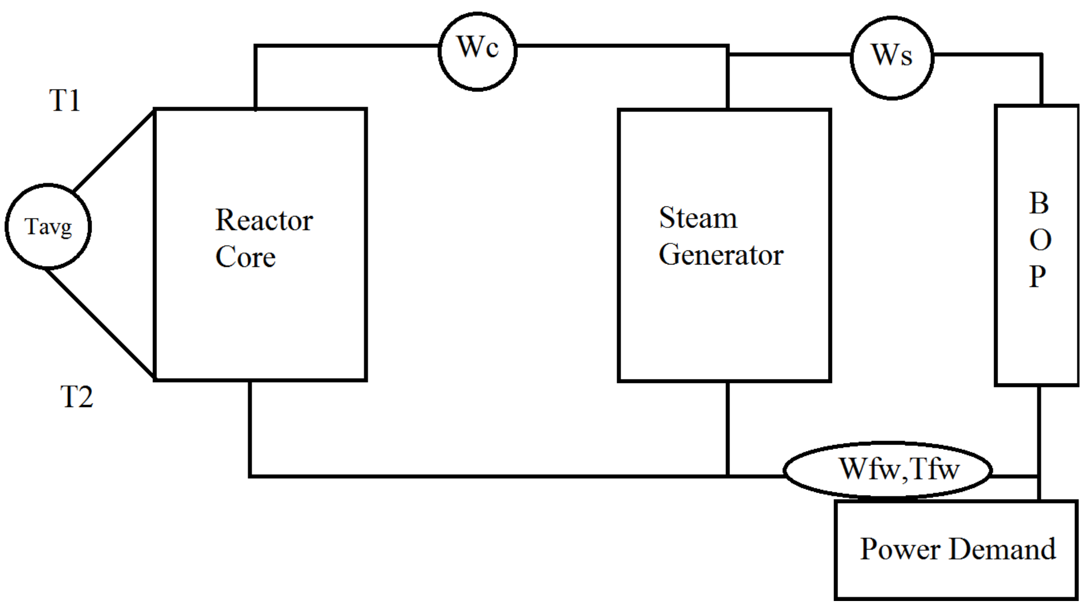

Figure 4. Diagram of reactor systems and PID controls.

EPRI guideline on ramp rates, the insertion itself should be ramped over time using Modelica's signal blocks of its standard library. This open-loop control implies that, given neutronics properties of the point reactor at some time, the desired gross power adjustment can be achieved via a lookup table. The feedwater flow rate of the secondary loop is also implemented as an open-loop controller.

3.2 PID Control

The proposed fine power adjustment is achieved through PID control. Simple closed-loop controllers use the difference between a reference signal r and a process variable y to create a control signal u; the difference between the reference signal and affected process variable is the error e. A PID controller uses *proportional*, *integral*, and *derivative* action to change the control signal that modifies the behavior of the process variable. The proportional action contributes the effect of the present error, the integral action accounts for past error, and the derivative action anticipates the effect of future error.

$$e \equiv r - y \tag{3}$$

$$u(t) = k_p e + k_i \int_0^t e(\tau)\,\mathrm{d}\tau + k_d \frac{\mathrm{d}e}{\mathrm{d}t} \tag{4a}$$

$$u(t) = k_p e + \frac{1}{T_i} \int_0^t e(\tau)\,\mathrm{d}\tau + T_d \frac{\mathrm{d}e}{\mathrm{d}t} \tag{4b}$$

In nuclear power plant modeling derivative action is frequently absent; most PID controllers reduce to PI controllers in nuclear power plant control. PID controls and variables are depicted in Figure 4.

3.2.1 Average temperature control

In previous work at the University of Tennessee a temperature-average controller on the core inlet and outlet temperatures was used to produce a power profile to meet power demand. The previous MATLAB/Simulink model uses a PI average temperature control to maintain the average of the primary inlet and primary outlet coolant temperatures. Using the primary coolant flow rate for actuation is more physical than the abstract temperature controller of the prior model. The coolant flow rate in turn affects the power output.

3.2.2 Steam Pressure

In the previous University of Tennessee nodal model of the steam generator, the steam flow rate is governed by the following differential equation.

$$\frac{\mathrm{d}W_s}{\mathrm{d}t} = \frac{W_{s0}(1 - C_{st}u) - W_s}{\tau_s} \tag{5}$$

Here W_{s0}, C_{st} and τ_s are parameters, and u is a controller input that is a function of turbine header pressure [5]. In a new scheme separate from pressure control, the steam flow rate control will be handled using a PID block from Modelica's standard library. The steam outlet pressure control will also be controlled with a PID block from the Modelica standard library.

3.2.3 Feedwater Temperature

Feedwater temperature in the MATLAB/Simulink model is calculated using a lookup table and 1D linear interpolation with turbine demand as the input; heaters, pumps, and condensers are not explicitly modeled. In Modelica there are libraries for such components, and a PID controller representing the heater can change the feedwater temperature of the secondary loop.

