Electric power consumption predictive modeling of an electric propulsion ship considering the marine environment

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**Abstract**

This study predicts the power consumption of an Electric Propulsion Ship (EPS) in marine environment. The EPS is driven by a propeller rotated by a propulsion motor, and the power consumption of the propeller changes by the marine environment. The propulsion motor consumes the highest percentage of the ships’ total power. Therefore, it is necessary to predict the power consumption and determine the power generation capacity and the propeller capacity to design an efficient EPS. This study constructs a power estimation simulator for EPS by using a ship motion model including marine environment and an electric power consumption model. The usage factor that represents the relationship between power consumption and propulsion is applied to the simulator for power prediction. Four marine environment scenarios are set up and the power consumed by the propeller to maintain a constant ship speed according to the marine environment is predicted in each scenario.

1. Introduction

In developing highly efficient ships with low noxious emissions, designers focus on replacing conventional propulsion systems to more efficient ones such as electric propulsion systems, to comply with the International Maritime Organization CO₂ emission rules. Electric propulsion systems differ in terms of power production from mechanical propulsion systems such as diesel engines and steam turbines, which generate torque directly from the main engine. An electric propulsion system produces power using a generator and achieves propulsion using a propulsion motor and propeller. This power transfer mechanism requires 10—15% less fuel than a mechanical propulsion system does. Even if an electric propulsion system incurs torque loss because of the engine, it can remain efficient owing to the hull resistance or propeller performance (Kim, 2007). The propulsion motor and generator are connected by a power cable, and thus, their arrangement is relatively flexible, thereby enabling reduction in the space required for the engine room. Consequently, the deadweight can be increased, and the amount of vibration and noise as well as the maintenance cost can be reduced (Kim, 2007). Electric propulsion systems can also be applied to Azipod propulsion with special ships, such as icebreakers and passenger ships, and could help in reducing their turning radius and improving their maneuverability (Kim, 2007; Koo, 2009).

Many attempts have been made to apply electric propulsion to merchant, passenger, and military ships (Hong et al., 2012; Kim, 2007; Koo, 2009). When designing an electric propulsion system, the power consumption must be predicted to determine the power capacity and analyze the dynamic characteristics of the system for verification in marine environments (Prempraneerach et al., 2009). Electric propulsion system research is generally focused on modeling dynamic characteristics, such as the power flow and starting current of the motor, and system design verification by performing simulations (Jeon, 2008; Kalsi and Nayak, 2005; Kim, 2013; Kwak, 2014; Lee et al., 2009; Zahedi and Norum, 2013). Researchers have also attempted to simplify the mathematical models to enhance the simulation efficiency.

The characteristics of a high-power electric ship propulsion system were modeled and analyzed in Jeon (2008). The author created a system model in accordance with the required shipping...
and conducted power analysis based on the load flow in the ship design. Kwak (2014) proposed a simplified electrical system model to reduce the time required to simulate an Electric Propulsion Ship (EPS). Kim (2013), using MATLAB/Simulink, modeled and simulated principal components, such as the generator, diesel engine, governor, motor, and Power Management System (PMS), for verification. For power consumption prediction, a method of conducting a preliminary estimation of the design power of a motion control system for a sea mining ship fitted with a tubular winning system was proposed by Bortnowska (2007). The power generation, distribution, and control concepts related to electric power systems and the described system design factors were dealt with by Bø et al. (2015).

In this study, we performed simulation modeling for the design and verification of efficient electric propulsion systems for EPSs. The simulation model consisted of two major parts: a ship motion model and an electric power consumption model. The ship motion model included models of three marine features, namely waves, wind, and current. This model was proposed to describe the marine environment for ship motion and propulsion at sea. To develop the electric power consumption model, we considered the electrical load to be caused only by the propulsion motor. The simulation model can be employed to predict the design electric power for propulsion and seakeeping by considering the effects of the marine environment load. We simulated the changes in the electric power consumption according to the marine environment by employing a usage factor, as suggested by Bortnowska (2007).

2. Marine environment action for modeling

The actions of waves, wind, and current were considered to model the marine environment for calculating the ship motion.

