Control Systems for a Dynamic Multi-Physics Model of a Nuclear Hybrid Energy System[*]

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ABSTRACT

A Nuclear Hybrid Energy System (NHES) uses a nuclear reactor as the basic power generation unit, and the power generated is used by multiple customers as combinations of thermal power or electrical power. The definition and architecture of a particular NHES can be adapted based on the needs and opportunities of different localities and markets. For example, locations in need of potable water may be best served by coupling a desalination plant to the NHES. Similarly, a location near oil refineries may have a need for emission-free hydrogen production. Using the flexible, multi-domain capabilities of Modelica, Argonne National Laboratory, Idaho National Laboratory, and Oak Ridge National Laboratory are investigating the dynamics (e.g., thermal hydraulics and electrical generation/consumption) and cost of a hybrid system. This paper examines the NHES work underway, emphasizing the control system developed for individual subsystems and the overall supervisory control system.

Key Words: nuclear hybrid energy system, modelica, control system, dynamic modeling

1 INTRODUCTION

Electricity markets in the United States are undergoing significant shifts in the traditional market structure. Factors such as mandates for renewable energy, overall carbon reduction, and the emergence of low cost natural gas supplies have strained the profitability of traditional baseload electricity suppliers, including nuclear power plants.

As the typical nuclear power generating station traditionally has only one customer—the grid—diversification of the customer portfolio in an integrated or hybrid manner may be advantageous. A representative NHES is depicted in Figure 1.

A hybrid energy system approach that directly couples base load energy suppliers and various energy customers (thermal and/or electric) with dynamic energy allocation, may be profitable and preferred in future energy markets. Possible scenarios include *ad hoc* energy allocation for product options that could be more profitable than traditional electricity generation. This could mitigate the possible load-following need—and subsequent cost increases—that significant renewable penetration may impose on nuclear power plants. For example, Figure 2 is a representative summary of the Electric Power Research Institute's (EPRI) recent study on the impact of renewable energy generation on grid variability [1]. Given current economic and political trends, future electrical grids will require highly variable operations that impose significant technical and economic challenges for power producers. Introducing hybrid energy

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systems may help create a path to achieving highly variable markets that are economically sound and do not compromise grid reliability.

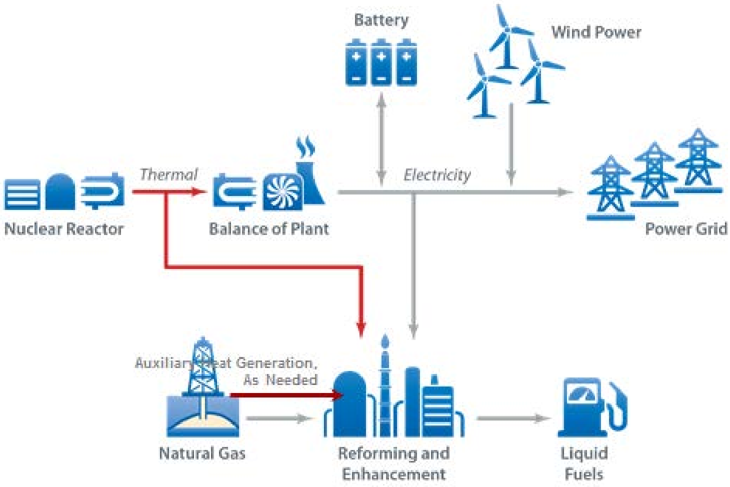

Figure 1. A representative NHES demonstrating a possible coupling scenario of both thermal and electrical energy with additional systems (e.g., an industrial process and energy storage system) [2].

