Comparing Thermal Library Modeling Suites for Integrated Modeling of Nuclear Power Plant and Power Grids

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***Abstract*— Decarbonization efforts in the United States has resulted in the increasing interest in flexible operation of nuclear power plants or thermal storage-based hybrid energy systems integrated with the power grid. Consequently, the need for rapid and effective modeling and simulation of such integrated systems is becoming critical. This requires modeling a approach that offers capabilities for multi-domain simulation that allows to model coupled phenomena accurately. This work focused on developing a proof of concept of such multi-domain models by designing a nominal model of a nuclear power plant balance of plant (BOP) system using the Modelica libraries. To model the thermofluidic domain, three libraries are evaluated, namely, ORNL's TRANSFORM, Modelon's ThermalPower, and Casella's ThermoPower. Next, the thermofluidic model is coupled with an electrical grid model built using the OpenIPSL. To understand the tradeoffs of each library, the response of each different model to power transients in the nuclear power plant was analyzed. Simulation results and modeling methods were compared. The BOP model in TRANSFORM was found to be stiff and may require more detailed component models, e.g. condenser and feed water heater, to model the BOP more realistically and rapidly.**

Keywords—flexible operation, balance of plant, electrical grid, Modelica, ThermalPower, TRANSFORM, ThermoPower, OpenIPSL.

I. Introduction

Ongoing decarbonization efforts are driving the integration of renewable energy sources into power systems, creating a challenging environment for the nuclear power plant to compete in producing low-cost electricity. In the United States, nuclear power plants (NPPs) are designed for baseload operation [1] and are operated at fixed speed. However, NPPs could in theory capable of "flexible operation," meaning the ability to adjust their output power and regulate frequency. However, this paradigm requires frequent power output variations that could cause significant stresses on materials that in turn may lead to early degradation. Therefore, the feasibility of operating the existing NPPs in load-following operation mode needs to be assessed to help with renewable energy integration. Major challenges to realize flexible operation of NPPs include the ability to rapidly design and analyze the feasibility of the various technologies, including component monitoring and degradation detection, testing, and optimization of operational strategies, in which modeling and simulation can be of substantial help.

Flexible operation of existing NPPs can be achieved either by core power ramping [2] or by the introduction of integrated energy systems (IES) [3], i.e., co-locating different energy sources and storage with the NPP. NPPS are traditionally operated to provide base load at constant speed, and thus, the existing models are limited to the reactor side only. Meanwhile, the power grid and balance of plant (BOP) models are simplified to a few transfer functions that only represent the steam turbine as fixed boundary conditions [4], [5]. To address this gap, efforts to develop models and tools that can be leveraged to rapidly design and analyze NPPs. The transient simulation framework of reconfigurable models (TRANSFORM) is an open-source, Modelica-based library developed at Oak Ridge National Laboratory to develop models conventional and advanced nuclear reactors, for example, it has been used to develop models for advanced and light water reactors [6]. Meanwhile, Modelon's Thermal Power library provides a comprehensive catalog for the modeling of thermal power plants, including small modular nuclear reactors and thermal power plants optimization [7].

Typically, NPPs consist of two main parts: Nuclear island and conventional island, also called the balance of plant (BOP). Nuclear island mainly contains nuclear reactors and systems that define a confined boundary for radioactivity and prevent accident or abnormal conditions. BOP houses the components that are required for converting thermal energy into electrical energy. This island mainly contains a turbine, generator, condenser, moisture separator, and other instrumentation and control systems. Steam is generated in the nuclear island, which is then directed to the turbine coupled with a generator that produces electricity and transfers it to the grid. The exhausted steam from the turbine is fed back to the steam generator after passing through the condenser for the next cycle.

In this paper, we targeted a 150MWth reactor's BOP model, shown in Fig. 1, designed by NuScale [8]. We examined ORNL's TRANSFORM, Modelon's ThermalPower and

Casellas's ThermoPower [9], [10] libraries to build and compare the catalog of existing components and equations used to model complex components such as multi-stage turbine, deaerator, and compressors. Simple power maneuvers transients were performed after connecting the different BOP models to an electrical grid model developed using the Modelica-based OpenIPSL library [11]. The models were built and simulated using the Dynamic Modelling Laboratory (DYMOLA) [12] software.

