Control and Instrumentation Strategies for Multi-Modular Integral Nuclear Reactor Systems

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***Abstract*—Simulation and control of an integral pressurized water reactor, with multiple units that operate in parallel and feed steam to a single turbine, is presented. Such a configuration requires mixing steam from two or more units in a steam header, with the steam from all the units maintained at the same operating conditions, with efficient operation of this configuration requiring advanced control strategy. The objective of this research is to evaluate and quantify the performance of a nuclear power plant comprised of two IRIS reactor units. The steam from two reactors flow into a common header connected to a single turbine, resulting in a steam-mixing control problem with respect to "load-following" scenarios, such as reduced consumption during weekends. To solve this problem, a single-unit IRIS Simulink® model, previously developed at the University of Tennessee, was modified to include a second unit, and was used to develop the control strategies under various operation transients.**

***Index Terms*—Integral Nuclear Reactors, IRIS, small modular reactors, steam mixing.**

I. INTRODUCTION

THIS research focuses on the use of IRIS (International Reactor Innovative and Secure) which is an Integral Primary System Reactor (IPSR) that houses the reactor core, steam generators, circulation pumps, and the pressurizer inside one common vessel. This reactor design is used as a platform for developing control strategies for multi-modular reactor systems and to study reactor control problems related to steam mixing.

Thus, it is important to develop a model to evaluate and quantify the performance of a nuclear power plant comprised of two IRIS reactor units operating simultaneously with a common steam header, which in turn is connected to a single turbine, resulting in a steam-mixing control problem with respect to "load-following" scenarios, such as varying load during the day or reduced consumption during the weekend, and its ability to detect small, controlled faults introduced either in sensor measurements or in the process itself.

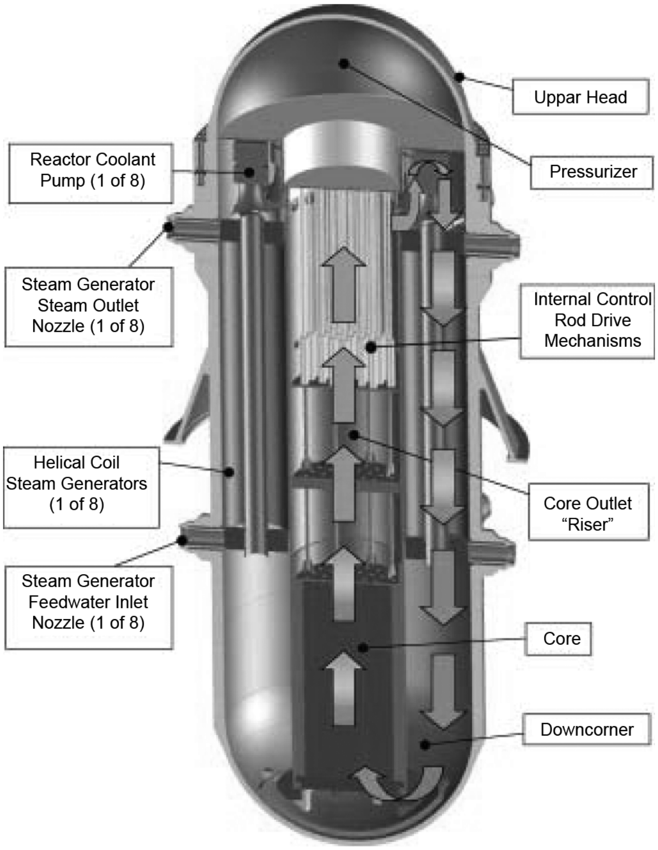

Fig. 1. IRIS primary system layout [3].

II. IRIS SYSTEM DESCRIPTION

The IRIS reactor is an IPSR with all main primary circuit components (core, control rods and drive mechanisms, steam generators, primary coolant pumps, and pressurizer) integrated into a single reactor vessel [1]. The upper head acts as the pressurizer to maintain constant primary pressure. Eight spool-type reactor coolant pumps, eight steam generators, and control rod drives are also housed in the reactor pressure vessel. Major components of the primary system are shown in Fig. 1, resulting in a pressure vessel diameter of 6.2 m, larger than a regular Pressurized Water Reactor (PWR), despite its lower power rating, but largely reducing the size and eliminating dozens of penetrations, virtually eliminating large Loss of Coolant Accidents (LOCA) and the number of possible small LOCAs [2]. The feedwater flow to a pair of helical coil steam generators has a common feed line, with the primary water being pumped up through the core and the riser, the circulation then reverses in a downward direction and the water is forced down by the immersed

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TABLE I
MAJOR IRIS DESIGN PARAMETERS [3]

General Plant Data	
Power Plant Output (net)	335MWe
Core Thermal Power	1000 MWth
Nuclear Steam Supply System	
Number of Coolant Loops	8
Steam Temperature/Pressure	317/5.8 °C/MPa
Feedwater Temperature/Pressure	224/6.4 °C/MPa
Reactor Coolant System	
Primary Coolant Flow rate	4700 Kg/s
Reactor Operating Pressure	15.5 MPa
Core Inlet Temperature	292 °C
Core (riser) Outlet Temperature	330 °C
Reactor Core	
Fuel Assembly Total Length	5.207 m
Active Core Height	4.267 m
Fuel Inventory	48.5 tU
Average Linear Heat Rate	10.0 kW/m
Average Core Power Density (volumetric)	51.26 kW/l
Fuel Material	Sintered UO_2
Rod Array	Square, 17 x 17
Number of Fuel Assemblies	89
Number of Fuel Rods per assembly	264
Outer Diameter of Fuel Rods	9.5 mm
Enrichment	4.95 Wt % U-235
Equilibrium	30 - 48 months
Average Discharge Burnup	60 000 MWd/tU
Reactor Pressure Vessel	
Cylindrical Shell Inner Diameter	6.21 m
Wall Thickness Cylindrical Shell	285 mm
Total Height	21.3 m
Steam Generators	
Type	Vertical, helical coil tube bundle, once-through, superheated
Number	8
Thermal Capacity (each SG)	125 MWth
# of Heat Exchanger Tubes (each SG)	656
Reactor Coolant Pump	
Type	Spool type, fully immersed
Number	8
Pump Head	19.8 m
Primary Containment	
Type	Pressure suppression, steel
Geometry	Spherical, 25 m diameter
Design pressure/temperature	1300kPa/200 °C

pumps through the region surrounding the helical steam generator tubes. The primary flow through the downcomer flows into the lower vessel plenum and then flows up through the core.

