Modelling, Simulation and Analysis of PHERB Powertrain

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***Abstract*—Popularity due to high fuel efficiency have made plug-in hybrid electric vehicles (PHEVs) gives a great transformation in reducing fuel consumption, fuel cost and gas emission. Marine transportation such as boat, ship, tanker, bulk carries, tow and tug also need the revolution replacing their diesel conventional with the hybrid electric vehicle. In this paper, plug-in hybrid electric recreational boat (PHERB) was presented. This research aims to present modelling and simulation of main powertrain PHERB based on a mathematical model in MATLAB/SIMULINK environment, in order to respond to power and speed through a drive cycle. The accuracy of the model is compared with advanced vehicle simulator (ADVISOR) software. The result of simulation main powertrain, fuel economy and emission of PHERB and ADVISOR model were compared, and the pro and con were discussed. This model can be used as a reference to build a hybrid electric boat in Malaysia environment.**

***Index Terms*—PHERB; Modelling; Simulation; ADVISOR.**

I. INTRODUCTION

Investigation on the reduction of emission, fuel costing and fuel consumption has become a main current issue today. The effective reduction of emission can solve environmental concern and consumption energy resources such as petroleum and can affect fuel costing too. Marine transportation is a contributor to pollution and high energy consumption. Hence, if marine transportation could be made to run on electric power, it would be even more efficient since electric motor efficiency is superior to the internal combustion engine make boats would not emit gases nor pollute the water and would run quietly [1].

Recently, plug-in hybrid electric vehicles (PHEVs) established as a promising alternative that uses electricity to transfer a significant fraction of fleet petroleum consumption [2] and to lessen emission. Based on Markel and Simpson [3], a PHEVs is a hybrid electric vehicle for the ability to renew its electrochemical energy storage with electricity from an off-board source. It used a big electric machine (EM) to the utility as primary driving force, which is more efficient than an internal combustion engine (ICE) and hence can decrease fuel consumption, emissions and process cost [4]. Currently, PHEVs powertrain was containing two separate EM functioning as the motor or generator depending on driving requirements [5] and have a large battery pack [6]. To overcome this issues, a new conceptual series-parallel PHEV for marine transportation known as a plug-in hybrid electric recreational boat (PHERB) was introduced. PHERB contains one EM which are can be operated as either an electric motor or generator in different time intervals, controlled by a special energy management strategy (EMS).

Up to date, many investigations are focusing on understanding the dynamics of the hybrid vehicles by developing the simulators [7-8] and the design of hybrid vehicles by testing structures of powertrain and EMS can be used before prototype begins. Power flow controlling, optimisation of the fuel economy (FE) and reducing the emissions also are a part of the current research [9-12]. The vehicle simulators is an essential for practical and experimental verification [13]. Several computer programs have been developed to define the process of hybrid electric powertrains [14], including advanced vehicle simulator (ADVISOR).

II. ADVISOR

The U. S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) were original develop ADVISOR to simulate and analyse light and heavy vehicles, including hybrid and fuel cell vehicles [15]. ADVISOR is a software based on MATLAB/SIMULINK. ADVISOR allows the user to perform analysis of the performance, emissions and FE of conventional, electric and hybrid vehicles [16].

To determine the required drivetrain torque, speed and power, ADVISOR utilises a backwards-looking vehicle simulation architecture, in which the required and desired vehicle speeds are used as the inputs. The ADVISOR model vehicle contains two separate EM which is used as the motor and generator, respectively and no ultracapacitor (UC) in the energy storage system (ESS). The proposed PHERB has one EM which operates as either a motor or generator at a time with specified by the special EMS and the UC bank for fast charging and discharging during the regenerative braking and fast acceleration. To simulate the proposed PHERB, a model is derived in MATLAB/SIMULINK environment. This model is proved by comparing the simulation results of the ADVISOR model and PHERB model.

III. PHERB PARAMETER AND SPECIFICATION

In PHERB powertrain [17], one EM was used as the main power source to drive the boat. The primary energy source of EM is the battery pack which supply continuous power to the boat while the secondary energy source is the UC pack which absorb the power pulses during regenerative braking and deliver power for peak acceleration. The ICE is set as a backup power source. In order to reduce the fuel consumption and harmful emission, it is only operated under certain conditions and will not be able on all the time. The size of the ICE can be decreased because its power is required only when the battery state of charge level is low. Besides that, to provide essential extra torque to support the EM in order to run the boat during high torque drive condition. Figure 1 shows a block diagram of the PHERB powertrain.