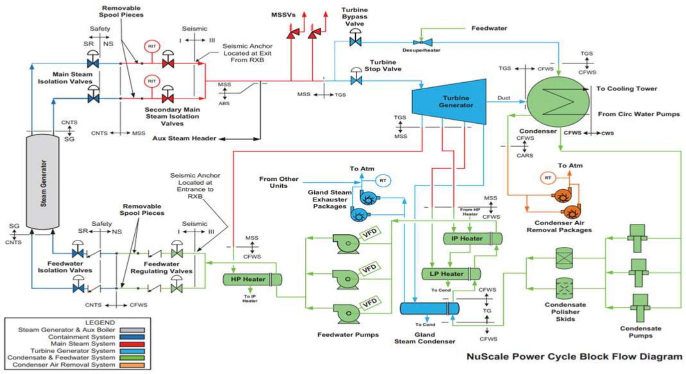


Fig. 1. NuScale BOP model diagram

This paper is organized as follows: Section II describes the method and models. Section III provides the results and the main findings of the study. Section IV concludes the paper and discusses possible future directions.

II. Method and Models

The three library suites, Modelon's ThermalPower, ORNL's TRANSFORM, and Casella's ThermoPower, were used to develop the target BOP model shown in Fig. 1. The first critical part of the BOP system is the steam generator (SG), which is responsible for steam production. The second major component is the condenser, which provides the boundaries for the BOP system. Because the primary focus of this study was to compare and evaluate the libraries from the point of modeling NPP flexible operation (i.e., using IES), the reactor was modeled using an equivalent transfer function. A ramp function was used increase the setpoint to emulate power maneuver transients. The components-oriented modeling details are provided in the following sections.

A. *ThermalPower by Modelon*

Modelon's ThermalPower library is one of the most comprehensive modeling, simulation, and optimization framework available for thermal power plant operation, including in-depth details of components for conventional and advanced reactors [7]. The templates provided in the library enable users to characterize, simulate and optimize large-scale thermofluidic systems quickly. In the sequel, the different component models developed using this library are described.

1) *Steam generator*

Fig. 2 (Left) shows the SG component developed using Modelon's ThermalPower and designed to provide saturated/superheated steam to the turbine component. Fig. 2 (Right) shows the sub- components of the SG, including a drum, riser, and recirculation pump. These components are designed to develop boiler, heat exchanger, SG, and other heat exchanger components. A constant heat source is added to the riser while steam is generated in the drum. The recirculation pump is added to provide the means of re-circulating the drum inventory, which is typically done by gravity in the target model SG.

Fig. 2 (Right) also shows the two PIDs. The first is the pressure controller that regulates the control valve to provide the steam supply pertinent to the pressure set-point. The second PID is the Drum's level controller. It was added to control the feedwater flow rate to avoid the water-solid condition in the drum.

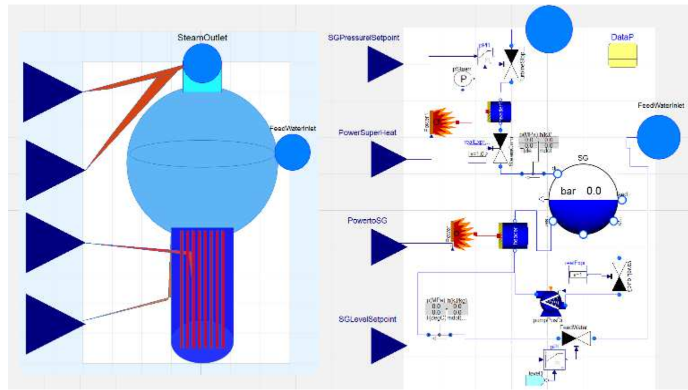


Fig. 2. Steam generator model developed in using the ThermalPower library

2) *Balance of plant components*

In this component, one high-pressure (HP) one-stage turbine component and two low-pressure turbines (LP1 and LP2), each with three stages of components, were leveraged from the Modelon's ThermalPower library to build the complete turbine model, as shown in Fig. 3. Fig. 3 (a) and Fig. 3 (b) show the icon and diagram layers, respectively. The steam extractions and stream flows were adjusted by introducing the valves with variable pressure drops.

This model contains two pumps, one for the condenser and the feedwater pump. The condenser's pump drives the flow from the condenser to the deaerator through two low-pressure heaters. The function of the deaerator is to remove the dissolved oxygen in the ratio of the steam on the surface of the liquid using Dalton's partial pressure laws. This steam is provided from the first HP turbine steam extraction as it has almost no dissolved oxygen. The second pump drives the flow through the feedwater heater to the SG component. The data for the modeled pumps was obtained from the target plant shown in Fig. 1.

