Dynamic Modeling and Simulation of Thermal-Electrical Energy Systems in MVDC All-Electric Ships with Small Modular Reactors

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***Abstract*—This paper presents a thermal-electrical model for all-electric ships with small modular reactors as the prime mover. The impact of the cooling system on the propulsion motor and generator's performance has been investigated. The study emphasizes the importance of considering the cooling system's design and operation in the all-electric ship's energy system. The study shows that neglecting the cooling system's effect on the propulsion motor may cause a temperature rise of up to $4^{\circ}C$ degrees and an overload of the generator by up to 5% in less than 10 seconds. The activation of the cooling system's pumps leads to a slight drop in voltage, which can impact the system's overall performance. The findings provide valuable insights into developing effective control strategies for the cooling system to improve the system's efficiency and reliability.**

***Index Terms*—All-electric ships, cooling system, medium voltage DC, small modular reactor, thermal-electrical energy system.**

I. Introduction

The maritime industry is facing increasing pressure to reduce greenhouse gas emissions and improve energy efficiency [1]. All-electric ships have emerged as a promising solution to meet these challenges. These ships rely on electric power generated by a prime mover, which can be powered by various sources such as batteries, fuel cells, or small modular reactors (SMRs). Among these options, SMRs are a promising candidate as they can provide a reliable and long-lasting source of energy for all-electric ships. However, the thermal-electrical modeling of an all-electric ship with an SMR as the prime mover is a challenging task, which requires careful consideration of the interdependency between thermal and electrical networks in the ship model and the effect of considering the cooling system demand in the electrical network of the ship.

Thermal systems play a critical role in all-electric ships by regulating the temperature of the ship's electrical components and maintaining safe operating temperatures. With the increasing use of electric power systems, heat generation within the ship has become a significant concern, and thermal systems are designed to dissipate the generated heat to prevent damage to sensitive electronic components. These systems can include cooling systems such as fans or liquid cooling loops, as well as insulation to prevent heat loss. The thermal system must also be designed to handle extreme conditions, such as high ambient temperatures, to ensure that the ship can operate safely in all environments.

The efficiency of electric components, such as electric motors in propulsion systems, can be affected by heat loss in all-electric ships. Excessive heat can reduce the efficiency of electric components, causing increased energy consumption and decreased performance. Therefore, maintaining optimal temperatures within the ship's electrical systems is crucial for maximizing the energy efficiency and reducing energy waste.

The interdependency between thermal and electrical networks in all-electric ships is also significant. The thermal system must be designed to handle the heat generated by the ship's electrical components and dissipate it efficiently to maintain safe operating temperatures. At the same time, the electrical system must provide power to the ship's thermal systems to operate efficiently. Therefore, the two systems must work together in harmony to ensure that the ship operates efficiently and safely. The design and optimization of the thermal and electrical systems are critical for achieving this goal and maximizing the overall performance of all-electric ships.

A. Literature Review

The interdependency between the thermal and electrical systems on board is crucial to ensure the optimal performance and energy management, which has led to a surge of research in the field of thermal-electrical modeling for all-electric ships. Several studies have focused on the energy management of all-electric ships, considering strategies such as multi-objective optimization and heterogeneous energy management. For instance, Li et al. [2] proposed a multi-objective coordinated energy dispatch and voyage scheduling strategy for a multi-energy ship microgrid. Backlund et al. [3] developed a classifier-guided sampling method for the design of all-electric ship energy systems. Meanwhile, Fang et al. [4] investigated optimal heterogeneous energy storage management for multi-energy cruise ships. These studies highlight the importance of efficient energy management in all-electric ships, especially with the increasing complexity of their energy systems.

