Complementing Renewable Energy Production with Small Modular Reactors

Richard BISSON[1], **Jamie COBLE**[2], **and Kevin TOMSOVIC**[3]

1. ***Department of Nuclear Engineering, University of Tennessee, 1004 Estabrook Dr, Knoxville, TN, 37996, USA (rbisson@vols.utk.edu)***
2. ***Department of Nuclear Engineering, University of Tennessee, 1004 Estabrook Dr, Knoxville, TN, 37996, USA (jamie@utk.edu)***
3. ***Department of Electrical Engineering and Computer Science, University of Tennessee, 1520 Middle Dr, Knoxville, TN, 37996, USA (tomsovic@utk.edu)***

Abstract: As inherently intermittent sources of renewable energy (such as wind farms) more fully penetrate the energy grid, peaking power is largely being supplied by carbon-emitting natural gas turbines. These gas turbines are favored due to their fast response from shutdown to full power. However, significant greenhouse gas emissions could be avoided if these plants were 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. The Westinghouse International Reactor Innovative and Secure (IRIS) small modular reactor (SMR) is used as a candidate reactor design for modeling, simulation, and control studies. The nodal IRIS model includes the primary system and steam generator; simple assumptions and correlation models are currently used for the balance of plant. Nuclear energy generation is described by the point reactor kinetics equations with six neutron precursor groups; currently, only temperature-based reactivity feedback terms are included, but power-based effects (e.g., xenon buildup) are being integrated.

The control scheme for the power peaking operation of the IRIS iPWR model would ultimately lead to the development of real operational mechanisms and principles in a grid with significant renewables capacity. The 350 MWe IRIS reactor is coupled with a roughly 100 MWe-capacity wind farm to evaluate the capability of the IRIS reactor to respond to quickly fluctuating power demand to provide power peaking and reserve power. The results of grid simulations show that fast response is possible, but system output is persistently lower than grid demand. New control strategies, including a supervisory control scheme, are being developed to improve plant response.

Keyword: Power Peaking, Small Modular Reactors, Operations and Control

1 Introduction

The International Reactor Innovative and Secure (IRIS) integral PWR is a fully integral small modular reactor with rated power of 1000 MWth, or 335-350 MWe [1]. Though it is not currently under development, the IRIS design has been extensively studied in the open literature and much engineering data and simulation results are available for it. With a rated power higher than that of most other SMRs, the IRIS may be more economically viable than lower power SMRs and easier to operate in tandem with small but highly variable renewable power sources such as wind farms or solar parks on the order of 10-200 MWe nameplate capacity. In such cases the IRIS plant may operate close to full power most of the time and ramp up or down according to grid operator demand while remaining within Electric Power Research Institute (EPRI) guidelines for ramp rates [2, 3]. The current study investigates load following operation of the IRIS reactor with on-line grid demand forecasting every two, five, or ten minutes. After a full concept of load-following operation and control algorithm is developed, the IRIS model will be integrated into grid-scale simulations to evaluate the feasibility and efficacy of load following with SMRs.

Typically nuclear power plants are operated in baseload generation mode at full rated power to maximize revenue. However, electrical grids with a large nuclear share or high renewables penetration require that at least some nuclear power plants be able to load follow [1, 2, 4]. A significant body of work has focused on power maneuvering that is categorized as load shaping or power shaping, such as that conducted at Columbia Generating Station near Richland, WA, by adjusting reactor recirculation flow and control rod insertion [3]. Greater attention is being given to load following wherein reactor power and generator 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., participation frequency control [2]. European Utilities Requirements (EUR) demand that nuclear power plants be capable of load cycling operation between 50% and 100% rated reactor power with change of electric output between 3-5% per minute [2]. This range of power maneuvering is achieved primarily by movement of various control rod bank types [2, 4].

Utah Associated Municipal Power Systems (UAMPS) and NuScale Power, LLC., have studied the possibility of very aggressive load following operation with 50 MWe NuScale modules[3]. In this study, the SMR power plant was operated in tandem with Horse Butte wind farm. The power profiles of the wind farm and local grid load are typical 24-hour profiles. Operational decisions include taking SMR modules offline for extended periods of low grid demand and/or sustained wind farm output, reactor power maneuvering, and bypassing the turbine to dump steam directly into the condenser for rapid power demand changes[3]. It is not considered an economical mode of operation because of the waste of steam and revenue lost from decreased electrical power generation. This has motivated interest in hybrid energy systems with additional functions such as storage, industrial process heat, and steam heating that allow for efficient use of fuel, more stable power, and avoiding revenue loss [5].

