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Revision 0

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Simulation of Power Dispatch from a PWR/SOEC System for Contingency Reserves

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U.S. Department of Energy

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Simulation of Power Dispatch from a PWR/SOEC System for Contingency Reserves

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SUMMARY

This report describes simulations that were performed to verify that a nuclear power plant (NPP) tightly coupled to a solid oxide electrolysis cell (SOEC) hydrogen production plant can qualify for participating in non-spinning and spinning and contingency reserve markets by providing spinning reserve power to the bulk electric grid in less than 10 minutes. Previous work with Sargent & Lundy developed a preliminary design and cost estimate for coupling an NPP to a 500 MW nominal SOEC plant, and this work builds on that effort by simulating their combined dynamic operation in a representative grid environment. For the simulations, a 4-loop pressurized water reactor (PWR) plant and a solid oxide electrolysis plant were modeled in Matlab/Simulink and connected to a representative grid modeled in RSCAD. Integrating these simulators is a key step toward using pilot-scale SOEC systems with a simulated PWR and power grid environment to verify concepts of integrated operations.

The simulations are based on dynamic data obtained from a 100 kW Bloom Energy SOEC system operated at Idaho National Laboratory (INL). Details of the Bloom SOEC system and the dynamic test that was performed to obtain the data are described in Section 2. A reduced-order PWR simulator was modified to incorporate combined electric and thermal power dispatch (CPD) and is referred to as a RO-CPD-PWR power plant simulator. Details of the RO-CPD-PWR simulator are presented in Section 3. A 500 MW SOEC plant was also modeled in Simulink, as described in Section 4. The grid model used in the simulations was developed in RSCAD and is described in Section 5. Finally, the integrated simulation results are presented in Section 6. These results verified successful coupling of the PWR, SOEC hydrogen plant and electrical grid, including electrical and thermal power coupling between the PWR and the hydrogen plant.

The key results of the simulation are shown in Figure S-1. The objective of the simulation was to show that the PWR/SOEC system (Generator G1) could curtail hydrogen production to dispatch power to the grid to replace power that is lost as Generator G2 ramps down from approximately 650 MW of generation to 240 MW of generation over a period of 10 minutes. In the simulation, Generator G2, which could represent a solar power plant, begins decreasing power generation at 2 minutes and has approximately 240 MW of power production 10 minutes later. To offset the loss of power from Generator G2, the SOEC hydrogen plant also starts ramping down shortly after Generator G2 starts decreasing power output. As the SOEC hydrogen plant ramps down, the PWR diverts power from the hydrogen plant to the grid, so the combined power output of Generators G1 and G2 to the grid is approximately constant at 1,150 MW during the simulation. In the simulation, the integrated PWR/SOEC system dispatched approximately 410 MW in 10 minutes, which represents 82% of the nominal capacity of the SOEC plant. This power dispatch capability could qualify as either spinning or non-spinning contingency reserves because the PWR turbine generator system is connected to the grid. A further key feature of the simulation is that the reactor power is maintained at nearly 100% during the simulation, which is the optimal use of the available nuclear energy.

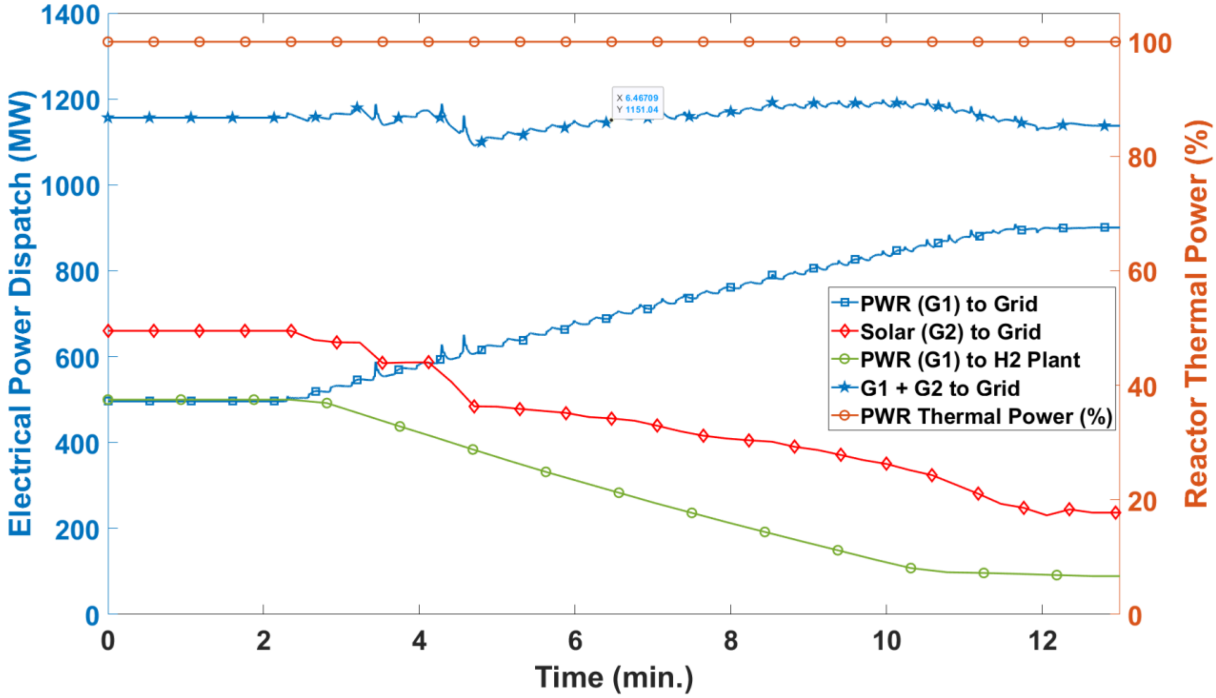

Figure S-1. Results of the integrated system simulation.

CONTENTS

FIGURES

ACRONYMS

BEA	Battelle Energy Alliance
RTDS	real-time digital simulator
DSL	delivery steam line
FDR	feedwater heater
HIL	hardware-in-the-loop
HOIL	human operator-in-the-loop
HP	high pressure
INL	Idaho National Laboratory
LP	low pressure
MS/R	moisture separator and reheater
MSIV	main steam isolation valve
NPP	nuclear power plant
O&M	operation and maintenance
PFD	process flow diagram
PI	proportional integral
PWR	pressurized water reactor
RO-TPD-PWR	reduced-order thermal power dispatch pressurized water reactor
RPV	reactor pressure vessel
TPD	thermal power dispatch
VRE	variable renewable energy
XSL	extraction steam line

SIMULATION OF POWER DISPATCH FROM A PWR/SOEC SYSTEM FOR CONTINGENCY RESERVES

1. INTRODUCTION

The United States' bulk power grid requires different types of operating reserves to ensure reliability. These reserves, along with other services, are referred to ancillary services that together function to maintain the reliability and resiliency of the bulk power grid. Operating reserves are divided into two sub-groups that include contingency reserves and regulation reserves. Contingency reserves consist of spinning and non-spinning contingency reserves that provide capabilities to respond to unscheduled power plant or transmission line outages, while regulation reserves include fast-response upward and downward regulation reserves that correct random fluctuations around normal load [1]. Increasing penetration of variable renewable energy (VRE) onto the grid increases the total reserve requirements. Spinning reserves, which are provided by large rotating generators, are particularly valuable because they provide mechanical inertia that assists in stabilizing the grid alternating current frequency that is affected by imbalances between power generations and grid loads. Fast-response regulation reserves also function to stabilize grid frequency but do not necessarily provide inertia to dampen rapid frequency changes due to load imbalances. Simulations described in this report illustrate that nuclear power plants (NPPs) coupled to dynamic hydrogen production plants can provide valuable spinning reserve services to the power grid.