Another crucial aspect of all-electric ships is the heat loss recovery system. Zogogianni et al. [5] investigated the use of a heat loss recovery system for next generation ships with high levels of electrification, while Ahmadi et al. [6] proposed an energy-efficient solution of fuel cell heat recovery in zero-emission ferry boats. In addition, Barone et al. [7] used dynamic simulations to optimize the sustainable energy design of cruise ships, with a focus on waste heat recovery. Waste heat recovery is an essential component of all-electric ships, as it not only improves energy efficiency but also reduces greenhouse gas emissions.

Thermal management is another critical aspect of all-electric ships. Webb et al. [8] proposed a system-level thermal management strategy for pulsed loads on an all-electric ship, while Yang and Ordonez [9] investigated a cold thermal energy storage system for reliable ship cooling under thermal cycling and cooling loss. In addition, Li et al. [10] proposed a robust coordination strategy for a hybrid AC/DC multi-energy ship microgrid with flexible voyage and thermal loads. These studies highlight the importance of thermal management in all-electric ships, especially with the increasing complexity of their energy systems.

Overall, the research in the field of thermal-electrical modeling for all-electric ships has made significant progress in recent years. With a focus on efficient energy management, waste heat recovery, and thermal management, researchers have developed various strategies to improve the performance and sustainability of all-electric ships. The interdependency between the thermal and electrical systems on board is crucial to ensure optimal performance and energy management. Further research in this field is essential to address the increasing complexity of all-electric ships and to develop more sustainable and efficient energy systems.

B. Research Objective

This paper focuses on developing a comprehensive thermal-electrical model of an all-electric ship, which is powered by a small modular reactor (SMR). The SMR is considered as the prime mover in the model. The interdependency of the thermal and electrical networks are modeled to ensure safe and efficient operations. The cooling network plays a crucial role in regulating the temperature of the SMR and power network components, which is important for maintaining their operational efficiency and safety.

The modeling approach used in this study takes into account the various operational parameters that affect the performance of the all-electric ship. The thermal-electrical model consists of the SMR, the cooling network, and the electrical system. The results of the simulation show that the performance of the all-electric ship is highly dependent on the interplay between the power network and the cooling network. Our study highlights the importance of considering and simulating both systems simultaneously, which is crucial for achieving safe and efficient operations of the all-electric ship. The findings of the study can help in the design and optimization of the all-electric ships, especially those that are powered by SMRs.

The rest of this paper is organized as follows: Section II describes the thermal-electric energy modeling and mathematical formulation of all-electric ships; Section III discusses the results in a case study; Section IV summarizes the key findings of the study and discusses potential future work.

II. Thermal-Electric Modeling of All-Electric Ships

Figure 1 illustrates an integrated thermal-electric model of a cutting-edge nuclear-powered shipboard energy system. The nuclear reactor is utilized as the primary energy source onboard the ship, with a significant portion of the thermal energy produced by the reactor utilized for electricity generation through a steam power generator [11]. The generated electricity can then be used for various purposes, including powering the electric propulsion system, meeting the general power demands of the ship, and powering the compressor cooling system.

The remaining thermal energy produced by the reactor can be employed to fulfill the ship's direct thermal demands. The cooling system, responsible for regulating the temperature of critical components, including the heating, ventilation, and air conditioning (HVAC) system and the electric propulsion converters, plays an essential role in the safe and efficient operation of the ship. The cooling system is a critical component of any electric propulsion system, as it regulates the temperature of the electric motor used in propulsion. The power consumption of the electric pumps that drive the cooling system has a significant impact on the ship's overall power demand.

On the other hand, the temperature of the electric motor directly affects its efficiency and power consumption. As the temperature of the motor increases, its efficiency decreases, resulting in increased power consumption. Therefore, it is essential to maintain the motor's temperature within a specific range to ensure optimal performance.