The condenser component is chosen from the ThermalPower library to model the steam-to-water heat exchangers. These heaters extract heat from the exhausted steam to reheat the feedwater to increase the plant's efficiency. Hence, the part of the exhausted vapor condenses. The condenser component was found to be the best option to model regenerative heat exchangers/feedwater re-heaters.

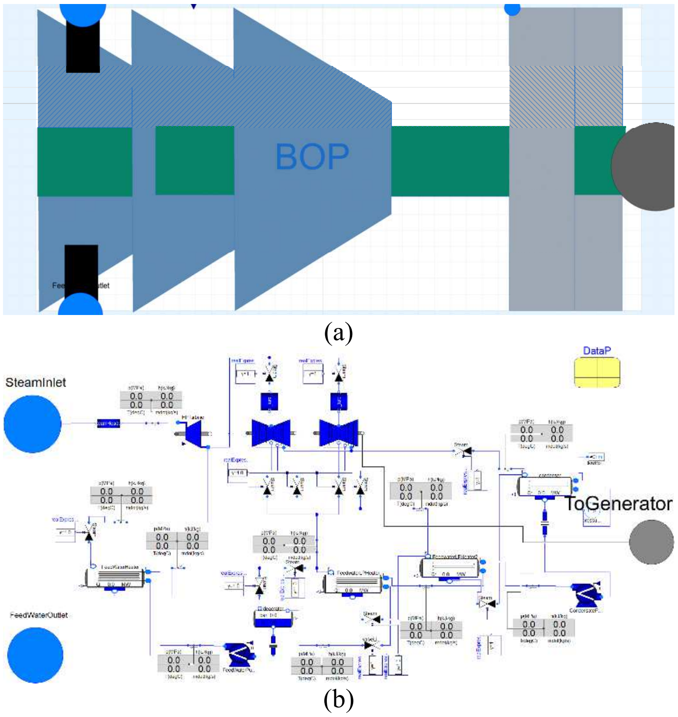


Fig. 3. Balance of Plant (BOP) Component Developed using ThermalPower

3) Final plant model as built-in ThermalPower

The models discussed above are combined and then interfaced to the electrical grid model developed using the OpenIPSL library via an Modelica interface [13]. This interface connects the mechanical flange of the BOP's shaft to the electrical generator, as shown in Fig. 4

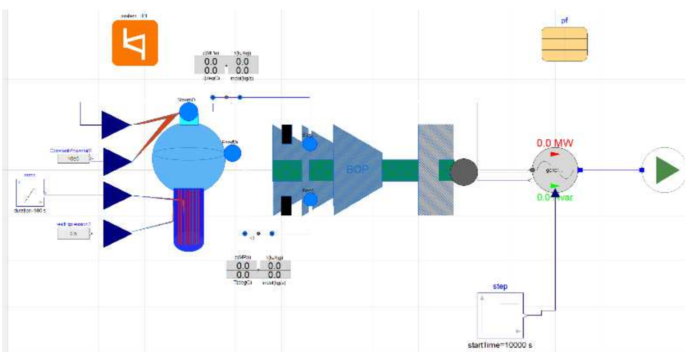


Fig. 4. Thermofluidic model coupled with a grid model (green arrow contains the power grid)

B. TRANSFORM by ORNL

TRANSFORM was also leveraged to build the target plant model (recall Fig. 1). This library can model thermofluidic, hydraulic, electrical, and neutronics models. The fluid library contains pre-build components that were required for developing the BOP, including steam turbines, heat exchangers, pumps, and condensers.

1) Four stage turbine

The template for a BOP with four stage steam turbine was developed as the HP and LP turbines. Each of these is shown in Fig. 5. First, the use small volumes and hydraulic resistances must be considered to couple the BOP components, as just connecting them would results in non-linear equations, which Dymola must solve and can result in unnecessarily long simulation runs. When using small volumes and hydraulic resistances to couple them, non-linearities will be largely elminated. When modeling, volumes were made very small (V=0.001m^3), and the resistances were set to unity. However, due to imperfect initial conditions (IC), pressure, temperature, and specific enthalpy change drastically and can lead to Dymola's solvers to fail. These volumes also provide a workaround to this issue, as increasing the volume smooths the change in pressure such that it happens much more gradually.