2 Modeling

The model simulated in this paper is a zero-dimensional lumped parameter nodal model of the reactor core and steam generator that was validated against a high-fidelity FORTRAN model developed at North Carolina State University [6, 7]. The balance of plant Simulink block uses lookup tables and empirical correlations to calculate turbine power and steam and feedwater properties.

2.1 Reactor Core

A nodalized lumped parameter model of the reactor system was constructed, shown in Fig. 1. The reactor core nodalization is implemented as Mann's model of heat transfer for one fuel node and two coolant nodes. The power level of the core is calculated using the point reactor kinetic equations (PRKE):

$$\frac{dP}{dt} = \frac{\rho - \beta}{\Lambda} P + \sum_{i=1}^{6} \lambda_i C_i$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} P - \lambda_i C_i$$

The total reactivity with linear thermal feedback is

$$\rho = \rho_{ex} + \alpha_F (T_F - T_{F0}) + \frac{\alpha_C}{2}[(\theta_1 - \theta_{10}) + (\theta_2 - \theta_{20})]$$

where ρ is the total reactivity of the system including external reactivity and thermal feedback effects. The reactivity term ρ_{ex} represents the feed-forward control associated with control rod insertion or withdrawal; T_f, $\theta_1$and θ_2 are the temperatures of the fuel, bottom, and top coolant nodes, respectively; and α_f and α_c are the related temperature feedback coefficients. Additional feedback effects, such as xenon build up during power maneuvers, are currently being integrated in the model.

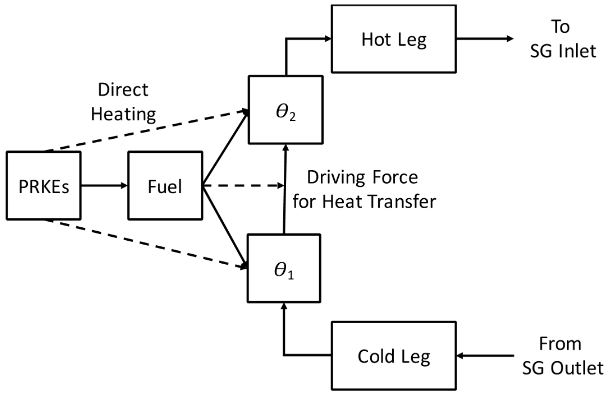

Fig. 1 Mann’s heat transfer model of the reactor core

2.2 Steam Generator

The helical coil steam generator (HCSG) model is a nodal moving boundary approximation of the primary loop-tube wall-secondary loop system with three phase regions—subcooled water, saturated two-phase mixture, and superheated steam—each divided into two nodes [6, 7]. The phase region determines the heat transfer properties between the tube wall and the secondary loop. A steam mass flow rate controller at the outlet is embedded in the HCSG.

2.3 Balance of Plant

The balance of plant uses lookup tables and empirical fits to calculate the fluid properties of incoming steam and outgoing feedwater [8]. It features open loop control of the secondary systems, with the feedwater temperature and flow rate being single variable functions of the exogenous electrical power demand.

3 Perturbation Studies

The following perturbation studies were carried out on the plant to evaluate system response to candidate actuator core variables. No core system variable controls were active during these simulations.

3.1 Core System Variable Perturbations

3.1.1 Reactivity Perturbation

Direct external reactivity steps of -\$0.10 and -\$1.00 representing control rod insertion were made into the model. The results of these perturbations appear in Fig. 2. The system exhibits a weak, nonlinear response to external reactivity insertion. The -\$0.10 step insertion results in little change in reactor thermal power while a -\$1.00 insertion causes a shift from the steady-state 95.68% rated power to 91.73% rated power.