Setting up and maintaining operating reserves adds cost to grid operations that system operators and plant owners must recover. Grid operations are optimized by committing and dispatching generators with the lowest available production cost, such that the sum of all the generator's output equals the load in each time interval. The dispatch optimization problem is solved using software that factors in numerous additional constraints associated with individual generators, such as minimum load point, minimum up and downtimes, and ramp rates as well as transmission line constraints between generator and load centers.

A fundamental aspect of maintaining operating reserves is the additional cost of keeping a subset of generators operating at partial load, so that they can increase output if needed. Keeping a subset of plants at partial load increases the number of plants that must be started, kept online and stopped, which results in increased fuel use and system operation cost per unit of energy produced. Furthermore, plants operating at partial load may have lower efficiency, especially when they are providing regulation reserve, which requires continuous changes in output over short periods. Transient operations associated with providing regulation reserves can also increase operation and maintenance (O&M) requirements due to increased equipment wear and increased staff actions [2].

Figure 1 illustrates in a simplified manner the required dispatch changes and potential cost impacts associated with providing operating reserves. The left panel shows an idealized dispatch of a small electric power system. Two baseload units provide steady power, while an intermediate load and two peaking units respond to variations in normal grid loads. In this idealized dispatch scenario, the intermediate load unit is assumed to be capable of rapidly increasing or decreasing output to provide operating reserves. Furthermore, it is assumed that additional units can be activated as needed to rapidly provide operating capacity for regulation or contingencies if units that are currently operating hit their full output. Of course, real generating units cannot be guaranteed to meet these idealized assumptions, so generator and grid transmission constraints must be considered. The right panel illustrates a dispatch scenario that provides the realistic reserves. In this scenario, lower-cost units reduce output to enable more flexible units to operate with sufficient margin that they can provide the needed reserves. Increased operation of higher-cost units increases the overall operating cost of the entire system. In any given hour, the cost of reserves is impacted by which generators are online, which generators can provide reserves, and possibly by complicated market rules associated with procuring and pricing operating reserves.

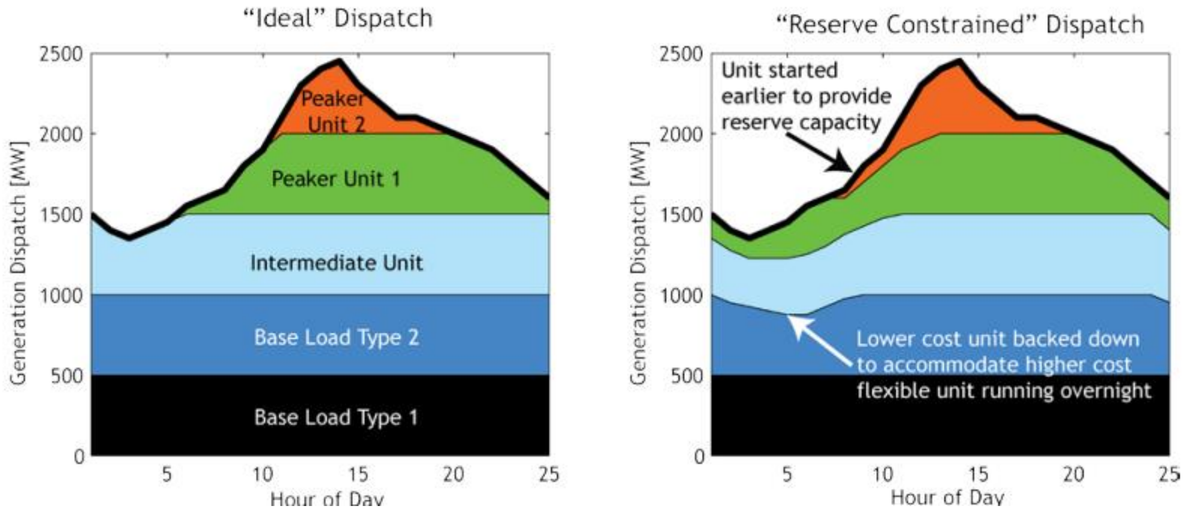

Figure 1. Simplified example of ideal and reserve-constrained dispatch (Source: [1]).

This report describes simulations that were performed to verify that a nuclear power plant tightly coupled to a solid oxide electrolysis cell (SOEC) hydrogen production plant can qualify for participating in the spinning contingency reserve markets by providing spinning reserve power to the bulk electric grid in less than 10 minutes. The simulations are based on dynamic data obtained from a 100 kW Bloom Energy SOEC system operated at Idaho National Laboratory (INL). Details of the Bloom SOEC system and the dynamic test that was performed to obtain the data are described in Section 2. A 4-loop Westinghouse pressurized water reactor (PWR) was selected for the nuclear power plant, and a dynamic reduced-order combined electric and thermal power dispatch PWR (RO-CPD-PWR) power plant simulator was developed in Simulink for the dynamic simulations. Previous work with Sargent & Lundy developed a preliminary design and cost estimate for coupling a nuclear power plant to a 500 MW nominal SOEC plant [3], and this work builds on that effort. The details of the RO-CPD-PWR are presented in Section 3. A 250 MW SOEC plant was also modeled in Simulink, as described in Section 4. The grid model used in the simulations was developed in RSCAD and is described in Section 5. Finally, the simulation results are presented in Section 6, and the conclusions are summarized in Section 7.

2. DYNAMIC SOEC SYSTEM OPERATING DATA

2.1 SOEC Overview

SOEC is a high-temperature method by which water (steam) is dissociated into hydrogen and oxygen gas (H_2 and O_2) at cathode and anode electrodes, respectively. In this work, stacks of SOECs are heated to temperatures up to 800°C within a furnace module, and then a cell voltage of approximately 1.3 V is applied to induce steam molecules splitting and H^+ cations and O^- anions separating through the solid oxide electrolyte, which acts as a separation membrane. The electric current passing through the stack of cells is directly proportional to the rate of hydrogen production. For example, four stacks of 50 electrochemical cells, with each operating at 1.3 V and with a current density of 0.7 A/cm^2, require a power supply of approximately 25 kW and 386 A and produce 0.75 kg/hr of hydrogen.