2.1. Wave action modeling

A regular wave is defined by Eq. (1) (Sorensen, 2013). Fig. 1 shows the coordinate system and directions of the waves, wind, and current. This model was proposed to describe the marine environment for ship motion and propulsion at sea. To develop the electric power consumption model, we considered the electrical load to be caused only by the propulsion motor. The simulation model can be employed to predict the design electric power for propulsion and seakeeping by considering the effects of the marine environment load. We simulated the changes in the electric power consumption according to the marine environment by employing a usage factor, as suggested by Bortnowska (2007).

\[ z(x, y, t) = z \sin(\omega t + \varepsilon) - k(x \cos(c) - y \sin(c)). \]  

where.

- \( \omega = 2\pi / T \): wave frequency
- \( k = 2\pi / \lambda \): wave number
- \( \lambda \): wavelength
- \( \varepsilon \): wave phase

Eq. (2) presents the definition of an irregular wave using a Fourier series with \( n \) regular waves (Sorensen, 2013). Each regular wave has a different amplitude, frequency, phase, and direction. These waves are superposed to generate an irregular wave similar to that in the real environment:

\[ z(x, y, t) = \sum_{i=1}^{n} z_i \sin(\omega_i t + \varepsilon_i) - k_i(x \cos(\chi_i) + y \sin(\chi_i)). \]  

where.

- \( n \): number of harmonic wave components
- \( x, y \): position on coordinate plane

Fig. 2 shows an irregular wave formed by the superposition of regular waves. Fig. 3 depicts the sea state generated by this irregular wave. Fig. 4 presents an example of the sea surface elevation of an irregular wave at the point (0,0) versus time. The sea surface elevation can be expressed using a Fourier series of regular waves in the time domain, wherein each wave has a random phase. According to meteorological changes, the marine environment worldwide changes with region and time. Consequently, the wave spectrum also changes. Moreover, even if the total energy of the wave spectrum remains the same, the energy distribution with respect to frequency is different. Thus, different environments may be generated according to the wave frequency. Despite this diversity, researchers suggested and used the standard wave spectrum with the appropriate assumptions for marine environments.

In this study, we employed the standard wave spectrum to generate an irregular wave (Yeom, 2012).

Eqs. (3) and (4) represent the International Towing Tank Conference (ITTC) and Joint North Sea Wave Project spectra, respectively (Lloyd, 1998; Sorensen, 2013). An irregular wave is generated using regular wave parameters, including amplitude, frequency, phase, and direction, which can be obtained from the wave spectrum.

\[ S(\omega) = \frac{173 \cdot H_1^2}{T_1^4} \omega^{-5} \exp \left( \frac{-692}{T_1^4} \omega^{-4} \right) \]  

Fig. 1. Coordinate systems and definitions of wind, waves, and current for modeling.

Fig. 2. Irregular wave formed by the superposition of regular waves to generate the marine environment.
\[ S(\omega) = \frac{320 H_{1/3}^2}{T_p} \omega^{-5} \exp \left\{ -\frac{1950}{T_p} \omega^{-4} \right\} \gamma^A, \]  
\[ \gamma^A = 3.3: \text{peakness frequency} \]

where.

- \( T_1 \): average wave period
- \( H_{1/3} \): significant wave height
- \( T_p \): peak frequency period
- \( \gamma^A \): peakness frequency

Further, \( \omega_p \) can be calculated using Eq. (5). The shape of the wave spectrum is determined by \( \omega_p \); hence, it is a crucial element that directly influences the irregular wave data.

\[ \omega_p = \frac{2\pi}{4.883 + 2.68 H_{1/3}} \]  

### 2.2. Wind action modeling

Wind is commonly composed of two elements: a mean value and a fluctuating component, both of which have direction and speed. Gusts that do not affect the wind direction are included only in the wind speed. A gust is a strong air flow at a particular moment, whereas wind involves a gradual variation. The effects of wind on objects differ according to the wind height because wind speed varies with height. Furthermore, although wind speed is a 3D phenomenon, it was considered to be a 2D phenomenon with (x,y) components in this research (i.e., the wind speed was considered only in the horizontal plane, which indicates that the wind speed was considered to be equal at every height). Wind was parameterized by speed and direction. The wind direction was defined, as shown in Fig. 1, and it was different from the wave direction. The wind direction refers to the direction in which the wind blows. Wind has a mean direction and mean speed as well as direction and speed variations within certain ranges. The wind load can be described in terms of the ship velocity using Eq. (6) (i.e., the Fujiwara wind load equation in a real sea environment condition) (Fujiwara et al., 2006):

\[ X_A = \frac{1}{2} \rho_A C_{AX}(\phi_A) U_A^2 A_T, \quad Y_A = \frac{1}{2} \rho_A C_{AY}(\phi_A) U_A^2 A_L, \]  

where.

