Modeling and Simulation of an Energy Management System for Plug-in Hybrid Electric Recreational Boat (PHERB) using Penambang Boat Driving Cycle

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Abstract. In order to ensure that the vehicle achieve an improvement in energy efficiency, reduction in emissions and fuel use, the good energy management system needed. This paper presents an innovation of water transportation namely Plug-in Hybrid Electric Recreational Boat (PHERB) on modeling and simulation results of an energy management strategy (EMS) for PHERB. In this work, firstly, through a power flow analysis, the vehicle components are sized to meet the expected power and energy requirements. Then, the model is tested numerically in the MATLAB/SIMULINK environment using the Penambang Boat drive cycle with the proposed EMS. The simulation results show that the PHERB model can be used as a reference to build a hybrid electric boat in Malaysia environment.

1. INTRODUCTION

Many studies show that every conventional engine type emission rates of carbon dioxide and fuel consumption were high [1-4]. Concern about this issue, Plug in Hybrid Electric Recreational Boat (PHERB) is introduced to improve the performance of boat and reducing the emission and fuel consumption. PHERB consists of only one electrical machine (EM) which acts as either a motor or a generator at one time while the energy storage system (ESS) is equipped with an ultracapacitor (UC) for fast charging and unloading during regenerative braking and rapid acceleration. Figure 1 displayed the proposed PHERB powertrain.
In this article, the suggested Energy Management Strategy (EMS) is introduced to the PHERB model to ensure that the vessel meets the driving efficiency goal without compromising the ideal working atmosphere to boost fuel economy and emissions. The PHERB model with special EMS has been mathematically developed numerically in MATLAB/SIMULINK. The Penambang Boat driving cycle was used in the PHERB model to evaluate PHERB efficiency.

2. METHODOLOGY

This research methodology is divided into four phases as illustrated in Figure 2.

2.1 PHERB parameter and specification

The design specification, parameter, and selection for the EM, ICE, and energy system storage (ESS) shall be carried out to define the key components of the PHERB powertrain. EM, ICE and ESS are sized according to the ship parameters, characteristics, and efficiency criteria (Table 1) based on the demand for steady-state boat capacity using the dynamic equation boat [6]. The type of boat chosen is a pleasure boat. In simulation, the length of the used boat is 12.4 m, and the density of the water is 1000 kgm^-3. The enlargement of the boat model begins with the calculation of the energy and strength of the boat required for typical driving scenarios, based on the parameters and design characteristics of the boat, based on the PHERB specification, parameter, and requirement. By means of an analysis of the power flow, the size and the limit of each portion are calculated to satisfy the specifications accordingly. Table 2 displays the scale and parameters used for PHERB.
Table 1. Parameter, Specification and Configuration

| Parameter and Specifications | Type of boat Configuration | Conventional boat Series | PHERB Series-Parallel |
|-----------------------------|----------------------------|--------------------------|-----------------------|
| Length overall, L           | 12.4 m                     | 12.4 m                   |                       |
| Length at waterline, L_{WT} | 11.0 m                     | 11.0 m                   |                       |
| Breath, B                   | 1.8 m                      | 1.8 m                    |                       |
| Draught, T                  | 0.64 m                     | 0.64 m                   |                       |
| Length between perpendicular, L_{PP} | 10.67 m | 10.67 m | |
| Density of water, \( \rho \) | 1000 kgm^{-3}             | 1000 kgm^{-3}            |                       |
| Total propulsive efficiencies, \( \eta_T \) | 0.9 | 0.9 | |

Table 2. PHERB Component Specification

| Component | Specifications |
|-----------|----------------|
| ICE       | 20 kW @ 3000 rpm |
| EM        | 30 kW AC induction motor |
| ESS       | 5 kWh, 6 Ah     |

2.2 PHERB in MATLAB/SIMULINK environment

All parts in PHERB obtain a mathematical model is combined. The boat performance is simulated in the MATLAB/SIMULINK environment with a special EMS and different driving cycle. Overall structure of PHERB model is illustrated in Figure 3.

