Dynamic Modeling and Simulation of Integrated Energy Systems with Nuclear, Renewable, and District Heating

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Abstract—**There is a paradigm shift in the energy industry towards green technologies which have incentivized nuclear and renewable-based energy production. The thermal power from the nuclear process could be optimally utilized to generate various end products thereby increasing the efficiency of nuclear power plants. A power plant being used for both electricity and heat is called an integrated energy system. One such integrated energy system coupling nuclear and wind energy resources by supplying electricity to the power grid and heat energy to a district heating network, is modeled and simulated in this paper. The dynamic model of the integrated energy system is developed using the Modelica language. Coordinated control is designed to ensure that the actual generation follows the demand associated with different end products. The performance of the dynamic model is evaluated for steady state responses and load following capabilities.**

Index Terms—**Integrated Energy Systems, Nuclear, Wind, District Heating, Modelica.**

I. INTRODUCTION

The transition towards clean resources to meet the energy requirements of the society has already been set forth in motion owing to global warming and the need for sustainable development. This stance in the energy industry has been initiated by the Paris agreement on climate which encouraged the utilization of low carbon resources such as nuclear, solar, wind, and hydro [1]. The increased deployment of solar and wind energy resources are, however, often hindered by their limitations such as variability and unpredictability. In contrast, nuclear power is more reliable and dispatchable, making it an important player in the clean energy mix [2].

A means of improving energy utilization is by employing integrated energy systems (IES), which is a combination of different generation resources supplying multiple forms of energy, such as electricity and heat, for consumption. In a tightly coupled configuration of IES, the hybrid energy systems are physically coupled with coordinated control which apportions the energy requirements of different subsystems dynamically [3], [4]. Thus, the IES contains different energy flows and material exchanges that must be modeled with sufficient fidelity to capture the non-linear behaviour of the system and its evolution with time [3]. Besides this, the dynamic interaction between different subsystems (modes of energy) and the coordinated control requires to be effectively modeled to evaluate its performance during both stable and transient conditions [5]. All these factors necessitate the development of a dynamic model of the IES.

Several works in the literature [6]–[10] have considered the optimal design and scheduling of different energy resources in IES. These works use quasi-static or steady-state models for describing the operation of IES. However, for safe and reliable operations of IES, the optimal dispatch levels must be translated into control signals for the sub-modules within IES. This requires the development of dynamic models with control architectures. Considering the requirement for modeling multi-energy flows, and the nonlinear, dynamic behavior of IES, Modelica is deemed to be a suitable modeling language. Modelica is a language that uses physics-based equations to model dynamic systems [11]. Properties such as acausality in equation description, inheritance capability, and object-oriented modeling make it suitable for complex systems formed by interconnecting different subsystems with multi-energy and material flows. The Modelica language in the Dymola environment is an effective tool for modeling real-world physical systems [12].

To facilitate the development of the dynamic model for nuclear reactors, the Oak Ridge National Laboratory (ORNL) has developed a package called the Transient Simulation Framework of Reconfigurable Models (TRANSFORM) in Modelica. This served as the backbone for the efforts by the Idaho National Laboratory (INL) to model a nuclear-based thermal energy distribution system [13] and a nuclear-based IES configuration producing hydrogen as an end product [4].

The main contribution of this paper is to develop an IES comprising of a nuclear plant as the primary source along with wind generation, supplying electricity to the grid and thermal energy to a district heating network (DHN). Consequently, the DHN model and its interaction with the nuclear energy system along with renewable energy generation are modeled. The control system is designed to ensure coordinated control between different subsystems while responding to the optimal dispatch signals. Besides this, the model evaluation for different scenarios is implemented considering varying weather conditions and demand signals.

The organization of the paper is as follows. In section II, different subsystems and their models are briefly discussed. Section III discusses the model behavior during different case studies considering varying operating conditions. Finally, conclusions and future work are discussed in Section IV.