IRIS is being designed to fulfill the advantages of the IPSR. It improves safety, reduces the site civil works, and improves plant availability for developed as well as developing countries with large or small electrical grids that can greatly benefit from such design. The development of autonomous and fault-tolerant control strategy is well-suited for remote deployment of small and medium reactors, such as the IRIS. Table I shows the major IRIS parameters currently found in the open literature [3].

Such novel, integral design includes the following advantages but is not limited to [3]–[6]:

- Scalable in power between 100 MWe and 350 MWe, the basic design being 335 MWe, or 1000 MWth, in modular configuration, allowing scalability as single unit, multiple units, multiple single units and multiple twin units (sharing auxiliary systems and common-header/turbine).
- Reactor core, pressurizer, eight steam generators, coolant pumps and control rod mechanism are all integrated into a single pressure vessel.
- Full natural circulation (safety feature).
- Is designed to be capable of accepting different cores. Fuel will be such that it will not pose any licensing problems.
- The long lifetime core is achieved using 5% enriched uranium for the first reactor core and 9% enriched uranium for successive reactor cores.
- The reactor refueling is needed only at the end of the first five years and once every eight years afterwards.
- Because of the high burn-up, less nuclear waste per unit of reactor power is produced than that in currently operating reactors.
- The reactor core is comprised of 89 Light Water Reactor (LWR) 17 × 17-pin fuel bundles containing 4.95% enriched $\mathrm{UO_2}$ fuel and is designed for a 3.5-year cycle with an average burn-up of 50,000 MWd/tU.
- Reactivity control is accomplished through solid burnable absorbers and control rods, and limited boron in the primary coolant [7].
- The primary coolant system uses eight helical-coil once-through steam generators and eight spool-type coolant pumps. The steam-regulated pressurizer is located in the upper portion of the 6.2 m-diameter, 22.2 m-high reactor vessel. Normal operating pressure of the primary coolant is 15.5 MPa (approximately 153 atmospheres or 2,248 PSI).
- All primary piping external to the reactor vessel is eliminated, thus avoiding the large loss of coolant accident by design.
- Since the whole control rod mechanism is mounted inside the vessel, control rod ejection accident is also eliminated by design.
- The integral design of the primary side is placed inside a 25 m-diameter compact steel vessel capable of withstanding 1.3 MPa design pressure, making it smaller than the traditional PWR pressure vessel.
- Annular downcomer is larger yielding a separation of the reactor vessel from the core. This way the vessel fluence is decreased by several orders of magnitude (from 10^{19} to $10^{14}\ \mathrm{n/cm^2}$), making the reactor vessel virtually free of radiation damage, eliminating vessel replacement or annealing, no radiation exposure to crew inside the containment, and substantial biological shielding reduction.

IRIS plant is one of the next generation nuclear reactor designs, that uses mostly established LWR technology (due to its maturity), allowing an accelerated deployment, and is a design that houses the steam generators, circulation pumps, and the pressurizer inside one common vessel. However, an extensive number of tests are still to be performed for new engineering aspects and components that incorporate not yet proven technology in the current PWRs [8]. Certain parameters are not directly measurable, such as the level of water in the steam generator tubing where the superheated steam is generated.

III. HELICAL COIL STEAM GENERATOR (HCSG)

The steam generator is a helical coil, once-through steam generator producing superheated steam. The reactor control requirements specify constant average coolant temperature across the core at constant steam pressure. In the HCSG system the primary water is on the shell side flowing from the top to the bottom of the vessel. The primary side heat transfer is sub-cooled, forced convection along the entire steam generator height, while the secondary fluid flows upward inside the 656 coiled tubes from bottom to top. The feed water flows into the sub-cooled region of the steam generator, and in this region the heat transfer is mainly due to single phase turbulent and molecular momentum transfer and the pressure loss is mainly due to wall friction. The saturated region begins when the bulk temperature becomes saturated. The heat transfer in the saturated boiling region is dominated by nucleate boiling, which is much more efficient than single-phase liquid or steam heat transfer. In the saturated boiling region, the generated bubbles do not disappear in the liquid core and the pressure loss is not only due to the wall friction but also due to the interfacial drag between the bubbles and the liquid. The saturated boiling region ends when critical heat flux is reached. When the steam quality reaches unity, the liquid evaporation ceases and the steam becomes superheated. The use of helical tubing reduces the size of the steam generator, and results in an efficient heat transfer with a larger heat transfer area per unit volume than straight tube steam generators. The HCSG system is regulated to supply adequate amount of steam to meet the turbine demand. A programmed feed-forward controller is used to maintain the outlet steam pressure, while preventing the carryover of water to the turbine system or dry-out of the steam generator tubes, minimizing the mismatch between the steam outlet flow rate and the feedwater inlet flow rate.

IV. IRIS SIMULINK MODEL

A. IRIS Model

A single-unit Simulink® model of the IRIS plant developed by Xu [9] is used in this work and includes reactor core and HCSG models. Originally, the main core model input was coolant inlet temperature (in degrees Fahrenheit), but was modified to accept power demand (in $\%$ power) by using a look up table that relates both input variables, based on North Carolina State University (NCSU) FORTRAN code [10], [11].

The helical coil steam generator is one of the critical components and a major contributor to the cost of IRIS design. Typical once-through steam generator equations can be found in [12]. The model was developed based on a previous dynamic model [13] and a Simulink model [14] for a traditional PWR plant. The reactor core fuel-to-coolant heat transfer model was developed by using the Mann's nodal model [15], and the classic point kinetics reactor model equations with six delayed neutron groups.

The feed water flow rate is determined based on NCSU's code, and is set according to the power demand—feed water flow program. In the simulations there is no feed-forward controller to quickly move the control rods based on changes on power load demands. The pressurizer model and the balance-of-plant (BOP) are not included in the simulation, and are assumed to be functioning well. Temperature of feed water is assumed to be fixed at $224^{\circ}\mathrm{C}$, which corresponds to 100% power. The main program is shown in Fig. 2 and the main outputs are:

- Moderator core inlet temperature $(\mathrm{T}_{\mathrm{cold}})$, referred to in the program as $\mathrm{T}_{\mathrm{pout}}$.
- Steam outlet pressure, $\mathrm{P}_{\mathrm{sout}}$ in PSI.
- Steam flow rate, $\mathrm{W}_{\mathrm{sout}}$ in lbm/s per tube, per steam generator.
- Steam outlet temperature, $\mathrm{T}_{\mathrm{sout}}$ in $^{\circ}\mathrm{F}$.
- Steam generator boiling length, Lb in ft.
- Sub-cooled length, Lsc, in ft.
- Feed water flow rate, W_{fw}, in lbm/s per tube per steam generator.
- Power profile $(\mathrm{P}/\mathrm{P}_0)$.
- Fuel temperature $(^{\circ}\mathrm{C})$.
- Coolant core outlet temperature, $\mathrm{T}_{\mathrm{hot}}(^{\circ}\mathrm{C})$.
- Average moderator temperature, which is defined as the average between moderator inlet and outlet temperatures, $\mathrm{T}_{\mathrm{ave}}(^{\circ}\mathrm{C})$.
- Core outlet moderator temperature, $\mathrm{T}_{\mathrm{hot}}(^{\circ}\mathrm{C})$.