![Figure 3. Overall structure of the PHERB model in MATLAB/SIMULINK environment](image)

2.3 PHERB Energy Management Strategy

During this process, the special EMS was created and combined with the PHERB portion. EMS in vehicles is an important component because it can have a direct effect on vehicle efficiency [6]. Improving automotive energy conservation can deliver substantial benefits, such as lowering fuel usage, reducing emissions, lower maintenance costs, reducing noise pollution and improving driving efficiency and ease of use. [7]. EMS has two primary requirements that are reversed and forward-looking. There
are six modes of operation that are mechanical reverse, regenerative reverse, EM only, EM and ICE mixed, ICE only and ICE recharged. All six modes of operation displayed in Figure 4 are based on the demand for forward or reverse vehicle power and the SOC level in the ESS. Three ESS SOC levels are medium, moderate and high. Another name for cruising in a water vehicle is forward mode and braking mode is also known as reverse mode.

**Figure 4.** EMS proposed for PHERB

In PHERB EMS, there are two requirements for PHERB drives that are forward mode and reverse mode. The forward mode and the reverse mode are determined by the power demand flow. When the power demand is greater than zero, it is known to be forward mode, and vice versa, reverse mode. The flow chart is shown in Figure 5.

![Flow Chart](chart.png)

**Figure 5.** Driver condition for EMS

Figure 6 displays the number of six operations in forward and reverse mode. In forward mode, four operations involved are ICE mode, ICE recharged mode, ICE or EM mode, and EM mode only. Reverse mode, thus, requires two operations consisting of regenerative reverse mode and mechanical reverse mode, respectively.
3. RESULTS AND DISCUSSION

Penambang Boat driving cycle is used to see the performance of PHERB performance in simulation. The PHERB model provided is used to simulate the driving efficiency and fuel consumption of the Penmabang Boat driving period. The Penambang Boat driving cycle is shown in Figure 7.

3.1 PHERB Simulation

Figure 8 – Figure 10 shows the simulated ESS current, voltage and power usage of the Penambang Boat drive cycle. The peak currents are due to the strong demand for power to achieve accelerated movement of the boat at the respective periods. The negative values on the graph represent the regenerative braking events of the hard-breaking loop. In the ESS voltage table, the voltage increases during regenerative braking and decreases during high current discharge while the demand for electricity from the EM is at its highest.
Figure 8. Current performance in PHERB ESS

Figure 9. Voltage performance in PHERB ESS

Figure 10. Power performance in PHERB ESS

Figure 11 – Figure 13 shows the simulated speed, torque and power of the EM. As shown in the figure, as the boat accelerates, the required EM torque increases rapidly, and when the speed is relatively steady, a much smaller torque is needed to overcome the resistance and drag the water to the boat. The average power demand from the EM is 5000 W at the speed level and the peak power demand is 1500 W during the acceleration at 39 rad/s.
Figure 11. Power performance in PHERB EM

Figure 12. Torque performance in PHERB EM.

Figure 13. Speed performance in PHERB EM

Figure 14 – Figure 15 displays the simulated propulsion speed and torque specifications for the Penambang Boat drive cycle. The maximum torque of the propeller, 350 Nm, occurs when the boat accelerates from a standstill to a steady speed. The needed torque then decreases as the Penambang Boat drive cycle consists only of mild accelerations and decelerations.
The simulated vehicle speed and the necessary speed for the Penambang Boat driving period is illustrated in Figure 16. As seen, the two curves are very well matched with a very small error of less than 0.05 m/s between goal and acquired speeds. Thus, it is expected that the PHERB will be able to provide driving efficiency as a traditional hybrid vessel under the actual driving conditions.

4. CONCLUSIONS

The results of the PHERB subsystems in terms of ESS current, ESS voltage, ESS output power, EM speed, EM torque, propeller speed, and propeller torque show that the PHERB can be used as reference model to build plug in hybrid recreational boat in Malaysia environment.
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