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Power Management Strategies Based on Propellers Speed Control in Waves for Mitigating Power Fluctuations of Ships

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***Abstract*— This paper proposes two novel Power Management Strategies (PMS) to enhance the electrical power quality in twin-screw All-Electric Ships (AES) during vessel-wave encountering. Soothing PMS (SPMS) focuses on mitigating power fluctuations of the propulsion system since it has significant impacts on the power system in extreme conditions. For this purpose, the PMS modifies propellers speed based on the in-and-out-of-water effect Loss Factor (LF) in wave collisions. This method does not require typical equipment, such as Energy Storage Systems (ESS), to moderate the variations. Hence, it decreases the ESS demand capacity and maintenance costs at the design and operation levels. An integrated ship model is introduced to determine this loss factor in waves thoroughly. Furthermore, due to the propeller dynamics in speed altering, an adaptive delay is embedded in SPMS to improve its efficiency, and an Advanced Soothing PMS (ASPMS) is developed. To determine this varying adaptive delay during an operation, a straightforward algorithm is proposed that does not impose the PMS to compute complex differential equations. Simulations reveal that both PMSs soothe the propulsion system power fluctuations and remarkably reduce the power system frequency and voltage variations. Meanwhile, the ASPMS surpasses the SPMS in terms of improving the power quality.**

***Index Terms*—All-Electric Ships, Power Management Strategy, Wave Collisions, Electric Propulsion System, Microgrid.**

I. Introduction

THE marine industry has devoted increasing interest to the electrical propulsion system in recent years. The rise in the power demand alongside contemporary concerns on energy conservation and environmental protection have motivated more investigations on the AES costs and benefits [1], [2]. The propellers power fluctuations in extreme conditions vastly impact the ship power system and pose challenges for the power system control, reliability, and stability [3]. Due to the hydrodynamic interactions and wave excitations, thrust loss and torque fluctuation are considered as inherent components of a ship propulsion system [4]. One of the prominent sources of the power fluctuations reported in the literature is the variations arising from the in-and-out-of-water effect [5]. In severe to extreme conditions, the sea elevation and ship motion result in large movements of thrusters relative to the water [6]. Due to the in-and-out-of-water impact, changes in the propeller submergence produce substantial transients in thrust and reduce AES electrical power quality. The in-and-out-of-water effect is sorted as low-frequency fluctuations and can be measured up to the propeller rated load [4]. Therefore, the in-and-out-of-water impact in different operating conditions and approaches for compensating the effects should be inspected comprehensively.

Besides, surveying PMSs to reduce the influence of the fluctuations on the ship power system is critical at the design and operation levels. A review of power management optimization methods in marine vessels is presented in [7]. In order to prevent blackouts, an approach for frequency control that reduces the propulsion system power allocation during a diesel generator outage is presented in [8]. A method for regulating power consumption and optimizing power generation planning by managing the propellers is provided in [9]. In [10], a power redistribution controller that dispatches the power from the loads with power variations to the thrusters is presented. The presented controller is based on a combination of frequency control and fast load reduction. In [11], the demand-side management takes the propulsion load and thermal load optimization into account. Then, a joint optimization model is introduced to coordinate trip scheduling and vessel power generation in different load situations. In [12], power generation and demand-side power management systems to optimize the operational cost of ships and lessen greenhouse gas emissions are explored. A PMS is introduced in [13] that controls the propulsion system along with splitting the power between various energy sources to improve fuel consumption efficiency. A method for reducing the propeller torque fluctuations and increasing the propeller lifespan during ship maneuvers is presented in [14]. In [15], a thorough approach to model the in-and-out-of-water influence on the power variations of the AES power system in model-based designs is proposed. The prediction of the propulsion system power consumption considering the marine environment is explored in [16]. A step modulation strategy for reducing the propulsion system thrust loss and fuel consumption is introduced in [17].

According to the literature, the state-of-the-art focuses on power-sharing between different energy sources, such as batteries, flywheels, and ultra-capacitors, to decrease propulsion system fluctuations [18]–[22]. Therefore, these approaches yield to elevate the ESS capacity and the design cost of a vessel. Although the above-mentioned methods use power re-allocation to mitigate these fluctuations, their main target is the variations caused by service loads like bow thruster in

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normal conditions. In other words, they do not explore decreasing the power fluctuations originated intrinsically from the propellers by the power re-allocation methods. Thus, these methods may not perform suitably during wave collisions in severe conditions. Furthermore, to investigate the performance of the suggested approaches, the literature is often deployed load profiles for the propulsion system derived from the specific experiential outcomes or voyage data records. Hence, the design and operation strategy based on these attributes does not ensure optimum and efficient performance under various scenarios. In this paper, innovative power management strategies for reducing the electrical power fluctuation in vessel-wave encountering are proposed to address these challenges. The PMSs regulate the propellers speed concerning the in-and-out-of-water effect during wave collisions and enhance the AES electrical power quality. Moreover, an integrated ship model is developed to precisely obtain the LF during these conditions in the PMSs and investigate the methods functionality thoroughly. This model considers the dynamics of the power system and ship motion, emphasizing the in-and-out-of-water impact on the power system. Thus, it can be used as a model-based design tool in the maritime industry.

The rest of the paper is organized as follows. Since the integrated ship model is an essential component in the PMSs for estimating the in-and-out-of-water LF and also plays a critical role in assessing the PMSs efficacy, first, it is presented in section II. Also, the suggested framework for attaining the propellers immersion depth and the corresponding LF is described in section III. Then, SPMS and ASPMS, which are based on adjusting the propeller speed during wave collisions, are explored in section IV. Next, a notional vessel is simulated using the presented model in MATLAB/Simulink simulation environment. The effectiveness of the PMSs is analyzed through two case studies, and the benefits and the contrasts of the approaches are discussed in section V. Finally, the conclusion of this study and future works are provided in section VI.

II. All-Electric Ship Model During Wave Collisions

An interconnected model for exploring the linked effects of ship motion and power system during vessel-wave collision is introduced in this section. It is implemented in the proposed strategies to determine the power system variations produced by the ship motion in waves. A framework of the model is shown in Fig. 1. The interactions between the electrical and hydrodynamic principles of the AES are inspected in this model. For a more explicit understanding of the interconnections between various study fields, the model is divided into three main parts: 1) the control model, 2) the hydrodynamic model, and 3) the power system model. The control model defines the route and the desired ship speed during a voyage, and its integrated approaches keep the ship on the right track. The power system model provides a comprehensive model of the ship microgrid. The central part of the power system, which connects other sections of the ship model, is the propulsion system motor and the motor drive.

Moreover, the hydrodynamic model is split into three sections: 1) the ship motion, 2) the propeller, and 3) the in-and-out-of-water effect. The hydrodynamic behavior of a ship during a maneuver is examined in the ship motion section. The in-and-out-of-water impact model investigates the wave collision impact on the propeller thrust based on their open-water characteristics. Finally, the dynamic responses of the propeller are provided by the propeller model. As stated, an accurate model is crucial in exploring the presented power management solutions. Thus, individual components of the ship model and their linkages are explained in the following sections in further detail.