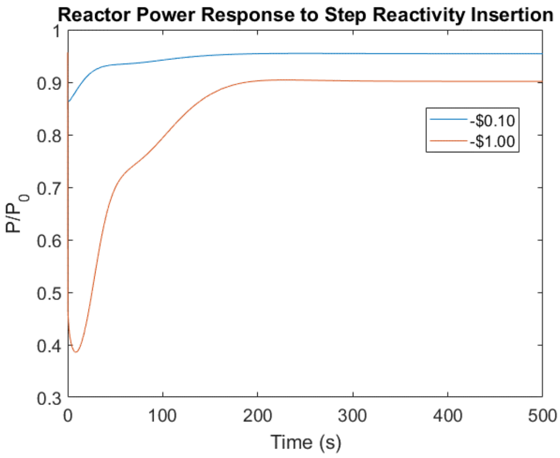

Fig. 2 Evolution of reactor power in response to negative reactive steps

3.1.2 Primary Coolant Mass Flow Rate Perturbation

The primary coolant mass rate was perturbed from its nominal value by 1% and 10% to evaluate the overall effect on reactor power. The resulting steady-state conditions are tabulated in Table 1. The low sensitivity of the response suggests that primary coolant flow rate control is an unsuitable candidate for power maneuvers in this model by itself, providing motivation for the development of an integrated supervisory control scheme.

Table 1 Primary Coolant Mass Flow Rate Perturbation Summary

Relative flow rate (W/W_0)	P/P_0
1.10	0.9509
1.01	0.9561
1.0	0.9568
0.99	0.9574
0.90	0.9638

3.2 Feedwater Mass Flow Rate Perturbations

The feedwater mass flow rate was perturbed from its nominal value by +1% to evaluate the effect on both reactor power and turbine power. The results appear in Fig. 3. The generator system is relatively sensitive to a step perturbation of 1% of the feedwater mass flow rate at 100% electrical power demand. A closed-loop controller approximating a programmable valve may be an ideal substitute for the feedforward program that is at this point only a function of the exogenous electrical power demand.

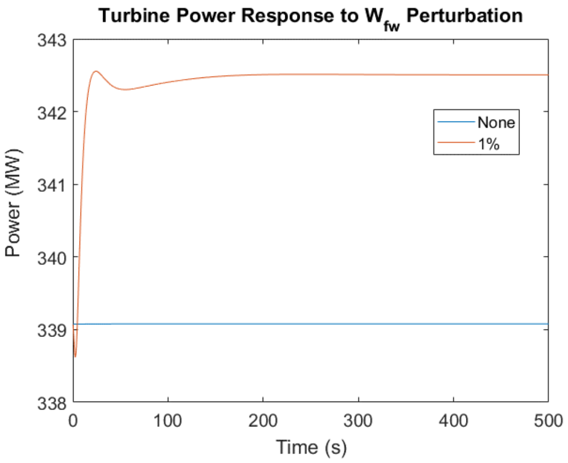

Fig. 3 Turbine power shift due to a small feedwater flow rate perturbation

4 Control Studies

4.1 Direct Reactivity Control

External reactivity ramps were conducted to evaluate the efficacy of control rod movement on managing electrical generation, shown in Fig. 4. The results suggest that for this system control rod movement should be accompanied by changes in the balance of plant state. The addition of a direct reactivity insertion by itself causes the turbine power to move off target. However, it may be implemented in conjunction with other closed-loop controls and maneuvers to achieve a desired power setpoint. This provides motivation for the development of a supervisory control system in the future.

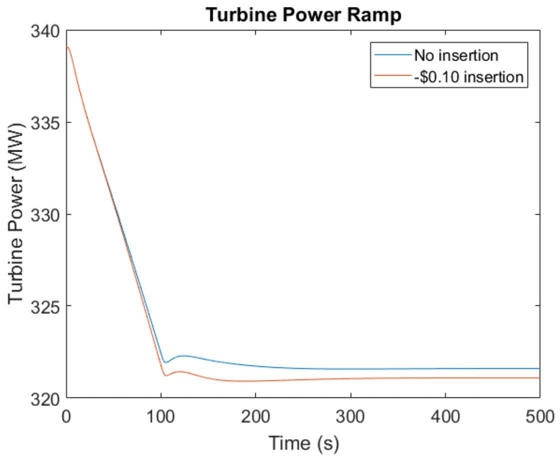

Fig. 4 Turbine power ramp in response to demand shift, with and without rod insertion

4.2 PI Core Temperature Control

A PI controller for the core temperature rise with an average temperature reference setpoint was developed in prior work at the University of Tennessee [7]. The controller makes an external reactivity insertion to maintain the setpoint average of the core inlet and outlet temperatures. The PI controller is turned on after steady-state is reached. The result of the simulation appears in Fig. 5, including a comparison of the original simulation steady-state power level without PI temperature control.

The efficacy of PI core temperature control was evaluated by varying the average temperature reference over time. The core response is plotted in Fig. 6. The resulting average temperature control shows a time lag, indicating that the PI control may not be sufficient for tight temperature control. Like other primary system controls investigated here, the effect on overall core power is small. However, this could be useful for developing fine controls and protecting the system from temperature excursions.

