Multi-domain Modeling of a Steam Power Plant with Power Grid

Kyle Warns
Mechanical, Aerospace, and Nuclear Engineering Department
Rennselaer Polytechnic Institute
Troy, NY 12180
warnsk@rpi.edu

Asad Ullah Amin Shah
Mechanical, Aerospace, and Nuclear Engineering Department
Rennselaer Polytechnic Institute
Troy, NY 12180
shaha11@rpi.edu

Miguel Aguilera
Electrical, Computer, and System Engineering Department
Rennselaer Polytechnic Institute
Troy, NY 12180
maguilo@gmail.com

Junyung Kim
Mechanical, Aerospace, and Nuclear Engineering Department
Rennselaer Polytechnic Institute
Troy, NY 12180
kimj42@rpi.edu

Luigi Vanfretti
Electrical, Computer, and System Engineering Department
Rennselaer Polytechnic Institute
Troy, NY 12180
vanfrl@rpi.edu

Hyun Gook Kang
Mechanical, Aerospace, and Nuclear Engineering Department
Rennselaer Polytechnic Institute
Troy, NY 12180
kangh6@rpi.edu

***Abstract*— This work documents the development and testing of a multi-domain Rankine cycle-based balance of plant and power grid model developed using the Modelica language. Steady-state and transient behavior of the coupled systems is analyzed. Results indicate that simplified models of either steam turbines or generators used in traditional single-domain simulations do not sufficiently capture all dominant system dynamics. Initiation of power transients in the power plant clearly impacted grid operating current, and faults in the power grid were shown to cause variations in torque experienced by the shaft of the steam turbine. Therefore, multi-domain models such as this are necessary for analysis in the power generation industries in order to capture the interconnected behavior of complex energy systems.**

Keywords—steam turbine modeling, Modelica, multi-domain modeling, OpenIPSL, Thermal Power, nuclear power plant

I. Introduction

Power generation is progressively shifting from the baseload generation and stacking paradigm to the utilization of a flexible mix of sources [1]. Alterations to classical generation include the integration of renewable energy sources such as wind and solar generation, the addition of flexible resources to existing power stations, and the development of load-following operational schemes [2]. These changes will affect the operation and reliability of both existing power plants and of the electrical power grid. Therefore, the need for detailed modeling of both existing and novel power generation systems and of their interactions within the overall grid ecosystem is crucial.

One of the baseload power systems being considered for this flexible overhaul is the nuclear power plant (NPP). Integration with hydrogen production facilities [3] and thermal energy storage and dispatch systems [4] have been investigated for improving NPP flexibility. A scheme for integrated energy system control system design was proposed in [5]. From the power grid community, [6] has analyzed the potential for resonance between high voltage DC (HVDC) lines and a nuclear generator. Resonances such as this will become more prominent features for concern and study as the electrical grid and operation of its constituents becomes more tightly coupled.

While these studies represent a positive move in the correct direction, they miss one important feature, namely, the interaction and feedback between electrical grid and power plant dynamics. Rather than capture these dynamics, models simplify the domains which are not their focus. Reference [5] uses inertias and boundary conditions to represent a generator and power grid, while generators or turbines are modeled in [6] using multi-mass models rather than detailed thermal-hydraulics.

Studies which investigate coupled system dynamics have been performed for gas turbines [7], but not for steam turbines or balance of plant (BOP) energy conversion systems of the type used by NPPs. Results of [7] demonstrated that traditional turbine-governor modeling of gas turbines failed to represent states which prominently influenced coupled system dynamics. This indicates that a shift in modeling focus from single-domain to multi-domain coupled models of power plants and an electrical grid is therefore necessary to capture the full dynamics of system interaction.

