SIMULATION OF FLEXIBLE SMALL MODULAR REACTOR OPERATION WITH A THERMAL ENERGY STORAGE SYSTEM

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Abstract

The surging penetration of variable renewable energy sources into power grids translates into an urgent need for dispatchable generators such as nuclear power plants to effectively balance grid demand. Even though nuclear reactors are used both as baseload and flexible power sources, with the reactor's power following the load demand, keeping the reactor at its rated conditions has several benefits, both from a technical and economic standpoint. This paper explores the integration of a two-tank thermal energy storage (TES) system with a light-water cooled Small Modular Reactor (SMR) as an alternative to address the flexibility requirements and, at the same time, minimise thermal power variation in the nuclear steam supply system. In this work, the dynamics of the coupled SMR-TES system are examined across various scenarios by means of dynamic models developed in the object-oriented modelling language Modelica. The aim is to analyse the potential impact of a TES on the operational strategies of a SMR in the context of highly fluctuating load demands. Through this investigation, the study aims at demonstrating that nuclear energy systems can satisfy the evolving grid requirements with minimal perturbations on the nuclear reactor's operation. The Modelica language proved to be effective for this application, allowing to model the overall system architecture by coupling independent models through a plug-and-play approach. The results show that the SMR is able to meet variable load demands exclusively by exchanging power with the TES, ensuring reliable energy supply and potentially managing power flows to enhance revenue streams.

1. INTRODUCTION

To achieve decarbonisation objectives, a profound transformation of the energy sector is foreseen, driven mainly by a growing penetration of variable renewable energy sources (VRE), such as wind and solar power, for electricity production. Nevertheless, the intermittent nature of VRE might lead to major imbalances between power supply and demand, imposing significant risks to the electrical grid stability and perpetuating the reliance on backup power generators.

As dispatchable and low-carbon power sources, nuclear power plants (NPP) could play an important role not only as baseload power generators but also in satisfying the residual load, given by the gap between power demand and VRE output. Within this framework, usually NPPs can be operated in baseload configuration or in load following operation. In most countries, NPPs have been employed as baseload power sources, maintaining reactor operation and, consequently, the electrical power output at nominal conditions. This operational mode offers technical and economic advantages, such as the reduction of thermomechanical stresses on the reactor's primary side and the maximisation of the load factor compared to the load following strategy [1, 2]. The latter solution is adopted in France, where the power of the nuclear fleet is modulated according to grid requirements. To capitalise on the benefits of maintaining the reactor at its rated conditions, the current endeavour involves addressing the dispatch priority of VREs, driven by their lower generation costs, by improving the flexibility of the NPP by minimising perturbations in the operation of the nuclear steam supply system.

A possible approach for tackling this challenge is integrating a thermal energy storage system (TES) into the reactor's power conversion cycle. Consequently, the electrical power output may be modulated by exchanging thermal power with the TES while the reactor operates at its rated power. Several studies have examined various configurations and the economic viability of combining a NPP with a TES, highlighting the advantages of

implementing this strategy to increase system flexibility and respond to the evolving dynamics of the electricity market [3 – 6].

In this work, the impact of coupling a two-tank thermal energy storage system, outstanding for its high technological maturity compared to other TES devices [7], with a light-water cooled Small Modular Reactor (SMR) is investigated. The objective is to propose a potential integration strategy where the TES is used to modulate the electrical power output (by storing the reactor's excess thermal power or increasing the electricity production beyond the rated conditions) and analyse the dynamic behaviour of this configuration in response to different scenarios in terms of flexibility requirements. Other applications for TES discharging, e.g., the supply of thermal power to drive industrial processes to decouple their demands from the nuclear power plant operation, are not addressed in this study. In this analysis, a dynamic simulator of the integrated architecture with a dedicated control system is employed to assess the impact of flexible operation on the reactor's primary side.