NCSU's FORTRAN model is a complete, comprehensive IRIS model, so it is interesting to compare the steady state values with those produced by that code. Table II summarizes the results obtained from Simulink and from NCSU FORTRAN code for a power demand of 100%. The steady state results indicate the Simulink model results are very close to those from the high-fidelity model (NCSU) and to those found in open literature [16].

B. IRIS System General Load Following Maneuver

Load following is the capability of a reactor to follow changes in the grid demand, for instance, reduced consumption over the weekend. The following is the sequence of actions during a load-following maneuver for the IRIS plant for the case of load change from 80% to 100%:

- Operator sets the desired load program (for example, 5% ramp change/hour).
- This creates an error signal between the desired load and the actual turbine output. The turbine header pressure (turbine inlet steam pressure) is directly correlated to turbine output.
- There is now a mismatch between turbine output and reactor power, which initiates a signal to move the control rods to increase the reactor power. This may be considered as a feed-forward control action.
- The $\{\mathrm{T}_{\mathrm{avg(reference)}-\mathrm{T}_{\mathrm{avg}}(\mathrm{measured})}\}$ error is generated based on $\mathrm{T}_{\mathrm{avg\ (reference)}}$ for the actual turbine output. The turbine output is used for calculating the percent power in the $\mathrm{T}_{\mathrm{avg}}$ vs. power program.
- As the error between the $\mathrm{T}_{\mathrm{avg(reference)}}$ and $\mathrm{T}_{\mathrm{avg(measured)}}$ increases, the control rods move to increase the reactor power.
- Turbine control valves move to maintain programmed steam generator pressure.
- Feed water flow versus load (desired) program determines the desired feed water flow for that load. The feed water control valve actuates to minimize the flow error.

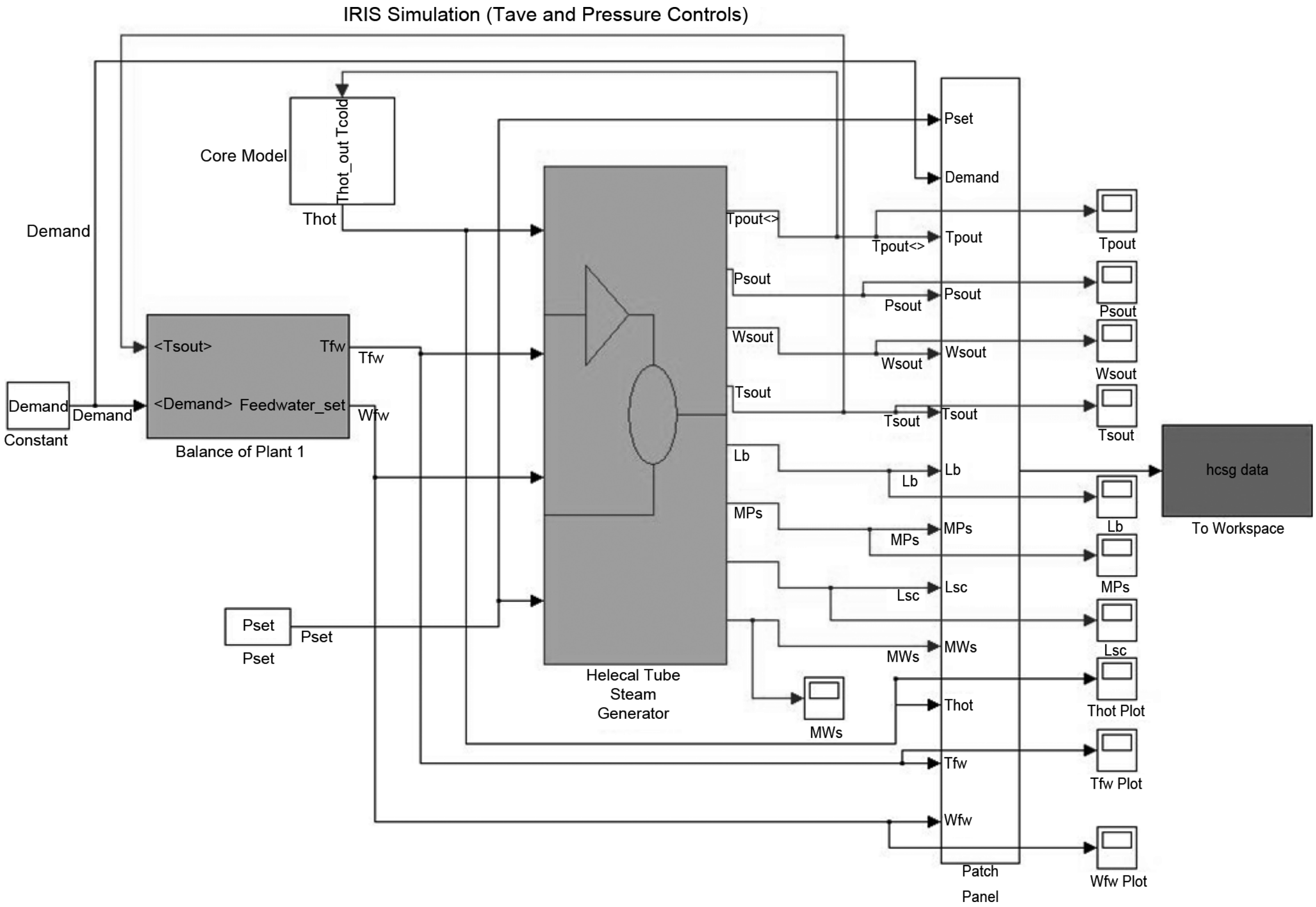

Fig. 2. IRIS complete SIMULINK model main screen.

TABLE II
STEADY STATE VALUES FROM SIMULINK AND NCSU MODEL

Reactor Power @ 100%	Simulink	NCSU	Design[16] Parameters at 100% Power (per SG, per tube)
Steam outlet Temperature (°C)	320	325	317
Steam flow rate (kg/s)	0.096	0.095	0.095
Feedwater flow rate (kg/s)	0.096	0.096	0.095
Feedwater temperature (°C)	202	191	224
Steam outlet pressure (MPa)*	5.8	5.94	5.8
T_{avg}* (°C)	310	310	310
T_{cold} (°C)	291	291	292
T_{hot} (°C)	329	329	328
Average fuel temperature (°C)	449	450	N/A

*Controlled variables.

