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Research on Energy Management Strategy of Hydrogen-electric Hybrid Tug Based on PMP Algorithm

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Abstract: This study addresses energy management challenges in hydrogen-electric hybrid tugs by proposing an energy allocation strategy based on operating condition recognition and optimization algorithms. Standard operating conditions were classified through cluster analysis, a hybrid system performance model was established, and the Pontryagin Minimum Principle (PMP) algorithm was employed to achieve optimal power distribution between hydrogen fuel cells and lithium batteries. Simulation experiments demonstrated that the proposed energy management strategy prevented the fuel cell from operating under high-power heavy-load conditions, with only brief periods of low-power idle operation. This effectively reduced the operational strain on the fuel cell, thereby enhancing its long-term durability. Experimental results indicate that this method significantly improves energy utilization efficiency, reduces energy consumption, and extends equipment service life, providing technical support for the efficient operation of hydrogen-electric hybrid tugs.

Keywords: Hybrid Tug; Operating Condition Recognition; Energy Management Strategy

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1. Introduction

As a pivotal hub for global trade, the green and intelligent transformation of port operations has become a core challenge for the international shipping industry in addressing climate change and sustainable development[1]. Tugboats, indispensable vessels in port waters, undertake critical tasks such as mooring, unmooring, and escorting large ships[2]. Unlike ocean-going vessels, their operational patterns exhibit highly dynamic, intermittent, and impact-driven characteristics[3]. During a complete operational cycle, tugboats frequently experience drastic fluctuations in working conditions—from “standby idle” and “high-speed maneuvering” to peak loads during “pushing/towing” operations, followed by energy recovery during “braking and returning.” Traditional fuel-powered tugboats, particularly those with diesel propulsion systems[4], often operate for extended periods in non-design efficiency zones under these complex conditions, leading to incomplete combustion, increased harmful emissions, and overall low energy efficiency[5]. With the International Maritime Organization (IMO)'s increasingly stringent carbon emission regulations and the advancement of domestic and international “dual carbon” strategic goals, developing clean and efficient new tugboat propulsion systems has become an urgent industry imperative[6].

Among various new energy technologies, hydrogen-electric hybrid systems are considered an ideal solution for deep decarbonization of vessels on fixed coastal routes like ports, thanks to their zero-carbon emissions, high efficiency, long range, and rapid refueling capabilities[7]. This system typically consists of a proton exchange membrane hydrogen fuel cell

(PEM-HFC) and a lithium-ion battery pack. The PEM-HFC serves as the primary energy source, efficiently and quietly converting hydrogen's chemical energy into electricity with only water and heat emissions, making it an ideal clean base-load power source. The lithium battery pack acts as a power buffer unit, leveraging its high power density and fast charging/discharging characteristics to meet tugboat's instantaneous peak power demands and recover braking energy[8][9]. However, the full potential of this hybrid configuration heavily relies on the intelligence of energy management strategies[10]. An efficient Energy Management System (EMS) must dynamically allocate power flows between the fuel cell and battery in real-time to optimize hydrogen consumption, equipment lifespan, and system efficiency under complex operating conditions[11]. While research on energy management for marine hydrogen-electric hybrid systems has made progress, significant gaps remain when applied to the unique context of tugboats.

Rule-based control strategies, such as thermocouple management and power-following approaches, are widely adopted due to their simple structure and ease of implementation[12]. However, these strategies often rely on engineers' empirical assumptions in their control logic. When dealing with complex loads featuring nonlinear towing height and strong time-varying characteristics, they exhibit poor adaptability and limited optimization depth. Fixed power allocation thresholds fail to accommodate dynamic operational modes, frequently causing frequent start-stop cycles, inefficient fuel cell operation, or excessive battery charging/discharging, thereby preventing true global optimization[13].