A. The Power System Model

An all-electric ship power system architecture concerning the typical power system of actual vessels is depicted in Fig. 2 [23]–[26]. Based on characteristics of contemporary operating AESs from [23], [24], the determined voltage of the primary bus for this analysis is 690 V/60 Hz. However, it should be highlighted that the goal of this study is to eliminate fluctuations originating

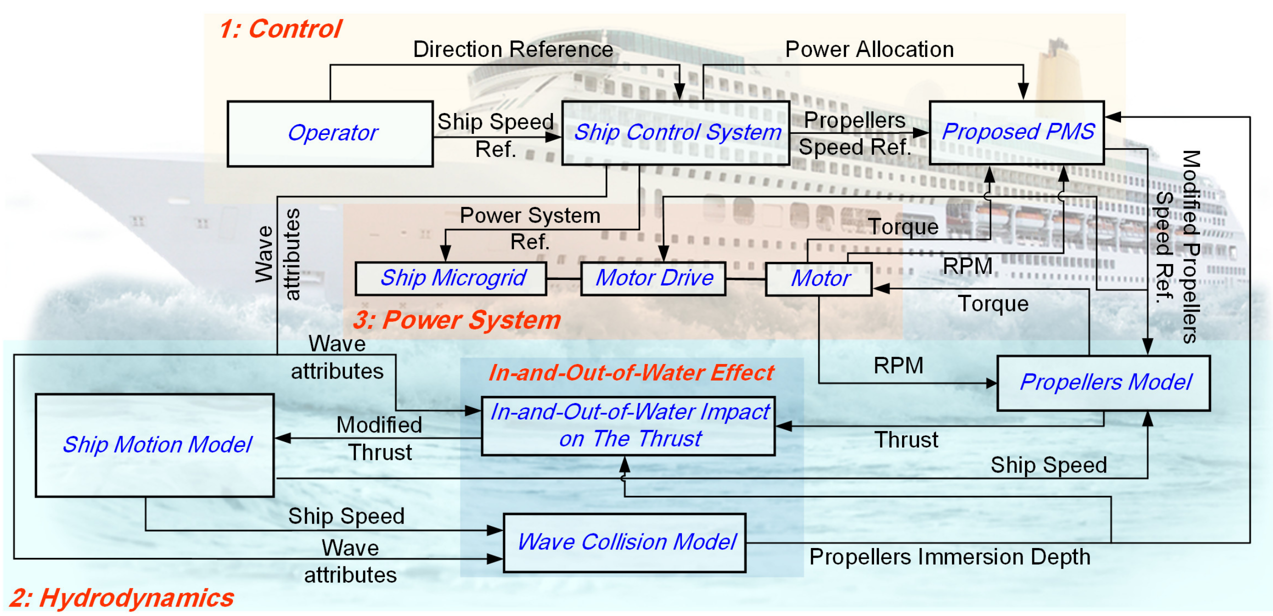

Fig. 1. The integrated model for estimating the in-and-out-of-water effect on the marine power system in wave conditions.

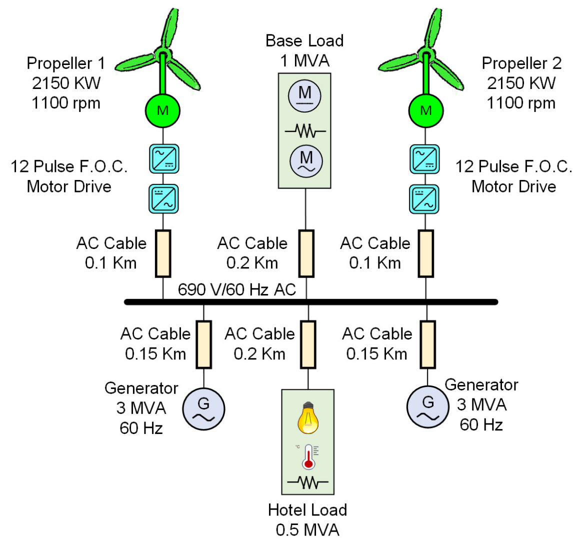

Fig. 2. The typical power system architecture of an AES.

from the propulsion system. Thus, the benefits of the subsequently proposed approaches are not restricted to this predefined structure. Two 3 MVA salient pole diesel generators provide power. IEEE AC1A standard excitation systems with non-controlled rectifiers control the field voltages of these generators [27], [28]. A standard dynamic model for the governor of the generators, which consists of temperature and speed control loops, is used in this study [25], [29]. A droop control method is derived for power-sharing in this multi-generator power system [30]. Droop control is preferred in modern vessels since it eliminates the need for communication between the governor controllers [31]. It permits the frequency and voltage to adapt in response to the active and reactive power demands. Since the propellers are the major consumers and their dynamic features have a notable influence on the power system, the focus of the power system model is on the propulsion system. The propulsion system has two 2,150 kW/1,100 rpm asynchronous motors. These motors are driven by 12-pulse field-oriented control drives [32]. This type of drive adjusts the stator current relative to the rotor flux and keeps an orthogonal angle between the magnetomotive force of the armature and the field flux. Hereby, it regulates the torque and flux of the motor independently. The rest of the typical loads in an AES are aggregated as the Hotel Loads and the Base Loads. The Hotel Loads are consumers that are used as hotel services in an AES, such as lighting, ventilation, and heating. The Base Load consists of other loads required for the ship operations, such as pump motors [33].

B. The Ship Control System

The control system primary goals are maintaining the speed of the ship and the travel route to their desired states related to the predefined journey duration and destination of the vessel [34]. Thus, the ship motion aspects, including ship speed and angles, are monitored in the control system [35]. According to the measured attributes and the desired ship speed and voyage route, the control system specifies the navigation and the power system references, such as the propeller expected speed, the rudder angle, and the power allocations. The motor drives set the propellers motors stator current to attain the propellers speed reference. Based on the open-water characteristics, the propeller model identifies the produced thrust, which results in the ship velocity change. The SPMS and the ASPMS are also embedded in the ship control. The detailed aspects of these methods are discussed in section IV.

C. The Hydrodynamics Model

The hydrodynamic model aims to explore ship movements under various conditions. Without losing the generality, this segment of the model focuses on the marine angles in vessel-wave conditions due to the primary emphasis of this study. The balance between the propeller thrust and vessel hull resistance determines the ship surge velocity during a voyage [36]. The ship velocity and direction are investigated in the ship motion model using hydrodynamic principles [26], [37], [38]. The relativity of the ship velocity to the produced thrust is demonstrated in (1) [36].

$$m\dot{U} = R(u) + T(1 - r_h) \tag{1}$$

where m denotes the total ship mass, U is the ship speed, $\dot{U}$ identifies the first derivative of U, r_h is hull resistance thrust reduction, and $R(u)$ is the total resistance of the ship while heading forward, including the wind resistance and the frictional resistance [35].

In the propeller model, the torque and thrust of the propeller are evaluated. The torque and thrust are usually expressed by two dimensionless terms: the thrust coefficient (K_T) and the torque coefficient (K_Q). These coefficients are acquired based on open-water tests and propellers geometrical characteristics [37]. K_T and K_Q are commonly defined as related to the advance coefficient (J_A), which can be identified by the advance velocity of the ship (V_a).

$$J_A = \frac{V_a}{nD} \tag{2}$$

The propeller thrust and torque are determined by the following formulas [39].

$$T = \mathrm{sgn}(n)\beta_T K_T \frac{\rho n^2 D^4}{4\pi^2} \tag{3}$$

$$Q = \mathrm{sgn}(n)\beta_Q K_Q \frac{\rho n^2 D^5}{4\pi^2} \tag{4}$$

where D is the diameter of the propeller, ρ is the density of the fluid (here water), n is the propeller rotational speed, T is the produced thrust, and Q is the torque of the propeller. In addition, β_T and β_Q are the thrust and torque loss factors representations. These coefficients are determined by the in-and-out-of-water effect model in the proposed framework. A comprehensive mathematical model-based method for obtaining these factors is presented in section III. The in-and-out-of-water effect model modifies the propellers thrust considering the LF, and the ship movements effects on the thrust in wave interactions are explored accordingly.

III. The In-and-Out-of-Water Effect on The AES Power System

In this section, a comprehensive model for investigating the in-and-out-of-water impact is introduced and merged with the hydrodynamic section in Fig. 1. This model enables the overall framework to examine the ship motion in wave collisions and explore the in-and-out-of-water influence on the electric power system. It is divided into 1) the wave collision model and 2) the in-and-out-of-water impact on the thrust. The following subsections look into how these components interact in the larger context.