2. DYNAMIC MODELS

The dynamic models developed to simulate the behaviour of the system, presented in the following sections, have been built in the object-oriented modelling language Modelica, specifically within the simulation environment Dymola. Modelica is considered a suitable tool for this kind of application, as it allows constructing the single subsystems of a complex engineering system independently and subsequently couple them through a plug-and-play approach. This methodology is facilitated by the features of this object-oriented modelling language, which, relying on an acasual equation-based approach, allows for a highly versatile interchangeability of models without the need to predefine inputs and outputs [8]. As a result, it is possible to build components from models available in existing libraries, extending and connecting them to simulate overall system's dynamics. This philosophy has been adopted also in this work, exploiting the models available in the open-source TANDEM library [9] to build a simulator of the system. This library has been developed within the framework of Euratom's TANDEM project, which aims at investigating the integration opportunities of light-water cooled SMRs into hybrid energy systems [10].

This section introduces the dynamic models on which the overall system is built upon, i.e., the nuclear steam supply system (NSSS), the conventional island - balance of plant (BOP), and the thermal energy storage system (TES). Thereafter, the overall model is presented. The latter dynamic model is used to explore the system's response in several scenarios, monitoring the behaviour of critical process variables such as the power flows and temperature and pressure levels of the system. As a result, it is possible to assess whether a certain perturbation or operational strategy causes the system to depart from its operational limits and their implications on the overall performance. In this context, it is possible to implement and investigate the impact of different control schemes to manage the operation of the integrated system, determining the most suitable strategy to meet on the one hand the external requirements and on the other hand internal constraints, such as those imposed by safety limits.

2.1. Nuclear Steam Supply System

The reference reactor design considered for the analysis and in the frame of the TANDEM project is the European SMR (E-SMR), a conceptual pressurizer light-water cooled SMR design. The operational parameters for this SMR are displayed in Table 1.

TABLE 1.   E-SMR DESIGN PARAMETERS [11].

Parameter	Value	Unit
Reactor thermal power	540	MWth
Core inlet temperature	300	°C
Core outlet temperature	324.5	°C
Primary coolant pressure	150	bar
Feedwater inlet temperature	163.8	°C
Steam outlet temperature	300	°C
Secondary coolant pressure	45	bar

The dynamic model for this NSSS is based on components from the ThermoPower library, an open-source library for the modelling of thermal power plants and energy conversion systems [12]. In addition, models dedicated to simulating the behaviour of specific nuclear reactor components, such as the core, the pressurizer, and the steam generator, have been developed within the scope of the TANDEM project. The core model relies on point kinetics equations to describe the neutronic behaviour, with the system's reactivity determined by the external reactivity insertion through control rod displacements as well as Doppler, moderator temperature, and Xenon poisoning reactivity feedbacks. The resulting fission power serves as a heat source in the fuel thermal model, which is used to assess the temperature levels in the fuel pellets, the cladding, and the fuel-cladding gap through the time-dependent Fourier equation. The primary coolant flow within the NSSS is simulated using components from the ThermoPower library's *Water* package, with a one-dimensional finite volume approach applied to model the coolant's thermal-hydraulics as it flows through the core subchannels, riser, downcomer, and once-through compact steam generator channels. Moreover, the system's pressure dynamics are governed by the pressurizer, which is modelled assuming thermal equilibrium between the liquid and vapour phases.

The latter model encompasses several actuators, namely sprayers and electrical heaters, that are regulated to keep the NSSS pressure close to its nominal value. This operation is overseen by a dedicated external controller, which also includes a second control loop dedicated to adjusting the external reactivity insertion in the core. In this scheme, a proportional-integral (PI) controller is used to regulate the reactivity insertion to ensure that the average core temperature remains at its setpoint value.

