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EFFECTIVENESS OF BATTERY-ULTRACAPACITOR COMBINATION FOR ENERGY SYSTEM STORAGE IN PLUG-IN HYBRID ELECTRIC RECREATIONAL BOAT (PHERB)

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Abstract

Plug-in Hybrid Electric Reactional Boat (PHERB) is a new innovation conventional boat for the recreational application used hybrid powertrain systems such as ESS, Electric Machine (EM) and Internal Combustion Engine (ICE). This paper study the effectives of battery-ultracapacitor combination used for Energy System Storage (ESS) in PHERB. In PHERB, battery-ultracapacitor is used in ESS to supply the power source to EM and ICE become a second power source to drive the boat. The work is illustrated through implemented numerically in MATLAB/SIMULINK environment with special energy management strategy for PHERB model. The power of the battery, the power of battery-ultracapacitor, the power of ESS demand, fuel economy and emission for PHERB were compared and analysed. The result shown that adding ultracapacitor in ESS in PHERB effected the power demand of ESS, fuel economy and emission.

Keywords: Battery, PHERB, Regenerative breaking, SOC, Ultracapacitor.

1. Introduction

In conventional boat powertrain, the main power to drive the boat is the engine using fuel. Mostly, diesel engines are used in the propulsion system. In this system, the gearbox is used to control the speed of the engine in a certain ratio. Thus, the propeller speed can also be controlled. A schematic illustration of conventional boat powertrain is shown in Fig. 1.

In this research, Plug-in Hybrid Electric Recreational Boats (PHERB) are presented in Fig. 2. To develop PHERB, the model and simulation of each component in PHERB such as Internal Combustion Engine (ICE) [1], Electric Machine (EM) [2] and Energy System Storage (ESS) is studied. The PHERB powertrain model has different time intervals controlled by a special energy management Strategy (EMS) to control the power flows according to automatic transmission, the PHERB can operate under multiple modes to suit the needs of the driving cycle including the ultracapacitor, which can work together effectively to improve the vehicle drive performance and energy efficiency [3].

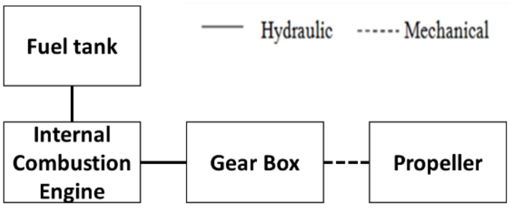


Fig. 1. Schematic illustration of conventional boat powertrain.

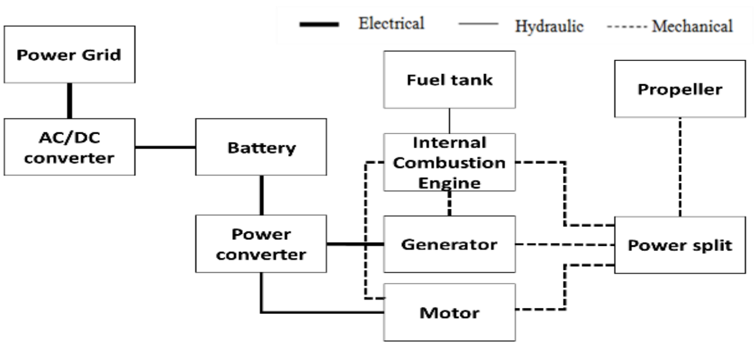


Fig. 2. Schematic illustration of PHERB powertrain [4].

Burke et al. [5] commented that, in hybrid vehicles, ESS is the most important to assist the engine or to recover the vehicle kinetic energy in the regenerative braking mode. According to Chau and Wong [6], in general, the ESS must have the capability to provide enough energy and power to drive the vehicle. Batteries is the most used for ESS as primer resources to drive the vehicle. Based on Burke et al. [5], the batteries provide the power required, however, the capability not optimize to achieve long cycle life. To overcome this problem, the combination of ultracapacitor and batteries in ESS for hybrid vehicles is studied. Table 1 stated the performance of batteries and ultracapacitor and it is shown that batteries have better energy density, however, lower power density compared with an ultracapacitor. Besides that, the cycle life of a battery is much shorter than an ultracapacitor, cycle the battery at high depth of discharge can significantly reduce the life of the battery [7, 8]. So that, the batteries can be optimized for energy density and cycle life and ultracapacitors can provide the power for both acceleration and regenerative braking.