II. MODEL DESCRIPTION

The dynamic model developed in this paper is built using the template designed by ORNL [14]. This framework provides sandboxes for each subsystem, thus enabling independent modeling of a subsystem that can function in both standalone and interconnected modes. The template also accommodates the control infrastructure by using signal buses for actuators and sensors along with individual control and event driver modules for each subsystem.

The IES configuration considered in this work involves a nuclear power plant and a wind power plant as generating resources. The electrical energy supplied to an infinite power grid and the thermal energy supplied to a DHN are the end products. A coordinated control among different subsystems is performed by a supervisory control system which provides set points for the control modules specific to each subsystem. The thermo-fluid modeling captures both the thermal and hydraulic behavior of the IES. The momentum, mass, and energy conservation are considered by incorporating pipe elements that model the behavior of flow channels. [3]. The subsystem models used in the work are briefly discussed in this section.

A. Nuclear Reactor

The primary heat-producing component which supplies the steam used by the multi-energy system is an integral pressurized water reactor (IPWR). In this study, the adopted IPWR has a nominal thermal power of 160 MWt and a corresponding electrical equivalent of 50 MW. The standalone model of the reactor is available in the HYBRID-NHES package [15]. These modules can be interconnected in parallel to function as the base supply plant.

The nuclear steam supply system (NSSS) functions using a primary coolant loop and a secondary coolant loop, which are associated with the shell side and the tube side of a steam generator, respectively. The primary coolant loop encompasses the reactor core, riser, pressurizer, and primary pump. In the primary loop, the coolant in the reactor core which is heated by the nuclear reaction moves upward through a riser and flows down through a steam generator, from where it is then pumped back to the reactor core. The pressurizer placed above the riser ensures that the primary coolant pressure remains at a nominal value during normal conditions. In the secondary coolant loop, the feedwater which enters the steam generator is converted into a superheated vapor by the heat transferred from the primary loop.

In the dynamic model, the nuclear subsystem has two fluid ports interacting with other subsystems, namely, the main steam-out port and the feed-water in port. The dynamics of the two-phase interaction within the pressurizer, the helical coil steam generator, and the reactor core dynamics are effectively modeled by equation representation in TRANSFORM [14]. The dynamic model of the reactor core, in particular, includes the thermo-fluid behavior modeled by fuel pin and coolant channel, and core neutronics represented by one group point kinetics. The equations describing the core neutronics are presented in [3].

The control module of the nuclear subsystem includes the control of core rod reactivity, pressurizer pressure, and primary pump mass flow rate. The core rod reactivity control maintains the core power output at the desired state. The pump control regulates the temperature of the primary coolant by controlling the corresponding mass flow rate. Both these control modules are achieved using PID controllers. The pressurizer pressure control is achieved using a hysteresis based on/off control for the associated liquid heaters.

B. Energy Manifold or the Steam/Water Distribution System

The thermal energy derived from the nuclear reaction has to be distributed among different subsystems to produce the multiple commodities desired from the IES. In this configuration, the hot steam from the nuclear subsystem is diverted to the balance of the plant for electricity generation and the DHN for space/water heating. The energy manifold includes valves to distribute the steam to multiple subsystems. The return streams are also mixed and sent back to the primary heat system in the energy manifold. This mechanism is realized by actuating the valves by signals from the associated control module.

The control module is capable of actuating the turbine control valve and the bypass valve by generating suitable signals. In the current model, the turbine control valve in the energy manifold is closed to a near maximum, thereby diverting most of the energy towards the balance of plant (BOP) for electricity generation. The bypass valve is closed to a near minimum allowing a small fraction of thermal energy into the DHN.

C. Balance of Plant (BOP)

The thermal energy which is not utilized by other subsystems is converted into electric supply in the BOP. It consists of the turbine generator set which is used for power conversion and the condenser for converting steam into water.

In the BOP, there exist the turbine control valve and the turbine bypass valve. The turbine control valve is controlled by a PID-based controller which controls the admission of the steam into the turbine for generating electric power. Using this valve, the control module functions to minimize the error between the setpoint determined by the supervisory control and the actual electrical power output. The turbine bypass valve is used to control the steam that is dumped into the condenser. The purpose of this valve is to regulate the steam generator pressure. The condenser is considered as a heat sink in this model.