2.2.   Conventional island - balance of plant

The BOP model is based on the Modelica ThermoSysPro library [13]. First, a thermodynamic optimization based on the CYCLOP tool [14] was carried out to define the optimal cycle (P, H) coordinates as well as the architecture of the cycle to be implemented (finding a good compromise between simplification and representativeness). Steam expansion is performed by high- and low-pressure turbine groups, with a designed cut-off pressure of approximately 7.5 bar, separated by a drying and superheating stage. Steam Generator (SG) feedwater is reheated in two stages with designed heating powers of approximately 37 MW and 48 MW. A quasi-static modelling is applied and this approach is considered suitable for the power ramps involved in the study, which are indeed slow (a few % Nominal Power per hour, see Section 2.4). Modelling of the partial cycle regimes applied are mainly determined by changing the thermal pinch point of the two-phase flow reheaters (through a Number of Transfer Unit modelling of the heat exchangers), as well as by changing the characteristics of the steam expansion line (which combines the effect of Stodola's ellipse law and the impact of steam humidity on flow expansion thermodynamic efficiency). Although these approaches to modifying irreversibilities can be improved, they appear to be reasonable for the changing power range of Section 2.4 and for a conceptual objective, in the light of a preliminary study [15]. The HP and LP turbine inlets are controlled by total steam throttling admission: both allows accommodating sliding pressure of steam expansion line. A second control is used to fill the steam temperature setpoint of 300°C at the SG outlet. It is worth mentioning that although other control approaches could have been applied, the stakes could be low in the scope of the study since the BOP modelling approach is quasi-static and, above all, the coupling to boiler operation is shown to be little modified (as demonstrated in Section 2.4).
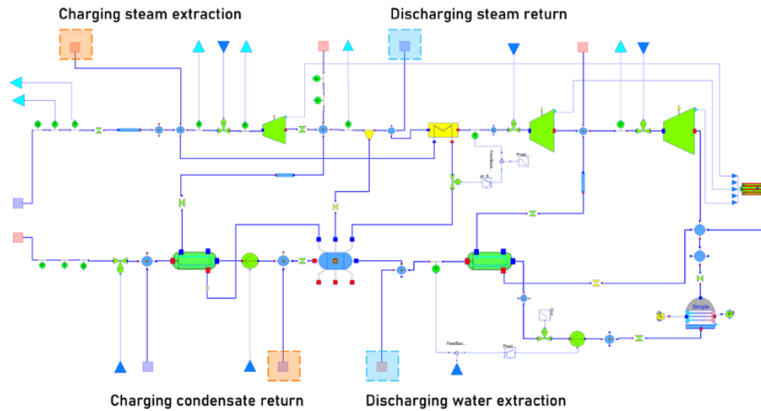

FIG. 1. Dynamic model of the BOP in ThermoSysPro.

2.3. Thermal Energy Storage

The reference technology for the TES considered in this work is a sensible heat storage system based on the two-tank configuration, recognised as a promising solution for integration with nuclear power plants [7]. In such systems, the thermal power extracted from the reactor's BOP is transferred to the sensible fluid flowing from the cold to the hot tank, where it is stored at a higher temperature. During discharge, the sensible fluid is cooled down to the cold tank temperature, releasing thermal power to produce superheated steam. In the considered configuration, the steam is exploited for electrical peaking, i.e., to increase the electrical power output of the system beyond its nominal level. The TES capacity, as well as the maximal charging and discharging powers, will be driven mainly by economic factors and could be estimated through a techno-economic optimisation of the overall system. However, such analysis falls beyond the scope of this work; therefore, a maximal peaking power of 20 MWe (corresponding to a maximal discharging power of 80 MWth) is assumed. Moreover, the storage capacity has been sized to be able to sustain continuous charging or discharging for a 24-hour period. The results from this preliminary sizing procedure, together with other design parameters, are summarised in Table 2.

TABLE 2.   TES DESIGN PARAMETERS.