3.2.4 Feedwater Flow Rate

Feedwater flow rate is another variable used for control with the difference between power demand and power generated or the secondary outlet temperature setpoint deviation as the error signal. It is also handled with a lookup table and 1D linear interpolation in MATLAB/Simulink. Although it will initially be handled in open-loop control, a PID control is also under consideration.

4 RESULTS

The reactor core model was tested for an initial steady-state power of 100% rated power. Perturbations were made to the control variables of the primary system in the steady state to create reactor thermal power movements, shown in Figures 5, 6, and 7. For the reactivity and flow rate perturbations, the cold leg (primary inlet) temperature is fixed.

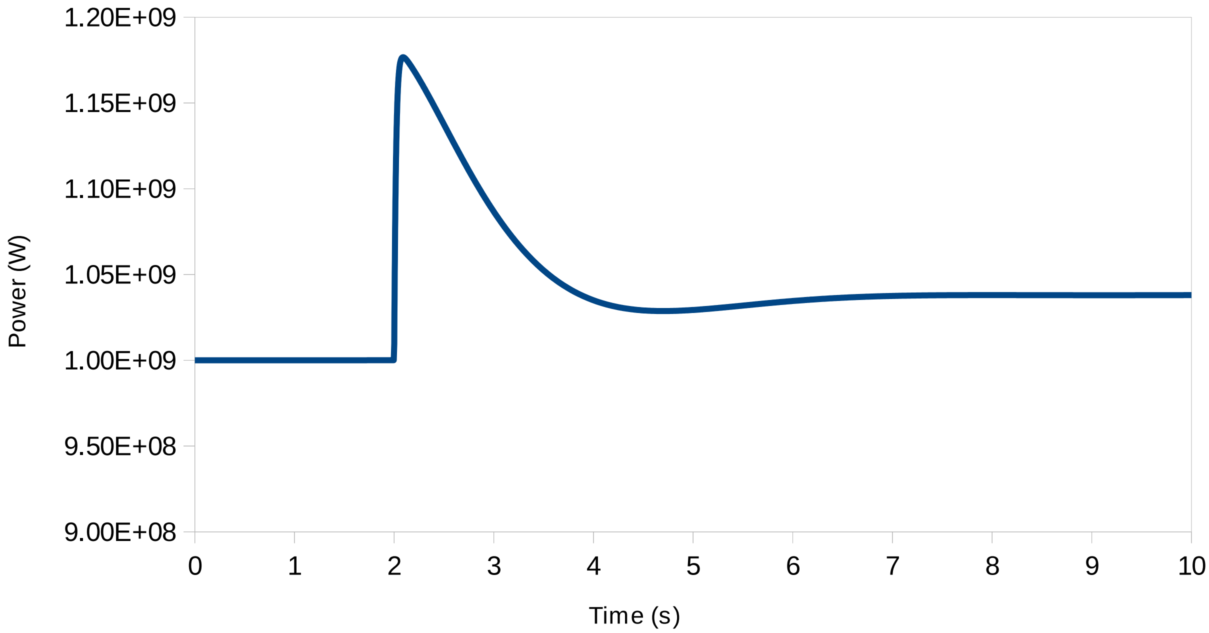

Figure 5. Step reactivity insertion of +0.001 = 15.4¢ yields 4% power increase, in agreement with the NERI-C report from the University of Tennessee [5]. Cold leg temperature is fixed at $292\,^{\circ}$C.

5 ONGOING WORK

5.1 Steam Generator and Balance of Plant

We are continuing work on handling the initialization of the nonlinear steam generator model and balance of plant. A simple yet more robust and physically meaningful balance of plant may also be developed. Modelica has tools and libraries for power engineering components. A realistic turbine, heater, pumps, and condenser can be added.

5.2 Renewables Integration

Using publicly available wind power data from the National Renewable Energy Laboratory (NREL) and electric utilities, realistic power profiles can be constructed in Modelica, or the actual data can be read into Modelica for a higher fidelity simulation. Studies with wind power similar to the work by UAMPS and NuScale will be conducted [4]. The economics of such load following operation will also be explored more fully. Under the collaboration at CURENT, the nuclear power plant model will be integrated into grid and electricity market models to analyze the engineering and economic feasibility of operating IRIS in load following mode for different scenarios.