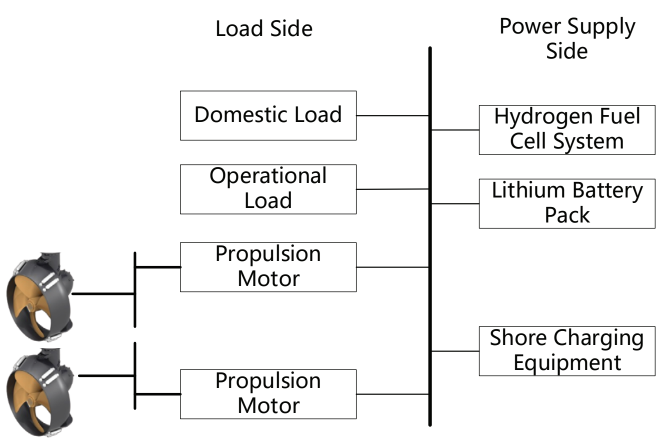
Control strategies based on optimization theory: Global o r instantaneous optimization algorithms represented by dynamic programming, the Pontryagin minimum principle, and model predictive control provide theoretical tools for addressing the aforementioned issues[14-16]. Among these, PMP transforms global optimization problems into a series of local instantaneous optimization problems by introducing co-state variables, achieving a favorable balance between computational complexity and optimization effectiveness[17]. This approach is regarded as a highly promising real-time optimization method. However, existing research often treats co-states (equivalent factors) as fixed values or merely adjusts them slowly with battery SOC when applying PMP. This approach fails to fully explore and utilize the inherent patterns of specific operational conditions. For instance, when anticipating high-power push mode, fuel cell output can be increased in advance to charge the battery for energy storage. Conversely, during coasting braking, fuel cell output can be reduced early to reserve space for energy recovery. PMP that ignores operational conditions essentially represents a “passive response,” with its optimization performance constrained by current instantaneous states, making it difficult to make forward-looking optimal decisions.

To this end, this paper proposes a power management method which combines the condition recognition and PMP algorithm, and realizes the dynamic balance distribution of power sources, and improves the overall performance of the system.

2. Architecture of Hydrogen-Electric Hybrid Towing System

The hydrogen-electric hybrid tugboat utilizes hydrogen fuel cells, lithium battery packs, and shore-based charging equipment as its power supply sources, while its load side comprises propulsion motors, propellers, and living loads. The energy flow must maintain a dynamic balance between the tugboat's required power and the output power of the power sources, with the core challenge being the coordination of power distribution between the hydrogen fuel cells and lithium batteries.

Figure 1: Architecture of Hydrogen-Electric Hybrid Towing System



3. Design of Energy Management Method for Hydroelectric Hybrid Tug

3.1 Model Construction of Hydroelectric Hybrid Tugboat Power System

The hydrogen fuel cell, lithium battery pack, and shore-based charging equipment serve as the power source for the tugboat, while the propulsion motor, propeller, living loads, and operational loads constitute the load side. The energy flow relationship of the hybrid power system is as follows:

$$P_B + P_F = P_M + P_A \tag{1}$$

In this formula, PB denotes the battery output power, PF represents the net output power of the fuel cell system, PM indicates the motor output power, and PA is the power consumption for the ship's living and operational loads.

To optimize the energy management strategy for hydrogen-electric hybrid tugs, modeling of hydrogen fuel cells and hydrogen consumption rates is required. The hydrogen consumption rate of hydrogen fuel cells is:

$$\dot{m}_{H_2} = \frac{N_{cell} M_{H_2}}{n_{H_2} F} I \tag{2}$$

Where: N_{cell} N_{cell} is the number M_{H_2} of fuel M_{H_2} cell units; =2 g/n_{H_2}mol is the n_{H_2} molar mass of hydrogen; =2 is the number of electrons in a hydrogen molecule; I is the output current of the fuel cell; F is the Faraday constant (96485 C/mol).