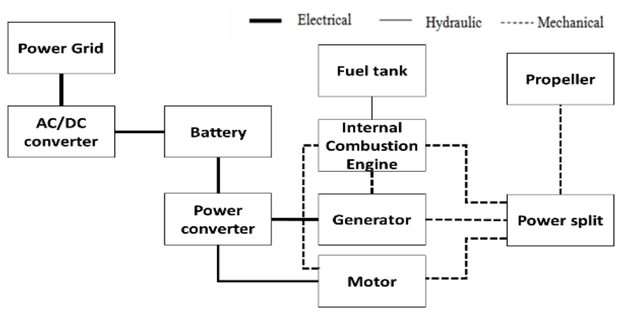

Figure 1: Block diagram of the PHERB powertrain

IV. PHERB ENERGY MANAGEMENT STRATEGY

The EMS is responsible for choosing in which mode that the vehicle is functioning. To control the dispensation of power amongst the components, several operating modes of the proposed EMS were built which is the mechanical braking, regenerative braking, motor only, engine recharge, engine and motor assist, and engine only mode according to the boat power demand in acceleration and deceleration and the state of charge (SOC) level of ESS [18-19].

The mechanical braking mode is initiated if the state of charge of both energy storage devices and/or the brake position is high. During the regenerative braking mode, the allocation of absorbed regenerative power depends on the percentage of brake position as well as on the state of the charge level of both storage units. EM only mode is activated when the state of charge level is high. When the ESS SOC is low, and the acceleration is low, the ICE will boost the boat while charging the energy storage devices. If the boat is cruising and the ESS has a moderate state of charge, then the vehicle can be either ICE recharge or EM only mode. If the vehicle acceleration is high, then the ICE will not have an opportunity to charge the ESS, and the boat will use the ICE only mode to operate.

V. PHERB MODELLING

The development of boat model begins with the calculations of boat energy and power requirements for typical driving conditions based on the parameters and target specifications of the boat based on PHERB specification, parameter and requirement. The size and capacity of each boat component are then determined through a power flow analysis accordingly to meet the requirements. Table 1 and Table 2 listed main component specification, parameters, specifications and requirements of PHERB [20].

Table 1
PHERB Parameters, Specifications and Requirements

Parameter and Specifications	
Configuration	Series-Parallel
Length overall, L	12.4 m
Length at waterline, LWT	11.0 m
Breath, B	1.8 m
Draught, T	0.64 m
Length between perpendicular, L_{PP}	10.67 m
Density of water, ρ	1000 kgm^{-3}
Total propulsive efficiencies, ηT	0.9
Performance Requirement	
Maximum speed	Over 30 km/h
EV range	10 km

Table 2
Main Component Specification of PHERB

Component	Specifications
ICE	20 kW @ 3000 rpm
EM	30 kW AC induction motor
Battery	Li, 5 kWh, 6 Ah

Combining of all components obtain a mathematical model of the PHERB. Figure 2 presented the boat performance for a given EMS and driving cycle is simulated in the MATLAB/SIMULINK environment.

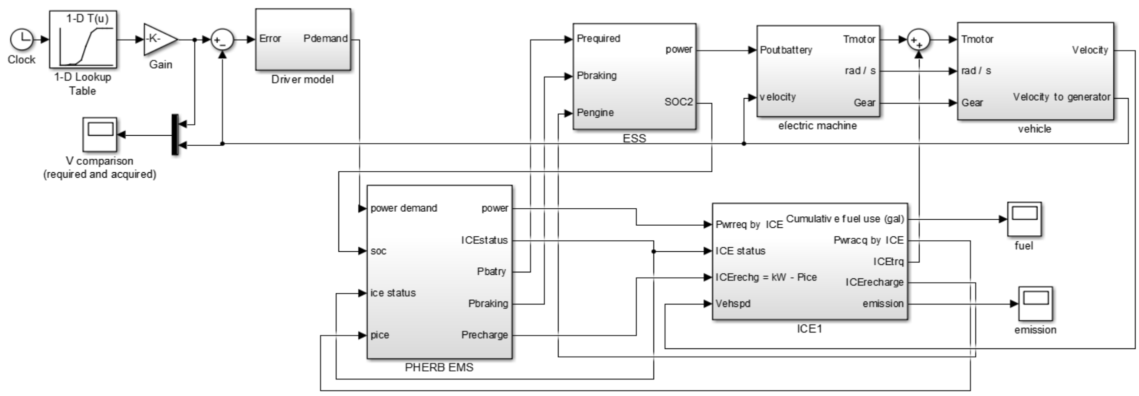

Figure 2: Overall structure of the PHERB model in MATLAB/SIMULINK

VI. SIMULATION RESULT

For a comparative study, the PHERB model is modified to incorporate the PHEV model in ADVISOR and energy management scheme**.** The driving cycle used is EPA Urban Dynamometer Driving Schedule (UDDS) and California EPA Air Resources Board Dynamometer Driving Schedules (LA92). It is illustrated driving cycle history time shown in Figure 4 - 5. The model validation is divided into four subsystems such as boat performance, ESS, EM and propeller model.