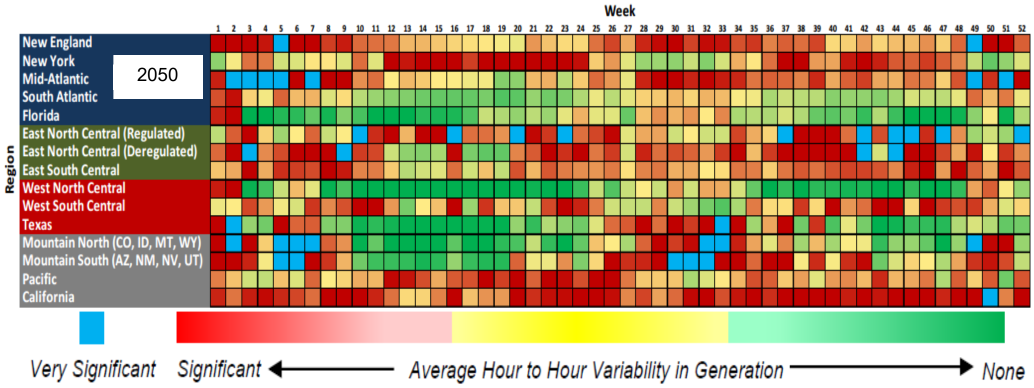

Figure 2. Prediction of electrical grid variability for regions of the United States in 2050. The color of the cells represents the variability. Regions approaching red and blue have demands that will be difficult and expensive for the electrical grid to meet—especially power producers operating under traditional market paradigms [1].

This paper presents background information on the methodology being developed to evaluate the economic merit of an NHES, with a focus on the development of the control systems of the dynamic multiphysics models in Modelica that play a key role in the economic evaluation. Additional information beyond the scope of this paper can be found in [3] and [4].

2 MODELICA: A DYNAMIC PROGRAMMING LANGUAGE

Modelica [5] is a nonproprietary, object-oriented, equation-based programming language used to conveniently model complex physical and cyber-physical systems (e.g., systems containing mechanical, electrical, electronic, hydraulic, thermal, control, etc. components). Given the complex and diverse range of physics involved in modeling a dynamic hybrid energy system it was determined that the multi-domain nature of Modelica would permit flexibility in modeling the appropriate physics of all systems and the associated control systems in one tool.

The modeling method in Modelica is characterized by Figure 3. The figure demonstrates the creation of generic models that can then be linked to create ever more complex models. Verification tests can then be performed to investigate the behavior of the model.

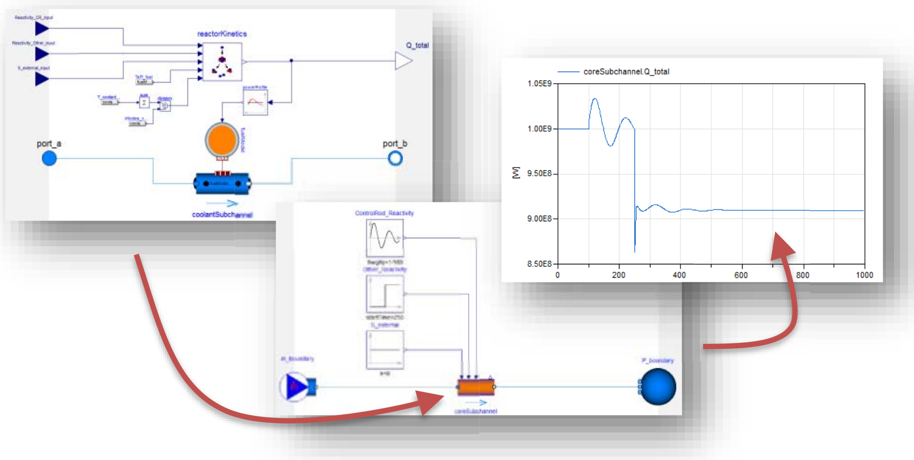

Figure 3. The top left image shows the creation of a more complex model from a collection of individual models that describe different physics based systems. In this case a reactor core sub channel model is created and is then tested in the bottom image. The top right image demonstrates the behavior (e.g., total thermal output) of the generated system in the assembled test case.

3 THE TIGHTLY COUPLED NHES

The reference hybrid energy system is referred to as a “tightly coupled” system. This coupling indicates that both the thermal and the electrical energy from the base load power supplier are integrated with one or more systems (e.g., industrial plant). The Modelica-based system under development is presented in Figure 4. The numbers in the figure correspond to the brief descriptions in Table 1. The dynamic model is used to provide non-economic figures of merit—such as the ability to meet specified energy demands and overall system stability and reliability—to supplement the economic cost evaluation.