There is clearly a need in the research community for modeling and simulation better suited to tightly coupled steam power systems. This work aims to address this need by developing a preliminary multi-domain model of NPP BOP and electrical grid. Individual models of the NPP steam generator (SG) and BOP, generator, and electrical grid were developed and then coupled to form a cohesive multi-domain model. Analysis of the model under transients and an investigation into the system dynamics was then performed for this model. The reminder of this paper is therefore organized as follows: Section 2 describes the single domain model development and testing process, Section 3 demonstrates the integration of each model into the multi-domain system, Section 4 presents the analysis and discusses the results, and Section 5 provides conclusions and directions for future work. To reiterate, this work acts as the first step towards accurate and detailed multi-domain modeling of steam power plants in a tightly coupled and modernized power grid.

II. SINGLE DOMAIN MODELS

Modeling was performed using Modelica due to the language's specialization in system-level multi-domain modeling. Development and simulation were done in the Dymola software, a Modelica-compliant Integrated Development Environment (IDE), version 2022x. Thanks to the graphical-object-oriented features of Modelica, modeling large systems often consists of using pre-built component models from existing libraries. In this work, two primary libraries were used: OpenIPSL [8] was used for the electrical grid and generator modeling, and ThermalPower [9] version 1.23 for the steam generator (SG) and BOP models. To emphasize the utility of replaceable models and libraries, in this work no new component-level models needed to be developed, rather, pre-existing components were assembled to build the entire multi-domain model. The following two subsections will focus on modeling thermal-hydraulic and electrical power domain.

A. Thermal-hydraulic Modeling

Thermal-hydraulic models of the BOP and SG were based on, but did not follow exactly, the BOP for a proposed small modular nuclear reactor [10]. While this means that the parameterization of the models was to a lower power rating than typical in commercial NPPs, the model structure itself was not affected. Figure 1 shows the model structure of the steam generator. Primary heating, superheating, and recirculation were all modeled phenomena. Two PI controllers were utilized to control steam pressure and SG level. Real inputs to the model are subsequently the two control setpoints and powers for primary heating and superheating.

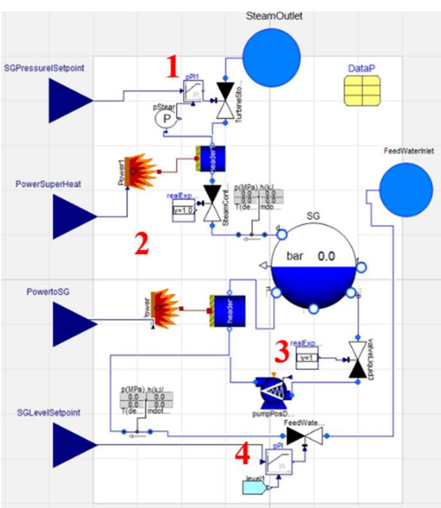

Fig. 1. SG Model: 1) Pressure Control; 2) Heating; 3) Recirculation; 4) Level Control

In the BOP model given by Fig. 2, the turbine is modeled using one high pressure (HP) and two low pressure (LP) stages. Steam was extracted from each of these stages to perform high- and low-pressure reheating of feedwater (FW). The condenser, condensate pump, and FW pump were all included as well. Steam to the turbine is generated by the SG model, and the FW exiting the HP FW reheater is passed to the SG model.

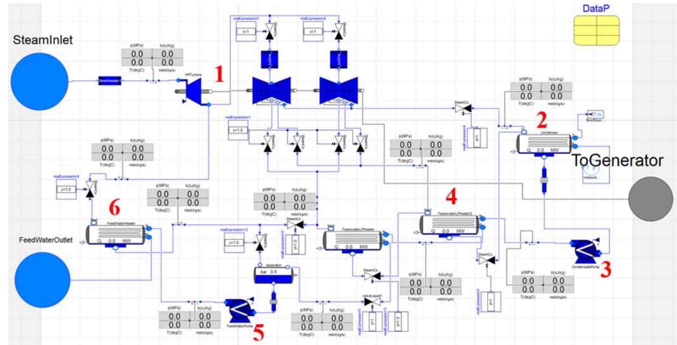

Fig. 2. BOP Model: 1) Turbines; 2) Condenser; 3) Condensate Pump; 4) LP FW Heating; 5) FW Pump; 6) HP FW Heating

Simulating the SG and BOP with a simple generator model from the ThermalPower library (configuration not shown), the turbine was controlled to operate at a pressure of 3.3 MPa and the electrical power generated was 44 MW.