A. The Wave Collision Model

The wave collision model surveys the ship motions during wave collisions consistent with the sea state and the wave characteristics. The corresponding coordinates and angles used in the wave collision model are shown in Fig. 3. In this figure, U is the ship speed, u is the ship x-axis velocity, v is the ship y-axis velocity, ψ_{wave} is the wave angle, θ is the vessel pitch angle, and φ is the ship roll angle. First, the sea state is estimated by the ship control system. Most modern maritime ships are equipped with sensors that monitor global ship motion at designated points relative to the center of gravity [40], [41]. These sensors provide large amounts of data regarding their operating condition, such as fuel consumption, acceleration, attitude, and ship position [42]. Marine vessels can estimate the sea state in which they are operating by analyzing these data. An overview of diverse sea state estimation methods proceeded is provided in [40]. However, in the absence of these motion sensors, long-term and short-term weather forecasts can supply adequate information regarding the operation region, and the engaging wave parameters can be approximated based on them [43]. After evaluating the sea state and the encountering wave attributes, if the ship faces an irregular wave, the wave collision model converts the wave into a superposition of regular waves. A regular wave is expressed related to the vessel coordinates as (5) [16].

$$\zeta(x,y,t) = A\sin(\omega t + \varepsilon - kx\cos(\chi) - ky\sin(\chi)) \tag{5}$$

where ω is the wave frequency, k is the wave number, ε is the phase of the wave, χ is the direction of the wave, and x and y are positions on the X- and Y-axis. Furthermore, an irregular wave is presented by (6).

$$\zeta(x,y,t) = \sum_{i=1}^{n}\begin{bmatrix} A(i)\sin(\omega(i)t + \varepsilon(i) - \\ k(i)x\cos(\chi(i)) - k(i)y\sin(\chi(i))) \end{bmatrix} \tag{6}$$

where n is the harmonic number of wave components. Then, depending on the orientation and attributes of each wave along the route, vessel roll and pitch are inspected. Closed-form mathematical expressions are established in the model to evaluate the wave-induced motions [44]–[46]. For instance, (7) formulates the ship roll angle in regular waves.

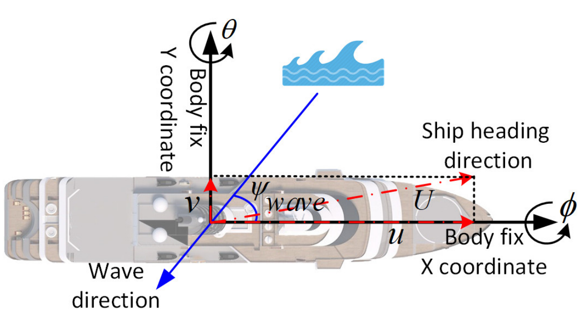

Fig. 3. The ship coordinate system and the wave direction angle.

$$J\ddot{\varphi} + \frac{2\pi J}{T_0}\mu\dot{\varphi} + Dh\varphi = M \tag{7}$$

In (7), J donates the ship inertia, T_0 is the rolling natural period, μ is the damping coefficient, D is the deadweight of the ship, h is the metacentric height, and M is the rolling moment of the vessel. In addition, $\dot{\varphi}$ and $\ddot{\varphi}$ denote the first and second derivative of the ship roll angle, respectively. Similarly, other ship motion angles are acquired.

Then, the model investigates the propellers submergence by the obtained angles during the voyage. Fig. 4 shows the presented method used in this model to attain the immersion depth of the propellers in wave collisions. In Fig. 4 scheme, the propellers submergence alterations in a vessel with two symmetrical propellers (also known as twin-screw ships) are examined considering the ship roll angle [15]. It is assumed that propeller1 and propeller2 are the propellers on the ship starboard and port sides. Propeller1 submergence variations in the presented method are expressed as (8).

$$S_1(t) = S_0 - \frac{B}{2\times\tan(\phi(t))} \tag{8}$$

In (8), S_1 is propeller1 submergence in waves, S_0 is the propellers immersion in calm water, and B is the ship breadth. Propeller2 immersion depth is stated in (9) as well.

$$S_2(t) = S_0 - \frac{B}{2\times\tan(-\phi(t))} \tag{9}$$

The same technique is used to determine the propeller submergence based on the pitch angle. The wave collision model calculates the propeller submergence altering for each regular wave. The total change in the propellers immersion depth at each moment is gained by the superposition of the waves effects.

B. The In-and-Out-of-Water Impact on The Thrust

The reduction of the propeller immersion depth in waves results in the loss of propulsion system thrust. The LF for the generated thrust is derived in the in-and-out-of-water impact on the thrust model, subject to the propeller submergence depth given by the wave collision model. Then, according to the obtained LF, the propeller thrust from the propeller model is amended and provided for the ship model. Thus, the in-and-out-

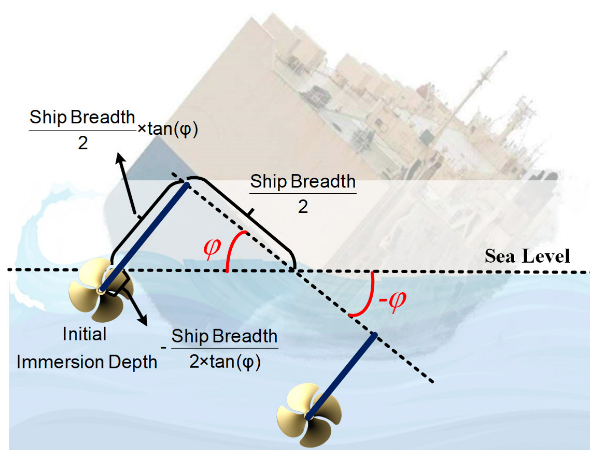

Fig. 4. Obtaining the propeller submergence depth method in a twin-screw ship under wave interaction condition based on the roll angle.

of-water impact on the thrust model quantifies the ship motion influences on the produced thrust during wave collision circumstances. Since this effect is essential during the ship operation, the LF is noted in numerous forms in the relevant researches. In this paper, a common term in literature is used for the in-and-out-of-water impact on the thrust [15], [47].

$$\beta = \begin{cases} 0, & h/R \le -0.48 \\ 1-0.675(1-0.769h/R)^{1.258}, & -0.48 < h/R < 1.3 \\ 1, & h/R \ge 1.3 \end{cases} \quad (10)$$

where β is the thrust LF caused by the in-and-out-of-water, R is the propeller radius, and h is the propeller submergence. The thrust LF is a non-dimensional index between 1 and zero, and as can be deduced from (10), it is dependent on the propeller immersion depth, which was obtained from the wave collision model. Thus, the interaction of the wave collision and the in-and-out-of-water impact on the thrust model leads to a proper modification of the produced thrust in terms of the LF. As a consequence, the ship motion model acquires an authentic value of the propellers produced thrust and estimates the ship motions accurately.

IV. The Proposed Power Management Strategies

In previous sections, the wave influences on the ship motion and decreasing the propellers submergence are explored. Moreover, a model for obtaining the in-and-out-of-water impact LF in waves is presented. Power fluctuations caused by the propeller immersion depth variations are major challenges in the marine industry. In order to proficiently mitigate these fluctuations and enhance the power quality and efficiency, two possible power management strategies are developed as follows:

1) The Soothing PMS (SPMS)
2) The Advanced Soothing PMS (ASPMS)

The main principles of these two approaches are the same, except that the latter incorporates a novel extension for improving the ability of the SPMS in enhancing the power quality. Thus, first, the concept of the SPMS, which is shared by both strategies, is explained in the following subsection. Then, the distinguishing embedded method of the ASPMS is discussed in the second subsection.

A. The Soothing Power Management Strategy (SPMS)

After estimating the sea state and acquiring the encountering wave characteristics from the ship control system based on the motion sensors data, the wave collision model provides the propellers immersion depth. Respectively, the propellers thrust LF is evaluated at each moment. During the occurrence of the in-and-out-of-water effect, the SPMS modifies each propeller speed reference in compliance with the opposing propeller LF. The speed adjustment representation for propeller1 is expressed in (11) and (12).

$$SMC_{p1} = -LF_{p2}(t)\frac{PA_2}{PA_1} + 2 \quad (11)$$

$$\omega_{p1}(t) = SMC_{p1}\omega_{0p1} \quad (12)$$

where SMC_{p1} is the speed modification coefficient for propeller1, LF_{p2} is propeller2 LF during the wave collision, ω_{p1} is the adjusted speed reference for the motor drive, and ω_{0p1} is propeller1 initial speed reference defined by the control system. Besides, PA_1 and PA_2 are the propellers power allocation determined by the ship control system depending on the operating condition. Propeller2 speed alteration can be stated likewise. The scheme of the proposed strategies is depicted in Fig. 5. In the following, the fundamental idea behind each term is clarified.