- The error between the desired load and turbine output is used to correct for the feed water flow by bumping the feed water flow for the given load.
- Increased feed water flow increases steam production, and consequently increases the steam pressure. The steam throttle valve is actuated to maintain the pressure.
- As the reactor power increases, $\mathrm{T}_{\mathrm{avg(measured)}}$ increases. The control rod motion stops once $\mathrm{T}_{\mathrm{avg(measured)}} = \mathrm{T}_{\mathrm{avg(reference)}}$.
- The pressurizer has no spray control (in IRIS) to reduce the pressure. There are heaters to increase the pressure. No active pressurizer level control, except for an on-off control action.

C. *IRIS Plant Used in Load Following Maneuvers*

When a power level perturbation is performed, several changes occur in the core from a neutronic point of view; the fuel and moderator temperatures change, the xenon level is modified, the power distribution skews, etc. These changes need to be adequately counterbalanced to keep both the core critical and the power distribution acceptable. The usual approach is to compensate for the reactivity change due to the power variation by adjusting the soluble boron concentration and moving a limited number of control rod banks. This, however, leads to large volume of liquid effluent, in particular toward the end of cycle, when the soluble boron concentration is low, and it is difficult to dilute. To avoid this, Westinghouse has developed the innovative mechanical shim (MSHIM) strategy in 1988, where the control rods and control banks are designed to allow load follow using only control rods.

According to Franceschini and Petrovic [7], MSHIM capability is a desired feature in AP1000, and it becomes almost a required feature for IRIS. Basically, due to its large inventory of the primary coolant, the dilution/boration strategy becomes not only more expensive, but may additionally be limited by the achievable dilution rate (in particular at the end of cycle).

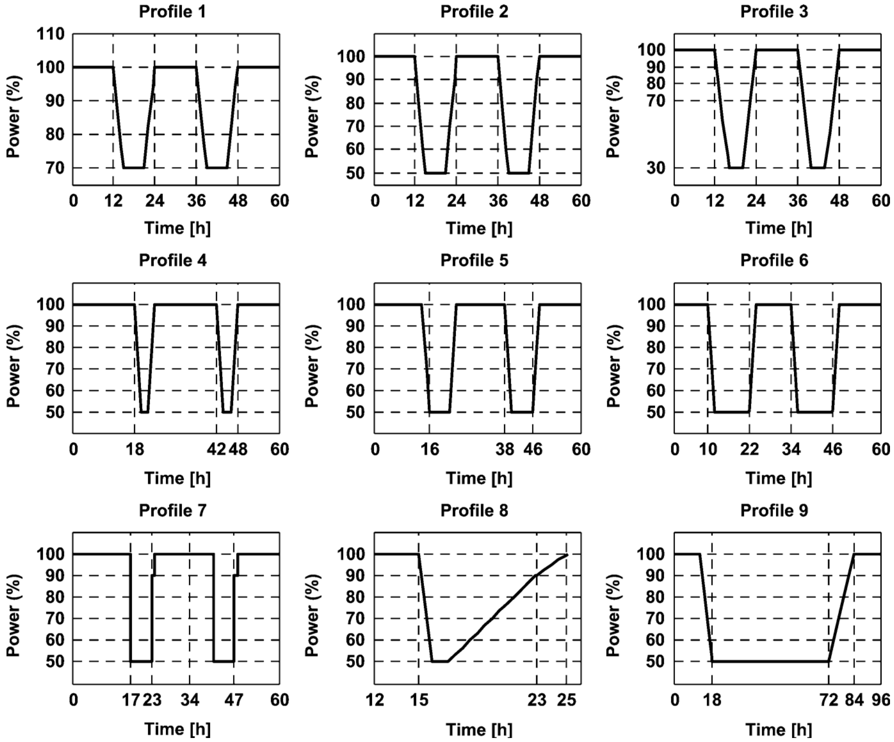

Fig. 3. Load following power demand profiles[7].

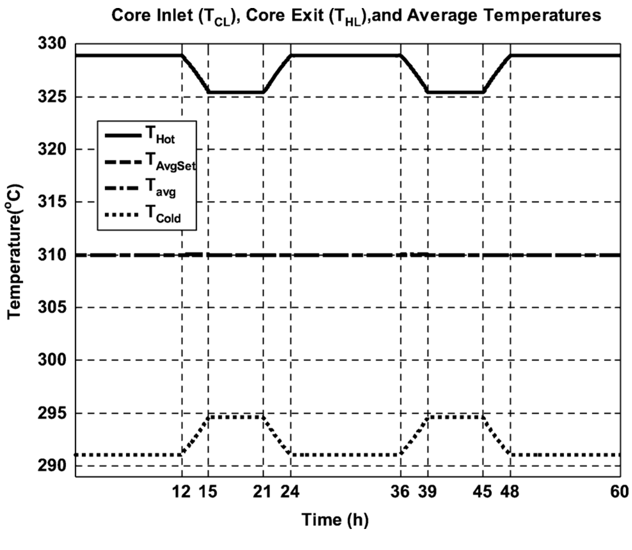

Fig. 4. $\mathrm{T_{ave}}$ changes for profile #1 load demand.

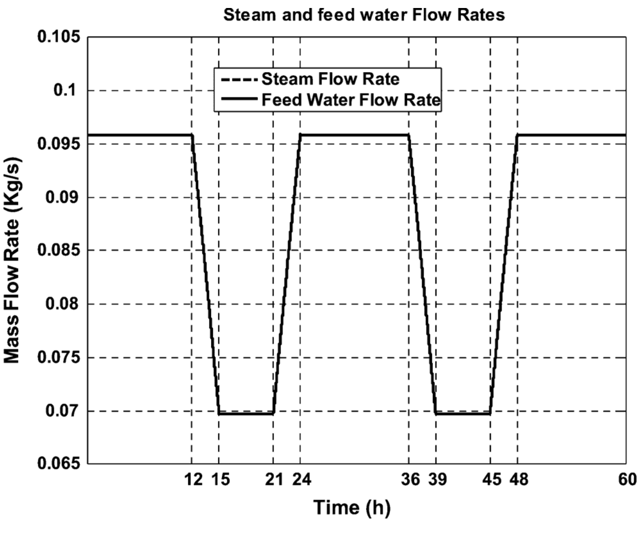

Fig. 5. Steam flow rate changes for profile #1 load demand.