In this paper, the model and simulation of ESS are studied as in PHERB, battery and ultracapacitor are used. So, the conventional hybrid ESS (battery used only) were compared to PHERB ESS to study the effect of using ultracapacitor in PHERB ESS in terms of power demand, fuel economy and emission.

Table 1. Performance comparison of batteries and ultracapacitors [9].

	Li-ion battery	Ultracapacitor
Energy density (Wh/kg)	50 - 80	1 - 5
Power density (W/kg)	1000 - 4000	1000 - 30,000
Number of cycles at 80% depth of discharge	3000 >	1000,000

2. PHERB Energy System Storage Development

In a hybrid vehicle, ESS be an important role. In PHERB powertrain model, ESS is a combination of battery and ultracapacitor. The block diagram of power balance requirements between the battery and ultracapacitor in PHERB is illustrated in Fig. 3.

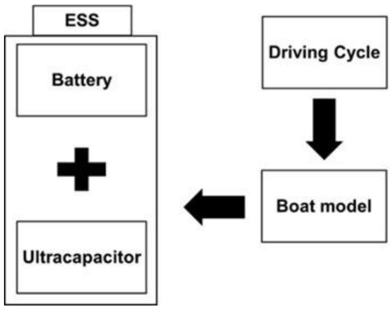


Fig. 3. Block diagram of power balance requirements.

Several types of energy storage devices have been considered for hybrid vehicle applications, such as batteries, ultracapacitors, flywheels and accumulators. The proposed PHERB powertrain employs the battery and ultracapacitor in its ESS unit to work together to meet the needs of high power. The power of the ESS unit is defined [10, 11] as**:**

$$P_{ESS} = P_{battery} + P_{uc} \quad (1)$$

where P_{ESS} is the power of the ESS unit, $P_{battery}$ the power from the battery pack and P_{uc} the power from ultracapacitor pack. Batteries tend to have high specific energy, however, low specific power, which is incapable of supplying a large request of power in a short time. While the ultracapacitor has low specific energy, however, it can supply a large burst of power. If the benefits of the battery and ultracapacitor can be combined together, then the storage and power flow requirements can be met by considering regenerative braking, electric assist and cycle life of the storage units.

2.1. Battery

PHERB model use battery as a main power for propulsion of the boat. The battery can be charged through regenerative braking and by the ICE. The inputs of the battery are the power demand and power braking while the outputs are the State of Charge (SOC), power, current and voltage. The battery needs many data of look-up tables for charging and discharging resistance and open circuit voltage. The full data of lookup tables is based on the lithium-ion battery. The output power can be calculated Eq. (2) [10, 11].

$$Pout = Vout \text{ x } Iout - I^2 out\ R \tag{2}$$

where R, V_{oc} and I_{out} are the internal resistance, the open circuit voltage of the battery and the output of current, respectively. Solving the quadratic equation (2), the output current can be determined by [10, 11].

$$lout = \frac{|Voc - \sqrt{Voc^2 - 4RP}\,|}{2R} \tag{3}$$

The maximum value of SOC is 1 while the high value is set to 0.8. The SOC of the battery can be determined by.

$$SOC = SOC_0 - \frac{1}{C}\int_0^t \eta I d\tau \tag{4}$$

where I is current, C is usable capacity, SOC_0 is the initial value of SOC and η is the efficiency of charging and discharging. Figure 4 illustrats battery model in MATLAB/SIMULINK.

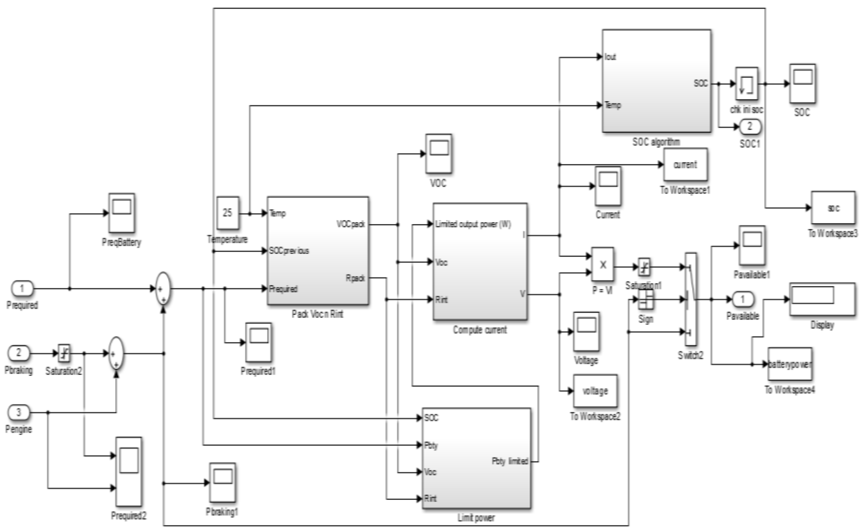


Fig. 4. Battery model in MATLAB/SIMULINK.