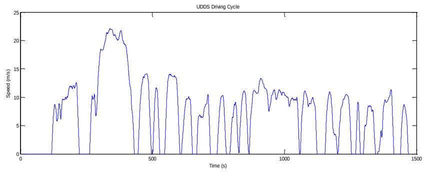

Figure 4: Time history of the UDDS driving cycle

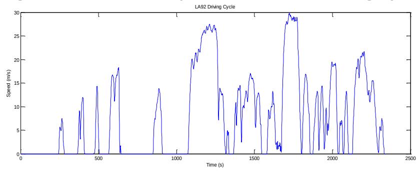

Figure 5: Time history of the LA92 driving cycle

In this boat performance model, the speeds and forces of PHERB model are compared and presented in Figures 6 - 7. There is a close match between the ADVISOR model and PHERB model. For ESS model, there are four elements such as ESS SOC, ESS current, ESS voltage and ESS power were evaluated. Figures 6-7 show the simulated results of ESS current and ESS voltage for the UDDS and LA92 drive cycle. The fast boat accelerations during the respective periods achieved when the peak currents are due to the high power demand.

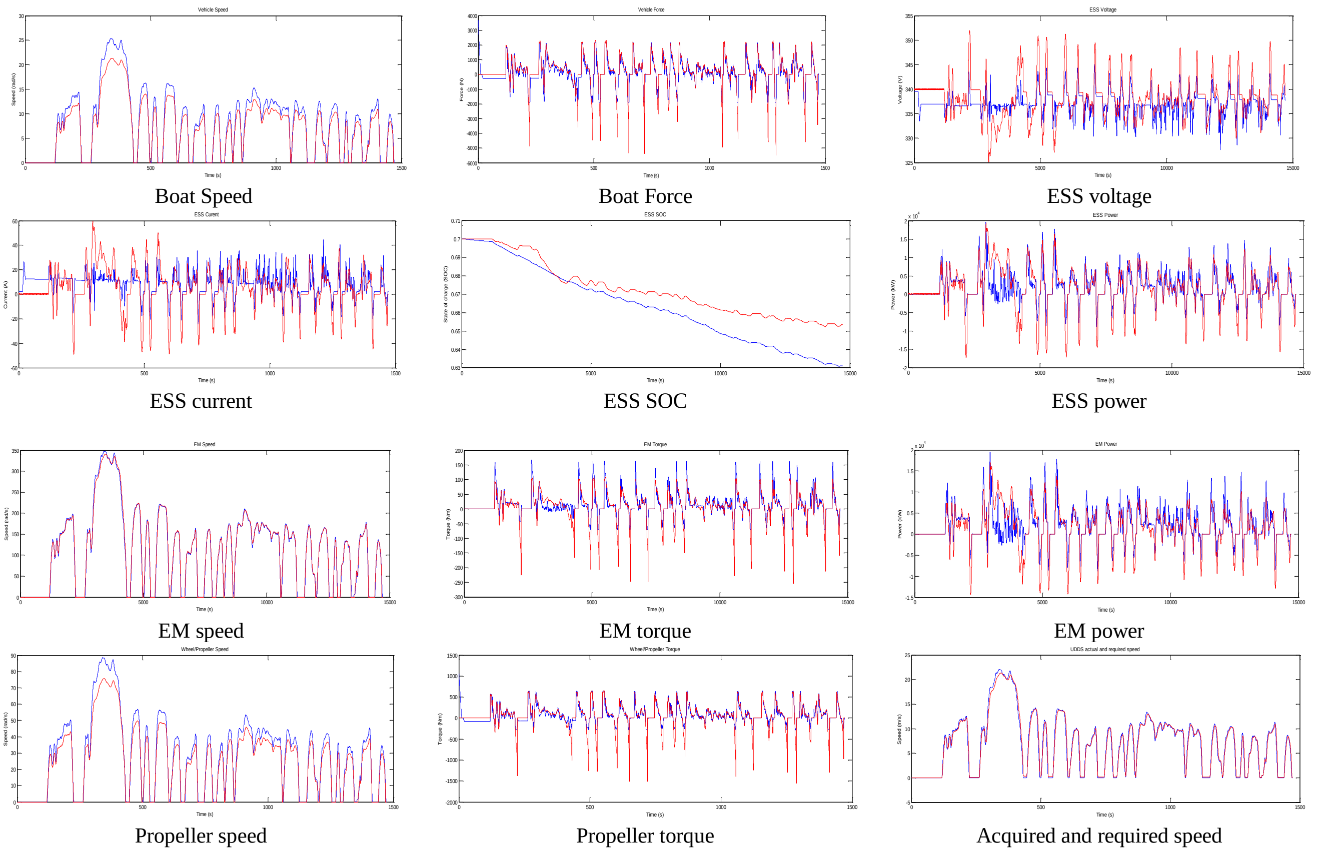

Figure 6: UDDS driving cycle (Blue: ADVISOR, Red: PHERB)

The regenerative braking event during the hard braking period in cycle occurs when negative values are achieved represent on the graph. In the ESS voltage graph, the voltage increases during recharging from regenerative braking and decreases during high current discharge when the power demand from EM is at peak. The PHERB model results for the UDDS and LA92 drive cycle exhibits values lower for the ESS current than that of ADVISOR model. For ESS voltage of PHERB shown a higher value than ADVISOR model. Such phenomenon is due to the power consumption of the boat under different EMS, and therefore can be accepted with a reasonable explanation. ESS SOC and ESS power are illustrated in Figures 6-7 for UDDS and LA92 drive cycle. For ESS power, the overall trends of the energy consumption and generation of the two models match rationally well. However, there are some differences between the ESS SOC results of the PHERB and ADVISOR model. This is because the PHERB model has a better EMS and can capture more regenerative braking energy. In EM model, EM speed, torque and power were studied. The EM speed and torque of the PHERB and ADVISOR model for the UDDS and LA92 drive cycle are included in Figures 6-7.