To perform electrolysis, a mixture of steam (H_2O) and hydrogen (H_2) is supplied to the cathode-side of the cells, typically with a volumetric composition of 95% H_2O and 5% H_2. Nitrogen (N_2) can be included in the cathode inlet gas mixture to control the partial pressure of H_2O and H_2. Supplied by either cylinder or dewar, N_2 may be also used as a purge gas for the electrochemical cells and H_2 product. The reactant steam includes approximately 5% H_2 to protect the ceramic electrode by maintaining a reducing environment. H_2 gas was provided by a recycle system. During operation, air is used as a sweep gas on the anode-side of the cell to dilute and remove oxygen (O_2) from the system. Diluting the product O_2 to less than 50% concentration in the air is important because pure O_2 at high temperature can cause uncontrolled oxidation and thermal runaway of the electrochemical process.

2.2 Bloom SOEC System Operating Modes (Control States)

To provide data from a physical SOEC system on which to base contingency reserve simulations, a test was performed at INL that included heating a Bloom SOEC system to approximately 800°C and producing hydrogen at 0.75 kg/hr. The test was performed as part of a Corporate Research and Development Agreement (CRADA 21CR9) between Bloom Energy and Battelle Energy Alliance (BEA).

Physical equipment at INL included an electric steam boiler, AC/DC power rectifiers, and a pilot-scale 100 kW Bloom Energy unit that operates in a manner that is relevant to full-scale PWR operations. A photograph of the Bloom prototype system is shown in Figure 2. The boiler was a Chromalox CSSB-100 electric boiler. Five separate CE+T America 30C3 power converters were connected in parallel converted 480 AC voltage to 400 DC voltage to operate the 100 kW Bloom Energy SOEC system. Each 30C3 power converter provides up to 30 kW of power rectification, so their combined power output is 150 kW, which is sufficient to provide 100 kW to operate the DC SOEC stacks that produce hydrogen from steam and also to power heaters, blowers, and other equipment in Bloom's SOEC system. Bloom's SOEC system converts the 400 DC fixed voltage power supply to a variable DC voltage as needed by the SOEC stacks and other DC equipment. This concept is similar to the expected arrangement at scales of 100s of megawatts (MW) in which electric power will be provided to the hydrogen plant at a fixed voltage, and the hydrogen plant will perform voltage modulation as needed.

Figure 2. Photograph of a Bloom prototype 100 kW SOEC system installed at INL.

The Bloom Energy 100 kW SOEC system has been operated at INL for over 5,000 hours. Results for the first 2,200 hours completed through September 2022 are summarized below. Hydrogen produced during the first approximately 400 hours was exhausted through a vent without dilution. Due to safety considerations, the rate of hydrogen production and exhaust was limited to less than 1 kg-H_2/hr. Several operational challenges were also encountered during this time, including steam generator control problems due to faulty vendor equipment, disruptions in 480 VAC utility power, and low inlet water pressure to the deionized skid due to a municipal pump failure. Thermal issues, such as rectifier/inverter overtemperature trips, were encountered during high-temperature periods. High winds caused an errant safety alarm associated with the exhaust system where the rapid drop in pressure falsely caused a blower failure indication. Each failure/issue was recorded, and corrective actions and resiliency controls have been added.

Figure 3 shows the hydrogen production rate as provided by Bloom, the measured DC power consumption, and the steam flow to the system for the duration of the test. Excursions in the 480 VAC utility power are especially evident in Figure 3. During one event, the excursion on one of the three-phase lines exceeded 650 VAC and dropped below 250 VAC, which resulted in damage to power converters. This problem was ultimately overcome by installing a backup power supply for the system to insulate the power converters from grid events. After approximately 500 hours of operation, a dilution fan was installed at the hydrogen outlet, and hydrogen production was increased to the maximum system rating of approximately 2.7 kg-H_2/hr. Except for brief time periods, hydrogen production was maintained near 2.7 kg-H_2/hr for the remainder of the test, as shown in Figure 3.

Of particular interest to this project is a dynamic “deload” test, which was performed after approximately 634 hours of operation, as shown in Figure 4. This test was performed to verify the ability of the system to respond to dynamic loading requests as a dispatchable power load. During this test, the system was ramped down from 100% power (106 kW) to 19.5% power (20.7 kW) in 10 minutes, as shown in Figure 4.

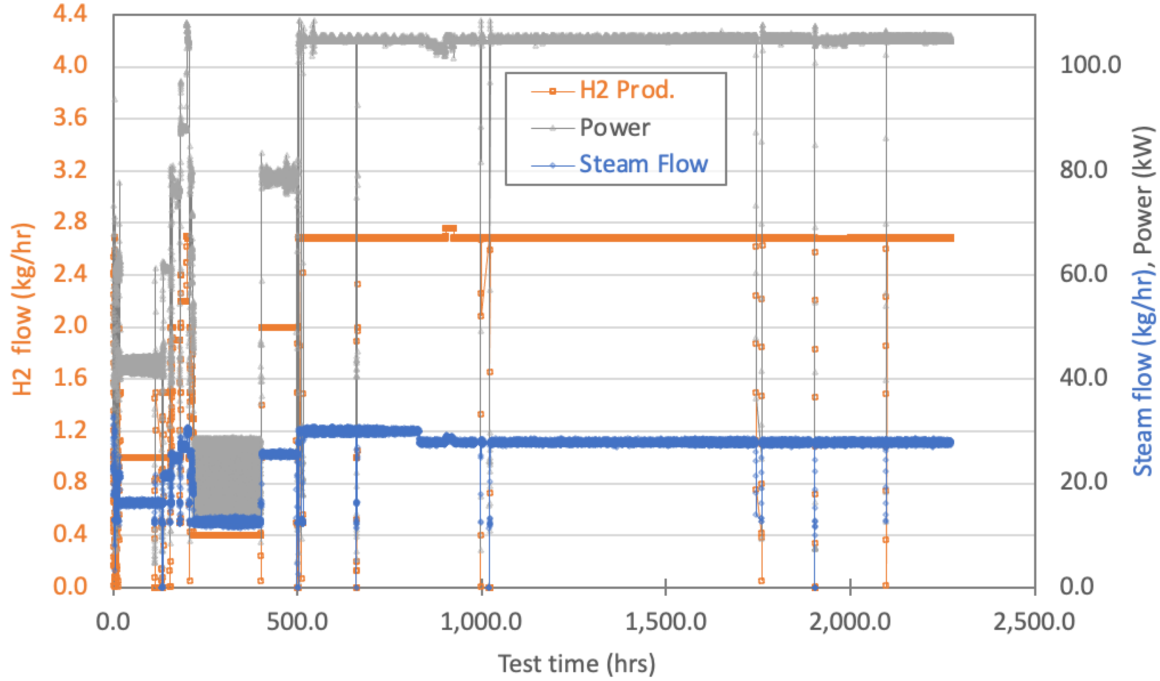

Figure 3. Operating data from the 100 kW Bloom SOEC system through September 2022.