B. Electrical Power Modeling

Modeling for the electrical power domain consisted of developing the generator and electrical grid using components from the OpenIPSL library. Key features of the generator, shown in Fig. 3 are the round rotor generator mathematical model (in the red no. 3), the PID controller which serves as a simple governor to coordinate between generator and turbine (red no. 1), and the interface which converts between variables of the ThermalPower and OpenIPSL libraries that is described in [11] (marked with a red no. 2). Simple PID control was chosen over a more detailed governor model in this work because explicitly including a governor was not required to observe and capture the multi-domain system's coupled dynamics. In this work, the PID alters the pressure setpoint of the SG's pressure controller.

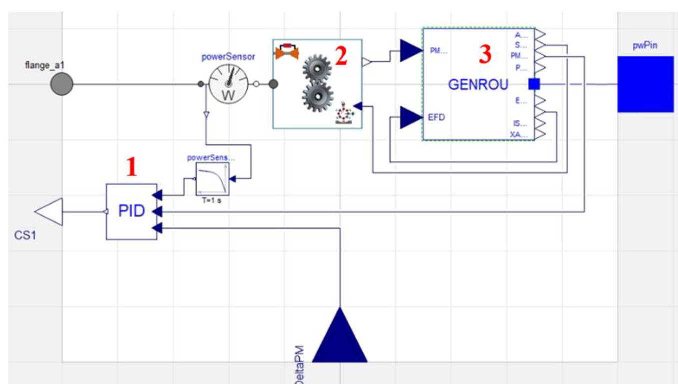

Fig. 3. Generator Model: 1) PID "Governor" Controller; 2) Library and Domain Interface; 3) Generator Mathematical Model

Most prominent in the model of the electrical grid in Fig. 4 is the fault model (red no. 2), which was used to induce a three-phase fault into the system, resulting in a transient. Also worthy of note is the variable load, which can increase the power demand at a specified time (red no. 1). The remaining components include substation buses (numbered and starting with a "B"), transmission lines connected them, and to the right of the figure an infinite bus model representing the reminder of the power grid. Meanwhile the Modelica record named *pf* allows specification of the power flow solution from an external tool, see more details in [12].

Connecting the generator and grid models formed the overall electrical domain of this work. Then further connecting the electrical and thermal-hydraulic domains formed the multi-domain model discussed in the following section.

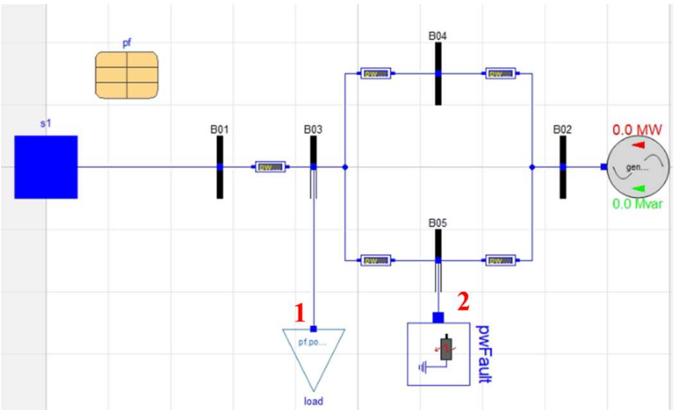

Fig. 4. Electric Grid Model: 1) Variable Load; 2) Fault Injection

III. Multi-domain Modeling

A. Model Construction

Referring to Figs 1, 2, and 3, the multi-domain model was formed by connecting the grey node *ToGenerator* in the BOP to the grey *flange_s1* of the generator and connecting the white node *CS1* of the generator (where CS is control signal) to the dark blue *SGPressureSetpoint* in the SG model. In this way, the model shown in Fig. 5 was developed. Note that in this view of the model, internal modeling of each subsystem is encapsulated within each respective icon.