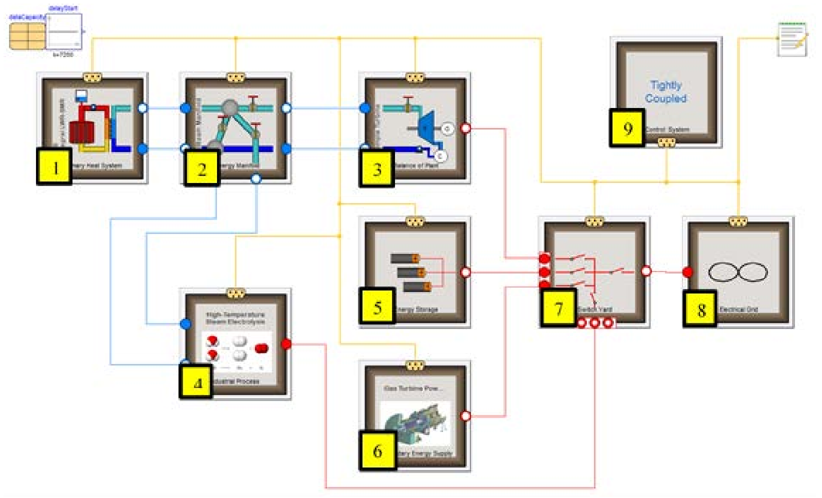

Figure 4. The tightly coupled NHES under development. The blue lines indicate fluid, the red lines indicate electricity, and the yellow lines indicate sensor/control signals.

Table 1. Description of the subsystems comprising a tightly coupled hybrid energy system.

Identifier	Component	Description	Example
1	Primary heat system	Provides baseload heat and power	Nuclear reactor
2	Energy manifold	Diverts thermal energy between subsystems	Steam distribution
3	Balance of plant	Serves as primary electricity supply from energy not used in other subsystems.	Turbine and condenser
4	Industrial process	Generates high-value product using heat from the energy manifold/secondary energy supply and electricity from the switch yard.	Steam electrolysis or desalination
5	Energy storage	Serves as energy buffer to increase overall system robustness.	Batteries and firebrick
6	Secondary energy supply	Delivers small amounts of topping heat required by industrial processes.	Gas turbine makeup
7	Switch yard	Distributes electrical load between subsystems.	Electricity distribution
8	Electrical grid	Sets the behavior of the grid connected to the NHES	Large grid behavior (not influenced by NHES)
9	Control system center	Additional systems are required to provide proper system control, test scenarios, etc.	Control/supervisory systems and event drivers

3.1 Economic Evaluation: Cost

To evaluate the economic merit of a given hybrid system, the Modelica model is coupled to Reactor Analysis and Virtual control ENvironment (RAVEN), a multi-purpose software framework developed by INL that allows for dispatching different software functionalities, including surrogate model generation and optimization routines [6]. As outlined in Figure 5, RAVEN supplies the dynamic model demand time histories for specific subsystems along with subsystem capacities (e.g., industrial process production capacity). The system control logic then operates the overall system to meet the supplied demand. At the end of the simulation, various figures of merit (e.g., ability to meet demand, reliability based on operation of components) are passed to RAVEN. RAVEN then creates simplified surrogate models of the dynamic system and performs a cost-based optimization. This optimization generates new capacity parameters, and the process repeats until convergence to an optimized system is achieved. Using a high-performance computing cluster, this process is applied for many different cases in parallel.

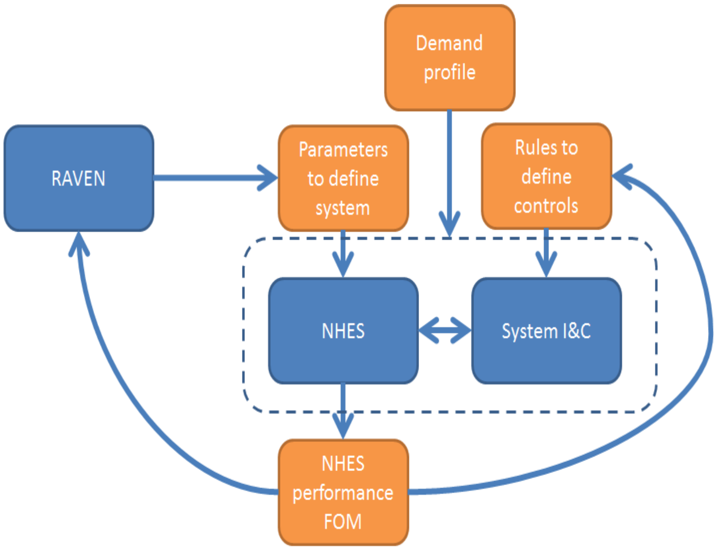

Figure 5. Modelica NHES dynamic model and RAVEN cost optimization process diagram [3].