As previously noted, the LF is a coefficient that ranges from zero to 1. It is 1 when the propeller is fully immersed in water and drops as the submergence decreases. The SPMS transforms the LF into a coefficient suitable for the propeller speed

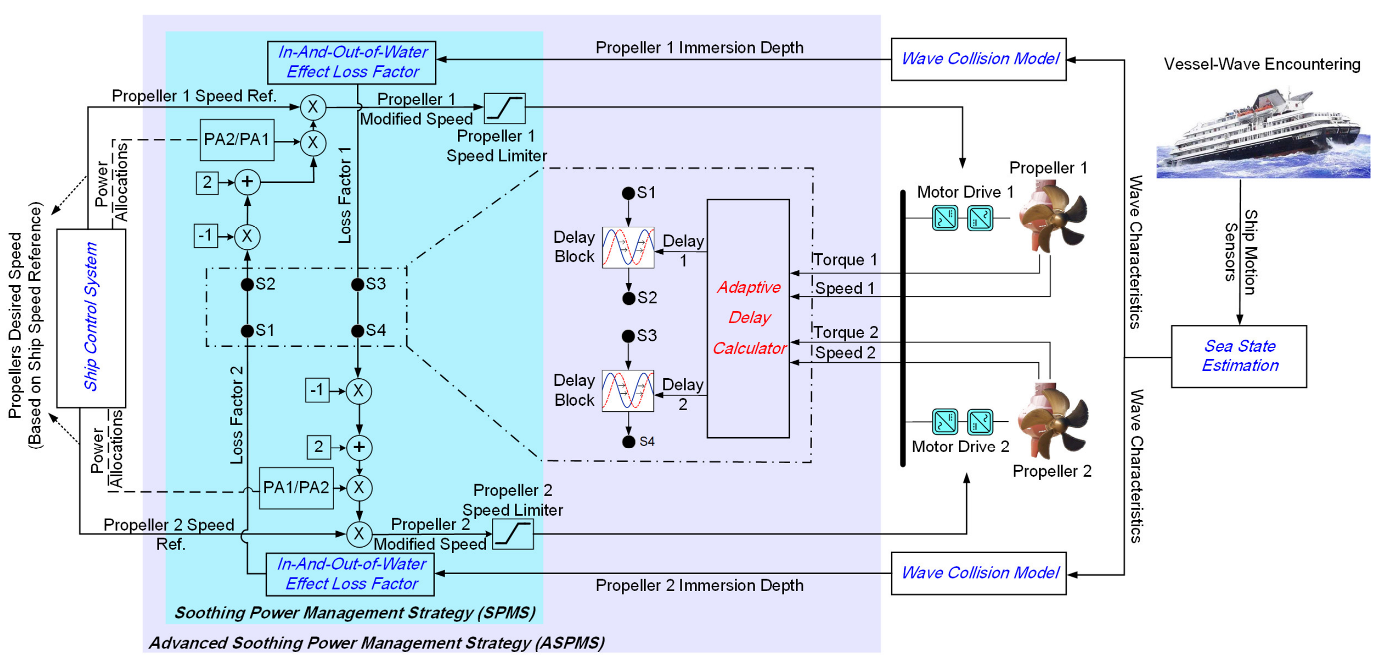

Fig. 5. Block diagram of the soothing power management strategy and the advanced soothing power management strategy for mitigating the power fluctuations of the ship propulsion system in wave collision states.

correction by reversing it into a negative value and adding 2 to it. Regarding (11), the parallel propeller LF is used to adjust each propeller speed in the strategy. Applying the modifying factor to the motor speed reference increases the propeller speed when the other propeller immersion depth decreases. Thus, the propeller power consumption rises when the opposing propellers electric power decreases. Therefore, the approach smooths the power fluctuating in the ship power system during extreme conditions. Moreover, for a proper function in maneuvering conditions, in which the allocated power consumption of the two propellers usually differs, the speed conversion indices time the power allocations ratio. Thus, as in (11), propeller1 speed modification index multiplies into the PA_2/PA_1 term. It is noteworthy that the propellers speed reference modification in this amplitude and time-scale does not substantially affect the vessel direction and routes. It is due to the relatively large inertia of propellers and marine vessels. Similar studies mentioned the negligibility of the power re-allocations impacts on the ship navigation targets in a similar timeframe [8], [10], [11]. Besides, according to the definition of the irregular wave in the presumed sea environments and the periodical features of the segregated regular waves, the impact of waves on ship motions is approximately symmetrical in a wave collision over a long period of time. Thus, it is expected that as long as the sea state remains the same during a sufficient period of time, the proportionate speed altering in the proposed strategies does not essentially impact the route and direction of the ship in an operating condition [48]. However, if the vessel journey path changes, the voyage route is re-adjusted by the ship navigation control via rudder angle change or the thrusters power re-allocation [49]. It does not influence the PMSs operation and can be done while they are functioning.

B. The Advanced Soothing Power Management Strategy (ASPMS)

The key aspect of the ASPMS is the same as that of the SPMS. However, the advanced one delays the initial LF before applying the speed modification to the propeller. Thus, the propeller1 speed revision expression, as stated in (11), is updated for the ASPMS as given below:

$$SMC_{p1} = -LF_{p2}(t - t_D)\frac{PA_2}{PA_1} + 2 \tag{13}$$

where t_D is the adaptive delay in this approach. This delay aims to coincide the minimum point of propeller1 LF with the peak of the power consumption increase of propeller2 in each wave encountering period, and vice versa. The delay is set in terms of the motor drive, the motor, and the propellers dynamic responses to the speed change. In addition, it varies depending on the amplitude of the required speed altering and is updated in each wave period. Thus, determining the optimum delay entails solving complex differential equations repeatedly and taking the dynamic responses of different electrical and mechanical segments of the ship into account. This challenge can complicate the control system and affects the power system stability.

Therefore, an adaptive delay calculator block is incorporated into the ASPMS to avoid the issue above, as shown in Fig. 5. This block employs an innovative and straightforward algorithm to provide an adaptive delay. The algorithm is depicted in Fig. 6. As it can be observed in Fig. 6, the process determines the time distance between the power consumption peak and the LF minimum point during the power fluctuation mitigation at each wave collision period. First, it multiplies the speed (ω) and the torque (Q) of each propeller. The result is electrical power consumption (P_e) of the propellers, as given in (14).

$$P_e = Q\omega \tag{14}$$

Comparing the first derivative of P_e sign with the LF first derivative sign, each propeller power peak lagging/leading status corresponding minimum point of the parallel propeller LF is analyzed. Afterward, the adaptive delay is set based on the lead/lag condition and the time distance between the propeller power peak and the opposing propeller LF minimum point. If the power peak leads to the LF minimum point, the algorithm decreases the difference from the previous delay amount. Otherwise, the discrepancy would be added to the prior amount of delay. Moreover, the suggested algorithm avoids altering the delay quantity during the transition times between wave periods. For instance, the delay amount is kept fixed through over/undershoots of the propellers power consumption in the course of the ASPMS operating. The adaptive delay algorithm takes the second derivative of P_e into account for this purpose. While the second derivative of the P_e is positive, it signifies that the power waveform has an upside convex. It is contrary to the phase in which the propeller speed increases for the power fluctuation mitigation. Thus, it can be deduced that the power is at a transient state after the last speed adjustment. Therefore, the approach blocks the delay calculation process until the next wave collision happens. In addition, a speed-limiting block is appended before feeding the updated speed reference to the motor drive to maintain the propeller speed within its restricted range. The proposed methods functionalities are simulated in the next section by utilizing the introduced ship model, and the results are examined.

V. Simulation

A ship model is simulated in MATLAB/Simulink environment using the interconnected model presented in

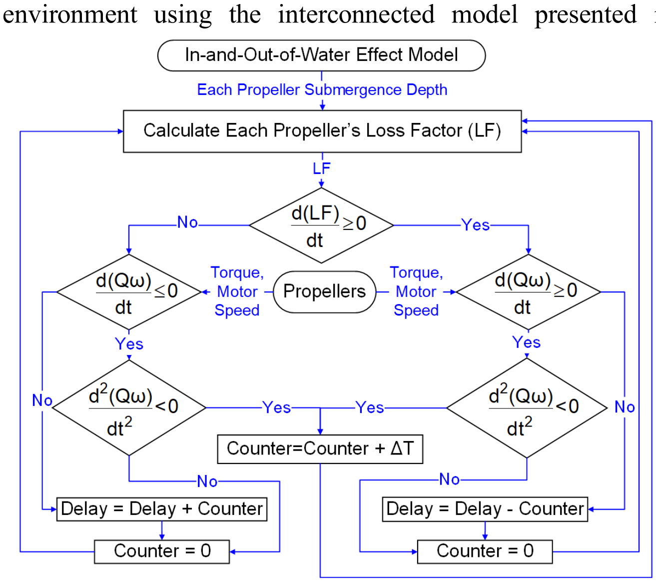

Fig. 6. The proposed algorithm for determining the adaptive delay in the ASPMS.

sections II and III, and the PMSs are implemented in the control system. For the wave collision operating condition, a 48 kiloton mass mariner vessel with 82.8 meter length and twin thrusters is modeled [14], [24]. The ship parameters are presented in Table 1. As previously noted, the in-and-out-of-water effect is considered as a low-frequency fluctuation in the literature [4]. Thus, regarding the converters in the propeller motor drive model and the ship motion hydrodynamics, the simulation time step is set to 60 µs.