D. Switching Yard and Grid

This is a logic-based subsystem that is used for various electrical interconnections in the IES. The routing of electrical power is performed by the switches in this subsystem. In the current IES configuration, the switching yard supplies the electrical power generated by the balance of plant and the wind power plant to the grid. The electric power grid is modeled as an infinite source or sink in the TRANSFORM and HYBRID-NHES packages [14], [15]. In this work, since only generating resources are considered, the grid assumes the role of an infinite sink.

E. Wind Power Plant

The wind power plant is modeled using the components of the open-source WindPowerPlants library [16]. The basic components used to model a wind power plant include the wind turbine, variable speed generator, associated pitch angle, and angular velocity/torque controller. The power coefficient which denotes the fraction of the kinetic energy utilized by the wind turbine is described as a function of the turbine design and the pitch angle [16]. The pitch angle is the angle of rotation of the turbine blades, which can be controlled to regulate the aerodynamic power produced. The wind turbine model is described by its characteristic pitch angle-dependent power coefficient-tip speed ratio profile. Hence, the wind velocity, pitch angle setpoint from the controller, angular velocity, and tip speed ratio are used in equations to determine the power output of the wind turbine. The pitch angle control for the optimum operating range and the power limiting range is also specified. A generic variable speed generator model is used for power conversion. The torque setpoint generated by the angular velocity controller is used as input by the variable speed generator. In the angular velocity controller, the control strategies for the two wind speed regions, i.e., power generating region and stand still region, are defined.

The electro-mechanical dynamics of the wind power plant are well captured by the model. The electrical transients, however, are neglected and the power conversion is assumed to be lossless. The electrical connector used in the WindPowerPlants library is not compatible with the TRANSFORM-based model. Hence, an interface to bridge this inconsistency is developed, which connects the quasi-static multi-phase connector to the electrical port.

F. District Heating Network (DHN)

The DHN model is adopted from the open-source DisHeatLib package which is built upon the IBPSA library [17]. Various component models such as the pipes, substations, heat load/demand, supply stations, heat exchangers, heat pumps, thermal storage, etc. are already available in this library. The DHN considered in the IES consists of 14 buildings and 12 pipes. The nominal supply temperature is 70° C and the nominal heat flow is 3 MWt. The standalone DHN is supplied by a station that functions as a pressure source with a preset supply temperature. A pressure controller along with a pump and a temperature controller is also present in the supply station. Each building houses a substation that supplies the heat demand for domestic water heating and space heating. The space heating is modeled as a radiator type demand where the return temperature depends on the room and supply temperatures. The hot water demand is supplied by a base station that has a tank and electric boost heater, and is considered as a demand with a fixed return temperature. The model is capable of capturing the thermal transients and time-domain hydraulic behavior [18].

G. Supervisory Control

The supervisory control unit is responsible for the coordinated control of different IES subsystems. The optimal dispatch signal intake from an external optimizer is converted into suitable signals for different control modules in the IES.

The adopted control strategy gives a high priority to grid electricity demand on the IES. With the presence of wind energy generation, the demand on the BOP reduces and hence the remaining energy can be utilized for thermal loads. The control architecture incorporates wind speed forecasts and demand forecasts to determine the required output from the BOP. Thus, the BOP setpoint is calculated using:

$$P_G^t = P_D^t - P_w^t(v^t) \tag{1}$$

where the grid demand on IES P_D and the wind power generation P_w (which is a function of velocity v) are used to determine the power generation P_G required at time t. The flowchart for the BOP control is presented in Fig. 1.

Therefore, the turbine control valve is actuated by the corresponding signal generated when the BOP setpoint is used in the BOP control module. The thermal inflow to the DHN is through the bypass valve in the manifold operating at a preset position. The thermal demand utilized by the DHN is controlled by lower-level controllers. The remaining energy is dumped into the condenser to regulate the steam pressure, which is performed by the pressure-controlled bypass valve in the BOP.