2) Balance of plant components

Fig. 5-1 to Fig. 5-5 shows the multiple components single-stage turbine, simple feedwater heater, pump, condenser, and SG that were built from the primary components available in the TRANSFORM library. In addition, there are several PID controllers in the SG model (see no. 5 in Fig. 5). One of these PIDs controls the steam bypass valve, which regulates the steam generator pressure by opening to the condenser vacuum. SG fluid level is controlled by the second PID, which governs the mass flow rate into the SG from an arbitrary feedwater source. Pumping (see no. 3 in Fig. 5) is performed using pumps that obey pump head vs. volumetric flow characteristic curves, such that pump head and flow rate are inversely proportional.

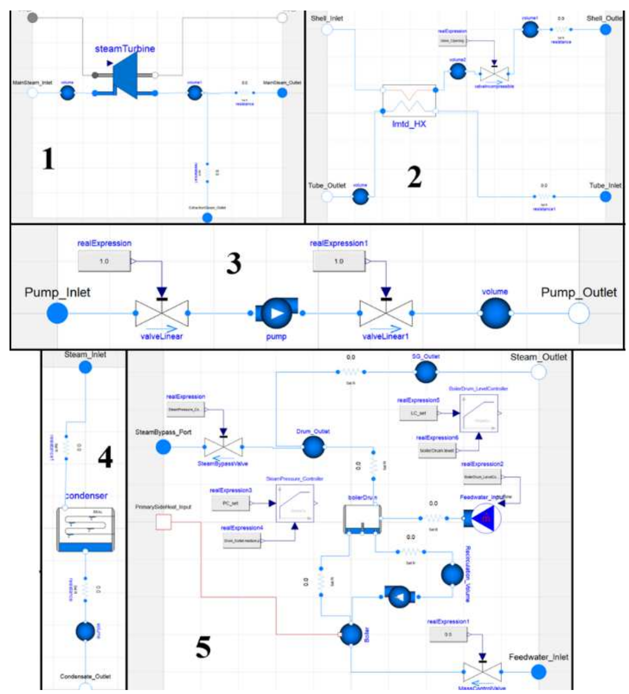


Fig. 5. BOP TRANSFORM Component Models: 1-Tubine_SingleStage, 2-Simple_feedwaterHeater. 3-CharacteristicPump. 4-Simple condenser, 5-SG_levelAnd PressureControl

These newly built components were then parameterized into a configuration modeling a BOP for a 150 MWth NPP, as shown in Fig. 1. The BOP model is shown in Fig. 5, which includes a few small volumes for mixing turbine extraction steam with feedwater heater (FWH) steam output and a turbine governor valve. An input connector was added to take signals representing the nuclear island heat transfer, and a flange connector was used to output the turbine shaft to a generator model. This final arrangement is given in Fig. 6 (a), which can be improved by encompassing the multiple essential components into function-based components, as shown in Fig. 6 (b). The ramp function was used to simulate power transients or set constant power to simulate steady-state operation.

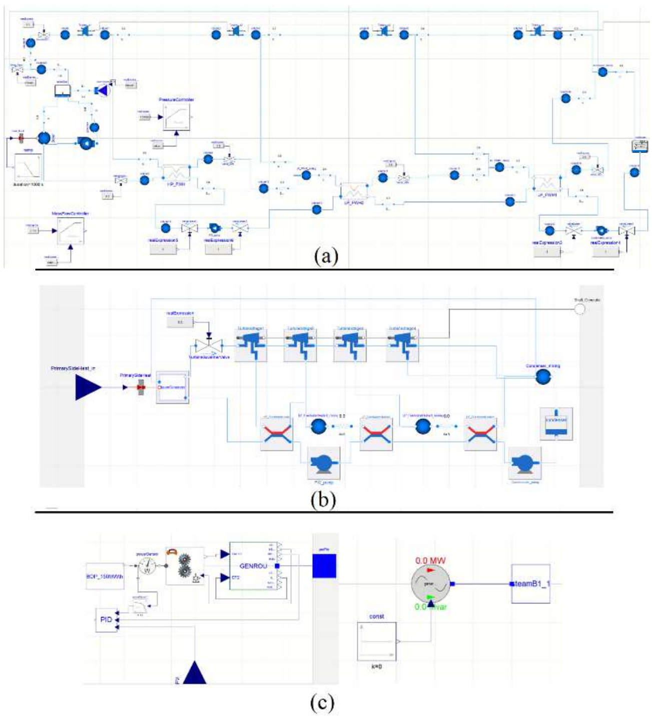


Fig. 6. BOP model (a) 150 MWth BOP model only (b) Improved visual for BOP (c) BOP coupled with OpenIPSL electrical grid model

C. Casella's ThermoPower Library

The ThermoPower library is an open-source Modelica library for the dynamic modeling of thermal power plants and energy conversion systems developed at Politecnico di Milano since 2002. It provides essential components for system-level modeling for the study of control systems in traditional and innovative power plants and energy conversion systems [10].