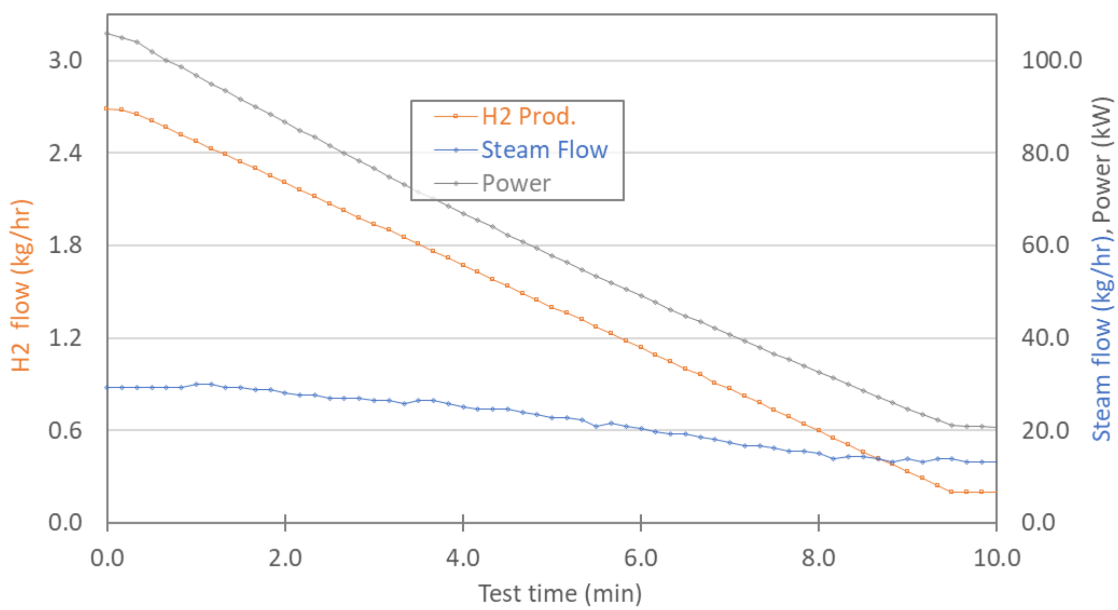

Figure 4. Results of a dynamic “Deload” test with a rapid ramp from 100 to 10% power.

3. THE DYNAMIC REDUCED-ORDER COMBINED POWER DISPATCH PRESSURIZED WATER REACTOR SIMULATOR

3.1 RO-CPD-PWR Simulator Introduction

The dynamic RO-CPD-PWR simulator was adapted from models that have been developed in previous work, including a Rancor Microworld model previously developed by INL and the University of Idaho [4] and reactor core and secondary system models previously published [5]. The details of initial simulator development were described in a milestone report submitted in July 2021 [6]. That report documents that the simulator achieved agreement with a full-scope, high-fidelity PWR simulator within +/- 15% for key parameters, including mass flow rates and fluid enthalpies in the main steam line, turbine system, and the TPD system. Although the initial simulator was validated for specific operating conditions, it had several limitations. First, it only included TPD and did not fully incorporate combined electric and TPD, so that it is referred to as a reduced-order TPD-PWR (RO-TPD-PWR) simulator. Second, the turbines in the initial RO-TPD-PWR simulator were modeled using a linear approximation that is valid for operations that are near the design operating point of the turbine system but not accurate for operations far from design conditions. Third, the initial simulator was not able to fully capture rapid transient phenomena, such as may occur during an off-normal event.

The new RO-CPD-PWR simulator was developed using Matlab/Simulink to overcome these limitations. Simulink is well-suited for modeling dynamic operations of a variety of power systems. Models of many components, including turbines, steam generators, heat exchangers, power transformers, and rectifiers, are available in open Simulink libraries to facilitate modeling [7]. An important feature of Simulink is that human operators can interact with the simulator while it is operating, so human operator-in-the-loop (HOIL) studies can be performed. Simulink is also widely used for hardware-in-the-loop (HIL) and power grid simulations, so it is a convenient software for contingency reserve simulations.

A primary requirement of the initial RO-TPD-PWR was that it be sufficiently simple to allow it to scale between lab-size equipment (~100 kW) and full-scale NPP (~1 GW) by adjusting only a few parameters in the models, such as fluid masses and heat exchanger areas. The initial RO-TPD-PWR simulator has approximately 50 parameters, compared to the more than 1,000 parameters in full-scope light water reactors simulators. Fewer parameters and a simpler simulation framework make reduced-order simulators highly useful to understand first-order relationships between parameters in the more complicated full-scope plant simulators. Developing the new RO-CPD-PWR simulator in Matlab/Simulink enables greater simulation accuracy for highly dynamic simulations and more convenient interfaces for co-simulations involving other real-time simulations, such as those for power grid, hydrogen production, and other industrial processes.

3.2 Reactor and Steam Generator Models

Figure 5 shows the schematic diagram of the overall system, which is identical to that of the initial RO-TPD-PWR simulator, while Figure 6 shows the implementation of the integrated system model in Matlab/Simulink. The conceptual design follows the equipment integration scheme analyzed using a full-scope, high-fidelity simulator in previous work [8]. The PWR consists of two separate coolant loops: a primary coolant circuit to carry heat produced in the core and a secondary coolant circuit to use the heat for electricity and heat applications. A steam generator produces steam using the heat from the primary coolant circuit. The secondary coolant circuit distributes some of the generated steam to the extraction steam line (XSL) for the tertiary heat application (hydrogen production in this case) and to the rest of the turbine trains to produce electricity. Steam to transport heat to the hydrogen plant is extracted from the main steam line upstream from the high pressure (HP) turbine, passed through a heat exchanger, and returned to the nuclear power plant condenser.

The reactor core and steam generator models follow the approach described by Poudel, Joshi, and Gokaraju [5]. In brief, the reactor core model captures the neutron dynamics within the core and the thermal hydraulics and convection heat transfer in the primary coolant system. The reactor core model assumes that the pressure in the reactor pressure vessel (RPV) is constant to simplify the simulation (perfect pressurizer control). This assumption is valid inasmuch as the primary system is not subjected to any dramatic transients during simulations, which is consistent with the key objective of the modeling to maintain the primary system at nearly steady state while flexing the secondary system. The steam generator is represented using a simplified three-lump model as advocated by Ali [9]. Additional details of the reactor and steam generator models can be found in the previous milestone report [6].