3.2 Electricity Demand Profile

The specific energy demand profiles that provide set points to the dynamic model capture the variability of a specific energy market. For example, in a region with large solar power installations, the net electricity demand—consumer demand minus renewable supply—profile would show significant reductions in demand in the middle of the day—the period with greatest insolation. Figure 6 demonstrates a characteristic demand profile and the associated contributions of each of an example set of power producers over the course of a year. The demand profile is read by the Modelica model and tracked by the dynamic model's control systems.

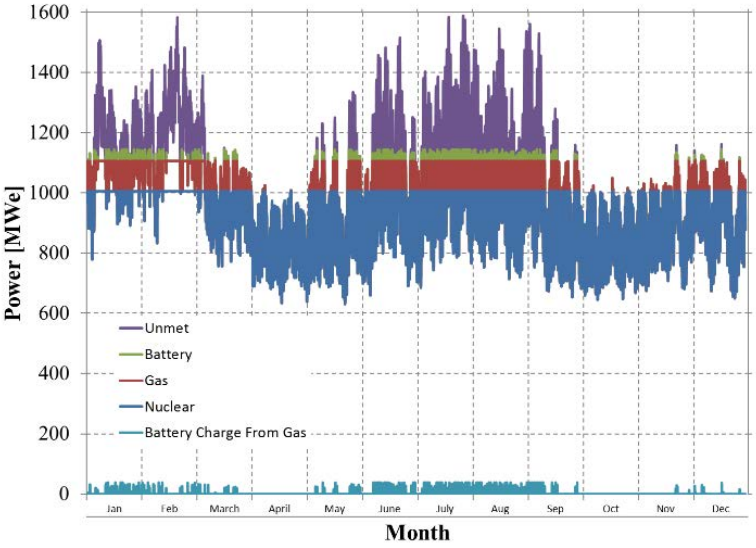

Figure 6. A one year electrical power hourly demand profile characteristic taken from the north-east region of the United States [7]. Each color represents the respective contribution of a subsystem energy supplier [7].

4 CONTROL SYSTEMS

Three subsystems (Balance of Plant, Secondary Energy System, and Energy Storage) are given demand profile set points from the supervisory control system. Subsystem controls employ primary PI controllers to monitor the actual response of the system and provide actuation signals to subsystem components both to match the demand set points and to stabilize the system. The Primary Heat System and Energy Manifold are discussed in more detail in this section.

4.1 Primary Heat System

The current NHES under investigation employs an integral pressurized water nuclear reactor based on the International Reactor Innovative and Secure (IRIS) [8]. A few important physical phenomena captured in the model include the two phase dynamic interactions of the pressurizer, the generation of steam in a helical coil steam generator, and the reactivity and thermal-hydraulic behavior of the nuclear core. The nuclear core model is shown in Figure 7 with its associated control system in Figure 8. This model integrates the coolant flow geometry and behavior, fuel behavior, and point kinetics neutronics behavior, with feedback from the fuel and coolant temperature. The current implementation of the core dynamics does not account burnup for and the impact of isotopic fuel changes.