- \( \rho_A \): air density
- \( C_{AX} \): x-component wind coefficient
- \( C_{AY} \): y-component wind coefficient
- \( C_H \): heel effect coefficient
- \( \phi_A \): relative wind direction
- \( U_A \): relative wind speed
- \( A_T \): front projected area
- \( A_L \): lateral projected area

The fluctuating component can be expressed using the first-order Gauss–Markov process, as in Eq. (7):

\[ \tilde{U} + \mu \tilde{U} = \omega \tilde{U}_{\text{min}} \leq \tilde{U} \leq \omega \tilde{U}_{\text{max}}, \quad \mu + \mu \tilde{\sigma} = \omega \tilde{\sigma}_{\text{min}} \leq \tilde{\sigma} \leq \omega \tilde{\sigma}_{\text{max}}, \]  

where.
A gust is described by Eq. (8), which indicates a Harris wind spectrum:

$$S(f) = \frac{4kU_10}{2 + f^2} f = \frac{1f}{U_10}$$

where:

- $L$: scale length (e.g., $L = 1800$ m)
- $k$: sea surface drag coefficient ($k = 0.0026$)
- $f$: frequency
- $U_{10}$: wind speed height at 10 m

### 2.3. Current action modeling

We only considered the mean current and restricted it to 2D with $(x, y)$ components. The 2D components describe only the surface current, disregarding that beneath the surface. The definition of current direction is similar to that of the wave direction. Current is parameterized by mean speed and mean direction. These parameters do not include the fluctuating component, and the mean value is equal at every depth. The current load can be expressed using Eq. (9) (Faltinsen, 1990; Park, 2011; Sorensen, 2013):

$$X_C = \frac{1}{2} \rho C_{CX}(\phi_C) U_{CA} a_T Y_C = \frac{1}{2} \rho C \int_{L_{pp}} dx \, C_{CV}(\phi_C) \left( \frac{A_L}{L_{pp}} \right) U_C^2$$

where:

- $\rho$: water density
- $C_{CX}$: x-component current coefficient
- $C_{CY}$: y-component current coefficient
- $\phi_C$: relative current direction
- $U_{CX}$: x-component of relative current speed
- $U_{CY}$: y-component of relative current speed
- $A_L$: front projected area
- $A_C$: lateral projected area
- $L_{pp}$: length between perpendiculars

### 2.4. Power consumption simulator modeling

The ITTC spectrum was used to generate irregular waves, and regular waves could also be evaluated. The wave model has two outputs. The first includes frequency, direction, amplitude, wave number, and phase, which can be calculated using the wave input parameters and wave spectrum in the wave model. The second output is the mean direction of the wave. The wind model also has two outputs: speed, direction, and the vector of mean direction and speed. The wave, wind, and current model can describe the marine environment for EPS propulsion and motion.

In this study, the simulation model consisted of the ship motion and electric power consumption models. We predicted power consumption in four marine environments: head, following, beam starboard, and beam port. The directions of wave, wind, and current on the ship were assumed to be identical for each environment. To simulate an actual marine environment, the representative statistical values of the marine environment were used. The same marine environment variables were used for each scenario while only the directions were changed. Thrusters are responsible for 70–90% of the total power consumption in an electric propulsion ship. Thus, the power consumption prediction of thrusters is particularly important in the power network configuration in the design stage. Therefore, to predict the power consumed in electric thrusters, we developed a model for power consumption in electrical thrusters and performed power consumption prediction simulations. For electric thrusters, the following two types of thrusters were considered: the main thruster that generates thrust for forward motion and the bow thruster that creates the thrust required for maintaining the heading angle. It was assumed that there is one main thruster at the stern and two bow thrusters at the bow. The power consumption estimation process is as follows, and it is illustrated in Fig. 5:

1. Calculate the external force due to the marine environment.
2. Calculate the ship motion due to the external force.
3. Calculate the thrust required for propulsion and posture maintenance.
4. Calculate the power consumption of the thrust motor for generating the calculated thrust.