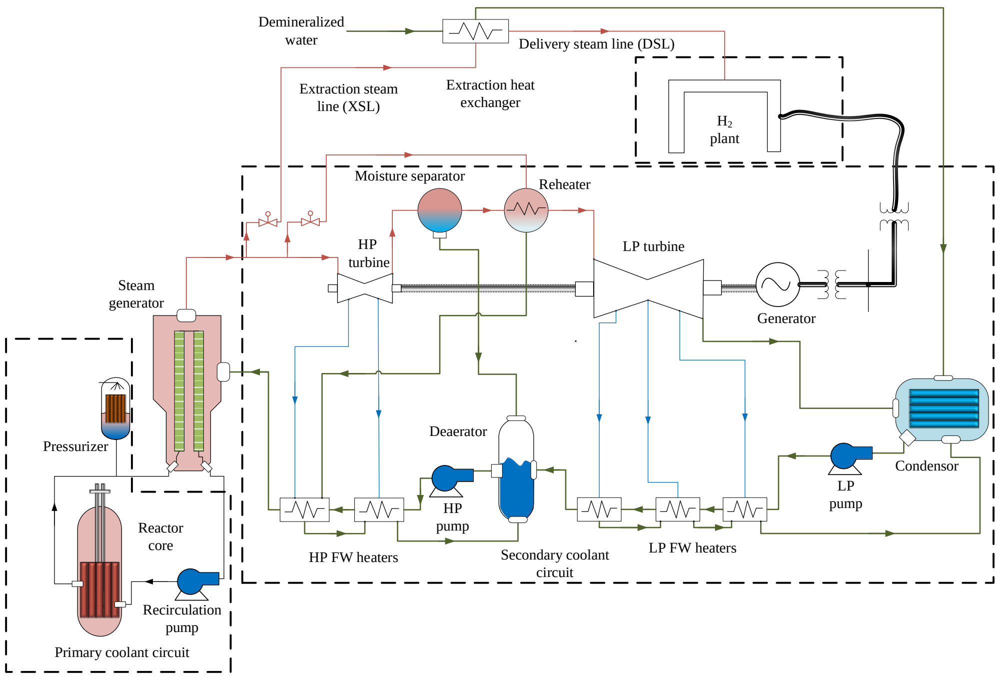

Figure 5. Diagram of the RO-CPD-PWR simulator connected to an SOEC hydrogen production plant.

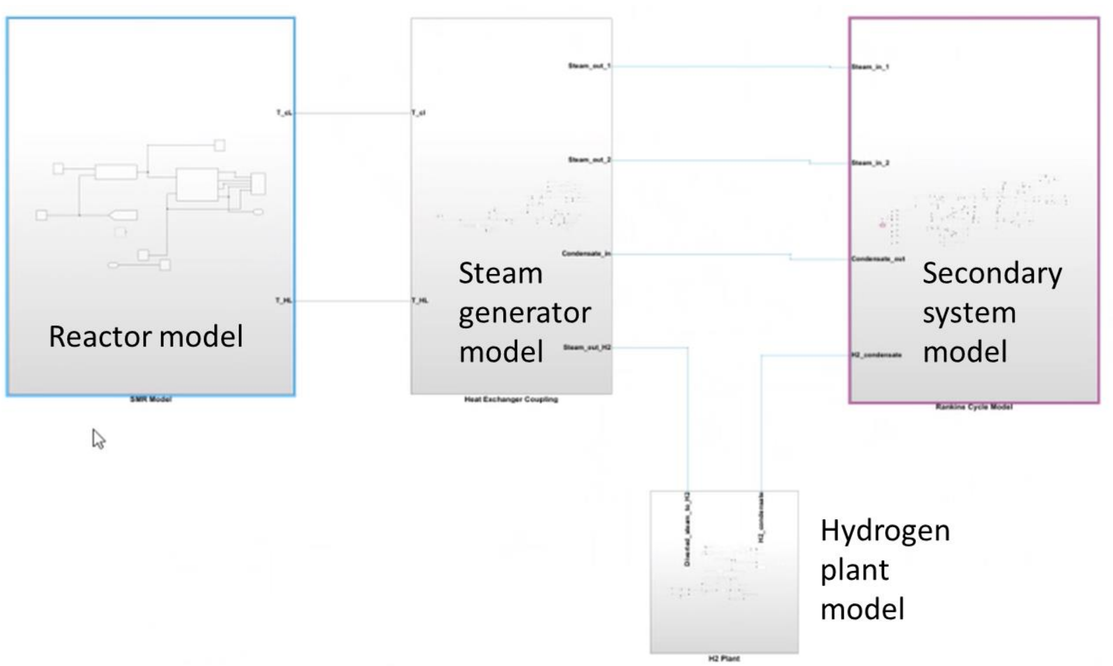

Figure 6. Integrated system in Matlab/Simulink.

3.3 Secondary System Model

The model of the secondary coolant circuit used in the initial RO-TPD-PWR simulator is based on the model developed by Ibrahim et al. [10] and is shown in Figure 7. The secondary side includes two HP turbines, three low pressure (LP) turbines, a moisture separator and reheater (MS/R), a deaerator, two HP feedwater heaters (HP-FWHs), three LP feedwater heaters (LP-FWHs), a condenser, one LP pump, and one HP pump. The steam dump line from the main steam line to the condenser, as featured in typical PWRs, is also included in the model. However, an extraction heat exchanger is included in the turbine bypass (steam dump) line, and it is relabeled as XSL. The extraction heat exchanger uses heat from the main steam line to generate demineralized steam for hydrogen production.

Figure 7 shows the nodal illustration of the reactor system to represent the thermodynamic state of different secondary coolant stages. Each circle corresponds to a component/element in the secondary circuit, which alters the thermodynamic state of the coolant. The concentric circles represent the closed-loop heat exchanger with main flow in the inner circle (tube-side) and the heating liquid in the outer circle (shell-side). The node numbers at the output of different components represent the thermodynamic stages considered in the secondary coolant circuit model.

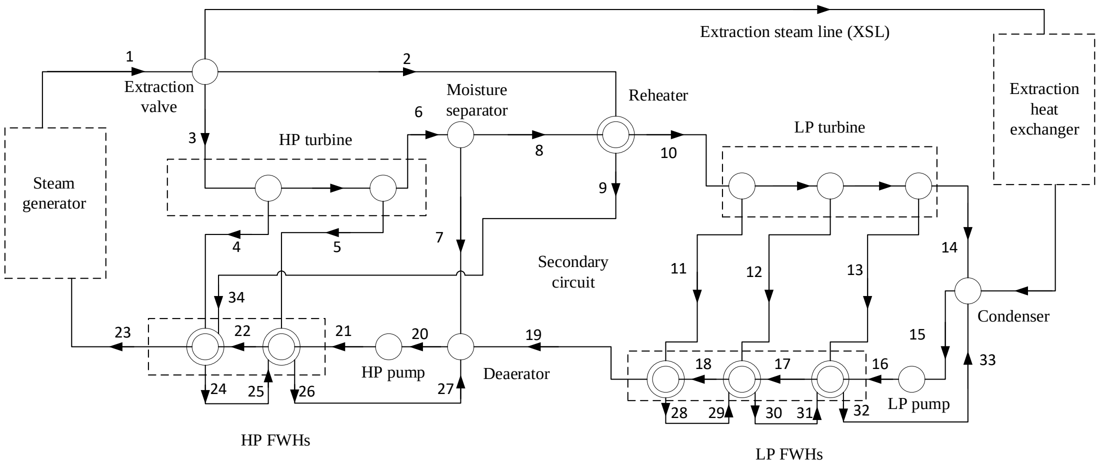

Figure 7. Nodal representation of PWR secondary coolant circuit used in the initial RO-TPD-PWR simulator.