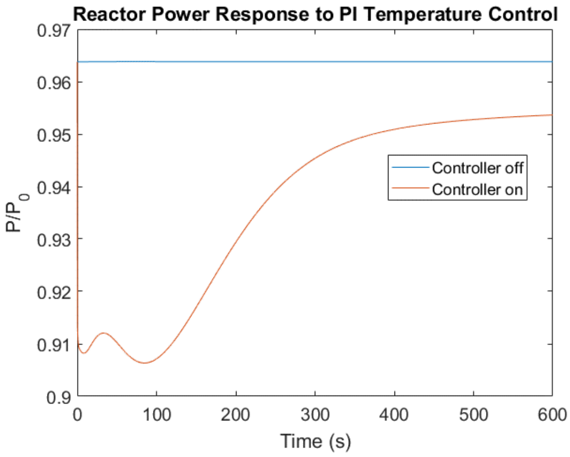

Fig. 5 Reactor power response to activating PI core temperature rise controller

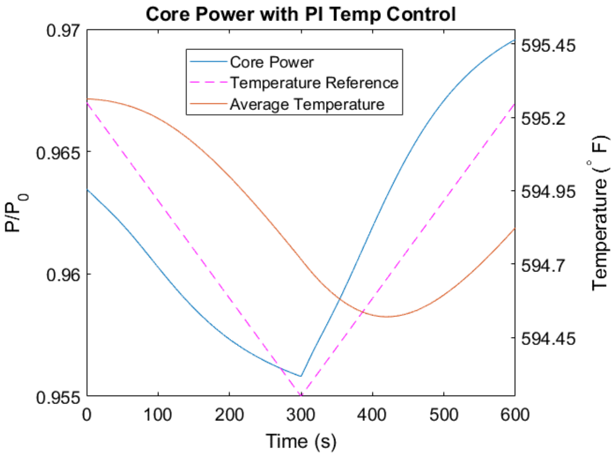

Fig. 6 Core power response to PI temperature controller with time-varying reference

5 Grid Simulation

5.1 Trapezoidal Profile

A simple sequence of ramp maneuvers was conducted by constructing a trapezoidal grid power demand (100%-90%-80%-80%-90%-100% over 25 minutes), a power ramp of 2%/min in both directions. The results of this load shaping simulation appear in Fig. 7 and Fig. 8. The turbine output changes due to the feedwater flow rate and temperature open-loop control, and the reactor core responds due to changes in the steam generator. The core response is linear. There exists a small mismatch between turbine output and grid demand due to the open-loop control of the feedwater temperature and mass flow rate for the balance of plant. Supervisory and feedback control strategies are being developed ameliorate this issue.