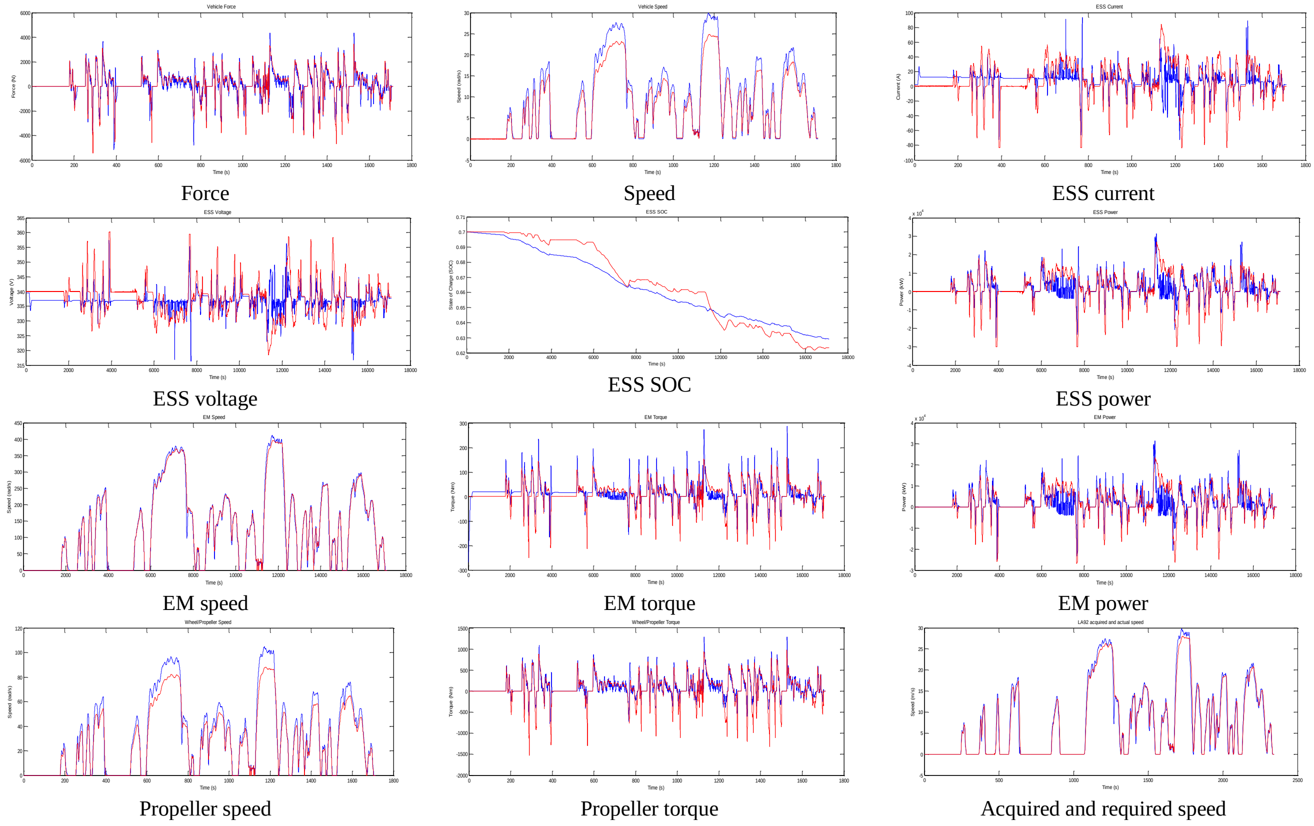

Figure 7: LA92 driving cycle (Blue: ADVISOR, Red: PHERB)

As shown in the simulation results, when the boat accelerates, the required motor/generator torque increases quickly, and when the boat reaches the relatively stable velocity level, a much smaller torque is required to overcome the resistance and drag to the boat. The speed and torque results in the simulation from two model are match and similarity.

The average power demand from the motor/generator is in the range 6-8 kW for UDDS and LA92 the velocity level, and the peak power demand is 22-24 kW during the acceleration. From the results shown in Figures 6-7, the EM power breaking for PHERB is higher than ADVISOR. The breaking power from EM can be used to recharge the energy system storage. The power results from the two model match reasonably well.

For propeller model, speed and torque propeller was discussed Figures 6-7 represent the propeller speed and torque requirement for the UDDS and LA92 drive cycle simulated by two model. The result for propeller torque display the maximum torque in UDDS at 600 Nm, and LA92 at 1000Nm occurs when the boat is accelerating from stop to the speed. The required torque then reduces since the drive cycle only consists of mild accelerations and decelerations. The overall results and trends match very closely.

The acquired and required speeds of the UDDS and LA92 drive cycle is plotted in Figures 6-7. It can be seen that acquired and required speeds agree reasonably well. The PHERB followed the required drive cycle speed very well for the standard drive cycle used.

VII. Fuel Economy and Emission Analysis