For simplicity, the number of nodes in the FWH train is reduced in the new RO-CPD-PWR simulator, as shown in Figure 8. The only significant differences are that the FWH lines exiting the HP turbine are combined and so are the ones exiting the LP turbine. The mass flow rates, temperatures, and pressures of flow through the steam generator, turbines, MS/R, condenser and feedwater pumps remain unchanged. The primary motivating factor for the simplification of the model is that the modeling approach does not have sufficient fidelity to accurately model the temperatures and pressures of the different stages within the turbines, so it was deemed inappropriate to predict and report those values. Those temperatures and pressures, along with other key steady-state system parameters, have been calculated using PEPSE and AFT modeling as described in [3]. Calculating the values of those parameters is required in detailed models to verify that the turbines and other components operate within acceptable parameter ranges, but those calculations are not required in dynamic integrated systems models that are intended to test equipment interoperability, grid interactions, and factors associated with having human operators acting as active elements in communications and control systems.

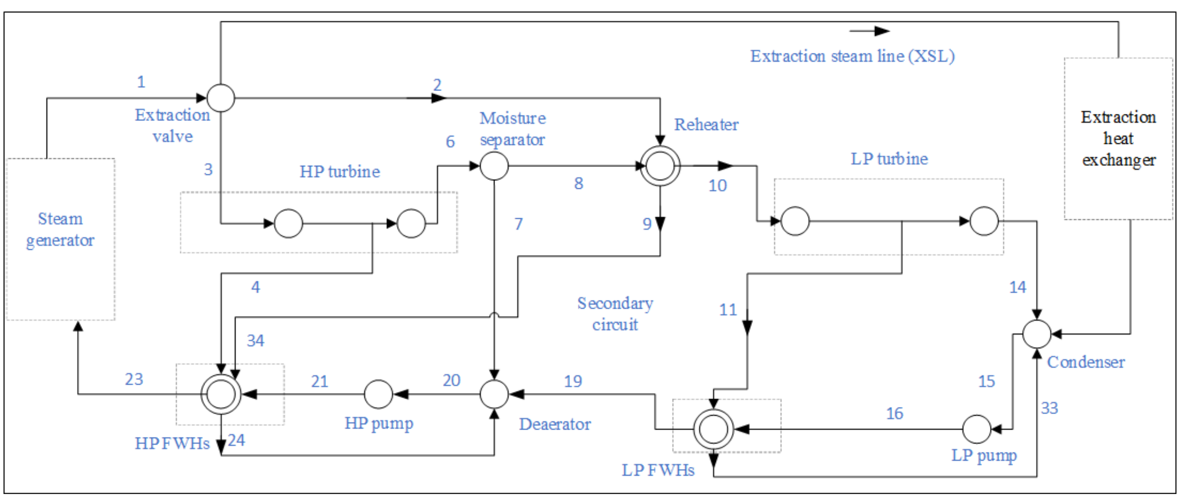

Figure 8. Nodal representation of PWR secondary coolant circuit used in the new RO-CPD-PWR simulator.

An initialization sequence is developed for the model to initiate the system at any steady-state condition, enabling it to be integrated with a power system model. This same block can be used for dynamic simulations. For initial condition, three variables are known: reactor power level, steam pressure, and the ratio of steam extracted for hydrogen production. The remainder of the variables are determined by calculations starting from those three variables. The initialization algorithm proceeds as follows:

1. Receive input parameters of reactor power (P_{th}) and percent steam extraction to the XSL (*%TPD*).
2. Determine main steam pressure.
3. Determine pressure at the inlets and outlets of as many components as possible.
4. Calculate ratios of mass flow rates in the secondary cycle, including the XSL.
5. Determine thermodynamic properties, including pressure, temperature, entropy, enthalpy, and moisture content at the inlets and outlets of all components.
6. Calculate the feedwater flow rate to the steam generator required to maintain the main steam pressure at a given value based on the given reactor power level.
7. Replace the term $U_v - c_{pi}\, T_{fi}$ in with $h_1 - h_{23}$ for the isobaric heat addition in the steam generator and back calculate the reactor primary side for the given reactor power level by zeroing the derivative terms. See [6].
8. Calculate the turbine work and heat consumed in producing demineralized steam for the hydrogen plant.
9. Calculate the hydrogen production rate based on demineralized steam flow rate and temperature.
10. Calculate turbine generator electrical power production and determine dispatch of electrical power to the hydrogen plant and the bulk power grid.

Once the system is initialized with zeroed derivative states, dynamic simulations can be started. During simulations in which the PWR simulator is transitioning from one state to another, such as 0% steam extraction to 15% steam extraction, the extraction flow controller steps the setpoint for percent steam extraction (*%TPD*) to follow a linear ramp. A proportional integral (PI) controller adjusts the feedwater flow rate to the steam generator as needed. The temperature and pressure of the main steam line are maintained, so they are constant for the given reactor power level. This control is necessary because the temperature of the feedwater entering the steam generator depends upon the percent steam extraction (*%XSL*). This dependency arises due to two factors. First, the temperature of the condensate exiting the extraction heat exchanger is different than the temperature of the condensate exiting the LP turbine. Second, heat provided to the FWHs comes from the turbine system and decreases as the percent steam extraction increases. Although the reactor power level remains constant in the simulation exercise discussed in this paper, another PI controller is integrated to operate control rods to maintain the average primary coolant temperature constant at a reference setpoint. The LP and HP feedwater pumps are also controlled to maintain their outlet pressure in a fixed ratio with main steam pressure.

4. THE SOEC HYDROGEN PLANT SIMULATOR

Detailed descriptions of the hydrogen plant models have been published in prior work [11]. The model hydrogen plant in this work closely mimics the previous design using Matlab/Simulink. Figure 9 shows a high-level process flow diagram of the SOEC system operating in electrolysis mode. Briefly, saturated steam is supplied by the hydrogen plant at 4–5 bar (g) through a heated line (#10 in Figure 9). A control valve meters the steam flowrate to achieve the desired utilization for a given current demand by the SOC stacks. To maintain a reducing atmosphere at the hydrogen electrode, product hydrogen is recycled to the hydrogen electrode inlet downstream of the steam control valve and upstream of the H_2 electrode heat recuperator, at a recycle rate allowing for an H_2 concentration of approximately 5% at the SOC stack inlet.