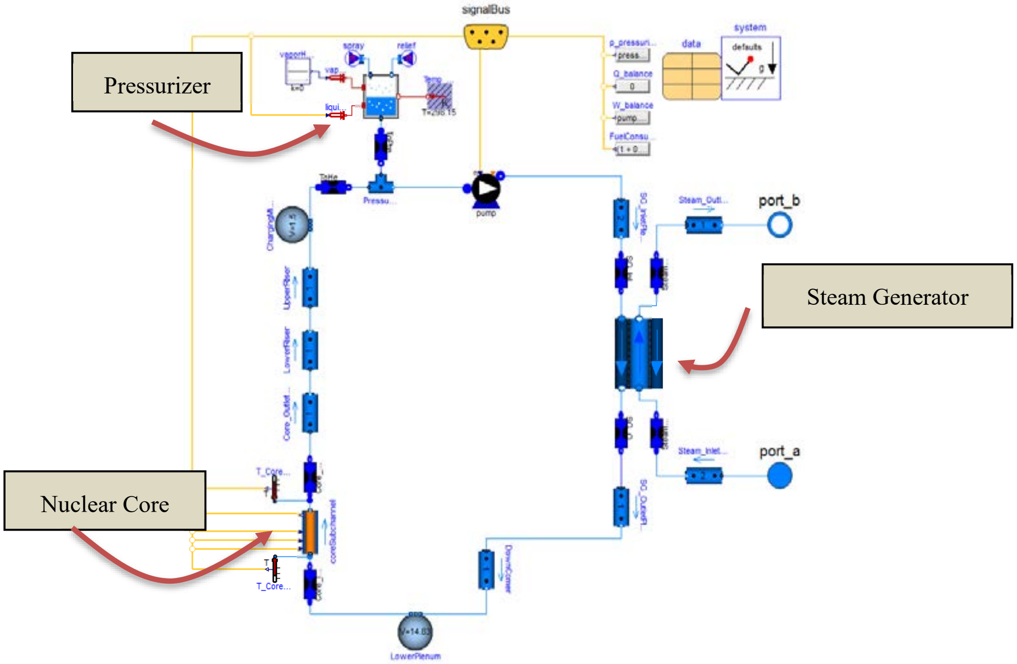

Figure 7. Modelica model of the Primary Heat System based on the IRIS reactor. The current implementation of this system requires only two controllers to keep the operation of the reactor stable, control rod reactivity control based on total power and pressure control with heaters in the pressurizer.

The control system monitors the total core power and controls the core rod reactivity to hold the Primary Heat System thermal power at the nominal state of 1000 MW. The controller is a standard proportional–integral (PI) controller with inputs normalized to approximately 1 to assist the solver with the numerical solution. Currently the system pressure is permitted to fluctuate within approximately 0.5 MPa of the nominal condition of 15.5 MPa. The liquid heaters of the pressurizer use a simple on/off controller with hysteresis that adds heat to increase system pressure when the monitored pressure drops to 15.0 MPa.

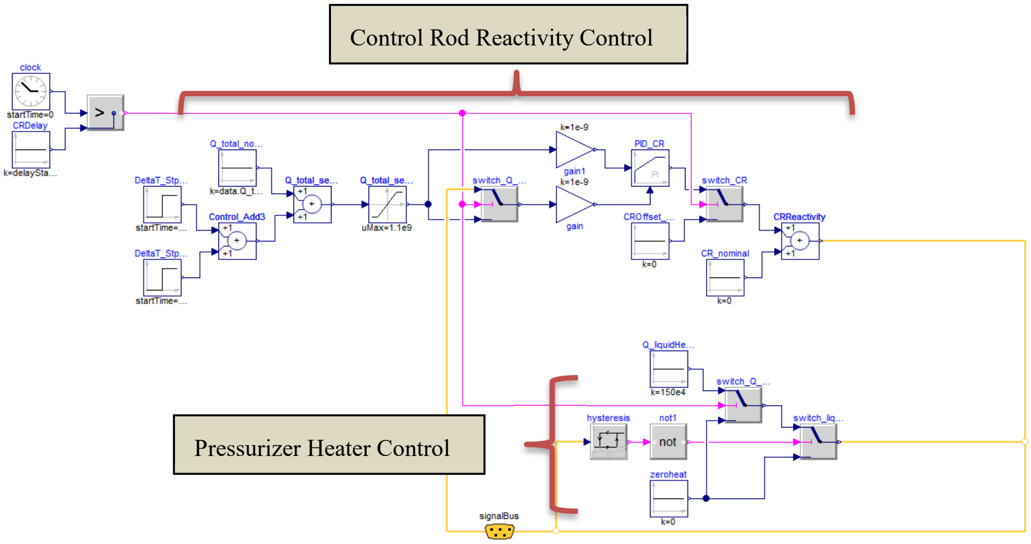

Figure 8. Control system for the IRIS Primary Heat System based on total core power and system pressure.

4.2 Energy Manifold

The current energy manifold under consideration is a purely thermal (i.e., steam/water) manifold (Figure 9). The energy manifold relies on controller logic to actuate distribution valves to handle large and slow power–set point changes to other subsystems, as specified by the demand profile. This actuation diverts hot steam coming from the primary heat system to the desired destination. The manifold also gathers return streams and directs the flow back the primary heat system steam generator at the proper temperature and pressure. Mixing and splitting volumes then add thermal mass to the system, dampening transient behaviors.