Therefore, MSHIM capability was specified as one of the operational requirements for IRIS. In particular, it is required that IRIS can perform load follow through MSHIM for the Westinghouse design basis load follow maneuvers, plus for additional power changes prescribed by the Electric Power Research Institute for Advanced LWRs. A version of the corresponding nine different power change profiles mentioned in Franceschini and Petrovic's research is shown in Fig. 3 and, for the first time, such profiles were used as power demand inputs to an IRIS model. The results of the first run profile are shown in Figs. 4–8. The $\mathrm{T_{ave}}$ controller in the reactor core unit is able to keep the values close to the set point (Fig. 4) by varying the external reactivity, hence $\mathrm{T_{hot}}$, making the reactor reach the necessary power to match the steam flow rate demanded by the turbine (Fig. 5). As the nuclear power varies (Fig. 6), so does the steam generator water level, varying the heat transfer area available for the steam to be heated (Fig. 7); this causes changes in $\mathrm{T_{cold}}$, while at the same time the pressure controller keeps the pressure as close as possible to the set point (Fig. 8) by varying the steam flow rate.

V. MULTI-MODULAR REACTOR PLANT CONCEPT AND CONTROL STRATEGY

A multi-modular reactor system consists of two or more nuclear power units that operate in parallel, with the steam from

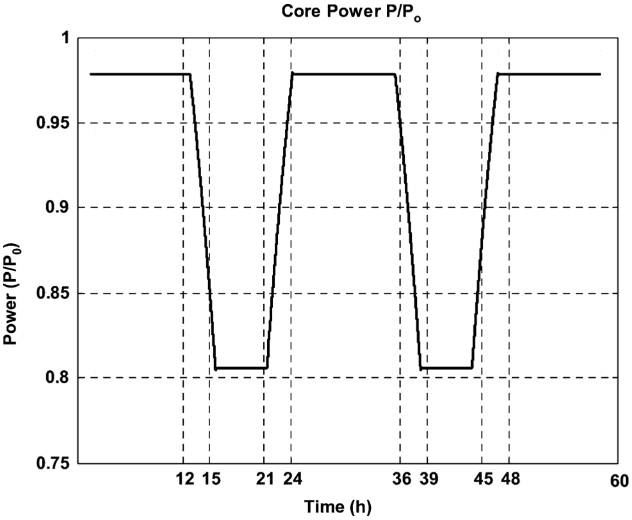

Fig. 6. Power changes for profile #1 load demand.

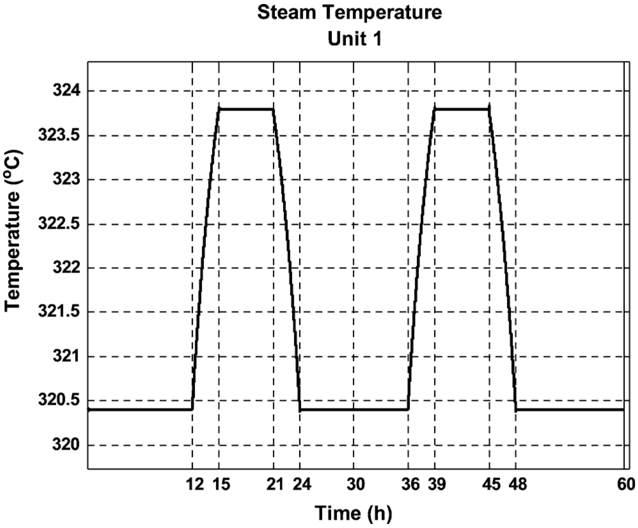

Fig. 7. Steam temperature changes for profile #1 load demand.

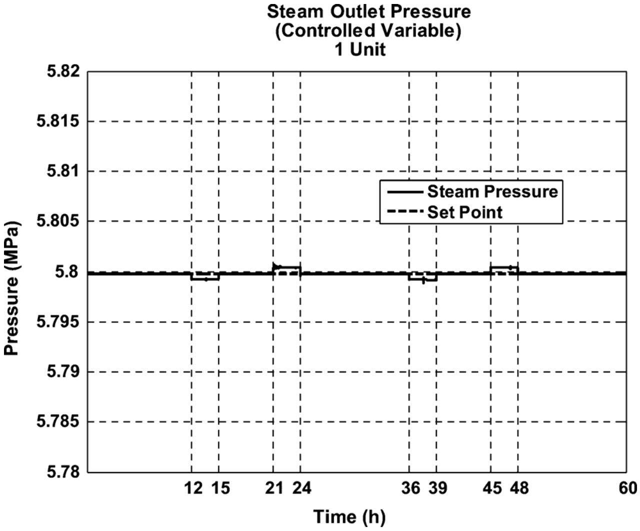

Fig. 8. Steam outlet pressure is controlled for profile #1 power load demand.

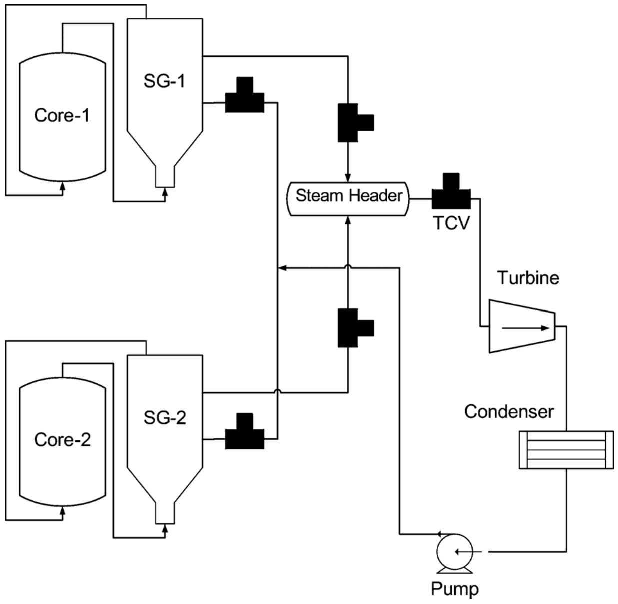

Fig. 9. Schematic diagram of an IRIS-type multi-modular power block.

different units flowing into a common header. Such power generating stations have the advantages of providing continuous power supply even when one of the units is down for maintenance, and load following features with the units operating at different power levels. In this study, the 1,000-MWth IRIS system was used as the platform, and generates about 350 MWe power.