Heat recuperators on the steam/H_2 and air lines recover heat from the gas products to heat the reagent gases to approximately 700°C. A trim heater provides additional heat to the incoming steam/hydrogen mixture, if needed. The trim heaters are used primarily during startup to raise the temperature of the reagent gases and SOEC stacks to the operating temperature, although they may also be used when the electrochemical stacks are operated at or near the endothermic regime to provide additional heat to the stack hot box. The steam/H_2 mixture flows from the trim heater directly into the fuel electrode where the steam is electrochemically converted to H^+ and O_2^- at a steam utilization of 60–70%. Product hydrogen and unused steam flow out of the cells, back through the steam/H_2 heat recuperator, and then to the condenser, which cools the product gas to less than 40°C and reduces the water content to less than approximately 7%. Finally, the wet product hydrogen is subjected to post-processing, including drying and compression.

An air blower feeds air to the air electrode as a sweep gas to maintain a product oxygen concentration at the air electrode of less than 50%. The air line includes a heat recuperator and trim heater that operate

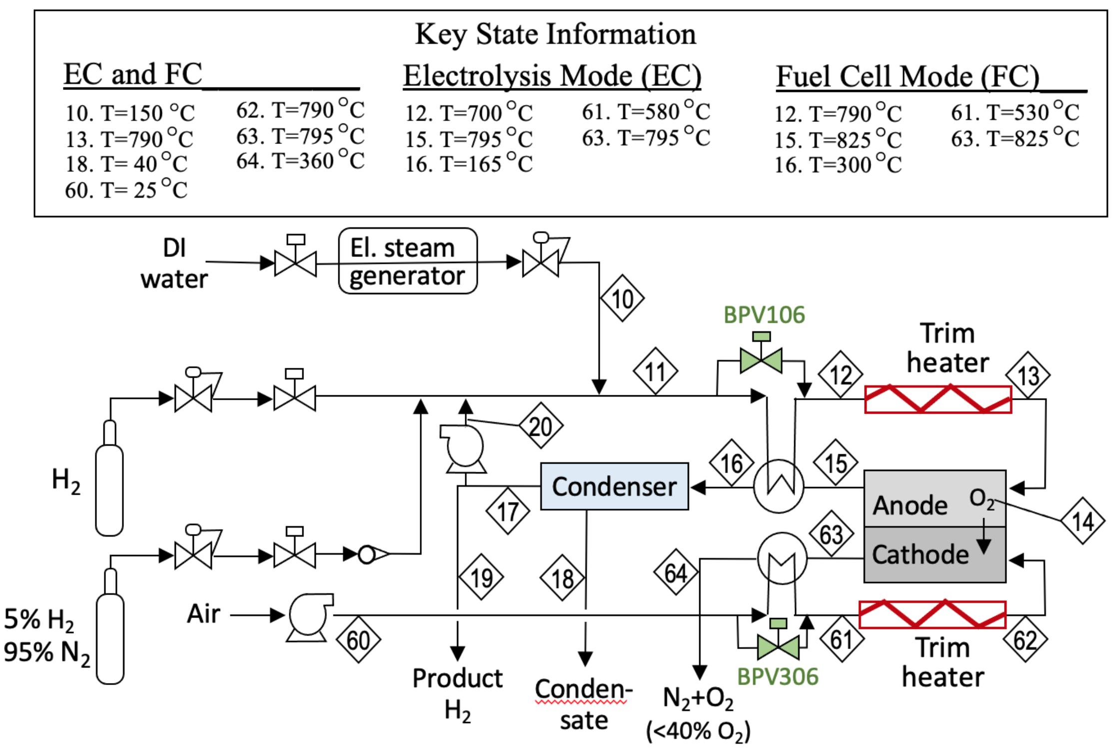

Figure 9. Process flow diagram of a simplified SOEC hydrogen plant.

with the same functions as the heat recuperator and trim heater in the steam/H_2 line. Heat from the product stream containing approximately 50% O_2 is captured in a low temperature heat recuperator that is not shown in Figure 9.

5. The Real-Time Grid Simulator

Real-time simulations are performed using Real-Time Digital Simulator (RTDS) software to validate the performance of the proposed droop-based controller. Simulation results demonstrate that PWRs coupled to large-capacity SOEC hydrogen production systems can provide contingency reserves to the power grid.

The IEEE 39-bus system, which is based on the renowned New England 10 generator power system is used to perform real-time simulations, as shown in Figure 10. This test system has been widely used to address small-signal stability in conventional power systems and fits the purposes of the current study. The system is modified by adding an SOEC hydrogen production system with a capacity of 500 MW to bus 39 (coupled to the 1,000 MW PWR generator G1). The generator G2 is considered to be a renewable energy solar power generator or other intermittent power source. The generator G1 is controlled with constant field voltage and constant mechanical torque over short time scales to emulate a nuclear power station. For these simulations, the curtailment of the SOEC system and inertia response are the only mechanisms that act to maintain grid functions. (There is no primary or secondary frequency control.)

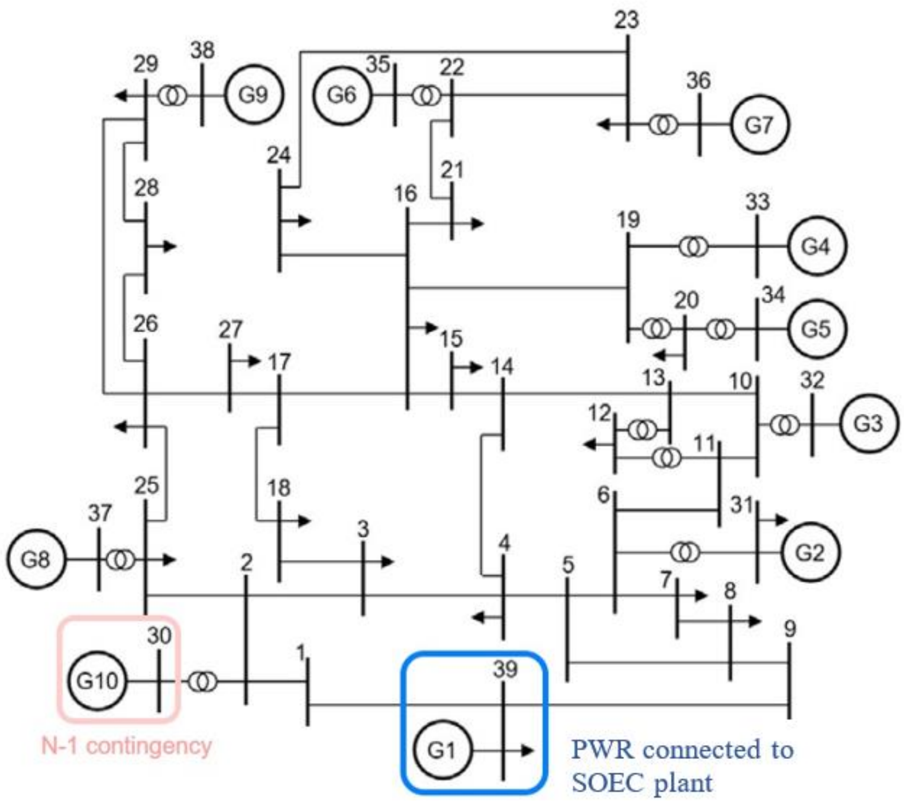

Figure 10. The IEEE 39-bus New England system.