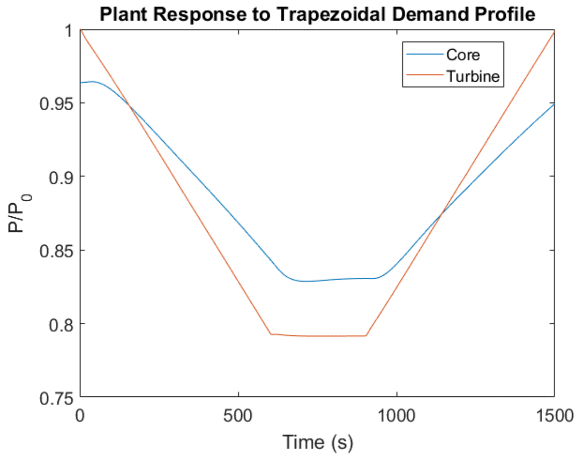

Fig. 7 Core and turbine response to exogenous electrical demand

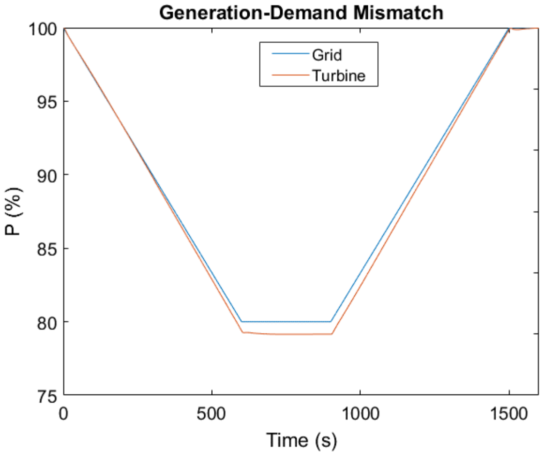

Fig. 8 Plot of generation-demand mismatch for a trapezoidal profile

5.2 Randomly Generated Profile

A more realistic grid demand profile was approximated with a random uniform distribution over the interval (85%,100%); the simulation results appear in Fig. 9 and Fig. 10. The excursions are suggestive of the most chaotic behavior that might be encountered in such short forecast intervals. The variable ramp rates may have meaningful implications for operation, especially with the inclusion of xenon feedback in future modeling efforts. Again a mismatch between turbine generation and grid demand manifests due to the open-loop control of the feedwater temperature and mass flow rate in the balance of plant.

Fig. 9 Core and turbine response to randomly generated plant demand

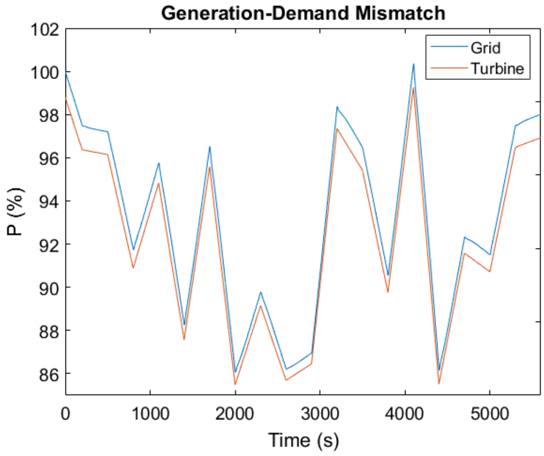

Fig. 10 Plot of generation-demand mismatch for randomly generated profile

6 Conclusions

Perturbation and control studies were conducted to evaluate the response of a nodal model of the IRIS reactor. The results suggest that open-loop control of external reactivity and primary coolant flow are not feasible methods for fast power ramping that may be necessary as intermittent renewables more deeply penetrate the grid. A simple grid simulation was conducted to evaluate the system response and feasibility of operation. Control of the balance of plant allows for sufficiently rapid generator power changes to meet grid demand. However, this is can result in revenue loss if the fission rate in the reactor changes modestly while electrical power to the grid shifts significantly to meet grid demand.

7 Ongoing Work

7.1 Supervisory Control Development

The current control scheme can be improved and developed further. More sophisticated controls of the reactor systems and balance of plant are being investigated. Fuzzy control, linear quadratic regulator, and model predictive control are some of the control paradigms under consideration, as well as an overall supervisory control hierarchy. A fuzzy controller using several actuators may improve the performance of feed-forward direct reactivity and primary coolant control alone.

7.2 Modeling in Modelica

A complete Modelica plant model is currently under development. There exists other physically motivated modeling of the IRIS reactor in Modelica that fully leverages the Modelica standard libraries for fluids and heat transfer for the primary system model [9, 10]. Current efforts have retained the nodal Mann's model of the reactor core heat transfer while using a steam generator model developed at ORNL for the TRANSFORM library [11]. A simple balance of plant model will be incorporated in the future. The balance of plant will include an ideal turbine, generator, condenser, feedwater pump, and feedwater heater. Instead of responding to a raw power signal, the system will regulate the generator rotational frequency.

7.3 Xenon Feedback and Control

Xenon isotope production and feedback will be integrated into the IRIS PRKEs to more realistically capture reactivity feedback effects. The reactivity feedback of xenon has the form

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

where α_{Xe} is the feedback coefficient and X_0 is the steady-state concentration of xenon-135. The addition of xenon feedback may have meaningful consequences for long term reactor operation and ramping over periods of several hours.

7.4 Grid and Renewables Integration

The Center for Ultra-Wide-Area Resilient Electrical Energy Transmission Networks (CURENT) has modeling tools developed in Modelica for simulation of electrical grid systems [12]. The Modelica-based IRIS model can be integrated into the CURENT grid model to simulate nuclear energy production in real time in order to evaluate plant behavior and the feasibility of load following under different grid scenarios. More realistic grid demands derived from real world data, as in Fig. 11, over longer time intervals will be incorporated into the standalone model to better approximate real operation and develop similarly suitable controls. Simulations with grid forecasting 5-10 minutes ahead will be conducted to evaluate performance and draw conclusions about engineering feasibility, economics, and compliance with regulatory guidelines.