The FE and emissions of PHERB model and ADVISOR model configuration recorded in Table 3 such as hydrocarbon (HC), carbon monoxide (CO), and nitrogen-dioxide (NOx) for was compared. The FE can be determined using Equation (1) [21-22] where D is the distance in miles and Vfuel is the volume of fuel consumed in gallons.

$$\mathrm{FE\ (mpg)} = \mathrm{D/Vfuel} \qquad (1)$$

A special EMS was developed for PHERB model. So that, SOC is an important part in EMS that gives the impact in FE and emission. The FE and emissions for UDDS and LA 92 drive cycle are given in Table 3.

Table 3.
The FE and emission

Driving Cycle	PHERB			
	Fuel Economy (mpg)	Emission (g/m) HC	CO	NOx
UDDS	74.71	0.415	0.215	0.000
LA 92	77.3	0.335	0.172	0.000
	ADVISOR			
Driving Cycle	Fuel Economy (mpg)	Emission (g/m) HC	CO	NOx
UDDS	62.3	0.508	0.630	0.172
LA 92	49.8	0.421	0.525	0.196

Table 3 exposed that the PHERB model achieved the improvement in the FE and emissions. Based on the analysis results, the FE of the PHERB is about 17 % increased than ADVISOR model in UDDS driving cycle and 36 % in the LA92 driving cycle. Hence, in emission comparison, PHERB model and ADVISOR model show the result of three type emission such as HC, CO, and NOx were decreased. This happens because ESS model in PHERB model has battery and UC bank, but in ADVISOR model has only the battery in the ESS. UC be an important role in improving the FE and emissions.

VIII. CONCLUSION

The results of the PHB model subsystems regarding ESS current, ESS voltage, ESS power ESS SOC, motor/generator speed and torque, vehicle speed and force and wheel speed and torque are within reasonable and predictable range of actual typical behaviour of the plug-in hybrid vehicle. The components of the boat subsystems are suitably sized as the vehicle is accomplished by achieving performance. In the previous discussion, it can be concluded that results of the PHERB mode are comparable.

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