6. SIMULTION RESULTS

The PWR, SOEC, and grid systems were integrated as described in Sections 3 and 4. The key results of the simulation are shown in Figure 11. The objective of the simulation was to show that the PWR/SOEC system (Generator G1) could curtail hydrogen production to dispatch power to the grid to replace power that is lost as Generator G2 ramps down from approximately 650 MW of generation to 240 MW of generation over a period of 10 minutes. In the simulation, Generator G2, which could represent a solar power plant, begins decreasing power generation at 2 minutes and has approximately 240 MW of power production 10 minutes later. To offset the loss of power from Generator G2, the SOEC hydrogen plant also starts ramping down shortly after Generator G2 starts decreasing power output. As the SOEC hydrogen plant ramps down, the PWR diverts power from the hydrogen plant to the grid, so the combined power output of Generators G1 and G2 to the grid is approximately constant at 1,150 MW during the simulation. In the simulation, the integrated PWR/SOEC system dispatched approximately 410 MW in 10 minutes, which represents 82% of the nominal capacity of the SOEC plant. This power dispatch capability could qualify as either spinning or non-spinning contingency reserves because the PWR turbine generator system is connected to the grid. A further key feature of the simulation is that the reactor power is maintained at nearly 100% during the simulation, which is the optimal use of the available nuclear energy.

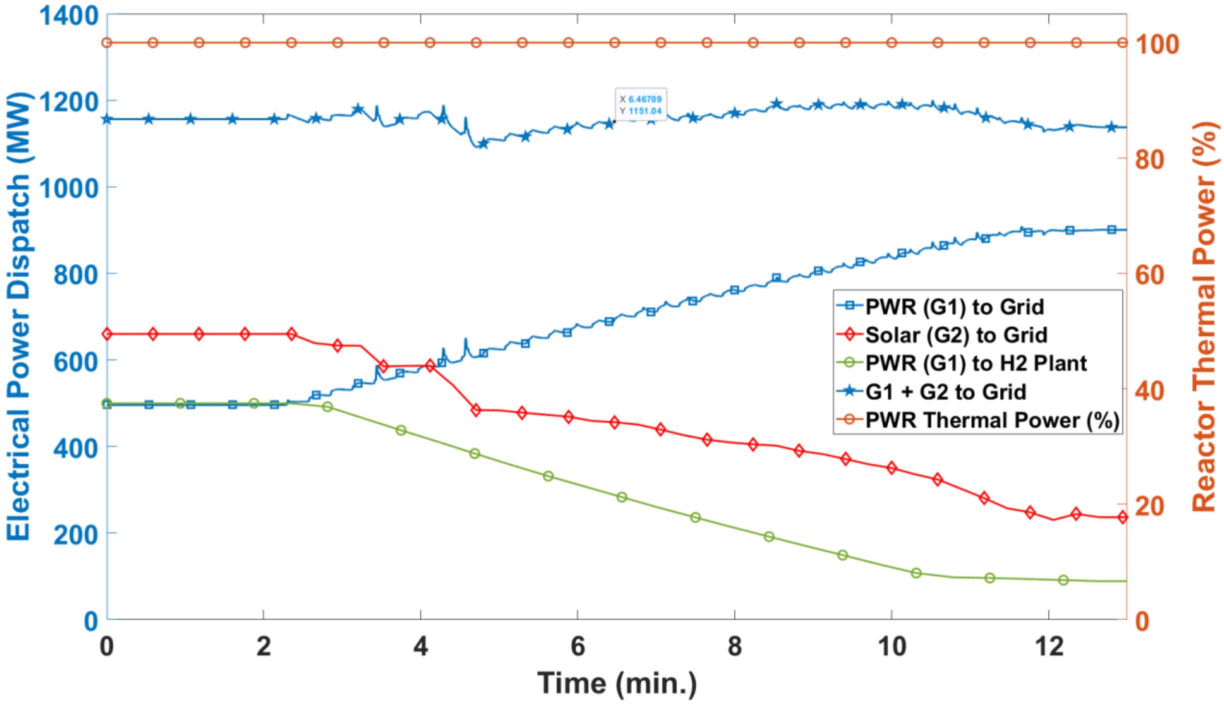

Figure 11. Results of integrated system simulation.

7. CONCLUSIONS AND RECOMMENDATIONS

This report describes simulations that were performed to verify that a nuclear power plant tightly coupled to a SOEC hydrogen production plant can qualify for participating in non-spinning and spinning contingency reserve markets by providing spinning reserve power to the bulk electric grid in less than 10 minutes. The simulations are based on dynamic data obtained from a 100 kW Bloom Energy SOEC system operated at INL. Details of the Bloom SOEC system and the dynamic test that was performed to obtain the data are described in Section 2. A 4-loop Westinghouse PWR was selected for the nuclear power plant, and a dynamic RO-CPD-PWR power plant simulator was developed in Simulink for the dynamic simulations. The details of the RO-CPD-PWR are presented in Section 3. A 500 MW SOEC plant was also modeled in Simulink, as described in Section 4. The grid model used in the simulations was developed in RSCAD and is described in Section 5. Finally, the integrated simulation results were presented in Section 6 and showed the successful coupling of the PWR, SOEC hydrogen plant, and electrical grid, including electrical and thermal power coupling between the PWR and the hydrogen plant. Integrating these simulators is a key step toward performing simultaneous HOIL and HIL using pilot-scale SOEC systems with a simulated PWR and power grid environment to verify concepts of integrated operations.

Effort is ongoing to robustly validate the RO-CPD-PWR simulator using a full-scope, high-fidelity generic PWR simulator from GSE Systems and also PEPSE models developed by Sargent & Lundy. As this work continues and the confidence in the validation of the RO-CPD-PWR simulator increases, this simulator and its components will be increasing valuable for validating models developed using other tools, such as Modelica®, and it is recommended that the RO-CPD-PWR simulator be made widely available with supporting documentation for that purpose. The limited number of parameters in the model and the relative ease of adjusting parameters and making design adjustments in Matlab/Simulink will make the RO-CPD-PWR simulator valuable for benchmarking and validating other models across a wide range of scales and design variations.

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