A. Multi-Modular Power Plant—General Concept

The work by Kim and Bernard [17] in the early 1990's focused on the simulation of a regular U-tube steam generator type multi-modular saturated steam PWR reactor plant capable of operating under normal operational transients with unbalanced loads. They proposed and evaluated a robust, digital closed-loop steam generator level controller for both existing and multi-modular power plants. In this system, the saturated steam PWR is operated as a constant pressure-constant flow primary loop with programmed core coolant average temperature that rises with increasing load, with reactor control being maintained by a combination of mechanical control rods responding automatically to load changes, and the soluble neutron poison, boric acid (H_3BO_3), responding to fuel burn-up changes [18].

B. IRIS Multi-Modular Concept and Control Strategy

The multi-modular reactor system used consists of two integral pressurized water reactors of the IRIS design and each unit has a rated power of about 350 MWe that operate in parallel, with the steam from the different units flowing into a common header, as shown in Fig. 9.

Such power generating stations have the advantages of providing continuous power supply even when one of the units is down for maintenance, and load following features with the units operating at different power levels. This two-unit model is based on the single model and has the same constants, initial conditions, etc.; but there are a few differences between the two versions, most notably a second T_{ave} controller and a steam pressure controller with a set of controller gains. Steam coming from both units is superheated and any pressure loss between the steam generator exit and the pressure header is neglected. Also, an additional demand input was added to the model to independently set the power in the second unit. But the most important changes are in some of the assumptions, specifically concerning the calculation of the temperature of the mixed steam. Some of the assumptions are the same for the single unit model, and are listed below for completeness;

- Unlike in PWRs with recirculation-type steam generators, where there is a sliding $\mathrm{T_{ave}}$ controller, the average core inlet-outlet temperature in the IRIS remains constant, with a set point value of $310^\circ\mathrm{C}$ $(590^\circ\mathrm{F})$ over the entire simulation.
- Steam pressure coming out of the HCSGs remains constant at 5.8 MPa ($\sim$ 841 psi) for the entire range of reactor operation.
- Feed water temperature is fixed at $223.9^\circ\mathrm{C}$ $(435.02^\circ\mathrm{F})$, corresponding to 100% power for entire simulations.
- There is no feed-forward controller to quickly move control rods based on changes in power load demands.
- Pressurizer and balance-of-plant models are not included in the simulation. These parameters are assumed to be at fixed values.
- Steam generator feed water flow rate is set based on FORTRAN code developed by NCSU, and is set according to a power demand—feed water flow program.
- Steam mixture temperature at the steam header is calculated assuming constant steam pressure (see bullet above), balance of mass and steam properties, and is calculated as:

$$\mathrm{h_T(t)} = \frac{\mathrm{h_1(t)\dot{m}_1 + h_2(t)\dot{m}_2}}{\mathrm{\dot{m}_T}} \tag{1}$$

$$\mathrm{\dot{m}_T} = \mathrm{\dot{m}_1 + \dot{m}_2} \tag{2}$$

Where:

$\mathrm{h_T(t)}$	is the temperature-dependent total enthalpy.
$\mathrm{h_1(t)}$ and $\mathrm{h_2(t)}$	are unit #1 and unit #2 temperature-dependent enthalpies, respectively.
$\mathrm{\dot{m}_T, \dot{m}_1, \dot{m}_2}$	are total, unit #1 and unit #2 steam mass flow rates, respectively.

The values of $\mathrm{h_T(t)}$ obtained from the combined steam temperatures are then used to determine the temperature of the mixed steam at the corresponding superheated steam pressure of 5.8 MPa (841 PSI) using a look-up table embedded in the Simulink model; this assumes that steam outlet pressure deviations can be neglected.

The control schematic of a twin-unit IRIS system, with HCSGs connected by the feed water line, is shown in Fig. 10. In this figure inputs to the model are located on the left hand side whereas outputs are on the right hand side. The control strategy is clear with the steam pressure of each unit being monitored and controlled by throttling the turbine control valve, hence changing the steam flow rate. The power demand governs the feed water flow rate to both the units.

C. Feedback Between Units

In a multi-modular nuclear power plant one of the most attractive aspects, both economical and practical, is that all units can operate at different power rates for most of their individual fuel cycles to allow only one of the units to be out for refueling at a time. So, it is expected that each unit will have its own feed water controller, and any primary system feedback between units will be very limited, in part because of the large reactor coolant system inventory of over $453\ \mathrm{m}^3$ $(16{,}000\ \mathrm{ft}^3)$, significantly larger than any other PWR, leading to some distinct impacts on the overall system behavior such as more time needed during cooldown/heatup, startup and dilution procedures, and most importantly a weak coupling between the reactor core and the steam generators also due to the low flow velocity, which in turn results in a characteristic residence time of about 40 seconds (compared to the 10 seconds in typical PWRs).

To simulate a stronger dependency between both units, other than that at the steam header, unit #2 has its feed water flow allowed to change based on the ratio of both instant power demands multiplied by the nominal power-dependent feed water flow of unit #1, i.e.,:

$$\mathrm{\dot{f}_2} = \frac{\mathrm{P_2(t)}}{\mathrm{P_1(t)}}\mathrm{\dot{f}_1(P_1)} \tag{3}$$

Where:

$\dot{f}_1$ and $\dot{f}_2$	are unit #1 and unit #2 feed water flows, respectively.
$P_2(t)$ and $P_1(t)$	are unit #1 and unit #2 time-dependent power demands.

Unit #2 feed water flow rate values calculated using (3) have an upper bound limit equivalent to the value of unit #1 operating at 100% power. This is particularly important in cases where $P_1(t)$ is lower than $P_2(t)$. In cases where $P_1(t)$ is greater than $P_2(t)$ the equation is a good approximation given feed water flow is fairly linear for any given power demand above 40%.

D. Multi-Modular IRIS Plant Used in Load Following Maneuvers

As stated earlier, load following is the capability of a reactor to follow changes in the grid demand; for example, reduced consumption over the weekend or load changes during the day. Hence, it is desirable from an economical point of view that a multi-modular reactor plant be able to do the same, although there are currently no regulations in this regard. For this purpose, the two-unit model with steam mixing is subjected to transients similar to profile 1. However, only the first 30 out of the 60 hours of this demand profile were simulated for three main reasons: running the whole profile is not necessary (and avoid repetition), it is time consuming, and is susceptible to numerical stability problems. Such instabilities are not uncommon and can happen, especially over long simulation times, so it is important to make sure that a stiff variable-step solver is used. There is no exact definition of stiffness for equations. Some numerical methods are unstable when used to solve stiff equations and very small step-sizes are required to obtain a numerically stable solution to a stiff problem. A stiff problem may have a fast changing