III. MODEL IMPLEMENTATION AND PERFORMANCE EVALUATION

The dynamic model of the IES is developed in the Dymola environment using the Modelica language based on the different abovementioned open-source libraries. The top-level architecture of the IES as viewed in Dymola is presented in Fig. 2. The inputs to the model include the wind speed forecasts, the electricity demand by the grid (that can come from optimal dispatch engines), and the thermal demand of the different buildings in the DHN. These are all read-in through files using Modelica utilities functions.

A. Steady State Operations of IES

The IES model is simulated for a time interval of 1 hour to validate the stability of the system and the functioning of the control architecture. During this interval, the demand on the BOP is on a slow rising ramp.

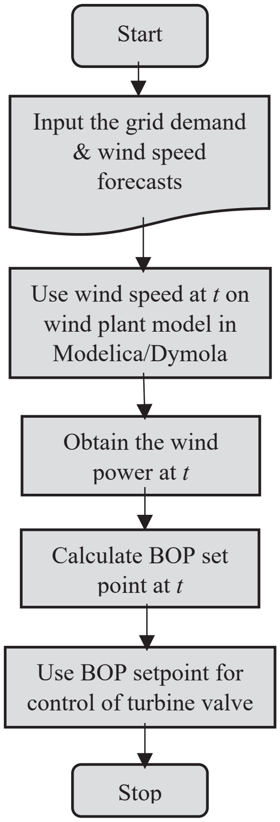


Fig. 1: The process flow for determining the BOP setpoint in supervisory control

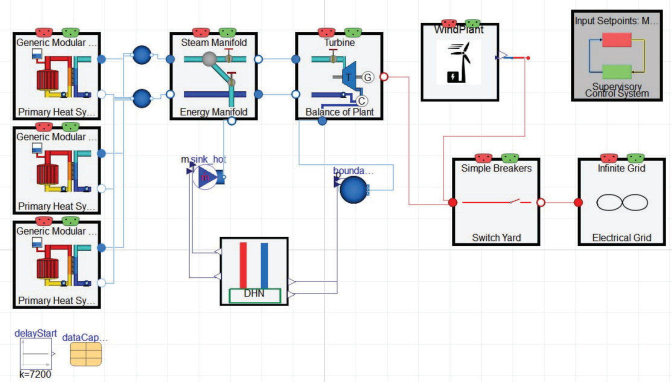
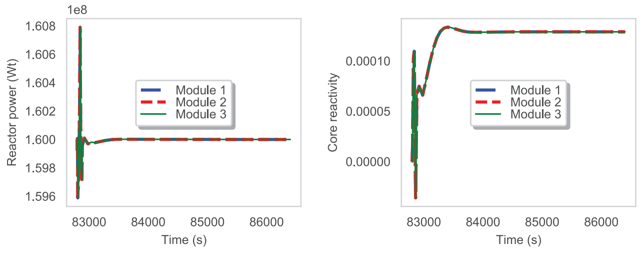


Fig. 2: Top level diagram of the IES with different subsystems in Dymola

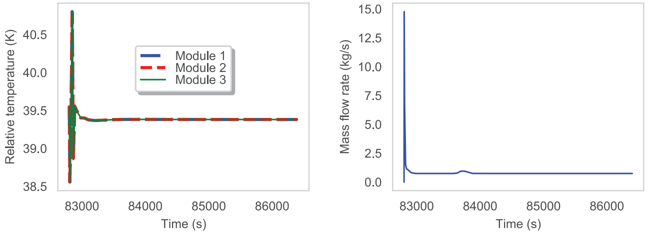
The nuclear power plant is made to function at base load irrespective of the electric and thermal demand. Therefore, a steady state controller is used to maintain the operation of each reactor module around the nominal thermal power. The thermal power generated by the three modules is shown in Fig. 3a. The core reactivity and the temperature difference between the hot leg and cold leg around the core also have stable responses, as seen in Fig. 3b and Fig. 4a, respectively. Core reactivity control and temperature control are performed by the control module in NSSS, and the response shows that the controllers function as desired. The mass flow rate from the energy manifold to the DHN is shown in Fig. 4b. There is no significant variation in mass flow rate as the bypass valve in the energy manifold that controls the flow of the heat transfer fluid into DHN is kept at a minimum position throughout the operation.