Moreover, it is presumed that the ship experiences an irregular wave, as per standard sea states [18]. Without losing the generality, it is supposed that the vessel is on the right track. Thus, the propellers power allocations are identical. The irregular wave is divided into two regular waves, as discussed in section III. The segregated periodic waves hit the front and port sides of the vessel. The two regular waves and the original irregular wave superposition are shown in Fig. 7. The characteristics of the two regular encountering waves are summarized in Table 2. The simulation period is set to one minute, relying on the wave characteristics. The following case studies examine and contrast the performance of the proposed solutions in compensating the power system variations in the designated sea conditions.

A. Case Study I

In this case study, the standard power system structure in Fig. 2, which is based on modern operational vessels, is developed to explore the PMSs. As seen in this figure, energy storage devices are not provided in the supposed AES power system for mitigating low-frequency fluctuations. Therefore, the advantages of the ASPMS and SPMS can be thoroughly explored and compared with the situation in which the power management does not contain these approaches to minimize the variations. The ship motion angles while encountering the regular waves from the front and port sides of the vessel are illustrated separately in Fig. 8 and Fig. 9, respectively. As it is shown, during wave collision from the front side, the roll angle stays unvarying, and the same happens to the pitch angle while the port side wave strikes the ship. Moreover, the immersion depth changes of the twin propellers during the initial irregular wave collision are depicted in Fig. 10. The propellers

TABLE 1
THE VESSEL AND TWIN PROPELLERS CHARACTERISTICS

Parameter	Value	Parameter	Value
Ship length (m)	82.8	Ship speed (knots)	15
Propeller immersion depth (m)	7	Propeller diameter (m)	5
Ship breadth (m)	37	Number of blades	4

TABLE 2
THE ENCOUNTERING WAVE CHARACTERISTICS

Parameter	Wave 1	Wave 2
Amplitude (m)	10	7
Vessel side of collision	Port side	Front side
Time period (s)	7	5
Relative direction (deg.)	90^{o}	0^{o}

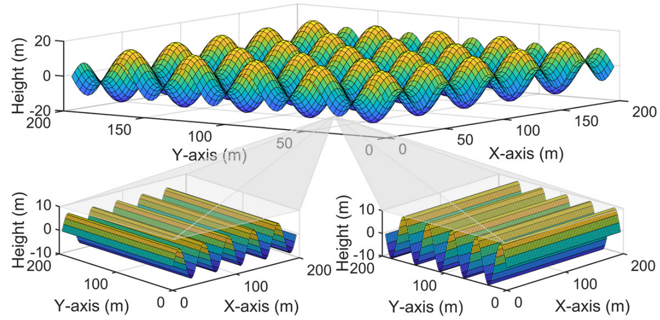

Fig. 7. The superposition of two regular waves and the derived irregular wave in the assumed vessel environment.

submergence shifts in this figure cause thrust loss. The issued LF of each propeller is shown in Fig. 11. It can be observed that at certain wave intervals, the followed thrust loss is up to 60 percent of the steady-state value. Each propeller speed reference when ASPMS is used during the wave collision scenario is seen in Fig. 12. Furthermore, a moment of deploying the latest adaptive delay is magnified in this figure. The SPMS speed adjustment figure is approximately similar to Fig. 12 but without delay to the modifications and resulting transients. In Fig. 13, the delay amount for each propeller, which applies to the propeller speed adjustment in the ASPMS, is illustrated. The

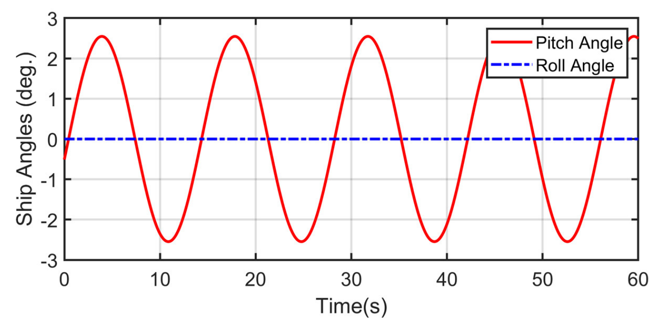

Fig. 8. The ship motion angles during the front side wave encountering.

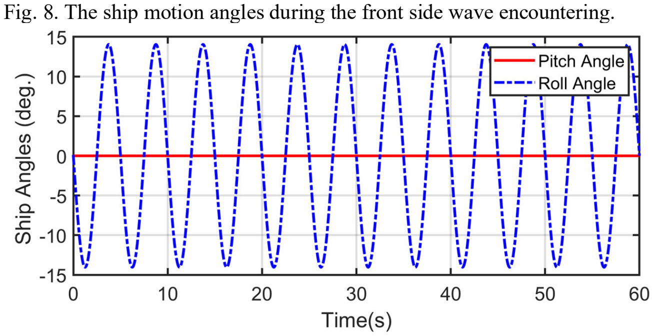

Fig. 9. The ship motion angles during the port side wave encountering.

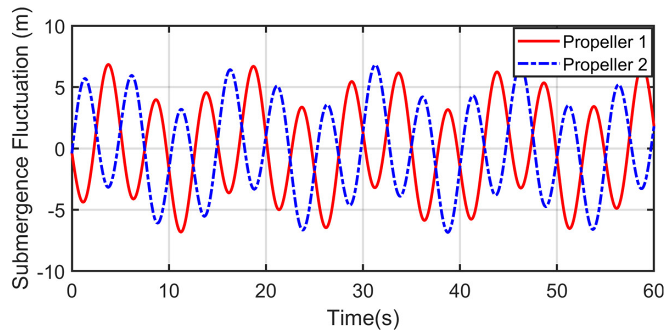

Fig. 10. The propellers immersion depth alternations during the irregular wave encountering.

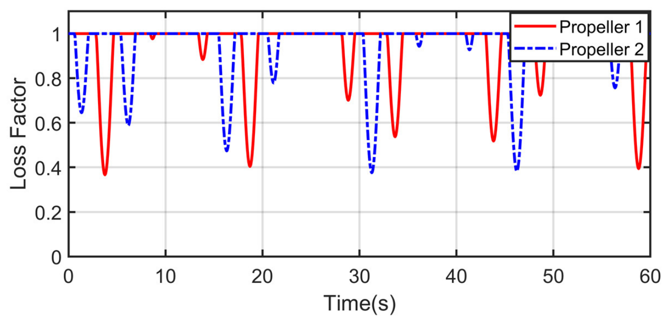

Fig. 11. The LF of the propellers during the irregular wave encountering.

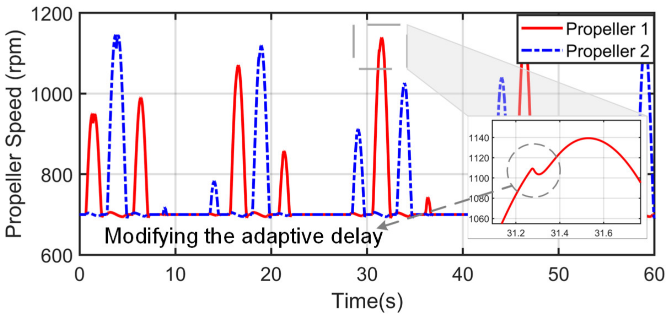

Fig. 12. The propellers motor speed adjustment by the ASPMS during irregular wave encountering.