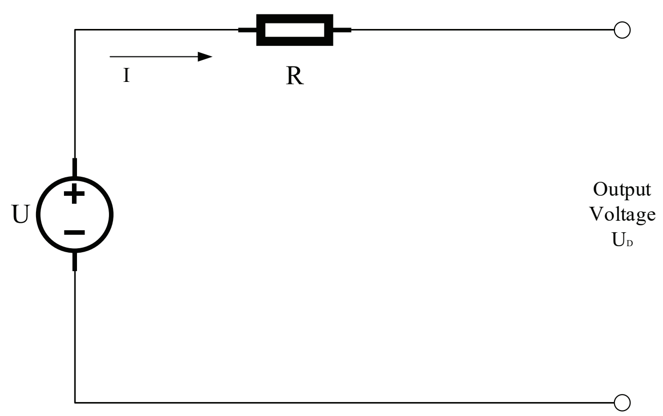
The efficiency of the hydrogen fuel P_F cell is P_F defined as the $P_{H_2} P_{H_2}$ ratio of the system's output power to the power consumed by hydrogen.

$$\eta_F = \frac{P_F}{P_{H_2}} = \frac{P_F}{\dot{m}_{H_2} S_{H_2}} \tag{3}$$

In the $S_{H_2} S_{H_2}$ formula, the high calorific value of hydrogen is 143 kJ/g.

As an auxiliary power source for hydrogen-electric hybrid tugs, the lithium battery $\eta_{dis}\eta_{dis}$is η_{chr} modeled η_{chr} using the R-int framework, as shown in Figure 2. , with its real-time discharge and charge efficiency values as follows.

Figure 2: Lithium Battery R-int Model



$$\eta_{dis} = \frac{1 + \ 1 - \frac{4RP_B}{U^2}}{2}, \quad P_B \geq 0 \tag{4}$$

$$\eta_{chr} = \frac{2}{1 + \ 1 - \frac{4RP_B}{U^2}}, \quad P_B < 0 \tag{5}$$

where R is the internal resistance and U is the open-circuit voltage.

To ensure the hydrogen fuel cell system and lithium battery pack meet the requirements of the entire tug's hybrid power system, the following boundary conditions must be satisfied:

$$\begin{cases} P_F^{\min} \leq P_F \leq P_F^{\max} \\ P_B^{\min} \leq P_B \leq P_B^{\max} \\ SOC_{\min} \leq SOC \leq SOC_{\max} \\ \dot{P}_F^{\min} \leq \dot{P}_F \leq \dot{P}_F^{\max} \end{cases} \tag{6}$$

In the formula, SOC denotes $\dot{P}_F \dot{P}_F$ the state of charge; represents the rate of change of the hydrogen fuel cell's output power; superscripts max and min respectively indicate the upper and lower limits of each variable.

The complete performance model of the hybrid system can be constructed by the energy flow relation, the efficiency and consumption rate of each component and the constraint boundary expression, which provides a theoretical basis for the accurate calculation of the required power of the towed vessel and the energy distribution, and ensures the scientific and reasonable energy management process.

3.2 Identification and Classification of Hydroelectric Hybrid Tug Operating Conditions

Given the highly repetitive and segmented nature of tugboat operations, their driving processes can be divided into distinct phases: departure initiation, pushing operations, departure and return, departure initiation, port entry, reverse towing operations, and port entry and return. During energy allocation, the required power of the tugboat motor depends not only on speed but also on the magnitude of towing force. Therefore, speed and power can serve as key indicators for identifying tugboat operating conditions. By extracting feature values from historical operational segments and conducting cluster analysis, the hydrogen-electric hybrid tugboat operating conditions can be categorized into seven standard modes, as detailed in the table below.

Table 1 Tugboat Operating Conditions

operating mode	Standard speed (kn)	Power range (horsepower)
berthing condition	0	200~700
slow speed condition	4	700~1000
service speed condition	10	1000~2000
General towing condition with departure and mooring	6	2000~4000
off-berthing dynamic positioning condition	0	4000~5000
full service speed condition	12	5000~6000
maximum towing condition/maximum speed of sailing	14	6000~7000

3.3 Construction of Energy Management Strategy for Hydroelectric Hybrid Tug

Based on real-time towing vessel power demand calculated from current navigation conditions and the hybrid system performance model, the PMP (Pontryagin's Minimum Principle) algorithm is employed to determine the optimal fuel cell output power. The power demand is then allocated to both the hydrogen fuel cell and lithium battery according to the energy flow dynamics of the hydrogen-electric hybrid system.