The ship motion model was constructed by adding the wind and wind load calculation models to the Marine Systems Simulator (MSS, NTNU open tool) model. The MSS model can be utilized to calculate the ship motion and seakeeping with waves and current. The wind and wind load calculation models can be used to calculate the effects of the wind load on a ship, while the electric power consumption model can be employed to predict the electric power consumed by the propulsion motors (main and bow thrusters). The thrusts of the propulsion motors depend on the ship motion and seakeeping in the marine environment. Using the ship motion and electric power consumption models, we developed a simulator that can be used to predict the power consumption of an EPS by considering the marine environment, as illustrated in Fig. 6. The ship motion is calculated with six degrees of freedom (DOFs) using the inputs of the wave, wind, and current model and ship data (added mass, ship body mass matrix, damping coefficient, restoring coefficient, motion response amplitude operator, drift data, main dimensions, and outputs) calculated using Ansys AQWA ver. 14, which is a commercial tool. We utilized the ship data converted into the variables available in the ship motion model. The configuration of the electric power estimation model is shown in Fig. 6. This model consists of the ship motion model and electric power consumption model. The ship motion model evaluates the ship motion according to the marine environment, and the electric power consumption model estimates the electric power required for
generating the thrust. The numbers ① to ④ in Fig. 6 correspond to the steps listed in the procedure shown in Fig. 5.

The relationships among the ship motion, external force of the marine environment, and thrust, which are used to estimate the electric power, are as follows:

\[
\sum_{j=1}^{6} (M_{ij} \ddot{x}_j + B_{ij} \dot{x}_j + C_{ij} X_j = F_{0ij} + F_{odij} + F_{c} + F_{mj} + F_{bj}, \quad (i = 1 \ldots 6))
\]

where.

- \( i, j \): Motion number (1: Surge, 2: Sway, 3: Heave, 4: Roll, 5: Pitch, 6: Yaw)
- \( x \): Translatory and rotatory displacement of motion
- \( \dot{x} \): Translatory and rotatory velocity
- \( \ddot{x} \): Translatory and rotatory acceleration
- \( M_{ij} \): Ship rigid body mass and inertia matrix
- \( m_{ij} \): Ship added mass and added inertia matrix
- \( B_{ij} \): Damping coefficient matrix
- \( C_{ij} \): Restoring coefficient matrix
- \( F_{0ij} \): Wave load matrix
- \( F_{odij} \): Wind load matrix
- \( F_{c} \): Current load matrix
- \( F_{mj} \): Main thruster load (thrust, at stern) matrix
- \( F_{bj} \): Bow thruster load (thrust, at bow) matrix

Table 1 presents the ship specifications. Fig. 7 depicts the ship model with the modified scale and bow and stern shapes. The usage factor \( C_p \), which indicates the ratio of the marine environment load to the electric power consumed to generate the thrust on the ship, is employed to predict the electric power consumption of the ship. The value of \( C_p \) can be determined by considering the thrust specifications of the propulsion motor, propeller characteristics, and ship speed. In this study, we employed a \( C_p \) value of 0.2 by referring to a previous paper (Bortnowska, 2007). It is impossible to obtain the accurate value of \( C_p \) because it is affected by the propeller diameter, RPM, pitch, and the interaction between the motor and propeller. Therefore, an approximate value was used. If the total thrust of all thrusters is \( T_p \) and the electric power consumed by them is \( P_c \), the relationship between these two elements can be approximated by Eq. (11):

\[
T_p = F_m + F_b, \quad P_c = T_p / C_p
\]

where.