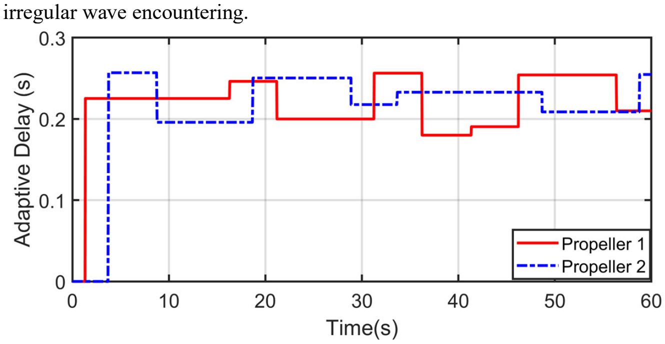

Fig. 13. The adaptive delay amount in the ASPMS during the irregular wave encountering.

delay is corrected after each wave cycle, and it is obtained by the delay calculation block shown in Fig. 5.

Furthermore, Fig. 14 and Fig. 15 show the frequency and voltage variations of the vessel power system in the wave interaction in the following scenarios: 1) The ship control system does not include the PMSs, 2) The SPMS is integrated into the propulsion system control, 3) The ASPMS is deployed in the ship control system. It is demonstrated in Fig. 14 and Fig. 15 that in the absence of the proposed PMSs, the maximum voltage and frequency variations are 4.6 and 3.3 percent, respectively. The SPMS reduces the maximum voltage and frequency variations to 3.1 and 2.5 percent, as seen in Fig. 14 and Fig. 15. Finally, by implementing the ASPMS, which includes the adaptive delay for aligning the minimum of the LF of one propeller with the peak of the electrical power of the parallel propeller, the voltage and frequency fluctuations are significantly decreased to 0.8 and 0.6 percent, as shown in Fig. 14 and Fig. 15. Thus, the SPMS reduces the voltage and frequency changes compared to the conventional control system even without the adaptive delay. However, utilizing the adaptive delay in the ASPMS boosts the method efficiency and results in more prominent fluctuations moderation. Using these methods to improve power quality can alleviate other applications constraints in achieving the permissible frequency and voltage variations based on design stage standards [50]. Furthermore, it reduces the necessity of deploying stabilized supply for certain loads, such as electronic circuits, that require more limited voltage and frequency fluctuations to function properly [51]. Since ASPMS and SPMS are suitable for maintaining the permissible power system fluctuations independent of the ESS, they can be beneficial at the operational and design level.

The mitigation of the frequency and voltage fluctuations is the outcome of compensating for electric power fluctuations by the PMSs in extreme conditions. Fig. 16 shows each propeller

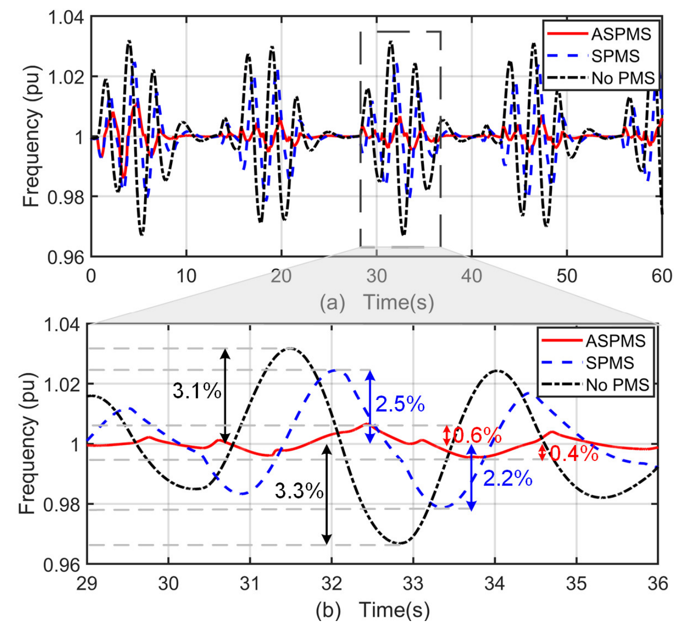

Fig. 14. Frequency fluctuations during wave encountering: 1) without utilizing the PMSs (black graph), 2) with the SPMS (blue graph), 3) with the ASPMS (red graph); a) for the simulation time from 0s to 60s b) for the simulation time from 29s to 36s.

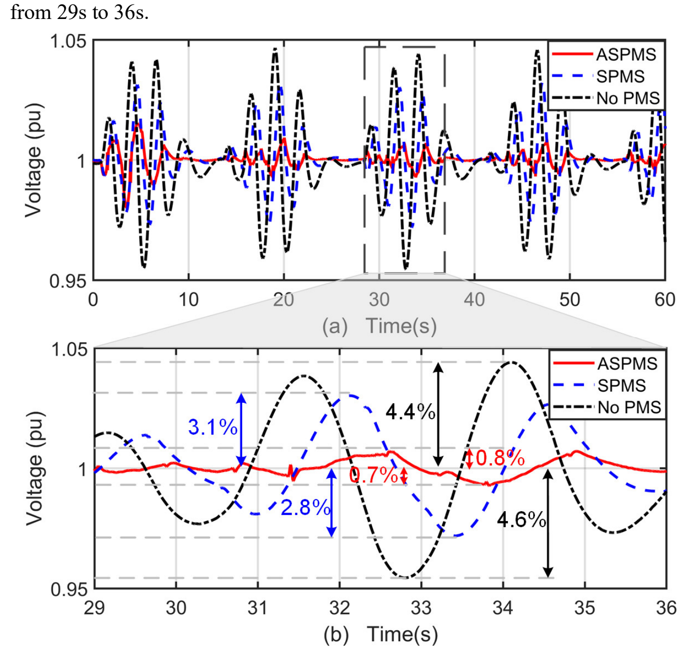

Fig. 15. Voltage fluctuations during wave encountering: 1) without utilizing the PMSs (black graph), 2) with the SPMS (blue graph), 3) with the ASPMS (red graph); a) for the simulation time from 0s to 60s b) for the simulation time from 29s to 36s.

and the total power consumption of the propulsion system. It is demonstrated in the previously listed case studies, which are: a) without the PMSs, b) with the SPMS, and c) with the ASPMS. It can be investigated from Fig. 16 that using the PMSs moderates the overall power fluctuations. The propellers power fluctuations reach 0.42 p.u. without the PMSs. However, employing the SPMS decreases the amplitude of the variations to 0.33 p.u. Engaging ASPMS results in a considerably less power fluctuation amplitude, which is 0.2 p.u. The time distances between the power consumption peaks and the LF minimum points are magnified in Fig. 16 (b) and Fig. 16 (c) for a better evaluation. It can be observed that the suggested adaptive delay in the ASPMS leads to the time gap reduction by up to 80% compared to the SPMS. As indicated, the decrease in the power oscillations lessens the necessity of ESS power capacity in the power system. To highlight this feature, single-sided spectrums of the low-frequency power oscillations amplitude are illustrated in Fig. 17 and Fig. 18. The figures are obtained by Fourier transform of power consumption variations, excluding the DC component. Fig. 17 shows the frequency spectrum of the power consumption without employing the proposed strategies in the ship PMS.

However, Fig. 18 displays the amplitude of the frequencies that the power consumption contains when ASPMS, as the advanced method proposed in this paper, is integrated into the PMS. It can be seen that ASPMS significantly soothes the low-frequency oscillations resulting from the in-and-out-of-water effect. The dominant low-frequency amplitude of the power fluctuation reduces about 85% by employing ASPMS. Since the low-frequency variations determine the battery power capacity at the design level [52], the EES sizing, ship investment cost, and weight can be reduced by utilizing the developed methods. In the next subsection, the functionality of ASPMS and SPMS is compared with the battery energy storage system in further detail.

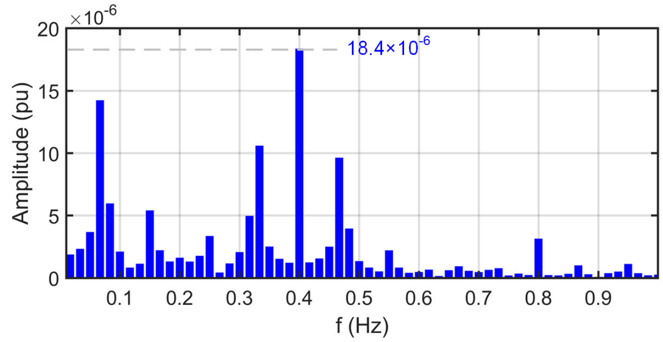

Fig. 17. The single-sided amplitude spectrum of power consumption during wave encountering without employing the proposed methods in the ship PMS.