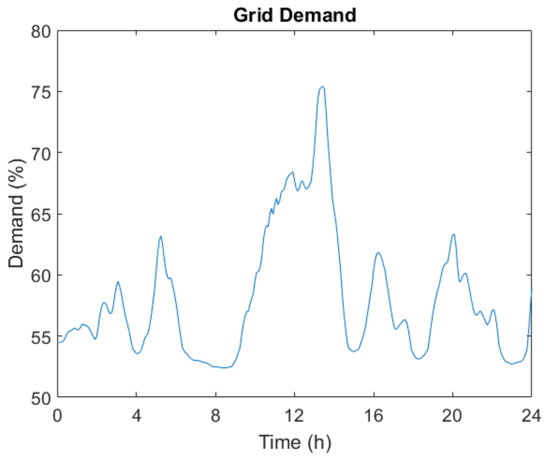

Fig. 11: A typical demand that might be placed upon the plant for a 24-hour period, calculated as the difference between overall grid demand and wind power supply

Nomenclature

SMR- Small Modular Reactor
iPWR- Integral Pressurized Water Reactor
IRIS- International Reactor Innovative and Secure
EPRI- Electric Power Research Institute
CURENT- Center for Ultra-Wide-Area Resilient Electrical Energy Transmission Networks
ORNL- Oak Ridge National Lab
PRKE- Point Reactor Kinetics Equations
HCSG- Helical Coil Steam Generator

Acknowledgement

This research was supported by the Engineering Research Center Program of the National Science Foundation and the Department of Energy under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

References

[1] M. D. Carelli *et al.*, "The design and safety features of the IRIS reactor," *Nuclear Engineering and Design,* vol. 230, no. 1–3, pp. 151-167, 2004.

[2] "Technical and Economic Aspects of Load Following with Nuclear Power Plants," Nuclear Energy Agency OECD2011.

[3] D. T. Ingersoll, C. Colbert, Z. Houghton, R. Snuggerud, J. W. Gaston, and M. Empey, "Can nuclear power and renewables be friends?," 2015.

[4] H. Ludwig, T. Salnikova, A. Stockman, and U. Waas, "Load cycling capabilities of German nuclear power plants (NPP)," *VGB PowerTech,* vol. 91(5), pp. 38-44, 2011.

[5] M. S. Greenwood, M. Sacit Cetiner, T. Jay Harrison, A. Lou Qualls, Askin Guler Yigitoglu, David L. Fugate, "Nuclear Hybrid Energy System FY16 Modeling Efforts at ORNL," Oak Ridge National Laboratory2016, Available: http://info.ornl.gov/sites/publications/files/Pub69372.pdf.

[6] B. R. Uphadyaya, J. W. Hines, J. M. Doster, R. M. Edwards, K. D. Lewis, P. Turinsky, J. Coble, "Advanced Instrumentation and Control Methods for Small and Medium Reactors with Iris Demonstration," University of Tennessee2011.

[7] B. R. Uphadyaya and S. R. P. Perillo, "Multi-Modular Integral Pressurized Water Reactor Control and Operational Reconfiguration for a Flow Control Loop," University of Tennessee Nuclear Engineering Department2011.

[8] J. R. Kapernick, "Dynamic Modeling of a Small Modular Reactor for Control and Monitoring," Master of Science, Nuclear Engineering, University of Tennessee, 2015.

[9] A. Cammi, F. Casella, M. E. Ricotti, and F. Schiavo, "Object-oriented modeling, simulation and control of the IRIS nuclear power plant with Modelica," 2005.

[10] D. Mikkelson, C. W. Chang, S. M. Cetiner, A. L. Qualls, J. M. Doster, and T. N. Dinh, "Small modular reactor modeling using modelica for nuclear-renewable hybrid energy systems applications," *Transactions of the American Nuclear Society,* vol. 113, 2015.

[11] M. S. Greenwood, "TRANSFORM-Library: A Modelica based library for modeling thermal hydraulic energy systems and other multi-physics systems," Oak Ridge National Laboratory, Available: https://github.com/ORNL-TRANSFORM/TRANSFORM-Library.

[12] M. S. T. Bogodorova, G. León, L. Vanfretti, M. Halat, J. B. Heyberger, P. Panciatici, "A modelica power system library for phasor time-domain simulation," presented at the IEEE PES ISGT Europe 2013, 6-9 Oct. 2013, 2013.