2.2. Ultracapacitor

Ultracapacitor model has two inputs including power demand and power braking while produces four outputs that are SOC, power, current and voltage. The capacity is a function of charge and discharges current and temperature. Norbakyah et al. 12], the capacity of the ultracapacitor is defined as follows.

$$C = I\frac{dt}{dv} \tag{5}$$

Equivalent resistance is also a function of current and temperature. SOC is able to know the capability of ultracapacitor storing electricity. The amount of SOC can be defined as below [10].

$$SOC = \frac{V_{OC} - V_{min}}{V_{max} - V_{min}} \tag{6}$$

where V_{max} is the maximum voltage while the V_{min} is the minimum voltage. The output current is calculated as the battery model. The ultracapacitor needs many data of lookup tables for charging resistance, capacity and efficiency of the ultracapacitor. The ultracapacitor model in MATLAB/SIMULINK is stated in Fig. 5.

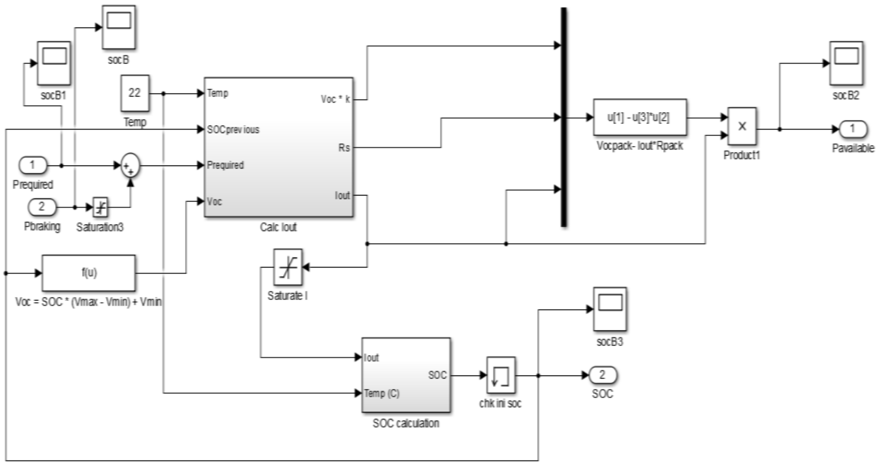


Fig. 5. Ultracapacitor model in MATLAB/SIMULINK.

3. PHERB Development

The boat type selected is a recreational boat. Table 2 lists the parameters of PHERB parameters, specifications and performance requirements.

In the simulation, the length of boat used is 12.4 m and density of water are 1000 kgm-3. 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 3 displayed the size and specifications used for PHERB [12].

EMS is responsible for choosing in which, mode that the vehicle is functioning. Several operating modes of the proposed EMS to control the dispensation of power amongst the components, including 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 SOC level of ESS [13, 14]. The illustrated of PHERB mode operation is shown in Fig. 6.

Table 2. PHERB parameters, specifications and performance 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, LPP	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 3. PHERB component and specifications.

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

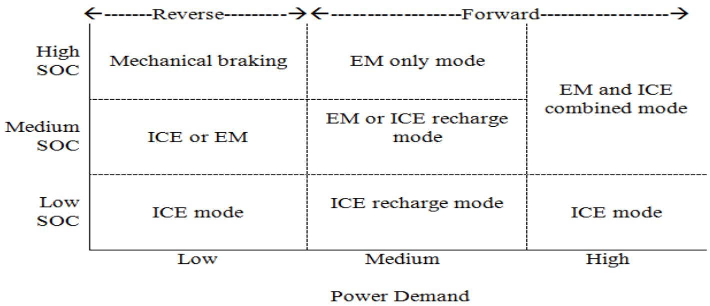


Fig. 6. PHERB EMS modes of operation [11].

The mechanical braking mode is initiated if the SOC 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 SOC level of both storage units. EM only mode is activated when the SOC 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 SOC, then the boat can be either ICE recharge or EM only mode. If the boat 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.