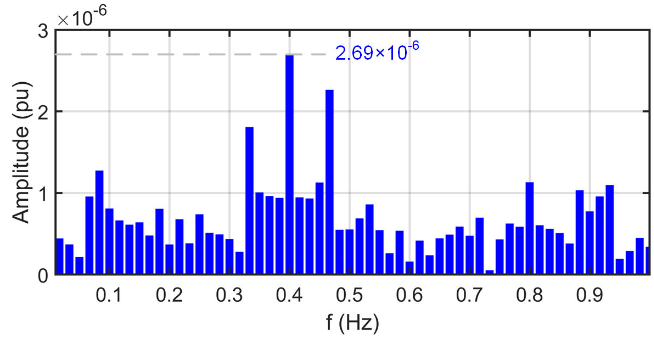

Fig. 18. The single-sided amplitude spectrum of power consumption during wave encountering when ASMS is integrated into the ship PMS.

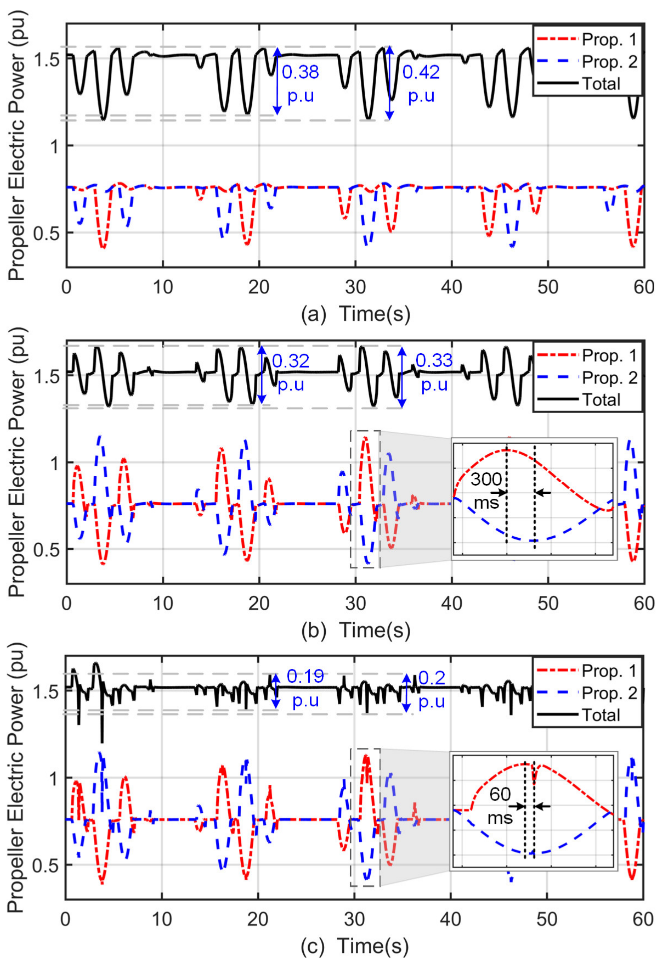

Fig. 16. Each propeller power consumption and the total power consumption of the propulsion system during the irregular wave encountering: a) without the PMSs, b) with the SPMS, c) with the ASPMS.

B. Case Study II

The state-of-the-art concentrates on utilizing various types of energy storage systems to decrease the propulsion system power variations and enhance the AES power quality. However, in this paper, the developed strategies do not require energy storage systems for this purpose. In this case study, the effectiveness of the proposed methods in power quality improvement is comprehensively contrasted with incorporating energy storage systems into the power system. Therefore, the demonstrated power system architecture in Fig. 2 is modified, and an energy storage system is implemented. Fig. 19 shows the adjusted power system topology simulated in this case study. For an adequate comparison, a lithium-ion battery, which is correspondent to compensate for the marine vessel low-frequency variations, is considered as the energy storage system [52]. A filter-based ESS energy management method, which is a promising and common method of energy storage control in contemporary ships, is employed in the power management system [52], [53]. In the filter-based approach, low-frequency power fluctuations are segregated by applying a low-pass filter to the power usage. Then, the resulting power variation is assigned to the battery for elimination. The filter cut-off frequency is related to the designated battery's performance and

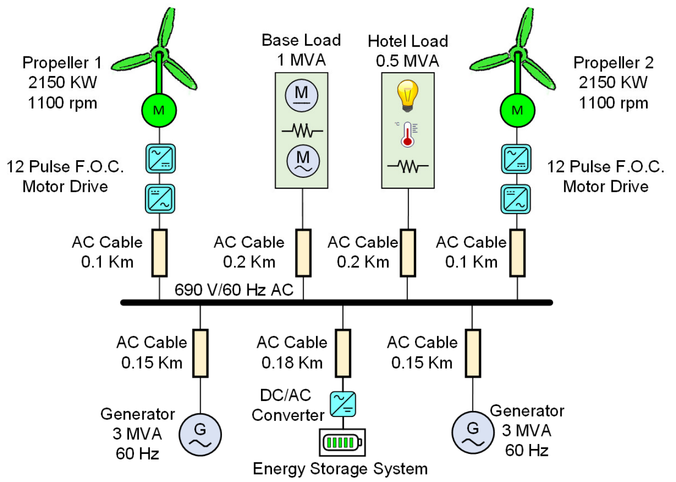

Fig. 19. The typical power system architecture in the AES with integrated energy storage system for mitigating power fluctuations.

affects the ESS investment cost. Concerning the nominal power consumption of the AES power systems and actual vessels specifications, the power capacity and the discharge time of the battery in this study are presumed 5 MWh and 5 hours, respectively [54]. Further details regarding the developed ESS model can be found in [22]. In addition, the cut-off frequency for the low-pass filter is assumed to be 0.2 Hz [55]. Similar to the prior case study, the power quality of the ship power system is examined through three various states: 1) the integrated energy storage is handling the power fluctuations, 2) the SPMS is integrated into the propulsion system control, and 3) the ASPMS is deployed in the ship control system. In the second and third states, the battery storage system in the power system is disregarded. Fig. 20 compares the power variations experienced by the diesel generators in the AES during the identified states. As shown in this figure, the performance of the energy storage system in preventing the propulsion system fluctuations from influencing the power system is significantly close to integrating SPMS into the control system. While the SPMS limits power fluctuations amplitude to 0.33 p.u, ESS in the power system decreases this amplitude to 0.28 p.u. However, ASPMS significantly outperforms these methods in terms of oscillation reduction and decreases this amplitude to 0.2 p.u. Fig. 21 and Fig. 22 demonstrate the frequency and voltage variations in the three predefined conditions. As expected, ESS diminishes the voltage and frequency variations similar to the SPMS. On the other hand, implementing SPMS

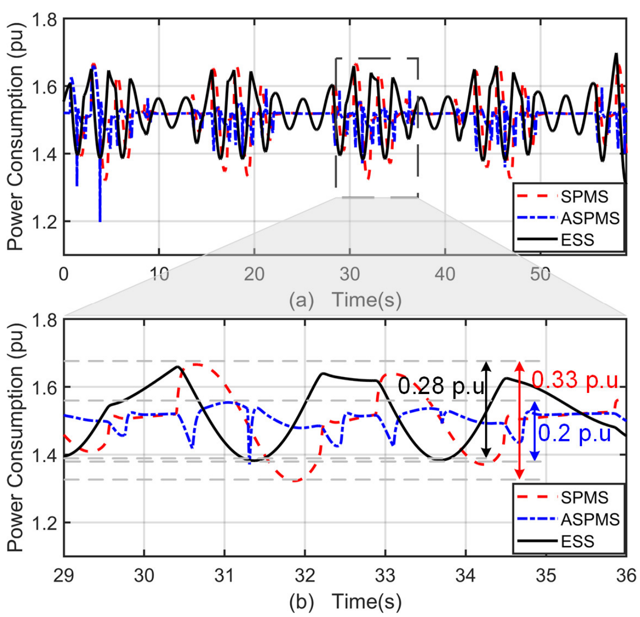

Fig. 20. Total power consumption of the AES power system during the irregular wave encountering: 1) with the ESS in the power system (black graph), 2) without the ESS and with employing SPMS in the ship PMS (red graph), 3) without the ESS and with utilizing ASPMS in the ship PMS (blue graph); a) for the simulation time from 0s to 60s b) for the simulation time from 29s to 36s.