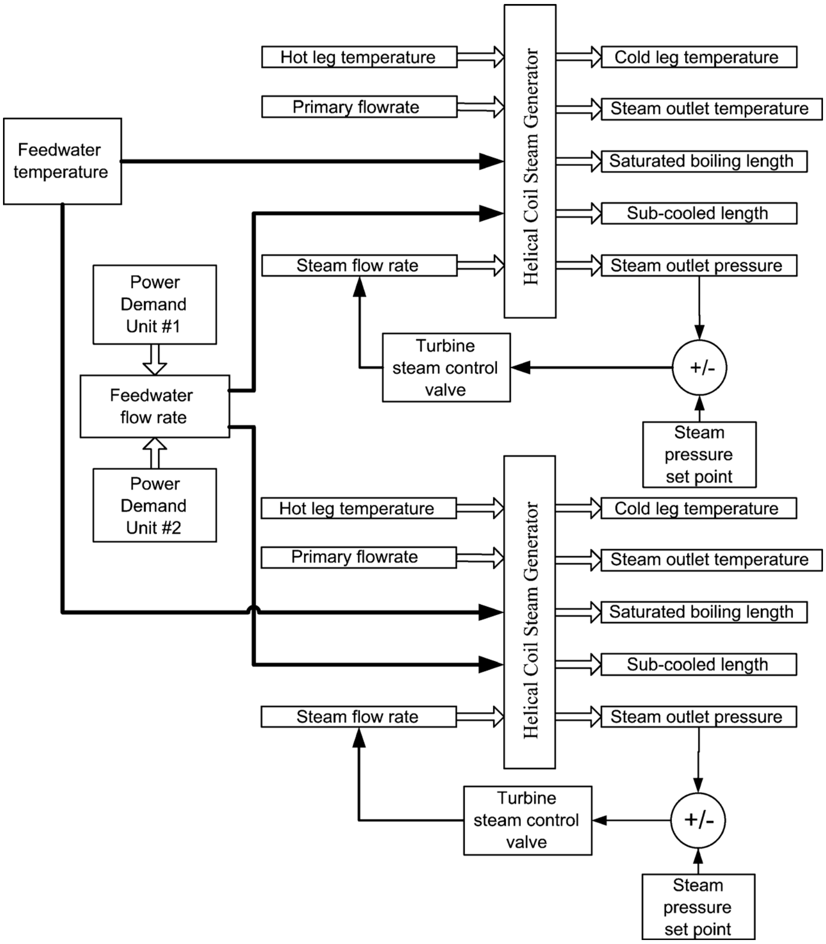

Fig. 10. Schematic of a Twin-HCSG control system connected at the feed water flow rate line.

component and a slow changing component (a large condition number, $\lambda_{\max}\lambda_{\min}$).

The results with the two-unit model using profile #1 load demand as input to the second unit and corresponding core power (Fig. 11), while maintaining the power level of the first unit at 100% are shown in Figs. 12 and 13 (results from first unit are not shown as there are no significant changes in this unit). The feed water flow rates to both units are shown in Fig. 12. In the figure, unit #1 flow rate is fixed corresponding to 100% power, but unit #2 varied with the power demand, and eventually matched the steam flow rate in both units. Fig. 13 shows the variations in the $\mathrm{T_{ave}}$ value for units #1 and #2 around the set point. In the figure, $\mathrm{T_{ave}}$ varied by about 1.5°C in unit #2 because it followed the load demand as the controller varied the external reactivity. Hence, the core inlet and outlet temperatures adjusted to maintain a constant average coolant temperature around the set point. The changes in the steam temperature at each of the reactor units and the temperature of the mixed steam in the common header are shown in Fig. 14. At first, both steam temperatures are the same, and remained constant in the first unit while it varied in time in the second unit because of the changes in the power demand. As the power decreased, the area available for heat transfer in the steam generator increased, thus increasing the steam temperature; conversely, the degree of superheat decreases following a power increase. The control strategy of regulating the average reactor temperature and the steam pressure is robust for this load following operation. The controllers are capable of maintaining both average coolant temperature and steam outlet pressure around their set points in both units.

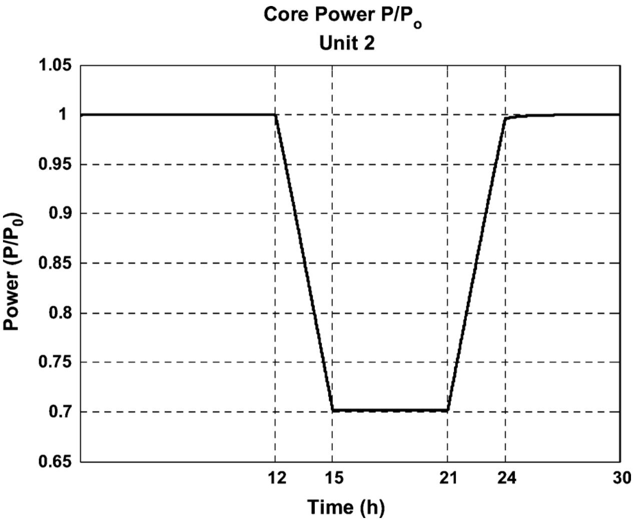

Fig. 11. Unit #2 core power profile.

E. Model Robustness

A perturbation case was investigated to analyze the capability of the model for detecting a small perturbation, therefore

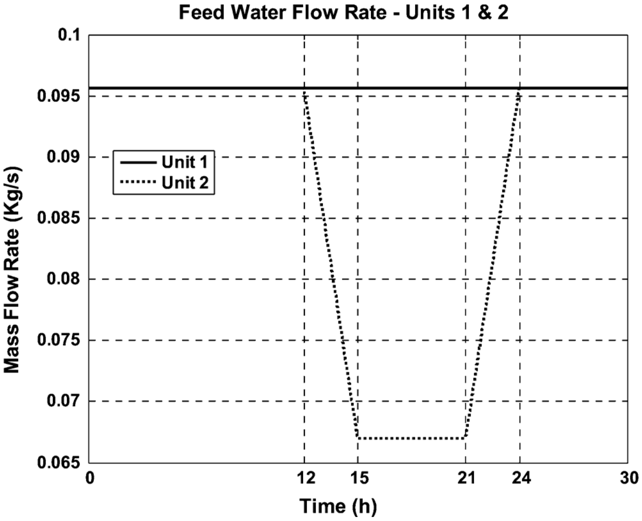

Fig. 12. Feed water flow rates for units #1 and #2.