Combining of all components obtain a mathematical model of the boat. The boat performance for a given EMS and the driving cycle is simulated in the MATLAB/SIMULINK environment. Figure 7 illustrates the overall structure of the PHERB model in MATLAB/SIMULINK.

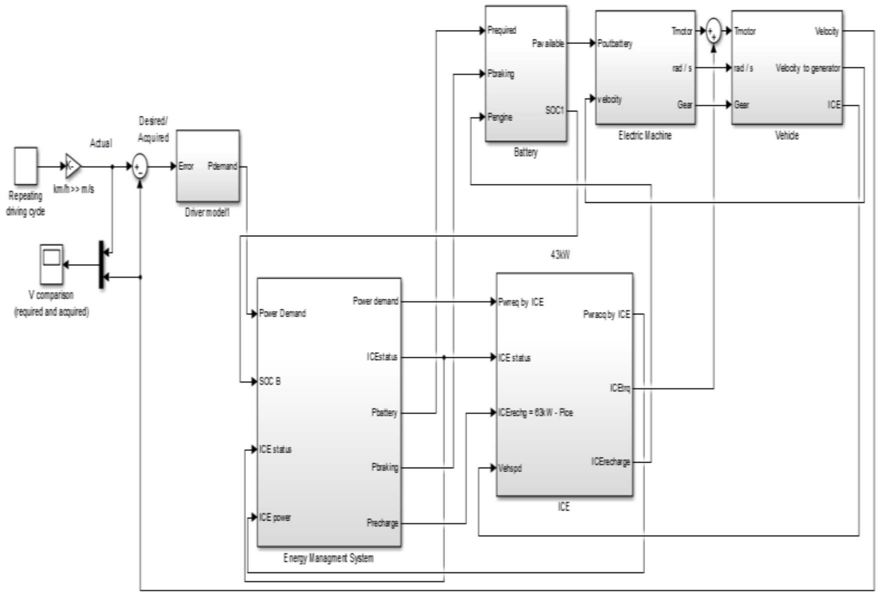


Fig. 7. Overall structure of PHERB model in MATLAB.

4. Results and Discussion

Kuala Terengganu (KT) river and Seberang Takir (ST) river driving cycle is simulated in PHERB powertrain model. In two scenario the power of battery, ultracapacitor, battery-ultracapacitor and power demand needed in ESS were analysed. Besides that, fuel economy and emission were compared between battery and battery-ultracapacitor combination used in PHERB model. Besides that, the comparison of fuel economy and emission using battery and battery-ultracapacitor in ESS were studied.

4.1. Power Energy System Storage Analysis

The route map of KT river and ST river is displayed in Figs. 8 and 9. The PHERB powertrain model is subjected to the first 2057 seconds of the KT river drive cycle and 575 seconds of ST river drive cycle. This cycle is developed to describe the driving style characteristic, which has not too aggressive and normally used for the recreational boat. Figures 10 and 11 illustrate this speed profile.

In Plug-in Hybrid Electric Vehicle (PHEV), ESS used the battery to supply power and PHERB used battery-ultracapacitor. ESS need fulfilment the power demand to give the high performance. The power demand needed using KT river and ST river is illustrated in Fig. 12. The speed profile demanded a peak positive power of 3.9 kW during motoring, peak negative power of 4.0 kW during regenerative braking and an average power of 2.0 kW for the whole period in KT driving cycle. For ST driving cycle, the speed profile demanded a peak positive power of 1.0 kW during motoring, peak negative power of 1.3 kW during regenerative braking and an average power of 1.1 kW. The different power of ESS for PHEV and PHERB using KT river and ST river driving cycle displayed in Figs. 13 and 14.

Fig. 8. KT river route map.

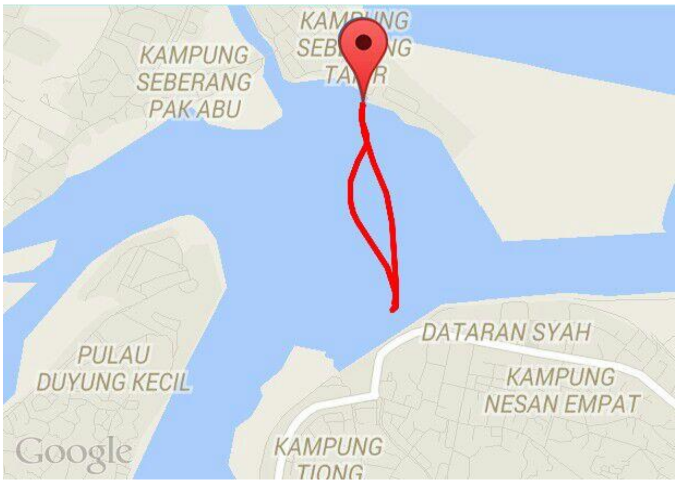


Fig. 9. The ST river route map.