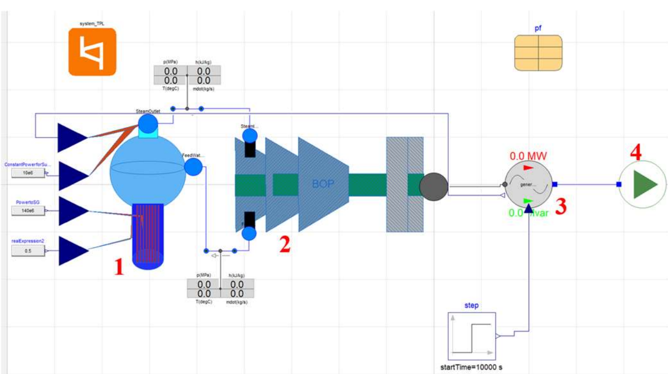

Fig. 5. Multi-domain Model: 1) SG; 2) BOP; 3) Generator; 4) Electrical Grid

Steady-state behavior of the model was then determined. Following that point only small modifications were made to the multi-domain model and its parameters in order to generate specific transient scenarios.

B. Steady-state Behavior

Selected steady-state results are shown in Figs 6 and 7. In both plots, the initial rise and fall of parameters are simply the expected initialization transient, as both the numerical solver and PI controllers in the model work to converge the model to its steady-state. While the controllers were not optimized specifically for this purpose, it can be noted that, considering the long timescales in the thermodynamic process, converging to the steady state was not a long process.

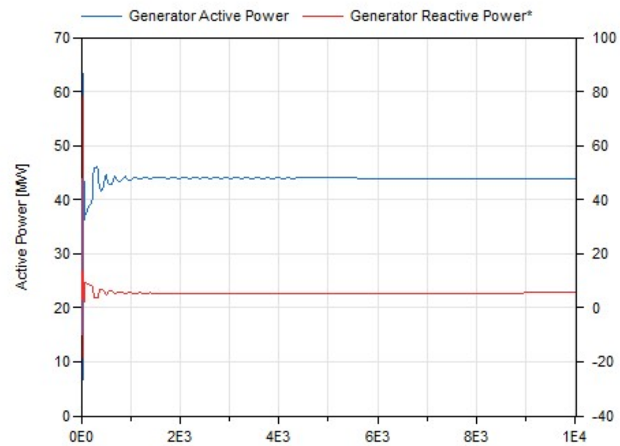

Fig. 6. Plot of steady-state generator active and reactive power (*indicates the reactive power on right vertical axis)

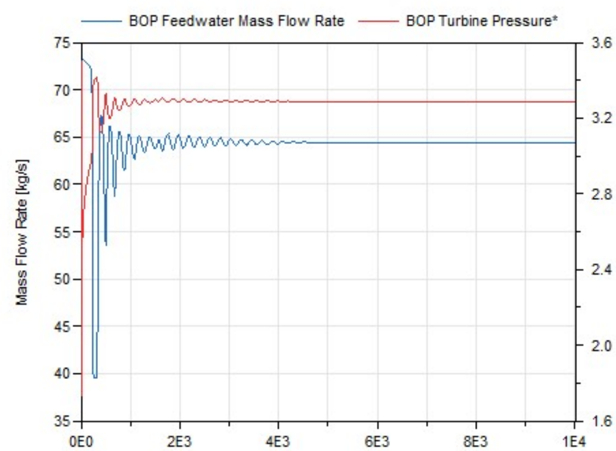

Fig. 7. Plot of steady-state BOP turbine pressure and feedwater pump mass flow rate (*indicates the turbine pressure on right vertical axis)