The power consumption of the cooling system and the temperature of the electric motor are interdependent, and changes in one can affect the other. For instance, if the power consumption of the cooling system increases, it can lead to a rise in the temperature of the electric motor, which in turn reduces its efficiency and increases power consumption. Similarly, if the temperature of the motor rises due to external factors, such as high ambient temperature, it can increase the power consumption of the cooling system. Therefore, it is crucial to model and optimize the cooling system and the electric propulsion system simultaneously to ensure their efficient and safe operations. The proposed thermal-electrical model can help in the design and optimization of the cooling system and the electric propulsion system by considering their interdependency, which can lead to more efficient, reliable, and safe all-electric ships.

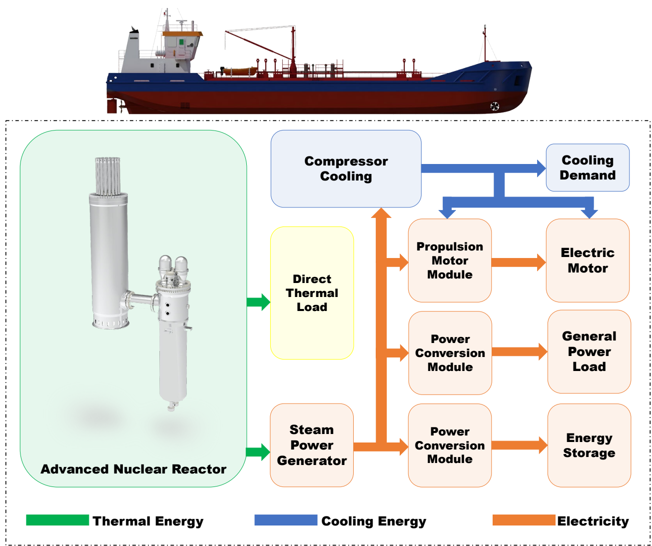

Fig. 1: The overall SMR-based all-electric ship energy system.

A. Two-zone Medium Voltage Direct Current (MVDC) Shipboard Power System

In this research, we employ a two-zone MVDC shipboard power system to assess the proposed thermal-electrical model [12]. The MVDC shipboard power system (SPS) model has been initially introduced by the Electric Ship Research and Development Consortium (ESRDC) [13] and then simulated through MATLAB Simulink [14]. The ESRDC model incorporates two 36 MW AC generators that provide power to a 12 kV two-zone MVDC network. There are different switchboards (SWBDs) that distribute the power flow throughout the entire network. However, since the ESRDC model includes aggregated loads, we made some changes to the model to include more information about different types of loads [15]. Figure 2 illustrates the overall structure of the modified two-zone MVDC SPS.

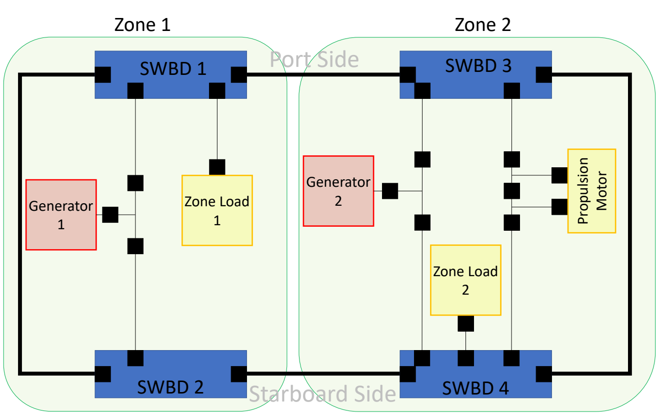

Fig. 2: The topology of a modified two-zone MVDC SPS.

B. Mathematical Formulation

In this section, all the mathematical formulation regarding different parts of the model is presented.

1) Nuclear reaction in the fuel: The nuclear reaction that occurs in the fuel of the SMR is represented by the following equation:

$$^{A}_{Z}\text{X} + n \rightarrow ^{A'}_{Z'} \text{X'} + \gamma + \bar{\nu}_e \tag{1}$$

where $^{A}_{Z}$X represents the fuel, n represents a neutron, $^{A'}_{Z'}$X' represents the fission products, γ represents a gamma ray, and $\bar{\nu}_e$ represents an anti-neutrino.