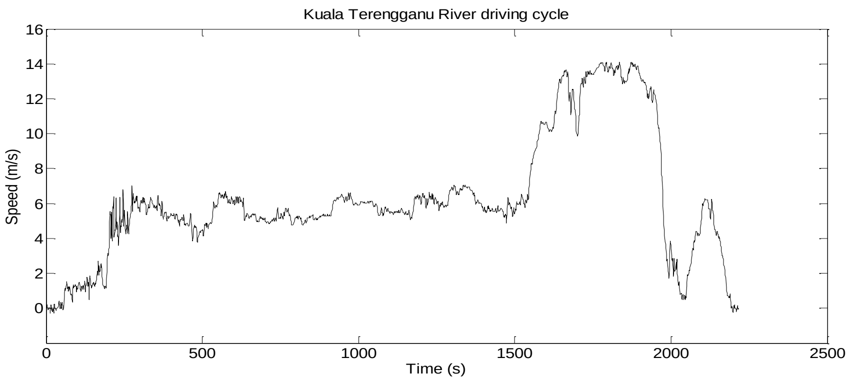


Fig. 10. KT speed profile.

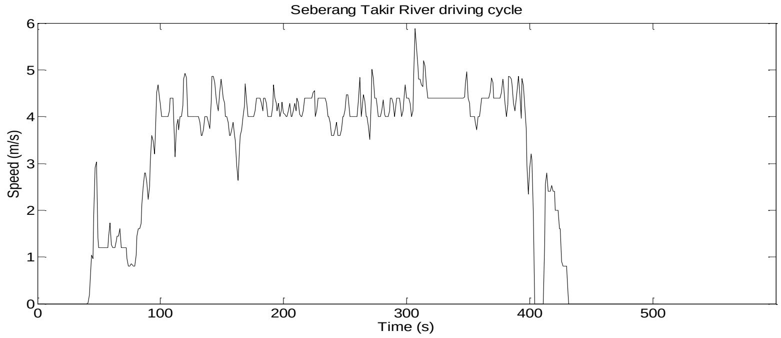
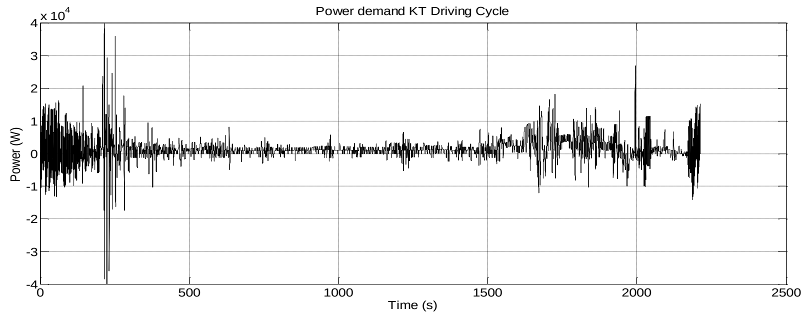
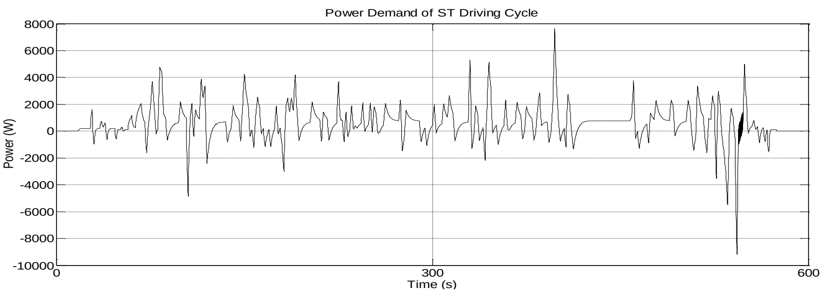


Fig. 11. ST speed profile.