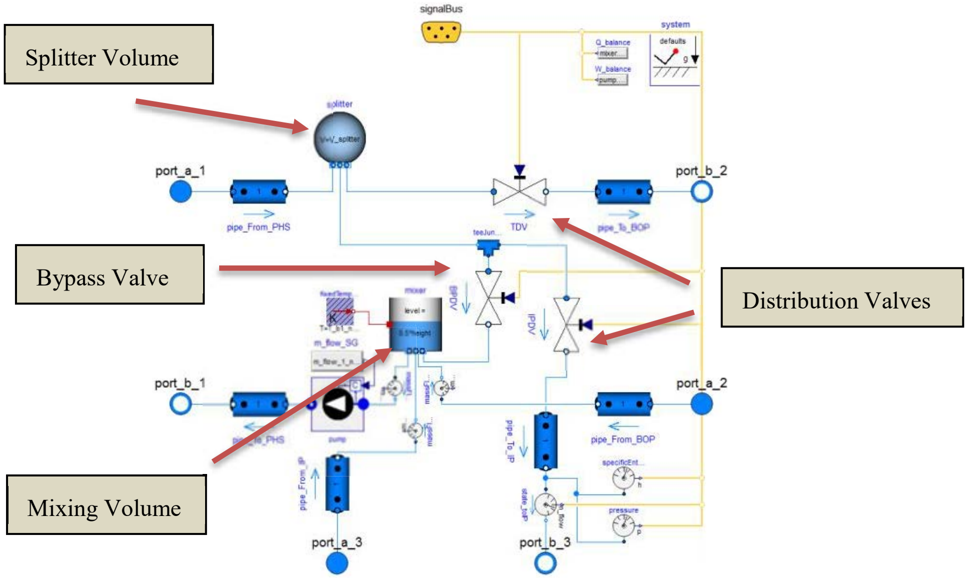

Figure 9. Energy Manifold for distributing and gathering steam/water streams from sub systems. The bypass valve is important for dampening pressure responses of the system when tracking demand profiles. The splitter and mixing volumes dampen transient thermal behavior.

The control system monitors the demand power set points of the Balance of Plant and actuates the turbine distribution valve to track the power using a PI controller. The bypass valve acts in a directly opposite response to the turbine distribution valve in order to limit pressure swings of the system. The position of the valve to the industrial process is held at a nominal point to set by the nominal operating point of the process. The industrial process then controls the flow rate it receives based on its internal pressure drop.

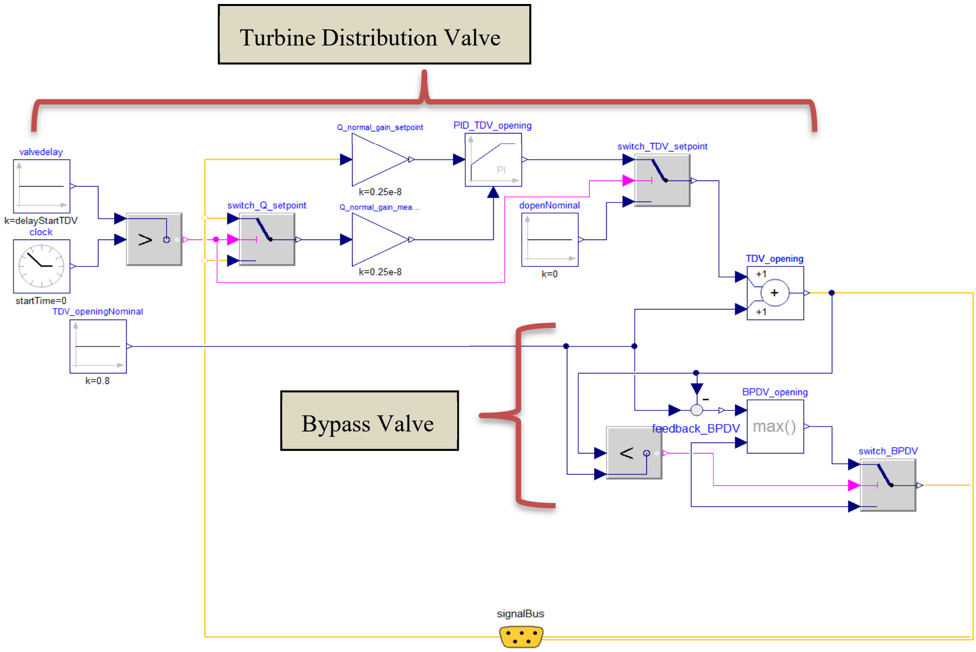

Figure 10. Energy Manifold control system. The turbine distribution valve is actuated to meet the demand profile set points of the Balance of Plant while the bypass valve acts exactly opposite the turbine distribution valve to dampen pressure swings within the system.

5 RESULTS

The following figures demonstrate the dynamic behavior of the controls for the Primary Heat System and Energy Manifold as demand power set points from the supervisory control system are followed. The simulation consisted of 14581 equations and simulated a two-week period in 2.3 hours.