3.3.1 PMP Algorithm

The PMP algorithm (Pontryagin minimum principle), first proposed in the 1950s, is a fundamental global optimization method for solving optimal control problems with constrained variables. It remains a cornerstone in modern control theory[18]. Under conditional constraints,

$$x(t)=f(x(t),u(t),t \tag{7}$$

In this formula, x(t) denotes the state variable, u(t) the control variable, and f the state equation.

The performance metric (objective function) is:

$$J=\varnothing\ (x(t_f))+\int_{t_0}^{t_f} L(x(t),u(t),t)dt \tag{8}$$

In the formula$t_0 t_f \varnothing$, represents the start time, the end time, the terminal cost, and L denotes the running cost.

Define the Hamiltonian function as:

$$H(x(t), u(t), \lambda(t), t) = L(x(t), u(t), t) + \lambda^T(t) f(x(t), u(t), t) \tag{9}$$

where is $\lambda(t)$ the ketechnical vector.

The consensual equation is:

$$\dot{\lambda(t)} = -\frac{\partial H}{\partial x} \tag{10}$$

The state equation is:

$$\dot{x}(t) = \frac{\partial H}{\partial \lambda} \tag{11}$$

The boundary conditions are:

$$x(t_0) = x_0 \tag{12}$$

$$x(t_f) = x_t \tag{13}$$

In the formulax_t, is the terminal state variable. At every time instant, the optimal control variable u*(t) minimizes the Hamiltonian function.

$$u^*(t) = \operatorname{argmin} H(x(t), u(t), \lambda(t), t),\quad u \in U \tag{14}$$

3.3.2 Energy Management Strategy for Hybrid Tug

The system employs the PMP algorithm for energy management of hydrogen-electric hybrid tugs, with the hydrogen fuel cell system's output power (PF) as the control variable, the lithium battery's state of charge (SOC) as the state variable, and the ship's equivalent hydrogen consumption (J) as the performance metric.

Performance metrics:

$$J=\int_{t_0}^{t_f}（\dot{m}_F(t)+\dot{m}_B(t)）dt \tag{15}$$

In this $\dot{m}_F\dot{m}_F$ formula, represents $\dot{m}_B$ the real $\dot{m}_B$-time consumption rate of hydrogen fuel cells, while denotes the instantaneous fuel consumption rate of lithium batteries.

The state equation of the system is

$$S\dot{O}C(t) = f(P_F(t), SOC(t), t) \tag{16}$$

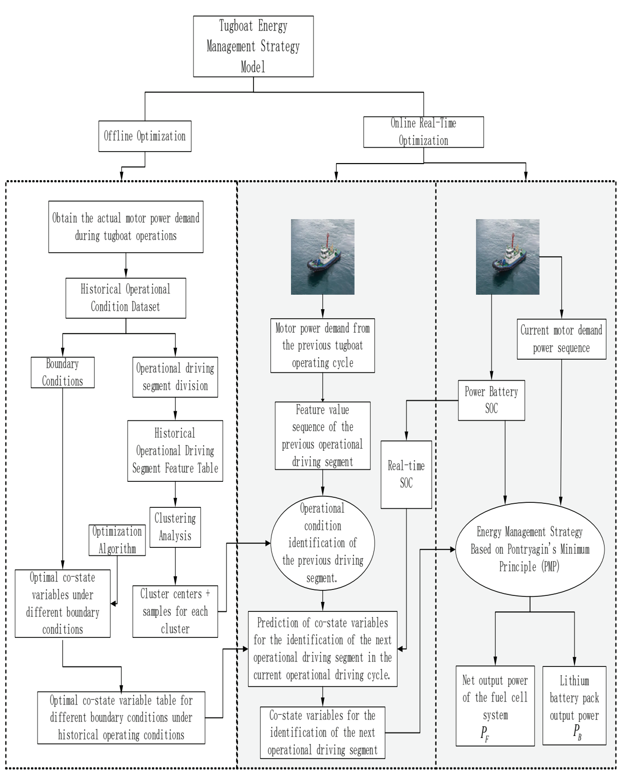
Construct the Hamiltonian function as

$$H_0(P_F(t), S\widehat{O}C(t), \alpha(t), t) = \dot{m}_F(P_F(t)) + \alpha(t)S\widehat{O}C(t) \tag{17}$$