Parameter	Value	Unit
Nominal charging/discharging power	80	MWth
Maximal electrical power output	190	MWe
Minimal electrical power output	140	MWe
Tank volume	53,579.9	m^3
Storage capacity	1.92	GWh
Hot tank temperature	260	°C
Cold tank temperature	190	°C
Tank pressure	1	bar

The dynamic model of the TES, displayed in FIG. 2, encompasses a tank, a pump, a control valve, and a heat exchanger model for both the charging and discharging sides. Mass and energy balance equations are implemented in the tank model to simulate the sensible fluid accumulation in the charging and discharging processes. The sensible fluid selected for this application is Therminol-66, a synthetic oil compatible with the operating temperatures of a light-water cooled SMR, with its thermophysical properties implemented in Modelica through a dedicated model. This fluid model is also used in components of the ThermoPower library, namely the pump and the control valve, included in the TES model. Furthermore, the heat exchanger model is based on a simplified, zero-dimensional approach, which does not account for the dynamic aspects of this component.

An external controller oversees the TES operation by adjusting the valve opening and, consequently, the flow rate from one tank to the next during both the charging and discharging phases. Specifically, two PI controllers are used to govern the valve operation to maintain the tank inlet temperatures at the desired setpoints, thereby limiting temperature fluctuations of the stored sensible fluid.

2.4. Integration into the overall system

An illustration of the overall model, together with the scheme of the NSSS and TES models described above, is shown in FIG. 2. The NSSS is directly coupled to the BOP model through a fluid exchange interface, requiring the introduction of an adaptor to ensure compatibility between exchanged variables due to the use of different libraries. During the charging phase, high temperature steam is extracted from the steam generator outlet and is delivered to the TES, where it condenses. The charging steam flow rate is regulated through a valve, which reduces the condensate pressure to match the return point pressure. On the other hand, electrical peaking is performed by increasing the rotational speed of the pump governing flow extraction from the feedwater tank. This feedwater evaporates up to superheated steam conditions during the TES discharging phase and is returned at the reheater's cold side inlet, as indicated in FIG. 1. The higher steam flow rate entering the low-pressure turbine stage results in an increase in electrical power output beyond its nominal level.

The charging and discharging operations, regulated by the charging valve opening and the pump rotational speed, respectively, are managed by an external controller to meet a given output power setpoint. In particular, if the power demand falls below the nominal value of 170 MWe, a PI controller adjusts the charging valve opening to reduce the power output of the system to the desired level. When the power demand is higher than the nominal value, a second PI controller is activated to regulate the pump's rotational speed and, consequently, the supplementary steam flow rate produced by discharging the TES.
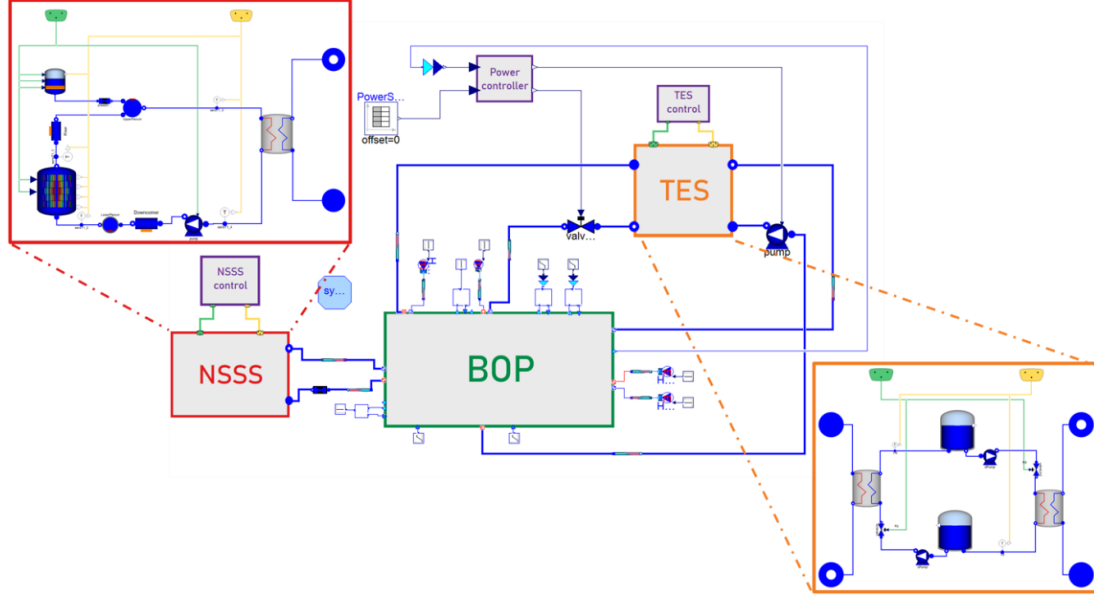