- \( P_c \): Total power consumption of thrusters [kW]
- \( T_p \): Total thrust of thrusters [kN]
- \( F_m \): Main thrust load [kN]
- \( F_b \): Bow thrust load [kN]
- \( C_p \): Usage factor describing the power consumption to generate the thrust by ship thrusters

2.5. Simulation scenarios

We predicted the electric power consumption using the simulator by calculating the ship motion and seakeeping. An autopilot model consisting of a Proportional, Integral, Derivative (PID) controller was employed to maintain the heading angle and the speed of forward advancement of the ship, and the electric power prediction simulation for the thrust on the propulsion motors—which expend electric power to generate thrust—was carried out. In the simulation, we assumed that thrust for ship advancement and maintenance of ship speed was generated by the propulsion motor (main thruster), which was located at the stern. The propulsion motor (bow thruster) at the bow could maintain a heading angle of 30°. The initial heading angle at zero ship speed was 0°. Fig. 8 shows the initial ship position, heading angle, forward advance, and acting direction of the marine environment. Table 2 summarizes the directions of the marine factors in the four scenarios investigated. When a ship moves forward at the speed of 10 kn (5.144 m/s) owing to the thrust of the main thruster, the thrust of the bow thrusters must be used to maintain the heading angle at 30° (based on global coordinate), and the electric power consumed by this was estimated. The thrusts of the main and bow thrusters are controlled by the PID controller and are used to maintain the ship speed and heading angle.

The conditions other than the directions of the marine factors in each case were set as listed in Table 3. The simulation time was 300 s, and the simulation step size was 0.02.

**Table 1**

<table>
<thead>
<tr>
<th>Specifications of the target ship.</th>
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<td>Dimension</td>
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<td>Lpp</td>
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<td>Breadth</td>
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<td>Draft</td>
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<td>Kyy</td>
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<td>Kzz</td>
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3. Results

3.1. EPS electric power consumption simulation results

Figs. 9–12 show the irregular wave sea states for the four scenarios. Fig. 13 shows the initial position (0,0) and ship route in each scenario based on the global fixed coordinate system defined in Fig. 1. The environmental effects cause the route to differ in each case from the required route labeled “Without environment loads” in Fig. 13, which is a route without environmental action.

In the two beam cases in which the external force of the marine environment is received from the side, the route deviation based on the “Without env.” route was larger than the cases of “head” and “following”. In all cases, the main thruster is operated to maintain the ship speed at 10 kn, and the resulting traveled distance was approximately 1500 m.

In the “head” and “following” cases, the environmental load was received on the bow (front) and stern (rear) of the ship, respectively. Fig. 14 shows the ship speed in each case, and it is noted that the ship speed variations were similar in all cases. The ship reached the highest speed of 14.579 kn (7.5 m/s) at 75 s, and then gradually slowed down to the set ship speed of 10 kn.
Figs. 15–18 show the predicted power required to maintain the routes according to the simulations. The upper section in each graph represents the electric power consumption of the main thruster for propulsion and ship speed control. The middle section depicts the electric power consumption of the bow thruster for heading angle control. The lower section shows the total electric power consumption of the main and bow thrusters.

In each case, the main thruster generated the thrust for propelling the ship; the maximum thrust was generated at approximately 43 s and the maximum power consumption was approximately 96 MW. The electric power consumption of the bow thrusters in the “head,” “following,” “beam starboard,” and “beam port” cases was continuously at the maximum value of 35 MW (17.5 MW × 2) for 50 s, and the heading angle was changed to 30°. After 50 s, the electric power consumption oscillated around half of the maximum value of 35 MW in the “head” and “following” cases, while it oscillated with a larger amplitude in the “beam starboard” and “beam port” cases. Figs. 19–22 show the roll, pitch, and yaw of the ship; the yaw angle is the same as the heading angle.

The yaw increased until approximately 45 s with an overshoot of 35° and started to converge to 30° after 45 s. The zone in which the heading angle increases for 45 s after the ship begins to move coincides with the zone in which the bow thruster consumes the maximum power. The “beam port” case showed a larger roll amplitude than the “head,” “following,” and “beam starboard” cases.