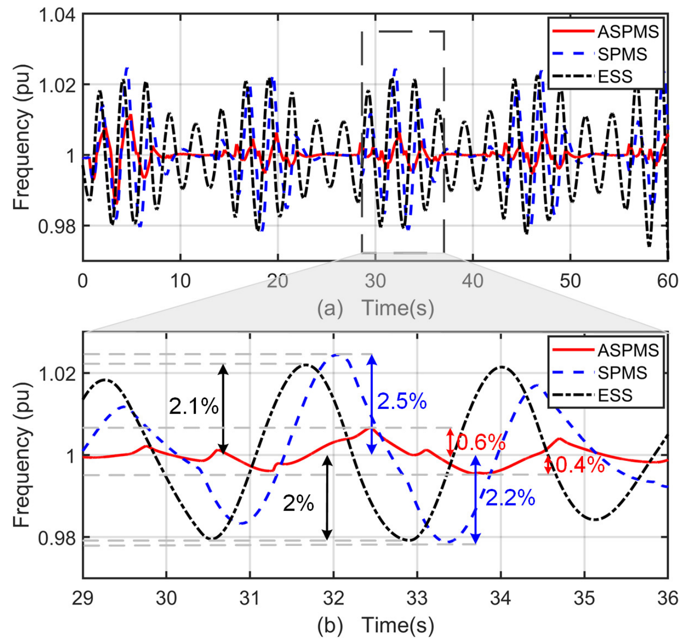

Fig. 21. Frequency fluctuations during wave encountering: 1) utilizing ESS (black graph), 2) utilizing the SPMS (blue graph), 3) utilizing the ASPMS (red graph); a) for the simulation time from 0s to 60s b) for the simulation time from 29s to 36s.

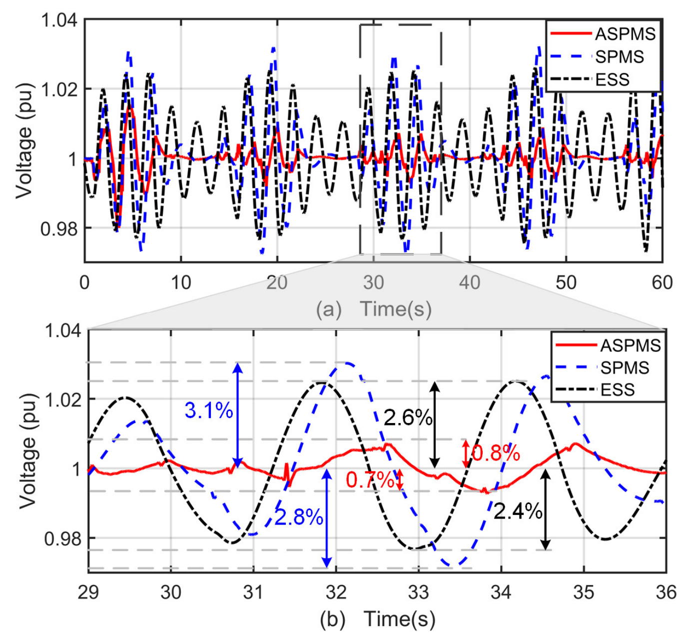

Fig. 22. Voltage fluctuations during wave encountering: 1) utilizing ESS (black graph), 2) utilizing the SPMS (blue graph), 3) utilizing the ASPMS (red graph); a) for the simulation time from 0s to 60s b) for the simulation time from 29s to 36s.

TABLE 3
SUMMARY OF THE PROPOSED STRATEGIES EFFECTIVENESS

Parameter	Conventional	Battery	SPMS	ASPMS
Voltage sag	4.4%	2.4%	3.1%	0.8%
Voltage swell	4.6%	2.6%	2.8%	0.6%
Frequency sag	3.3%	2%	2.2%	0.4%
Frequency swell	3.1%	2.1%	2.5%	0.6%
Power fluctuation amplitude	0.42 p.u	0.28 p.u	0.33 p.u	0.2 p.u
Alignment points time distance	-	-	300 ms	60 ms
Investment cost escalation	×	✓	×	×

in the ship control system does not raise the design cost and lowers the ship weight. Thus, the SPMS can lead to decreasing the fuel consumption and greenhouse gas emission in a long-term operation. ASPMS has a superior effect on improving the power quality in this case study, too. The voltage and frequency changes by utilizing ASPMS are 72% and 76% lower than adopting ESS for power variation mitigation during the wave collision.

The simulation results illustrate that load fluctuations cause significant frequency and voltage variations due to the relatively slow responses of prime mover compared to the electrical machinery. Deploying the proposed power management strategies in the vessel propulsion control system significantly mitigates the electric power consumption, frequency, and voltage fluctuations in the ship power system. As a result, it reduces the generators load stress, electrical equipment failures, and downtime/maintenance costs, which are some of the adverse effects of wave collisions. Furthermore, the presented approaches achieve these objectives while excluding energy storage systems. Therefore, employing these approaches decrease the energy storage requirements at the design level. Even comparing with the ESS impact on power quality, the simulations revealed that the SPMS acts similar to a battery storage system in decreasing fluctuations, and ASPMS surpass them both significantly. As a result, the proposed solutions lower the ship operating and design costs, and they are beneficial for high-speed vessels with weight or size constraints.

It is noteworthy that since the existing vessels in the maritime industry typically use LVAC/MVAC grids, in this paper, a 0.69kV modern ship power system operating at 60 Hz is utilized to evaluate the developed PMSs [23], [24]. Nevertheless, according to the U.S. next-generation integrated power system roadmap, MVAC and high-frequency ship power systems are anticipated in a 10-15 years time frame. In addition, the MVDC power system is a goal to be achieved beyond that. The proposed strategies in this paper improve the performance of the ship power management system and reduce variations of the propulsion system power consumption under severe conditions. Thus, the contributions of the methods are not restricted to the simulated power system type and voltage level, and the presented strategies can be beneficial for future configurations as well. For a better perspective, Table 3 summarizes the performances of the proposed methods and their impacts on increasing the electric power quality. In this table, the conventional PMS (the control system lacks SPMS and ASPMS) and engaging batteries in the power system can be compared with incorporating SPMS and ASPMS into the ship power management system.

VI. CONCLUSION

In this paper, two novel PMSs for moderating the propulsion system power fluctuations during wave collisions have been proposed. Unlike typical modern ships, these PMSs do not engage energy storage systems. Instead, their main focus is the regulation of the propellers speed considering their submergence. The first PMS (SPMS) adjusts propellers speed references according to the in-and-out-of-water effect. The same approach is engaged in the proposed advanced PMS (ASPMS), but an adaptive delay is assigned to the speed modifications. The purpose of this delay is to align the minimum point of the propeller loss factor (LF) with the power peak of the opposing propeller in each wave cycle. An algorithm for obtaining the delay in ASPMS is also developed. In addition, an integrated ship model is presented to provide the requisite LF for PMSs in wave collisions precisely. The given model includes a straightforward method for comprehensively exploring the submergence depth of the propellers and the effect of the in-and-out-of-water on the AES power system. The performance of the PMSs and the effectiveness of the integrated adaptive delay in the ASPMS are examined through two separate case studies, each including three distinct scenarios. According to the simulation results, the ASPMS, as the more advanced PMS in this study, reduces the power, voltage, and frequency fluctuations up to 50, 87, and 88 percent, respectively. In addition, the performances of the suggested method are compared to the ESS influence on the AES power quality. The simulations demonstrated that the SPMS advantages in power quality enhancement are similar to adopting batteries in the power system, while the ASPMS outperforms them substantially. Although the SPMS and the ASPMS reduce the energy storage system requirements, ship design, and operating costs, they notably enhance the AES power quality. Therefore, they are advantageous methods for high-speed AESs, as they lower the weight and volume of the ship. Future works will extend the PMSs and combine them with other electrical control systems in an AES to account for more exhaustive constraints in various marine operating situations.

ACKNOWLEDGMENT

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