Generator active power converged to 43.9 MW and reactive power to 5.44 Mvar. Turbine pressure converged to 3.28 MPa and FW mass flow rate to 64.5 kg/s. While not particularly insightful values on their own, these results do indicate that the steady-state model behaves in the desired way and operates at approximately the same process parameter values as similar proposed systems [10]. This comparison was used as the means of validation of this model, as it was not designed to exactly mirror a specific design but rather to follow the same physical trends.

IV. Transient demonstration and discussion

After verifying the steady state performance of the model, transient simulations of the system were conducted. Two scenarios were considered: 1) a power transient in the SG, modeled by ramping up the power input to the SG, and 2) an electrical grid fault (i.e., symmetric three-phase short-circuit), induced using the fault component included in the grid model.

A. Steam Generator Power Transient

Simulation of a power transient in the plant side was performed by replacing the constant input power in the SG model with a ramp function that increased input power from 140 MWth to 145 MWth. Figure 8 shows the turbine pressure and mass flow rate, which displays both the transient behavior in the model initialization, and the action of the control systems to stabilize the plant after the ramp is applied.

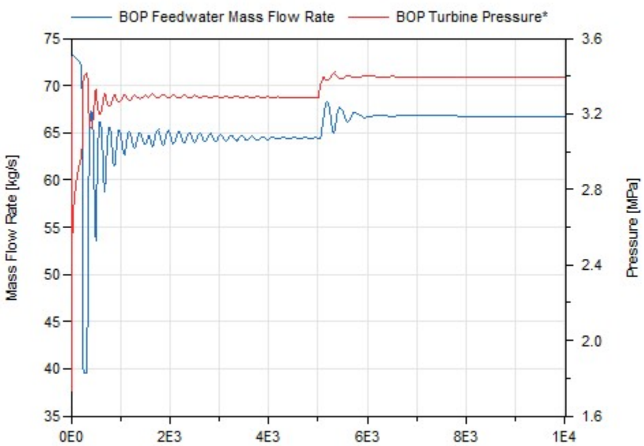

Fig. 8. Power transient BOP turbine pressure and feedwater pump mass flow rate (*indicates the turbine pressure on right vertical axis)

Power produced by the generator and per-unit current of the grid over the course of the transient are given in Fig. 9. As would be expected in a tightly coupled system such as this one, the power production tracks with the primary SG power.

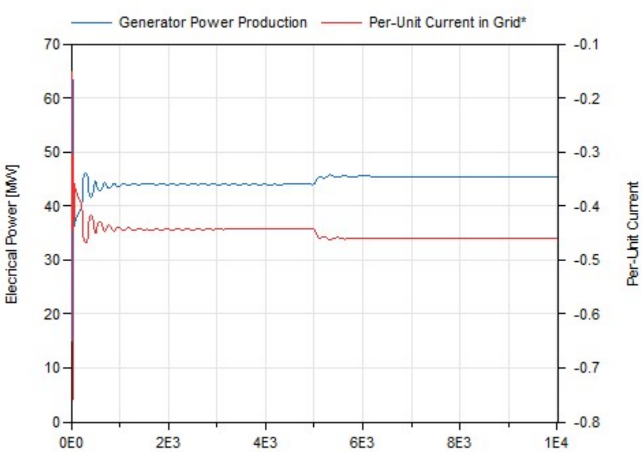

Fig. 9. Plot of generator power produced and current in power grid during plant side power transient (*indicates the per-unit current on right vertical axis)

B. Electrical Grid Transient

Using the fault injection component in the electrical grid model, a short circuit was induced in the power grid. Impact on per-unit current in the time span of the transient is shown in Fig 10 in which the short circuit current spike can clearly be seen. Generator power production shows a similar spike as a result of the short circuit. Rapid change to the generator further resulted in a change to the torque experienced by the turbine shaft, as shown in Fig. 11.