1) Balance of plant components

A model with a four-stage steam turbine and three feed water heat exchangers are developed, as shown in Fig. 7 (a). It is assumed that the BOP model is connected to a small modular reactor generating 150 MWth of thermal energy. To simplify a model, the header component, which is heated up by fixedHeatFlow component, was used to model the SG. The steam from the steam generator is fed to a steam turbine. It is worth noting that there are four stages in the turbine, and a part of the steam flow at each stage is extracted in order to heat up the condensed water. Valves for steam flow (i.e., ValveVap in the ThermoPower lib.) are used to avoid flow reversal. Exhaust steam from the first feed water heat exchanger flows into a `Mixer` component that mixes it with the steam from the second extraction. Feed water heat exchangers are represented by using 1-dimensional fluid flow model pipes (i.e., Flow1DFV2ph in ThermoPower library) and cylindrical metal tube models. Steam after the fourth stage of the turbine is the exhausted steam, and it goes to the condenser. Fig. 7 (b) and Fig. 7 (c) show the ThermoPower BOP model coupled with the OpenIPSL-based electrical generator and grid model.

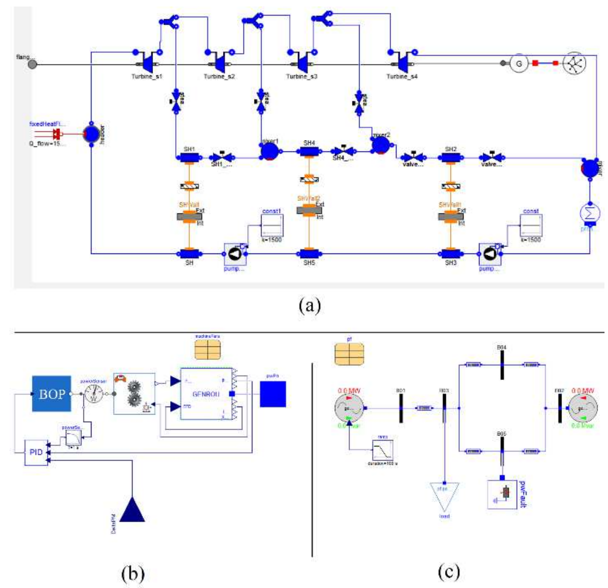


Fig. 7. ThermoPower BOP model (a) 150MWth BOP model only (b) BOP model coupled with OpenIPSL electrical Generator (c) BOP model coupled with generator and generator coupled with grid.

III. Results and Discussion

The models shown in Fig. 4, Fig. 6 and Fig. 7 were initially compiled and initialized with the boundary conditions as given in Table I. Additional effort was made to initialize all the three models with approximately the same steady-state values. Due to sparsely available data and modeling differences between the libraries, the values were set at the positions shown in column 1 of the Table I. Since this study aimed to evaluate libraries suites for the design and analysis of NPP flexible operation using IES, the relevant transients were mimicked by varying the input power to the BOP.

Table I. Steady-State initial condition for all three models

Parameters	***Thermal Power***	***Thermo Power***	***TRANSFORM***
SG Outlet Pressure (MPa)	3.3	3.09	3.5
SG Outlet Temperature (C)	284.5	235.49	242.56
Steam flowrate at SG Outlet (Kg/s)	64.3	66.82	70
SG Inlet Temperature (C)	140.0	120	153
Steam flowrate at SG Outlet (Kg/s)	64.3	66.82	70
Condenser pressure (MPa)	0.0077	0.0081	0.0081