FIG. 2. Dynamic model of the integrated system.

3. CASE STUDIES AND RESULTS

The dynamic behaviour of the system is investigated in different case studies, each imposing electrical power setpoints to be satisfied by the considered architecture. While a comprehensive analysis of the design and operation of such systems would require a techno-economic optimisation, providing the most convenient storage capacity and power flows within a given timeframe, this work focuses on two illustrative profiles for the electrical power demand. These curves, constructed following the trend of the electricity market over a 24-hour period, are solely intended to showcase a potential application of the simulator. In the considered operational strategy, the electrical power output of the system is decreased by charging the TES during periods of low electricity prices, whereas the TES discharging is performed when electricity prices are high compared to the daily average.

Two electricity price profiles were selected to determine consistent power setpoints, sampled from a weekday and a weekend day in mid-April 2024. The curves stem from the German electricity market, which is characterised by a high penetration of VRE, whose availability strongly influences electricity prices. This applies especially during the weekends, where a high solar power output, combined with a low electricity demand, may result in negative electricity prices during the midday hours, as shown in the first panel on the right-hand side of FIG. 3. In such cases, ramping down the reactor's electrical power output could reduce economic losses. Given these market trends, two power demand profiles varying between 140 and 190 MWe were constructed. These operational limits are determined by the maximal charging and discharging capacities; hence, a lower power output would be only achievable by performing load following with the NSSS, thereby losing the advantages of maintaining the reactor at nominal conditions.

For each case study, the dynamic response of the system is analysed in terms of actual electrical power output, impact on the NSSS fission power, and TES tank filling level. The simulation outcomes demonstrate that the system can cope with highly variable load demands with a limited impact on the NSSS conditions. Notably, the core power variation, which remains below 0.2%, is driven primarily by reactivity feedback mechanisms triggered by a variation of the steam generator inlet temperature, which in turn affects the NSSS moderator temperature in the considered transients. This behaviour is particularly pronounced during the charging phase due