2) Heat generation in the SMR: The heat generated in the fuel due to the nuclear reaction is given by:

$$Q_{SMR} = \Delta mc^2 \tag{2}$$

where Q_{SMR} represents the heat generated in the SMR, Δm represents the change in mass due to the nuclear reaction, and c represents the speed of light.

3) Energy balance equation: The energy balance equation for the SMR is represented as follows [16]:

$$Q_{SMR} = \dot{m}_{in} c_p (T_{in}^{SMR} - T_{out}^{SMR}) - \dot{m}_{out} c_p (T_{out}^{SMR} - T_{in}^{SMR}) \tag{3}$$

where $\dot{m}_{in}$ and $\dot{m}_{out}$ represent the mass flow rates of the coolant (water) entering and leaving the reactor, respectively, c_p represents the specific heat of the coolant, T_{in}^{SMR} and T_{out}^{SMR} represent the temperatures of the coolant entering and leaving the reactor, respectively.

4) Thermal efficiency: The thermal efficiency of the SMR is quantified as follows:

$$\eta_{SMR} = \frac{\text{Useful heat output}}{\text{Heat input}} = \frac{\dot{m}_{out} c_p (T_{out}^{SMR} - T_{in}^{SMR})}{\Delta mc^2} \tag{4}$$

5) Generator modeling: The generator is driven by the high-temperature steam produced by the SMR, which can be described as follows.

$$P_{el} = \eta_{gen} P_{th} \tag{5}$$

where P_{el} represents the electrical power output of the generator, η_{gen} represents the efficiency of the generator, and P_{th} represents the thermal power input to the generator.

6) MVDC network modeling: The electrical power generated by the generator is supplied to the MVDC network of the all-electric ship. The equations that describe the MVDC network are presented as follows.

$$P_{in} = P_{out} + L_{eq} \frac{dI_{eq}}{dt} + R_{eq} I_{eq} \tag{6}$$

where P_{in} represents the total power supplied to the MVDC network, P_{out} represents the total power consumed by the loads in the MVDC network, L_{eq} represents the equivalent inductance of the MVDC network, I_{eq} represents the equivalent current flowing through the MVDC network, and R_{eq} represents the equivalent resistance of the MVDC network.

$$V = I_{eq} R_{eq} \tag{7}$$

where V represents the voltage of the MVDC network.

$$P_{out} = V I_{out} \tag{8}$$

where I_{out} represents the current flowing through the loads in the MVDC network.

7) Power flow modeling: The power flow equation for the MVDC network is described as follows:

$$P_{in} = P_{out} + P_{loss} \quad (9)$$

where $P_{loss} = I_{eq}^2 R_{eq}$ represents the power loss in the MVDC network.

8) Energy Efficiency: The energy efficiency of the all-electric ship is quantified as:

$$\eta_{ship} = \frac{\text{Useful power output}}{\text{Total power input}} = \frac{P_{out}}{P_{in}} \quad (10)$$

9) Electric motor modeling: The electric propulsion system of the all-electric ship consists of electric motors that convert electrical energy into mechanical energy to drive the propellers. The equations that describe the electric motors are given as follows.

$$P_m^{prop} = T_m^{prop} \omega_m^{prop} \quad (11)$$

where P_m^{prop} represents the mechanical power output of the electric propulsion motor, T_m^{prop} represents the torque output of the electric motor, and ω_m^{prop} represents the rotational speed of the electric motor.

$$P_m^{in,prop} = P_m^{prop} + P_m^{loss,prop} \quad (12)$$

where $P_m^{in,prop}$ represents the electrical power input to the electric propulsion motor, and $P_m^{loss,prop}$ represents the power loss in the electric propulsion motor.