Figure 11 depicts the behavior of the pressurizer pressure in the Primary Heat System. The pressure slowly decreases over time due to ingress of the cooler primary loop water into the pressurizer. Eventually the pressurizer liquid cools enough that the liquid heater control turns on until the pressure rises back to the nominal 15.5 MPa. The is a cyclic behavior that continues throughout the simulation with a frequency dependent on the dynamics of the energy manifold.

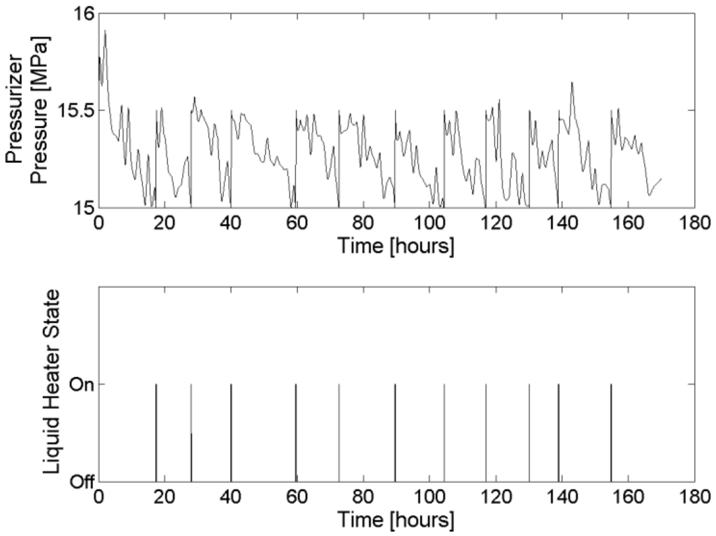

Figure 11. Pressurizer pressure in the Primary Heat System depicting an oscillatory behavior due to the dynamics of the Energy Manifold and the liquid heater compensation to raise the pressure from the minimum of 15.0 MPa to the nominal of 15.5 MPa.

Figure 12 demonstrates the ability of the system to be held relatively constant at the nominal thermal operating power of 1000 MW using only reactivity control. The behavior shown is once again dependent on the behavior of the Energy Manifold via the dynamic boundary conditions of the steam side of the helical coil steam generator.

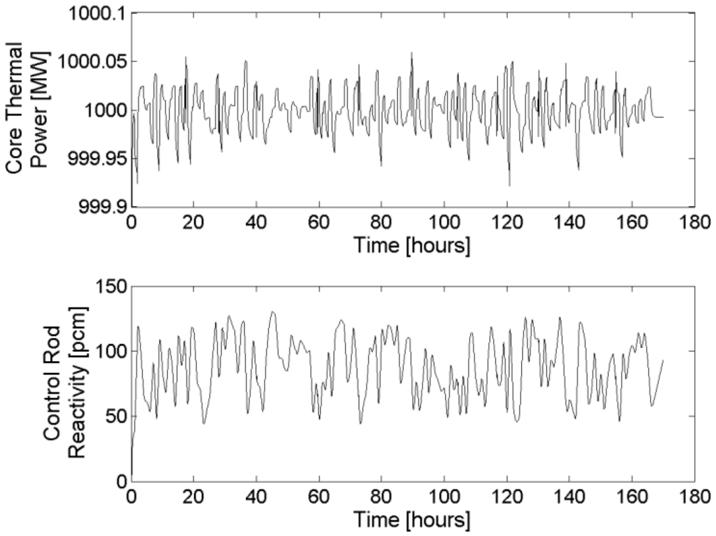

Figure 12. Core thermal power and the control rod reactivity behavior necessary to keep the Primary Heat System operating at a nominal thermal power level of 1000 MW.

Figure 13 demonstrates the actuation of the valves in the Energy Manifold required to match the aggressive demand profile. The valves act opposite of each other in order to limit the impacts on other subsystems (e.g., significant pressure deviations from nominal). Physical limitations of the system (e.g., transport delay, pressure limits, etc.) prevent exact following of the set point. However, in addition to physical limitations, the PI controller parameters also can have a significant impact on the ability of the system to precisely load follow. This may be an area of additional research in the future.