In this $\alpha(t)\alpha(t)$ formula, the state variable (x) takes $\alpha(t)$ different $\alpha(t)$ values under different $\alpha(t)S\dot{O}C$ operating $\alpha(t)S\dot{O}C$ conditions, corresponding to distinct energy distribution outcomes. The product of these variables is equivalent to the battery's real-time hydrogen consumption rate.

Construct an energy management strategy model for hydrogen-electric hybrid tugs, as shown in Figure 3. The model primarily consists of an offline optimized energy management method and an online real-time optimized energy distribution approach, with the latter further divided into two stages: operating condition identification and tug operation.

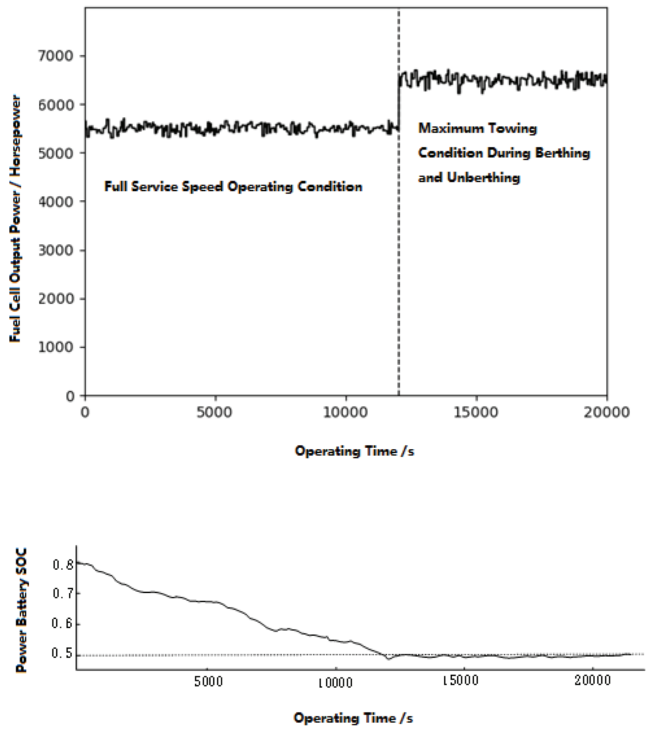
Figure 3 Energy Management Strategy Model



4. Experimental Verification

A Simulink model was developed in MATLAB to simulate a segmented energy management strategy for optimal equivalent hydrogen consumption and SOC maintenance across the entire ship. Case studies were conducted under conditions where the tugboat transitions from service speed to maximum towing or maximum speed. The simulation parameters included an initial SOC value of 0.8 and a target SOC value of 0.5, as shown in Figure 4.

Figure 4 Simulation Result Diagram



Simulation test results demonstrate that during the tug's transition from service speed to maximum towing or cruising speed, the power battery SOC curve shows a high initial SOC. The tug's hybrid system executes an energy management strategy optimizing equivalent hydrogen consumption, causing the SOC to gradually decrease. When the SOC reaches the preset threshold, the system maintains an energy management strategy to stabilize the power battery SOC at approximately 0.5. The fuel cell output power curve reveals that under the optimal equivalent hydrogen consumption strategy, the fuel cell's output fluctuates around 5,000 horsepower, a characteristic inherent to the fuel cell's operational properties. When implementing the SOC maintenance strategy, the fuel cell's output increases due to the boundary condition of SOC stabilization. This power boost achieves the goal of maintaining the power battery SOC.