10) Cooling demand modeling: The electric motors generate heat during operation, which must be removed to prevent overheating. The cooling demand of the electric motors can be represented as follows.

$$Q_{cool}^{prop} = \dot{m} C_p \Delta T^{prop} \quad (13)$$

where Q_{cool}^{prop} represents the cooling demand of the electric propulsion motors, $\dot{m}$ represents the mass flow rate of the cooling fluid, C_p represents the specific heat capacity of the cooling fluid, and ΔT^{prop} represents the temperature difference between the inlet and outlet of the cooling system for the electric propulsion motor.

11) Pump power modeling: The cooling fluid must be circulated through the electric motors using pumps, which consume electrical power. The power required to run the pumps can be represented as follows:

$$P_{pump} = \dot{m} \Delta P_{pump} \quad (14)$$

where P_{pump} represents the power required to run the pumps, ΔP_{pump} represents the pressure difference across the pump, and other variables have the same meaning as in the cooling demand equations.

12) Efficiency of electric propulsion system: The efficiency of the electric propulsion system depends on both the electrical and thermal performance of the system, which is quantified as:

$$\eta_{prop} = \frac{P_m^{prop}}{P_m^{in,prop}} = \frac{T_m^{prop} \omega_m^{prop}}{P_m^{in,prop}} \quad (15)$$

The efficiency of the electric propulsion system is affected by the temperature of the electric motors, as the power loss in the electric motors increases with the temperature. Therefore, the efficiency of the electric propulsion system can also be represented as:

$$\eta_{prop} = \frac{T_m^{prop} \omega_m^{prop}}{P_m^{prop} + P_{cool} + P_{pump}} \quad (16)$$

where P_{cool} represents the power required to meet the cooling demand of the electric motors, and P_{pump} represents the power required to run the cooling pumps.

13) Interdependency of thermal and electric networks: The electric propulsion system and the cooling system are interdependent, as the cooling system affects the temperature of the electric motors, which in turn affects the electrical performance of the electric propulsion system. Therefore, the power input to the electric motors must be adjusted to account for the power loss due to cooling and pumping, which is affected by the temperature of the electric motors. This can be represented as follows.

$$P_m^{in,prop} = P_m^{prop} + P_{cool} + P_{pump} + P_{trans} \quad (17)$$

where P_{trans} represents the power required to transfer heat from the electric motors to the cooling fluid.

Overall, the thermal and electric networks of the all-electric ship are interdependent and must be designed together to achieve optimal performance and efficiency.

III. Case Study

In this study, a two-zone MVDC network is used to model the SPS in Simulink. In addition, the heat loss of electric propulsion part is modeled based on (12)-(17). Furthermore, the coolant network with all the pumps and heat exchangers are modeled to show the impact of the coolant system on the temperature of the electric motor and the electric demand of SPS. All simulations are run on a laptop with Core i7 - 1.5 GHz CPU, 16 GB RAM, and NVIDIA GeForce MX230 GPU. All the power flow and operation simulations are conducted in MATLAB 2022 Simulink.

Figure 3 presents the speed diagram of the propulsion motor system during the case test in this study. The investigation incorporates several distinct scenarios, including sharp acceleration (seconds 5 to 7), steady state (seconds 7 to 17), sharp deceleration (seconds 17 to 20), and soft deceleration (seconds 25 to 30). The rated speed of the propulsion motor is considered to be 1800 rpm, while the full rated speed and 60% of rated speed are simulated as steady state situations. Figure 4 shows the power consumption of electric propulsion motor. The power consumption of a motor does not have a linear relationship with its speed. As a result, reducing the speed of the motor from 100% to 60% can cause a sharp decrease in power consumption, i.e., from 42 MW to less than 10 MW. This non-linear behavior is the main reason for the significant power reduction observed during sharp deceleration of the motor. Notably, the simulation outcomes of these scenarios offer significant insights into the performance of the propulsion motor system under various conditions, which are pertinent for the optimal design and operation of the motor system.