4. Discussion

We simulated the changes in the electric power consumption according to the marine environment by employing a usage factor, as suggested by Bortnowska (2007). The power consumption sections of the main thruster were divided into two sections: 0–100 s and post 100 s. Compared to the other cases, in both the power consumption sections, the “head” case in which the marine environment acts in front of the ship, consumed the maximum power. This is because the external forces of wave, wind, and current acted in a direction opposite to the forward moving direction of the ship. In contrast, compared to all other cases, the “following” case consumed the lower power in both the power consumption sections because the ship receives the external force of the marine environment at the stern; because the external force is received from the stern to the bow direction, the external force is added to the thrust in parallel to the forward-movement direction of the ship. Thus, the ship speed of 10 kn can be maintained with a small thrust and power consumption. In the cases of “beam starboard” and “beam port,” the ship received the external force of the marine environment at its sides, and in both the sections, the “beam starboard” case consumed more power than the “beam port” case. The reason for this is as follows: The external forces acting on the ship can be divided into x and y elements based on the global fixed coordinate system, and in the “beam starboard” case, the x-element external force acts opposite to the direction of the forward motion of the ship unlike in the “beam port” case. Furthermore, the “beam starboard” and “beam port” cases exhibited larger route deviations from the “Without env.” route than the “head” and “following” cases because the environmental loads acted on the sides of the ship in the former two cases. Moreover, the electric power consumption of the bow thrusters became high to maintain a heading angle of 30°. The total power in Figs. 15–18 indicates the sum of the main and bow thrusters’ electric power consumption.
The bow thruster consumed the maximum power of 35 MW for 50 s after startup in all cases, which showed similar tendencies. After 50 s, the two beam cases consumed more power than the "head" and "following" cases. The beam starboard and "beam port" cases showed similar power consumption and maintained high power loads. This is because, in the beam case, in which the ship receives the external force at the side, the yawing of the ship is more severe than in the other cases. The "head" case demonstrated greater power consumption in all sections as compared to the "following" case, whereas the "following" case exhibited a very low power load. This information can be considered when determining the generator capacity necessary to handle the electrical load. Finally, the usage factor can be determined by considering the thrust specification of the propulsion motor, propeller characteristics, and ship speed; however, we used the usage factor of 0.2 in reference to Bortnowska (2007). If we use the usage factor considering the abovementioned characteristics, we can obtain a more exact result of the electric power consumption for each environment case.

In this study, the effects of the external force of marine environment were determined, and the thrust of the main thruster required to maintain the ship speed under an external force and the resulting power consumption could be predicted. Moreover, we predicted the electric power consumption required by two bow thrusters (17.5 MW) to maintain heading angles from 0° to 30° in marine environments. These results can be applied when designing electric propulsion systems for the dynamic positioning systems of ships and offshore plants in specific ocean areas or along specific routes to determine the propulsion system, capacity, or type of thruster needed, considering the marine environment. In particular, the results of this study can be used in designs that require selection of the power generation capacity and the equipment capacity of electric propulsion systems and consideration of the response characteristics of the system according the variations of power load.


5. Conclusions

This study proposed models of three environmental features to simulate real sea states. The subsequent ship motions and position changes were analyzed with six DOFs using a ship motion model. A simulation for estimation of electric power consumption was developed by integrating an electric power consumption model with the ship motion model and considering the marine environment load. The power required to maintain the ship speed and heading angle was predicted in each investigated scenario using
Fig. 15. Power prediction: head.
Fig. 16. Power prediction: following.
Fig. 17. Power prediction: beam starboard.
Fig. 18. Power prediction: beam port.
Fig. 19. Roll, pitch, and yaw: head.
Fig. 20. Roll, pitch, and yaw: following.
Fig. 21. Roll, pitch, and yaw: beam starboard.
Fig. 22. Roll, pitch, and yaw: beam port.
the proposed simulator. Among the four environment cases, the “head” case consumed the maximum power, followed by “beam starboard,” “beam port,” and “following”. The time taken to change the heading angle from 0° to 30° was approximately 50 s in each case. The power consumption pattern for 50 s after start of the ship was as follows. In the case of the main thruster, the power consumption steadily increased for 50 s, and gradually decreased and converged after 50 s. In the case of the bow thruster, the power consumption was the largest for 50 s, and then, the power consumption exhibited different trends in each case.

The results of this research can support decision making and provide base data for the design of electric propulsion systems, including power generators and propulsion motors (main and bow thrusters). Extension of this model and its combination with PMSs or other electrical control systems could enable it to be applied to software- or hardware-in-the-loop systems by considering the marine environment.

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