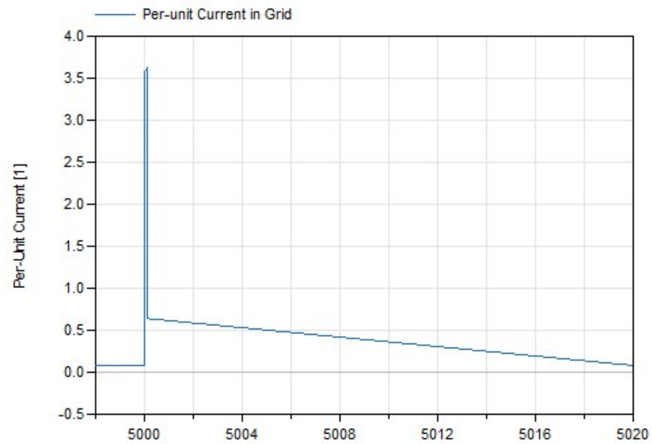

Fig. 10. Plot of per-unit current in electrical grid due to short circuit transient

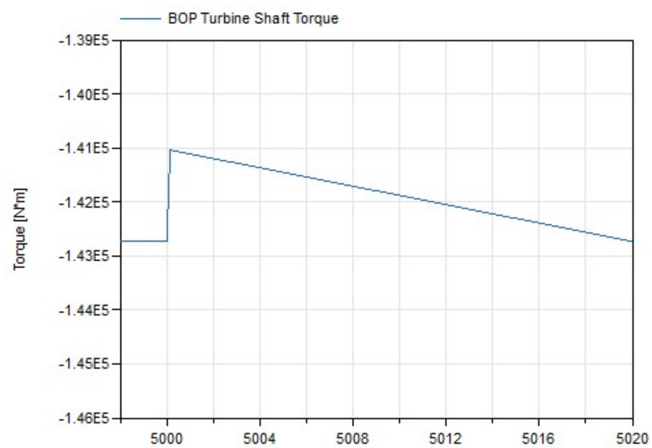

Fig. 11. Plot of torque experienced by turbine shaft in BOP

C. Discussion

Use of the multi-domain model to simulate transients of different origin, i.e., either in the power plant or in the power grid, yielded results which demonstrated the clear interplay between each system. Power transients originating in the steam plant were shown to effect active electrical current in the power grid. Ramifications of this become clearer when a full-scale power grid with multiple sources of generation is considered. In such a scenario, the planning required to treat multiple events of this type occurring in rapid succession will be very challenging, and the consequences of failing to balance the effects of all sources could be potentially very dangerous for the safe operation of the NPP.

Alternatively, mechanical impacts on the steam turbine were generated via a short circuit in the power grid. This second result in particular has significant impact for further analysis, as predicting and controlling torque to the turbine shaft is vital for accurate estimation of shaft life or predicting component failure.

V. CONCLUSIONS

This work presented a multi-domain model of a Rankine cycle-based low power NPP BOP coupled with a model of the electrical grid. In both industrial and research communities, single domain modeling has consistently been the norm, but this work lays the foundations of demonstrating that multi-domain modeling is required to fully capture the dynamic interactions between these two complex systems. After development of the multi-domain model, two transient scenarios, one originating in the power plant and one in the electrical grid, were each demonstrated. Interaction between the coupled models was successfully observed, as a power transient in the steam generator altered the current of the grid, and a short circuit of the grid caused a change in torque experienced by the turbine's shaft.