Conclusion

The overall operational data indicates that the fuel cell never operated under high-power heavy-load conditions, with only brief periods of low-power idle operation. This energy management strategy for the towing vessel effectively reduces the fuel cell's workload, thereby enhancing its long-term durability. Meanwhile, the power battery consistently operates within an efficient range, which slows down performance degradation and improves both battery lifespan and overall system efficiency.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

[1] Shen, J., Li, F., Li, M., et al. (2021). Prediction of PM10 concentration in port clusters considering regional spatiotemporal correlation characteristics. Journal of Transport Science and Engineering. Advance online publication. https://doi.org/10.16544/j.cnki.cn43-1494/u.20250811001

[2] Liu, M., Luo, C., & Zhang, J. (2018). Research on safety limiting factors of tugboat fleet through restricted straight sections. Journal of Safety and Environment, 18(2), 566–570. https://doi.org/10.13637/j.issn.1009-6094.2018.02.99

[3] Deng, Q., & Lei, B. (2020). New developments in tugboat power systems. Marine Electric & Electronic Engineering, 40(5), 18–20.

[4] Liu, X. (2024). Current status and development trends of new energy tugs. China Ports, (11), 48–50.

[5] Liu, J., Sun, Y., Wang, K., et al. (2025). A review of energy management research for fuel cell hybrid electric vehicles. Mechanical Engineer, (12), 92–96.

[6] Song, L., & Liu, W. (2025). Application status and development trend of new energy ships. Marine Equipment/Materials & Marketing, 33(11), 52–55.

[7] Li, Z., Zhao, X., Zhu, H., & Chen, J. (2023). Engine-propeller matching design for multi-mode hybrid harbor tugs. Ship Engineering, 45(S1), 301–304.

[8] Zhang, Y., Chen, L., & Zhu, J. (2018). A review of hybrid ship power plants and energy management. Ship Science and Technology, 40(5), 1–7.

[9] Gao, D., Shen, A., Chu, J., et al. (2015). Energy management and control strategies for hybrid ships. Journal of Shanghai Maritime University, 36(1), 70–74.

[10] Lan, X., Shen, A., Gao, D., et al. (2016). Optimal control of energy management systems for hybrid ships. Chinese Journal of Power Sources, 40(9), 1859–1862.

[11] Li, L., Tao, F., & Fu, Z. (2025). Research on condition-adaptive energy management strategy for PHEV. Computer Simulation, 42(2), 147–154.

[12] Guo, X., Yuan, Y., & Tong, L. (2024). Energy management strategy for diesel-electric hybrid ships based on Pontryagin’s minimum principle. Journal of Harbin Engineering University, 45(11), 2176–2184.

[13] Xu, S., & Wu, Z. (2014). Research on global optimal energy management strategy for HEV based on PMP. China Mechanical Engineering, 25(1), 138–141.

[14] Li, P., Zhang, J., Zhang, C., et al. (2025). Research on low altitude multi UAV path planning method based on improved A * algorithm. Journal of Transport Science and Engineering, 41(4), 61–68. https://doi.org/10.16544/j.cnki.cn43-1494/u.20205529002

[15] Zhang, D., Zhong, X., Wang, X., et al. (2024). Analysis of the development status and trends of intelligent connected transportation technology based on WOS. Journal of Transport Science and Engineering, 40(3), 144–152. https://doi.org/10.16544/j.cnki.cn43-1494/u.20230607204061987

[16] Liu, C., Zhang, J., Fan, X., et al. (2024). Dual induction logging inversion method based on quadratic programming. Journal of Henan Polytechnic University(Natural Science), 43(6), 49–56. https://doi.org/10.16186/j.cnki.1673-9787.2023070034

[17] Liu, Y. (2025). Research on energy management strategy for fuel cell hybrid heavy-duty truck based on statistical characteristics of working condition parameters [Doctoral dissertation]. Chongqing University of Technology.

[18] Hou, S. (2024). Research on energy management strategy for new energy vehicle hybrid power system [Doctoral dissertation]. Jilin University.