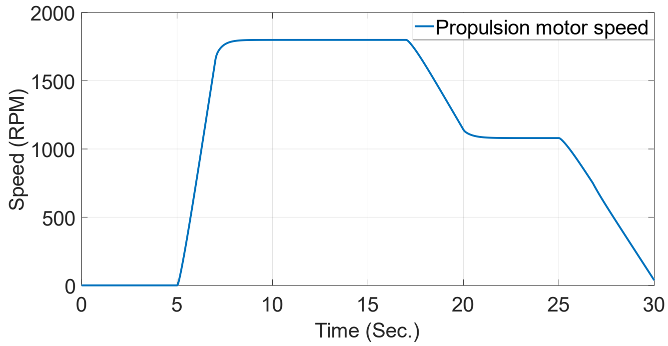

Fig. 3: The propulsion motor speed profile that consists of sharp acceleration (seconds 5 to 7), steady state (seconds 7 to 17), sharp deceleration (seconds 17 to 20), and soft deceleration (seconds 25 to 30).

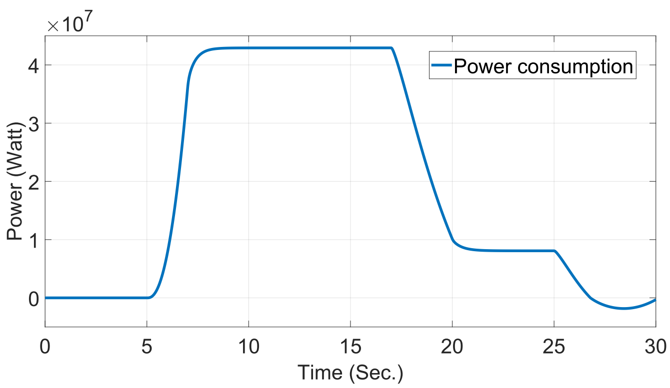

Fig. 4: The propulsion electric motor power consumption.

Figure 5 shows the temperature of the stator inside the electric motor of the propulsion system with and without considering the cooling system. It is shown that after 15 seconds, the temperature rises more than 112 $°C$ and the cooling system starts working to cool the motor. In addition, Fig. 6 shows that the cooling system starts at approximately second 15 and runs for about 10 seconds. The study demonstrates that the motor temperature can rise by more than 4 degrees and enter a dangerous zone within 10 seconds when the coolant system is not considered. Since the lifetime of electric motor windings is dependent on the fourth power of winding temperature, making it crucial to monitor the temperature and heat loss within the motor. Failure to do so can lead to premature degradation and failure of the motor.

Figure 7 displays the MVDC SPS voltage, comparing the scenarios with and without the consideration of the cooling system. It is observed that the voltage experiences a minor drop due to the activation of pumps in the cooling system at approximately second 15. Given that the pumps in certain architectures possess high rated powers, it is imperative to consider the potential influence of coolant pumps on voltage drops.

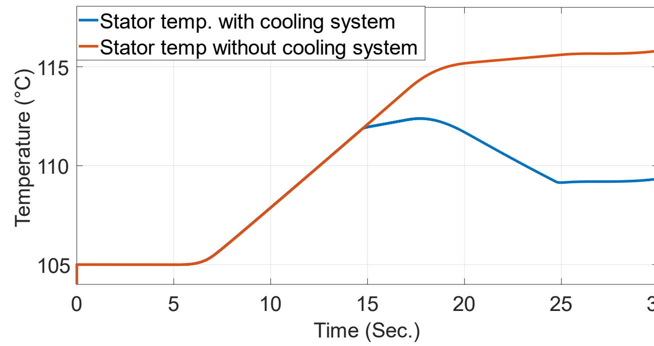

Fig. 5: The stator temperature of the electric propulsion motor with and without the cooling system.

