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Editorial

Advancements in Power Management Systems for Hybrid Electric Vessels

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With the growing urgency of climate change, environmental regulations governing the maritime industry have become increasingly stringent, imposing significant restrictions on ship emissions. In response, the industry is shifting towards hybrid and fully electric vessels, reducing reliance on conventional diesel-based propulsion [1]. These advanced vessels integrate diverse energy sources, including fuel cells, photovoltaic systems (PV), batteries, and supercapacitors [2]. However, the integration of these heterogeneous energy sources, coupled with variations in electrical topologies [3], ship capacities [4], and operational conditions [5], introduces substantial complexities to the development and management of shipboard power systems (SPSs).

Unlike terrestrial power networks, SPSs must operate with high reliability under diverse and often unpredictable conditions. As localized microgrids that lack the support of a robust external power grid, ensuring stable power quality remains a critical challenge [6]. This necessitates a re-evaluation of key research questions that distinguish SPSs from conventional terrestrial energy systems:

1. What strategies can be employed to ensure the long-term reliability and stability of SPSs?
2. How can power quality be effectively maintained in SPSs across varying operational scenarios and routing conditions?
3. What methodologies can optimize the efficiency of SPSs to minimize emissions and operational costs?

This Special Issue aims to address these challenges by advancing research on critical component reliability, with a particular focus on batteries and fuel cells, power quality enhancements, and operational efficiency improvements. Emphasis is placed on state-of-the-art control methodologies, including Particle Swarm Optimization (PSO) and Extended Kalman Filter (EKF)-based control strategies, as well as optimization techniques and Energy Management Systems (EMSs) utilizing Model Predictive Control (MPC), multi-time scale approaches, and layered architectures. Additionally, this Special Issue explores novel diagnostic frameworks using Long Short-Term Memory (LSTM) networks and predictive analytics based on clustering techniques to enhance the monitoring and management of SPS.

The first theme addresses reliability issues in critical components of SPSs, specifically batteries and fuel cells, in terms of their prognostics and protection. Advanced diagnostic techniques play a key role in predicting component degradation, enabling proactive maintenance and extending system longevity.

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A marine lithium-ion battery capacity prognostic method is presented in Contribution 1 based on LSTM and an improved Crested Porcupine Optimization (ICPO) algorithm under dynamic operating conditions. Key features are extracted from battery data to facilitate accurate capacity prognostics. Furthermore, Density-Based Spatial Clustering is introduced in Contribution 2 using voltage data to forecast variations in battery voltage, allowing for the early detection of potential faults. The results indicate that the DBSCAN clustering algorithm demonstrates superior effectiveness and accuracy in identifying irregular battery clusters. Contribution 3 proposes an attention-based prediction model utilizing Convolutional Neural Networks (CNNs) for long-term power allocation, optimizing the lifespan of fuel cells and lithium batteries by enhancing energy distribution strategies. Similarly, Contribution 4 demonstrates that a trained Back Propagation (BP) neural network can create an offline strategy library, providing intelligent energy distribution recommendations that effectively reduce lithium-ion battery degradation by 28%.

The second theme focuses on improving power quality in SPSs, particularly in terms of harmonic suppression and enhanced control performance, both of which are crucial for vessel servo systems. However, the inherent nonlinearity of motor systems presents significant challenges in achieving precise control.

To address this, Contribution 5 proposes an Extended Kalman Particle Filter (EKPF), which combines a particle filter to identify motor resistance and inductance, thereby improving high-precision control performance. Meanwhile, Contribution 6 introduces a fractional-order controller tuned by PSO and the Oustaloup approximation algorithm to suppress harmonics induced by motor operations, ensuring smoother performance.

The third theme addresses power efficiency challenges, primarily by optimizing fuel consumption through advanced Energy Management Systems (EMSs) under dynamic operating conditions.

For example, MPC is utilized in Contribution 7 to analyze working conditions and dynamically adjust EMS strategies, enabling the optimal management of generators and batteries while minimizing energy waste. To further enhance overall efficiency, the Equivalent Consumption Minimization Strategy (ECMS) is employed in Contribution 8 to balance power distribution among fuel cells, batteries, and ultracapacitors, ensuring optimal energy utilization. Moreover, Contribution 9 explores an advanced approach that considers the battery State of Charge (SOC) alongside power generation source characteristics across various operating modes. This approach results in significant improvements in system efficiency and operational reliability. Furthermore, a Bond graph is used in Contribution 10 to model the various energy sources of hybrid propulsion ships. Based on the proposed model, optimal operational scenarios and reduction ratios are then formulated for different maritime regions, thereby improving propulsion efficiency.

By integrating these advanced computational and control strategies, this Special Issue seeks to facilitate the transition towards more resilient, efficient, and sustainable shipboard power systems. Looking ahead, the future of SPSs is poised to integrate hydrogen-based technologies [7], providing a promising avenue for further reducing emissions and enhancing energy sustainability. However, this transition presents new challenges in hydrogen generation, onboard storage, transportation, and safe and efficient hydrogen consumption in marine environments. Furthermore, as hydrogen becomes a primary energy carrier, ensuring the reliability, efficiency, and stability of SPSs will require innovative control strategies, advanced diagnostic frameworks, and resilient system architectures. Addressing these emerging challenges will be essential to unlocking the full potential of hydrogen-powered SPSs and achieving a truly decarbonized maritime industry.

The evolution of SPSs towards full electrification represents a transformative milestone in sustainable maritime transport. Achieving this vision will require continuous innovation

in energy storage, power management, and system resilience to facilitate widespread adoption and long-term viability. With advancements in battery and hydrogen technologies, future SPSs will not only improve operational efficiency but also significantly contribute to global decarbonization efforts, making maritime transport cleaner and more sustainable than ever before.

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