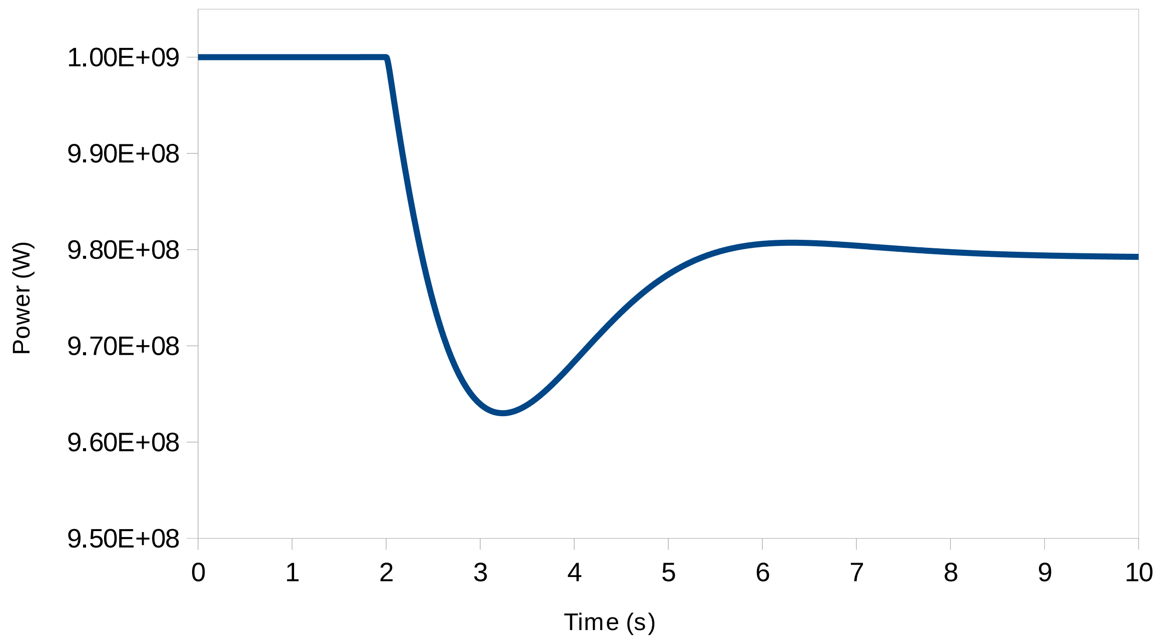

Figure 6. **Step cold leg perturbation of $+0.75\,^{\circ}$C.**

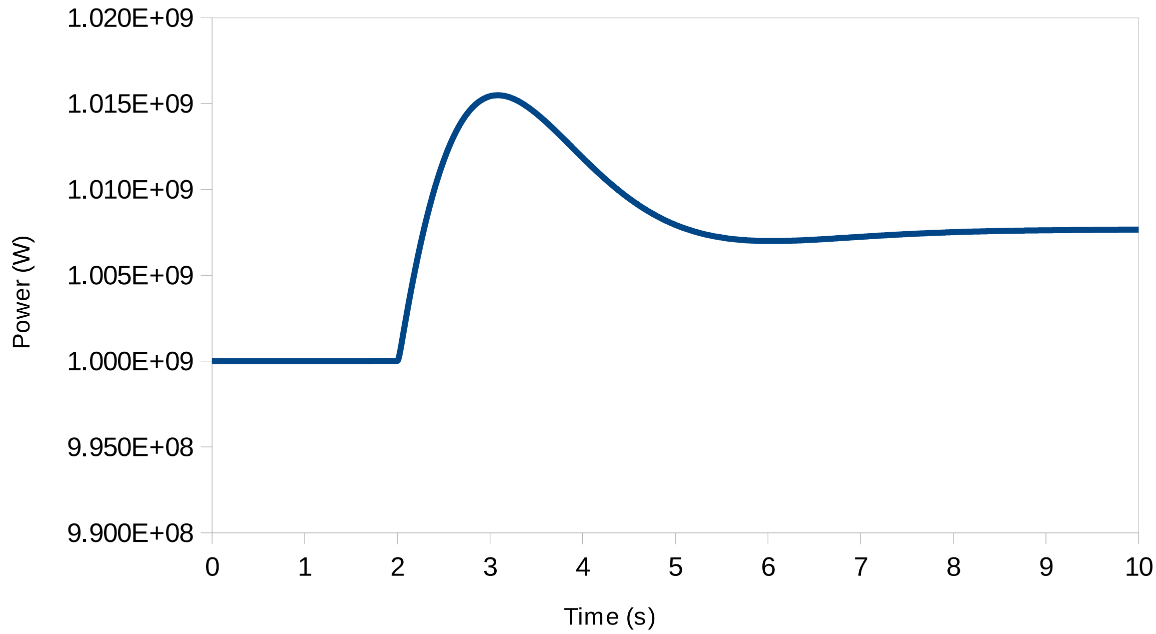

Figure 7. **Step coolant mass flow rate perturbation of +1%.**

5.3 Reactivity Feedback

Future work includes modeling the effect of neutron poison feedback during load following. The inclusion of iodine and xenon adds hysteresis to the system and may limit power ramp rates over short durations. With this addition the open-loop control described in this paper cannot be readily applied to scenarios with rapidly varying and complicated power demand profiles. An approximation of the effect of xenon reactivity feedback would be proportional to the deviation from the steady state concentration of xenon. The reactivity worth of xenon may be calculated from perturbation theory [9].

$$\rho_{Xe} = \alpha_{Xe}(X - X_0) \tag{6a}$$

$$\rho^{eq}_{Xe} = -\frac{\sigma^a_{Xe}X(t)}{\Sigma_a} \cong \frac{\sigma^a_{Xe}X(t)}{\nu\Sigma_f} \tag{6b}$$

There is also the possibility of modeling and investigating the effect of boron concentration fluctuation arising from coolant density changes [10].

$$\rho_B = \alpha_B(C - C_0) \tag{7}$$

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