It is seen from Fig. 5 that the power production by the wind power plant is near zero and therefore, the grid demand and the BOP demand setpoints are the same. Additionally, the actual generation by the BOP and the IES matches the demand. The load following characteristic is achieved by the supervisory control and associated lower level controller in BOP. The enthalpy associated with the inflow and outflow of the water in DHN is presented in Fig. 6a. The heat flow from the supply station to various buildings is a constant. The enthalpy in the return flow is varying, as it depends on the utilization and ambient temperature. The hot water and cold water temperature profiles of the DHN are shown in Fig. 6b. The supply temperature is always at 70° C whereas the return temperature depends on the heat demand of individual buildings in the network. The initial transients appearing in the figures at the start of the simulation is due to model initiation. This does not represent the behavior of the physical system and can be neglected.



(a) Thermal power of reactor modules (b) Core reactivity of nuclear modules

Fig. 3: Reactor module operating conditions



(a) Core temperature difference (b) Mass flow rate from manifold to DHN

Fig. 4: Reactor temperature and DHN inflow

B. IES Characteristics with Varying Demand and Generation

The load following capability of the IES is evaluated by performing simulations over a 24-hour duration with varying wind profiles, electricity demand, and thermal demand. A day in the month of December is selected to perform the case study.

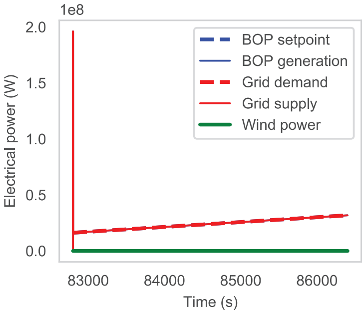
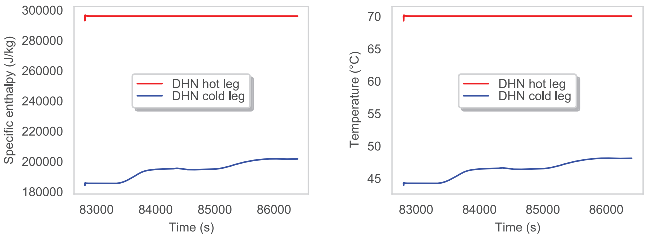


Fig. 5: Electric power generated by different subsystems and the corresponding setpoints



(a) Specific enthalpy

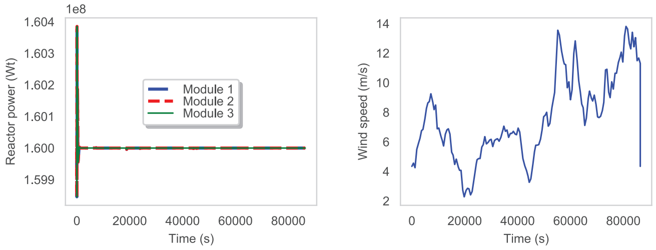
(b) Temperature

Fig. 6: Supply and return condition of the district heating network

The reactor thermal power is maintained at the base load condition, which is made to operate at nominal thermal power as shown in Fig. 7a. The wind speed profile shown in Fig. 7b is fed into the dynamic model of the wind plant to determine actual power generation. The electricity demand on the grid and the wind power forecasts are further used to determine the demand on BOP. Different electric power profiles are presented in Fig. 8. It is observed that the supervisory control in tandem with the lower level controllers ensure that the actual generation of the BOP and IES as a whole follows the desired setpoints.