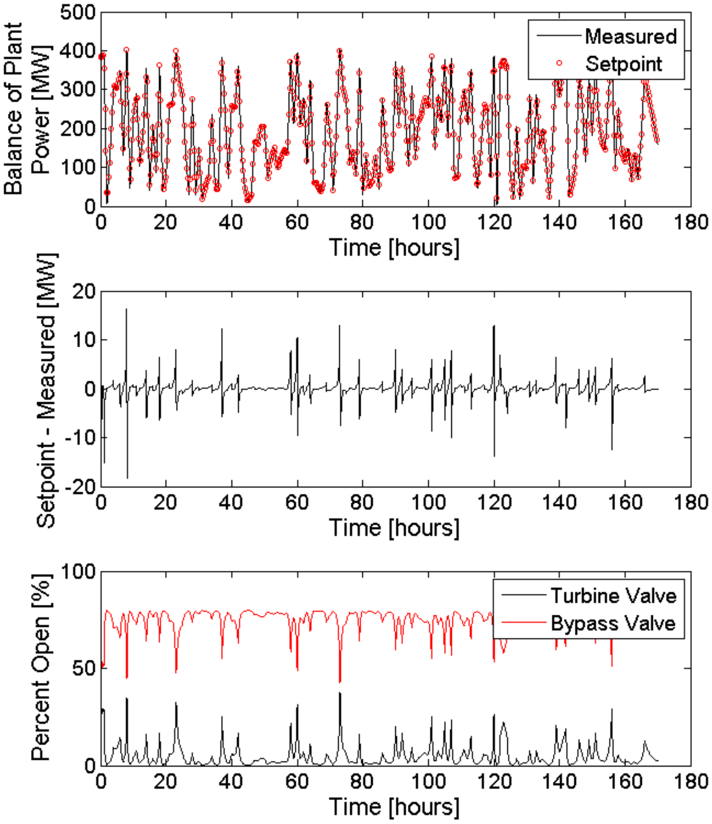

Figure 13. Balance of Plant generated power compared to the set point provided by the supervisory control system. The dynamic behavior of the turbine and bypass valves work together to meet the specified power and dampen impacts on the connected subsystems.

Figure 14 presents the overall ability of the tightly coupled energy system to meet the electricity demand profile. The ability of the system to meet the demand is a complicated problem. An important factor in this current result is the Energy Storage whose limited capacity provides for portions of time where excess electrical energy was wasted due to the storage being at maximum capacity and where electricity was unable to be provided due to the capacity having reached a minimal charge limit. As each subsystem physics and controller tuning are included and improved the ability of the NHES system to meet the demand will vary.

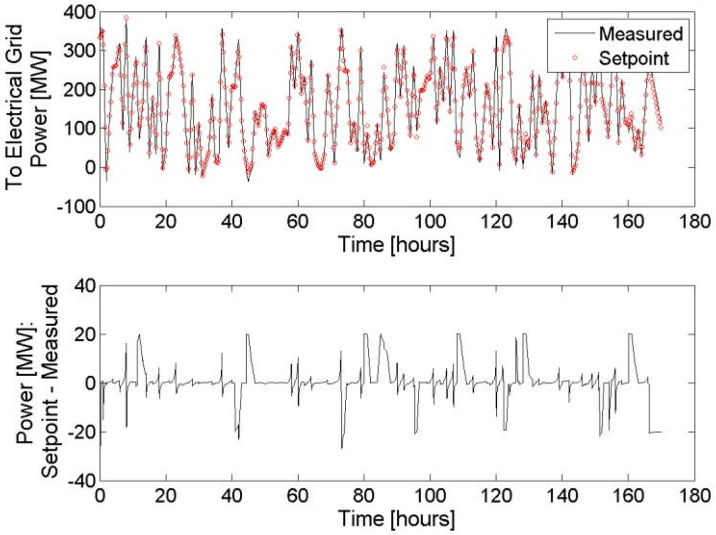

Figure 14. Result of the power delivered to the grid compared to the set point demanded. Periods of over and under production are evident. Additional studies investigating economics and impact of subsystem capacities (e.g., energy storage capacity) will be carried out in the future.

6 CONCLUSIONS

A multi-physics model of an NHES system has been created using the open-source programming language Modelica. The approach used divides the model into various subsystems which are independently developed and controlled. These subsystem models have been integrated to explore the dynamics of a tightly coupled energy system. The simulation of a week of power demand illustrates the complex dynamics of the system and the capability to model stable systems for further investigation and development.

Future work will continue to mature the models and couple the simulation with the RAVEN framework. This coupling will lead to an optimization process which will be used to explore the economic merits of various hybrid energy systems.

7 ACKNOWLEDGMENTS

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