to the significant impact of the condensate return temperature on the feedwater state. During the charging phase, the reactor output exceeds its rated capacity of 540 MWth, highlighting the need to improve the NSSS control strategy to avoid potential safety concerns. It is worth mentioning that the average core temperature always remains within the allowed limits, meaning that no external reactivity needs to be injected by the NSSS controller. Lastly, the state of charge of the TES, represented by the liquid level in the two tanks, is monitored in the lower part of FIG. 3.
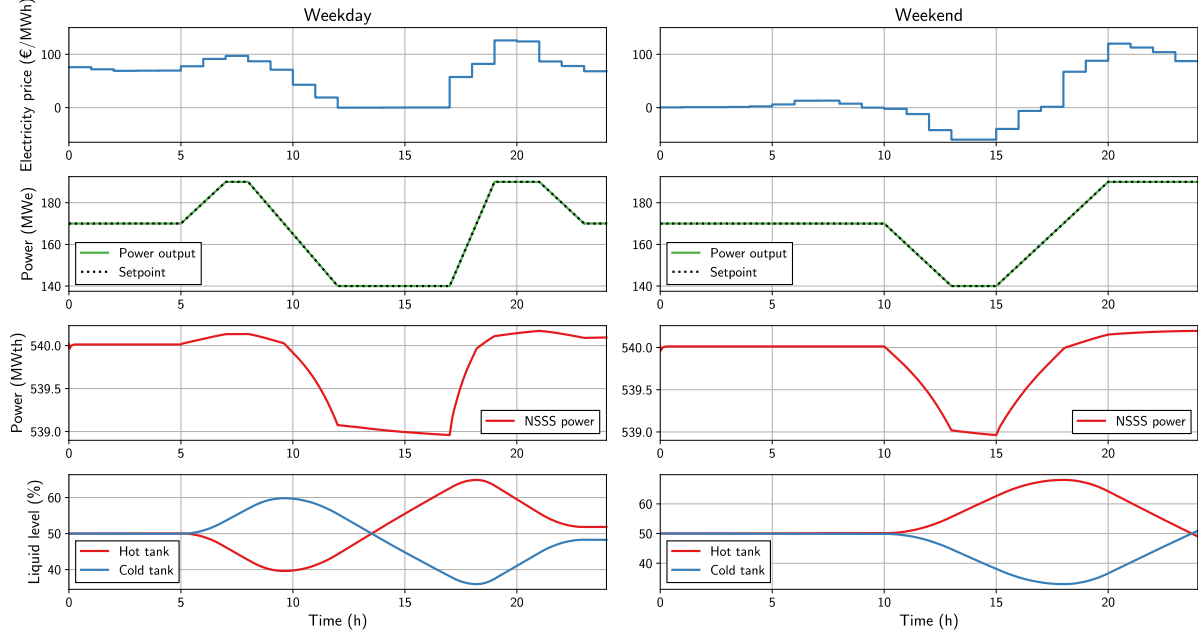

FIG. 3. Simulation outcomes in the two case studies.

While a comprehensive economic analysis of the system is beyond the scope of this work, it is possible to estimate the impact in terms of revenues obtained from the electricity market by comparing baseload operation, i.e., maintaining constant power output at 170 MWe, with the flexible operation facilitated by the TES examined in this study. In both case studies, the ability to manage the electrical power output according to the market evolution significantly enhances the revenue streams of the integrated system. Economic competitiveness improves particularly during the weekend, when electricity prices range from being negative up to peak prices in the evening. As a result, by regulating the power output consistently with this trend, revenues increase by 23% compared to baseload operation. This figure could be enhanced by ramping down the reactor's power to further reduce the electrical power produced by the system during times of negative electricity prices, thereby minimising financial losses. The benefits of flexible operation are less remarkable in the weekday scenario, with an increase in revenues limited to about 5%. This difference arises from the lower variability of electricity prices throughout the day, making TES charging less advantageous.

4.   CONCLUSIONS

In this study, a dynamic simulator of a light-water cooled SMR coupled to a two-tank thermal energy storage system is introduced. One of the key advantages of such configurations is their capacity to provide a variable electrical power output, coping with the VRE intermittency and its impact on the electricity market, while leveraging the benefits of maintaining the nuclear reactor at nominal conditions. The dynamic model has been tested with respect to two power output profiles, and the simulation outcomes demonstrate that the integrated system could meet such highly variable power demand by exploiting TES charging and discharging with minimal perturbations on the NSSS.

It should be acknowledged that the preliminary dynamic models proposed in this study rely on assumptions, such as the static approach adopted to model the BOP and TES heat exchanger, which will have a significant impact on the representativeness of the dynamic behaviour of the system.

In conclusion, the dynamic simulator for this configuration represents an initial effort towards developing a comprehensive framework for analysing such systems, encompassing a reliable dynamic representation and a techno-economic optimisation of its design and operational strategy, with the objective of assessing the impact and economic viability of such flexible power generators in the context of increasing VRE penetration. In this context, a techno-economic optimisation of the system would allow for the exploration of different operational modes (e.g., combining the reactor's flexible operation with TES charging and discharging) and evaluate the performances of the considered architecture in a broader range of scenarios, gaining a deeper understanding of its economic competitiveness.

ACKNOWLEDGEMENTS

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