Two transients were analyzed, with the transient initiating conditions are given in Table II. The simulation was executed $t = 0$ to 5000 s so that the models would reach a steady-state, and then a transient was introduced at $t = 5000$ s. The electrical power from the generator was observed for each case, as given in Fig. 8 and Fig. 9. Apart from the difference in the steady state values due to modeling differences in each libraries, the variables reached the steady-state values given in Table I. It should be noticed that the SG level controller was modeled in both models that use ThermalPower and TRANSFORM to control the feedwater flow. This allows the system to adjust the other variables following the power variation. In the model that uses ThermoPower, a simple header with a `HeatFlow` (a component in ThermoPower) was considered instead of a complete SG model. Although less detailed, the model was smooth and could converge the steady state values without needing a level controller. However, introducing this simplified model required additional work to determine and specify the intitial conditions (ICs) by executing the runs and updating the ICs repeatedly. As shown in Fig. 8 and Fig. 9, the difference in the steady-state electrical power was due to the difference in the steam extraction at each turbine stage. It was challenging to adjust the loss coefficients (resistances) without actual plant data being available. In Case 1, a transient was introduced by increasing the input power to the SG by 2 MWth, while in Case 2 the input power was reduced by 0.5 MWth over 1000 s. The outputs (electrical power from a generator) for Cases 1 & 2 are shown in Fig. 8 and Fig. 9, respectively.

It was observed that the TRANSFORM model does not show the expected behavior under the transient conditions, while the output power in the other two models showed the expected dynamic performance. This result can be used to highlight what is probably the critical difference between TRANSFORM and the other two libraries. In terms of the models, the TRANSFORM model is considerably stiffer and less robust than the others. This means that changes to either inputs or initial conditions cause the model to barely change or change so drastically that the simulation will fail. The maximum power ramp that could be applied was approximately 2 MWth and a decrease of 0.5MWth with the TRANSFORM model. Meanwhile, with the other two models power ramping up and down of about 20MWth could be successfully simulated. This difference is due to one important reason: TRANSFORM, unlike the other two libraries, is not explicitly designed with these high-fidelity two-phase fluid medium system applications in mind. Meanwhile, ThermoPower and ThemalPower are tailored to applications related to thermal and power systems, which will cover multi-phase flow systems.

Conversely, TRANSFORM was not developed for these specific types of applications. It is a significantly newer library and was partly designed to demonstrate how Modelica could serve a growing role in the nuclear industry. Because of this, ORNL's TRANSFORM has models of neutron kinetics and reactor cores, which is not available in either of the other two libraries. One could envision that when using TRANSFORM would typically be to develop a lower fidelity BOP model connected to a detailed nuclear island, with the BOP included more for completeness than to actually gather high fidelity results. To provided additional insight to these observations, an equation-based comparison of the key modeled components and the way of solving them is discussed in the sequel.

Table II: Transient initiating conditions

Transient Cases	Initiating Conditions
Case 1: Power ramping up by 2MWth	Simulation time = 5000s Duration =100s
Case 2: Lowering power by 0.5MWth	Simulation time = 5000s Duration = 1000s

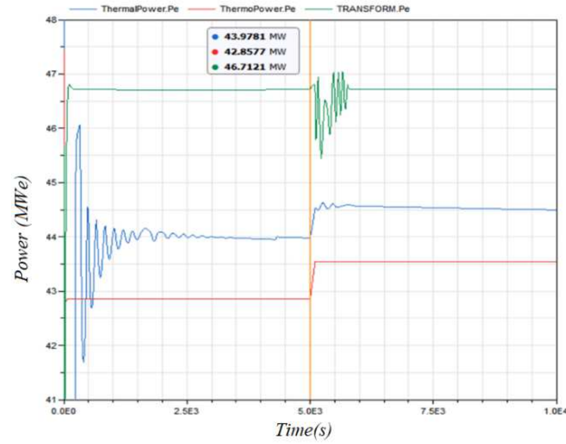


Fig. 8. Electrical output power comparison for case 1

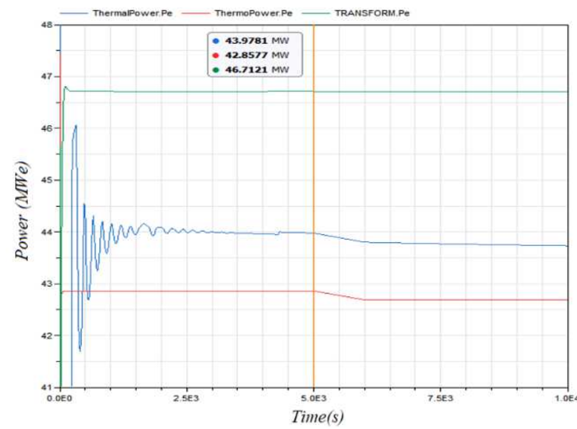


Fig. 9. Electrical output power comparison for case 2

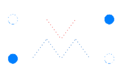
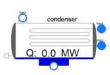
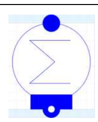
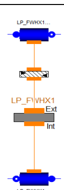
A. Choice of Numerical Solvers: DASSL vs. Esdirk45a