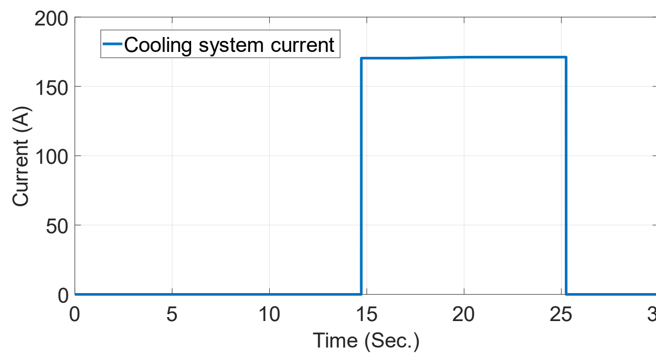

Fig. 6: The current of the cooling system.

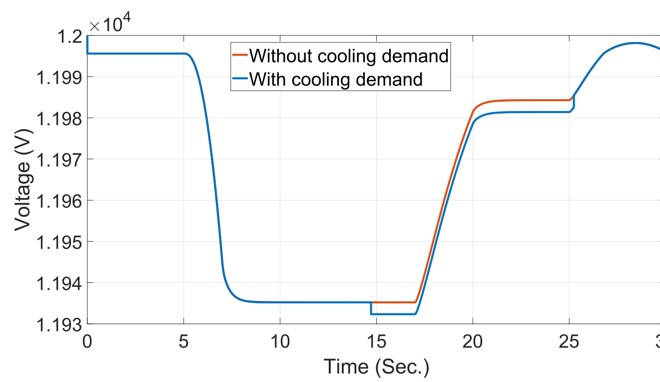

Fig. 7: The MVDC SPS voltage with and without the cooling system.

Figure 8 depicts the output power of one of the two generators, comparing the scenarios with and without the inclusion of the cooling system. The results show a notable increase in the generator's output power following the initiation of the cooling system. Specifically, the analysis reveals that the output power may rise from 90% to 95% of the rated power, primarily due to the activation of pumps in the cooling system. Notably, it is crucial to ensure that these power fluctuations do not push the generator into an overload situation, emphasizing the importance of controlling the SPS network's operation.

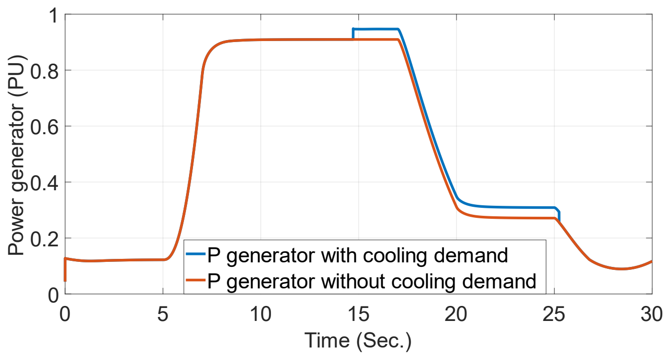

Fig. 8: The output power of one generator with and without considering the cooling system.

IV. Conclusion

In this paper, a thermal-electrical energy model was developed for all-electric ships with small modular reactors. The model was leveraged to investigate the impact of the cooling system on the propulsion motor and generator's performance. The results of the case study indicated that neglecting the cooling system's effect on the propulsion motor may cause a temperature rise of up to 4 degrees and an overload of the generator by up to 5%. Furthermore, the activation of the cooling system's pumps leads to a slight drop in voltage, which can impact the system's overall performance. The study highlights the importance of considering the cooling system's design and operation in the all-electric ship's power system. The findings provide useful insights to the development of effective control strategies for the cooling system to improve the system's efficiency and reliability.

Future work could focus on developing advanced cooling system designs and control strategies that can effectively manage the system's thermal and electrical performance. Additionally, further research could investigate the system's response to other operational and environmental factors, such as varying loads, pulse loads, ambient temperatures, and humidity levels, to provide a more comprehensive understanding of the all-electric ship's energy system.

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