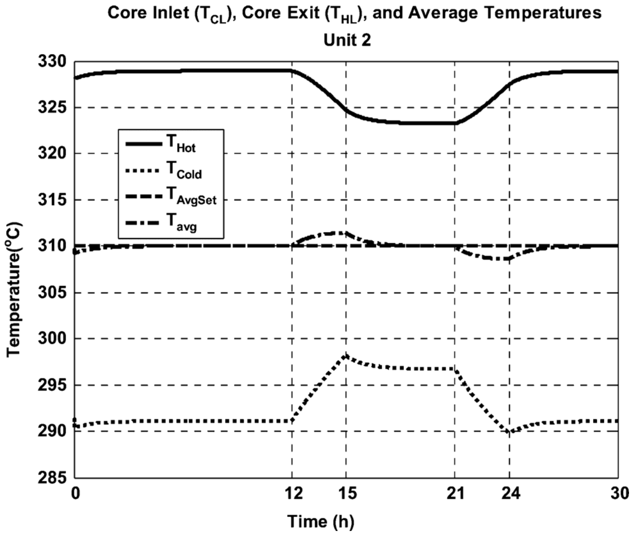

Fig. 13. Unit #2 average coolant temperature.

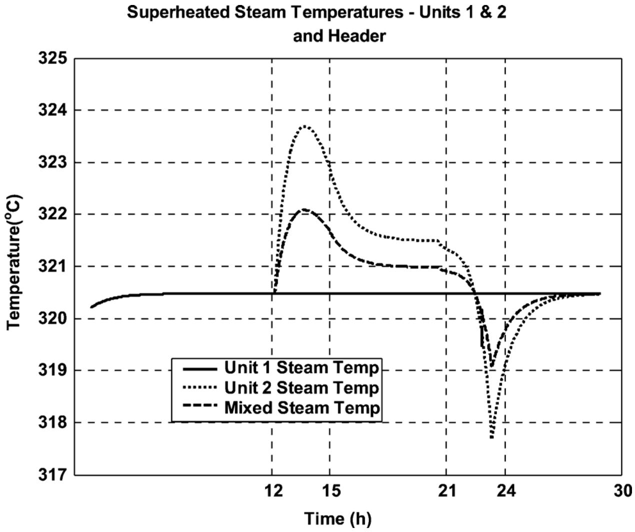

Fig. 14. Units #1 & #2 and mixed steam header temperatures changes.

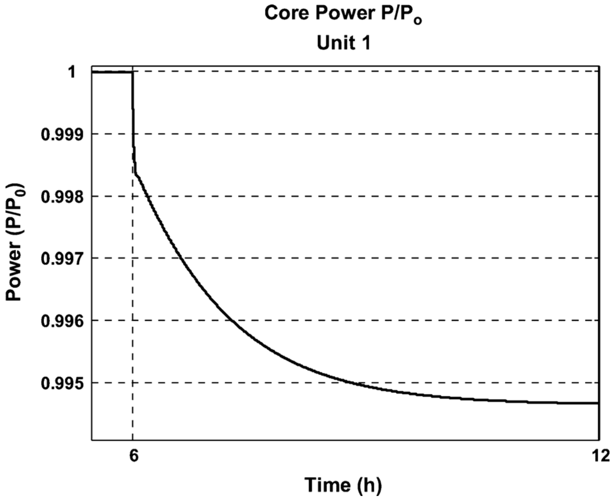

Fig. 15. Unit 1 core power profile for a $2.8^\circ \mathrm{C} \mathrm{T}_{\mathrm{cold}}$ sensor fault.

testing its robustness and sensitivity. In this paper a positive $2.8^\circ\mathrm{C}$ ($5^\circ\mathrm{F}$) step perturbation in $\mathrm{T}_{\mathrm{cold}}$ temperature measurements in unit #1 was introduced at $\mathrm{t} = 6\mathrm{h}$ (as a sensor error), with both units operating steadily at 100% power. This step change in the reactor core moderator inlet temperature sensor readings (faulty measurements), misled the $\mathrm{T}_{\mathrm{ave}}$ controller into reacting by decreasing the total reactivity. At first, the power immediately decreased by 0.2%, and then asymptotically decreased until the total power settled about 0.6% below the initial value, as shown in Fig. 15.

VI. CONCLUDING REMARKS

The IRIS Simulink model was studied and tested in this research to be used later on in a steam-mixing scenario. The core steady state results are compatible with the literature, and once connected to the helical coil steam generator model, the steady state values are comparable to those obtained using the high fidelity NCSU IRIS FORTRAN code. Both $\mathrm{T}_{\mathrm{ave}}$ and steam pressure control worked well for different power demand scenarios, with simulations taking around 30 minutes to complete. Special attention was given using this model to simulate fast changing transients, especially close to inflection points in the profiles, as it became numerically unstable due to the model stiffness and length of simulation. Sometimes, different proportional-integral gains were used in the core model that helped avoid such instabilities, but it involved a few iterations; generally, faster changing transients required smaller proportional gains.

Several load demand profiles were investigated, and the simulation results demonstrated that the IRIS design was adequate for load following applications. But some discretion must be given in applying load following profiles, especially profile 7, because it is an unreal situation given no real life power system can be required to go from 100% power to 50% instantaneously. Finally, the current Simulink model does not include other vital components and systems such as pressurizer, balance-of-plant, feedwater heaters, and associated controllers. Also, a feed-forward controller to quickly move the control rods, following changes in power load demands, is not included in the model.

This makes the reactor power response slower compared to that of a more complete model.

The model was then extended to include a second unit, with the objective of evaluating and quantifying the performance of a nuclear power plant comprised of two IRIS reactor units operating simultaneously, with the superheated steam from both units flowing to a common header. This in turn is connected to a single turbine, resulting in a steam-mixing control problem with respect to "load-following" scenarios, such as changing electricity demand. The simulations involved only load following profile number one because the objective was to check if the model would be able to operate in load-following mode and its ability to detect small, controlled faults introduced either in sensor measurements or in the process.

A series of perturbation cases were investigated: Three involved the moderator average temperature controller in the primary system by perturbing $\mathrm{T}_{\mathrm{hot}}$ or $\mathrm{T}_{\mathrm{cold}}$, and four involved the secondary system by perturbing the feed water flow rate or temperature. In all the cases, the unit not being subjected to the fault showed no effect due to this fault. The exception was only for the mixed steam temperature or pressure in the header, even when the units are connected by a common feed water flow pipeline. In all the cases the steam pressure and $\mathrm{T}_{\mathrm{ave}}$ controllers in both units performed as expected, maintaining the process values well within the set points.

Finally, it was possible to conclude from simulations that, for small variations in process variables, both units are somewhat independent of each other even with a common feedwater line connecting both steam generators, and are able to perform well even under such variations, with the strongest connection between the two units being located in the steam header. The simulation results show the feasibility of having two IRIS units in a single power plant sharing a common turbine-generator system.

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