Future research efforts shall branch into multiple directions based on this work. Topics to be addressed first include the comparison of results obtained using a multi-domain steam turbine model versus using a traditional turbine governor and multi-mass model. Analysis comparing these modeling approaches will yield clear differences in the dynamics captured by each modeling approach and are expected to show that the impact of some system states can only be captured using multi-domain models. Following this analysis, the further extension and refinement of these models will be conducted, both to perform deeper analysis into the impacts of transients such as sub-synchronous oscillations and to include further domains, such as the physics models of a nuclear island. While modeling at this breadth, investigation will be performed in-depth into the impact of dynamic interactions on neutronic behavior and phenomena within a reactor core. In summary, this work is to act as a steppingstone to much further analysis and hopefully to simulation models which are able to effectively guide the transition into a new power generation environment.

ACKNOWLEDGMENT

This paper is in part supported by and is performed in conjunction with United States Department of Energy Federal Grant number DE-NE0008760, in part based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Advanced Manufacturing Office, Award Number DE-EE0009139, and in part by Dominion Energy.

REFERENCES

[1] L. Max, J. Olson and A. Petersson, "Impact on nuclear power plant operation of a changing generation mix," Energiforsk, 2021.

[2] S. M. Bragg-Sitton, J. Gorman, G. Burton, M. Moore, A. Siddiqui, T. Nagasawa and H. Kamide, "Flexible nuclear energy of clearn energy systems," National Renewable Energy Lab. (NREL), Golden, CO (United States), 2020.

[3] K. Frick, P. Talbot, D. Wendt, D. Boardman, C. Rabiti and S. Bragg-Sitton, "Evaluation of hydrogen production feasibility for a light water reactor in the midwest," Idaho National Lab, Idaho Falls, ID (United States), 2019.

[4] D. Mikkelson, K. Frick, S. Bragg-Sitton, C. Rabiti and J. Doster, "Initial performance evaluation and ranking of thermal energy stroage options for light water reactor integration to support modeling and simulation," Idaho National Lab (INL), Idaho Falls, ID (United States), 2019.

[5] R. Ponciroli, G. Maronati and R. Vilim, "Development of a reference governor-based control scheme for integrated energy systems," Argonne National Lab (ANL), Argonne, IL (United States), 2019.

[6] S. Kovacevic, D. Jovcic, S. Aphale, P. Rault and O. Despouys, "Analysis of a potential low frequency resonance between a 1GW MMC HVDC and a nearby nuclear generator," Electric Power Systems Research, vol. 187, p. 106491, 2020.

[7] M. Aguilera, L. Vanfretti, T. Bogodorova and F. Gomez, "Coalesced gas turbine and power system modeling and simulation using Modelica," in Proceedings of the American modelica conference, 2018.

[8] M. de Castro, D. Winkler, G. Laera, L. Vanfretti, S. Dorado-Rojas, T. Rabuzin, B. Mukherjee and M. Navarro, "Version [OpenIPSL 2.0.0] - [iTesla Power Systems Library (iPSL): A Modelica library for pahsor time-domain simulations]," *SoftwareX,* vol. 21, 2023.

[9] "Thermal Power Library," Modelon Inc., [Online]. Available: https://modelon.com/library/thermal-power-library/.

[10] NuScale Power. LLC, "NuScale Standard Plant Design Certification Application - Chapter Ten Steam and Power Conversion System Revision 2," United States Nucleaer Regulatory Commision, Gaithersburg, MD, 2018.

[11] F. J. Gómez, M. Aguilera Chaves, L. Vanfretti and S. H. Olsen, "Multi-Domain Semantic Information and Physical Behavior Modeling of Power Systems and Gas Turbines Expanding the Common Information Model," in IEEE Access, vol. 6, pp. 72663-72674, 2018, doi: 10.1109/ACCESS.2018.2882311.

[12] S.A. Dorado-Rojas, G. Laera, M. de Castro Fernandes, T. Bogodorova and L. Vanfretti, "Power Flow Record Structures to Initialize OpenIPSL Phasor Time-Domain Simulations with Python," 14th International Modelica Conference, Linköping, September 20-24, 2021.