Dymola provides several single and variable step-size integration algorithms [14]. Users can select one based on the model stiffness and size. DASSL and LSODAR are the multiple-order and adaptive time-step-based integration algorithms available in Dymola. These algorithms vary the step size based on the output's ability to converge and are relatively faster than fixed step Runge-Kutta-based methods (Radau-IIa, Esdirk34a, Esdirk45a, etc.). As discussed earlier, the TRANSFORM model failed to compile using the DASSL, as the model was stiff, contained many events, and required stricter tolerance. On evaluating the model closely, it was found that the components, such as the feedwater heater and condenser components, do not depict the complete representation of the heat transfer to the feedwater with condensation as modeled in ThermalPower and ThermoPower library suites. There may be some differences in the Turbine and SG components, but their effect is insignificant as their simple model compiles easily using the DASSL algorithm.

B. Condenser and Heat-Exchanger component models

Table III provides the component models, icon layer, and their contribution to model stiffness/non-stiffness. In each BOP model, the available model for condensers and heat-exchanger were tested before selecting the most suitable one. In BOP, it should be kept in mind that the steam from each turbine extraction condensed in each feedwater heater while transferring heat to the feed water. To provide the exact simulation of this behavior, we required a specific model of a heat exchanger (e.g., similar to the one in Modelon's ThermalPower library) or a similar type of heat exchanger that provides the shell and tube side heat exchange with condensation. This was found to be the limitation of both TRANSFORM and ThermoPower libraries. Similarly, as shown in Table III, the condenser model available in TRANSFORM and ThermoPower can be modeled in depth with tube and shell sides so that boundary conditions can be specified in more detailed.

Table III: Condenser and Heat-Exchanger components comparison

Libraries	ICON Layer	Reasons
TRANSFORM (Ideal condenser)		The only condenser model in TRANSFORM. Does not provide modeling flexibility on the tube side.
HeatExchanger (`Simple_HX_A`)		Heat exchanger models were simple tube and shell side. This component is not well for a two-phase steam heat exchanger.
ThermalPower (Condenser also used as heat exchanger)		The four port condenser can be used as a heat exchanger. This heat-exchanger model was found to be the best fit for feedwater reheaters.
ThermoPower (Ideal condenser with prescribed pressure)		This model is also an ideal condenser that does not provide modeling flexibility on the tube side.
ThermoPower (Simple heat exchanger model was built)		This feedwater reheater model was developed from scratch as all the available models didn't serve the purpose of vapor to a fluid heat exchanger.

IV. Conclusion

In this paper, three Modelica libraries were used to model the BOP of a nuclear power plant. The ultimate goal was to evaluate the current available Modelica-based libraries for the rapid development of advanced energy systems that can be used to perform integrated simulation of NPPs and power grids.

The BOP model plays a crucial role in achieving NPP flexibility using IES. Three Modelica library suites: ORNL's TRANSFORM, Modelon's ThermalPower, and Casella's ThermoPower, were compared as they can be used to achieve the ultimate goal of integrated modeling and simulation of nuclear power plants and power grid models.

While TRANSFORM is designed explicitly for advanced reactor modeling and is available as open-source, the library would require additional developments to provide the same level of modeling fidelity and flexibility offered by ThermalPower and ThermoPower when it comes to the requirements to model the BOP. Another alternative would be to add all the reactor kinetics and nuclear reactors models to ThermoPower or Modelon's Thermal Power library. The latter part will require more effort and time, but it would provide a more user-friendly approach for integrated modeling. Ultimately, the simulation results show that there is a clear potential for integrated power grid and NPP modeling and simulation using Modelica, which will help in developing NPP flexible operation schemes with IES, such as those using co-located thermal storage. Future work includes the development of detailed model of the required heat exchanger with condensation needed to make TRANSFORM more flexible and other potential developments.

Acknowledgment

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