The thermal demand of two representative buildings in the district heating network is shown in Fig. 9. It is evident from the figure that the lower level PID controllers at the building and supply station level ensure the thermal load following by each building in the DHN. The enthalpy and the temperature of the supply and return flow in DHN are presented in Fig. 10. The profile of the return temperature and the specific enthalpy of water in the cold leg is in direct opposition to the thermal demand profile of the DHN, which can be observed from the two representative buildings in Fig. 9. Therefore, the state of water in the cold leg is dependent on the thermal demand and utilization by the buildings in the network. The temperature of the supply however, is always maintained at 70° C.

The mass flow rate incoming from the NSSS to the energy manifold and outgoing from the energy manifold to the DHN is shown in Fig. 11. As discussed earlier, the mass flow rate into the DHN is maintained by the bypass valve in the energy manifold which is kept at a minimum position without much variation throughout the operation. Also, the mass flow rate into the DHN is a very small fraction of the total primary flow rate.



(a) Thermal power of reactor modules

(b) Wind speed profile

Fig. 7: Reactor output and wind profile

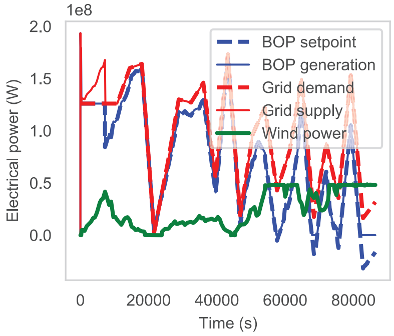
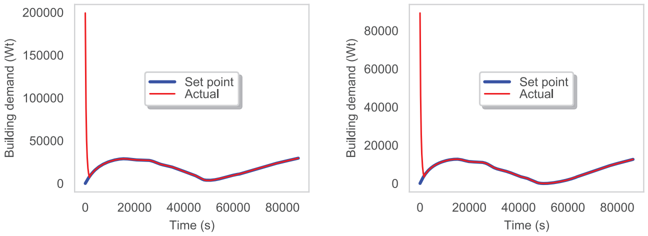


Fig. 8: Electric power generated by different subsystems and the corresponding setpoints



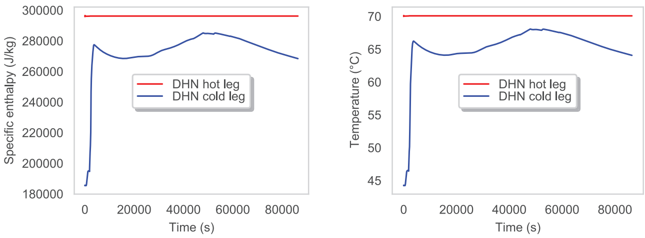
(a) Building 1

(b) Building 5

Fig. 9: Thermal demand and flow to representative buildings

IV. CONCLUSION

An integrated energy system comprising of nuclear and wind power plants as generating resources, grid as electrical load, and district heating as thermal load was designed and studied in this paper. The dynamic model of the IES was developed in the Modelica-based Dymola platform using several component models. The control architecture, steady-state response, and load-following capability of the IES were evaluated. It was observed that the various components and associated controllers in the IES faithfully follow the setpoints generated by the supervisory control during both steady state and load following conditions. Besides this, the dynamic response was found to be satisfactory, as it did not exhibit



(a) Specific enthalpy (b) Temperature

Fig. 10: Supply and return condition of the district heating network

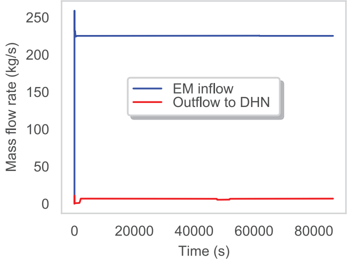


Fig. 11: Inbound and outbound mass flow rate in the energy manifold (EM)

unwarranted oscillations or overshoots during normal operating conditions. Using the integrated energy system for multi-commodity supply offers efficiencies that can lead to energy economic competitiveness.

Although the thermal, hydraulic, and mechanical transients are well captured by the developed model, it lacks fidelity in electrical modeling. Particularly, the reactive power is not considered in the model and many sub-components assume lossless power conversion, which will be addressed in future work.

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