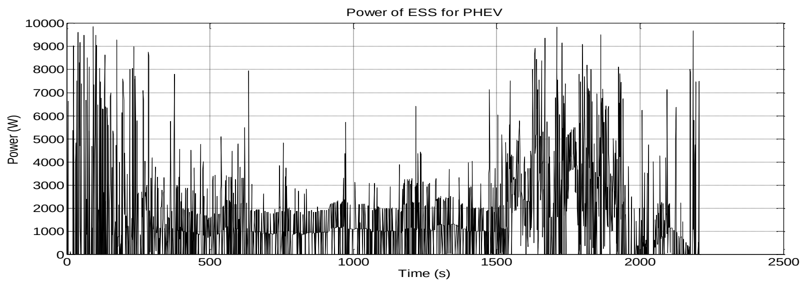


(a) KT river.

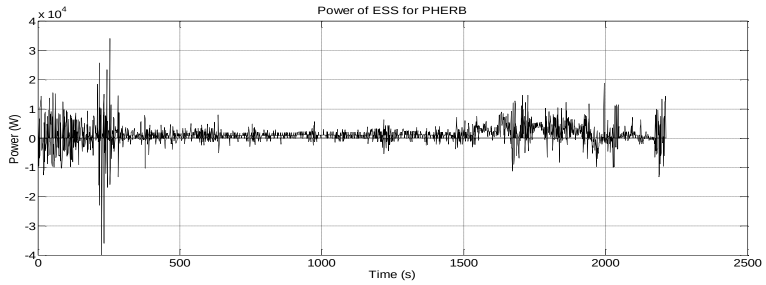


(b) ST river.

Fig. 12. Power demand using KT river and ST river driving cycle.

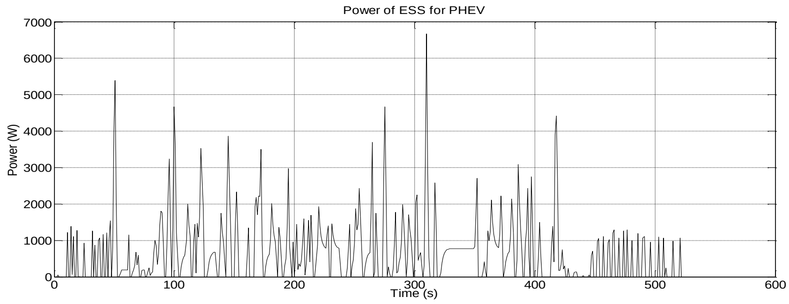


(a) PHEV.

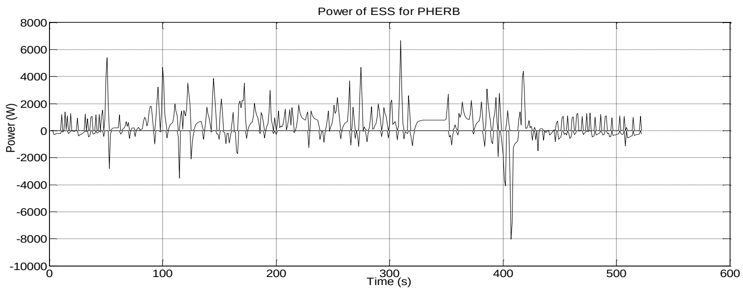


(b) PHERB.

Fig. 13. The different power of ESS in PHEV and PHERB using KT driving cycle.



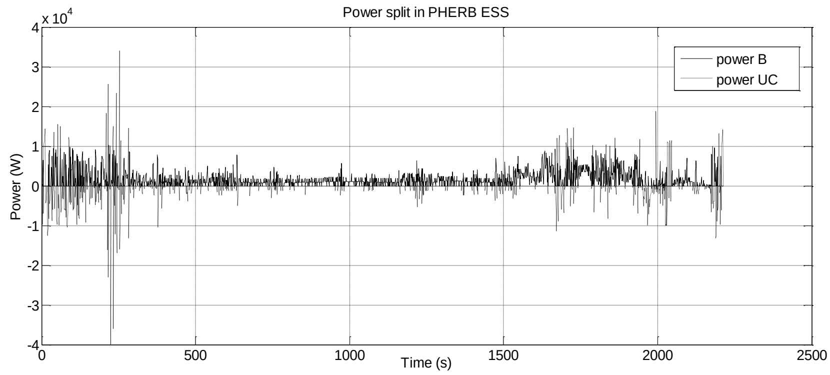
(a) PHEV.



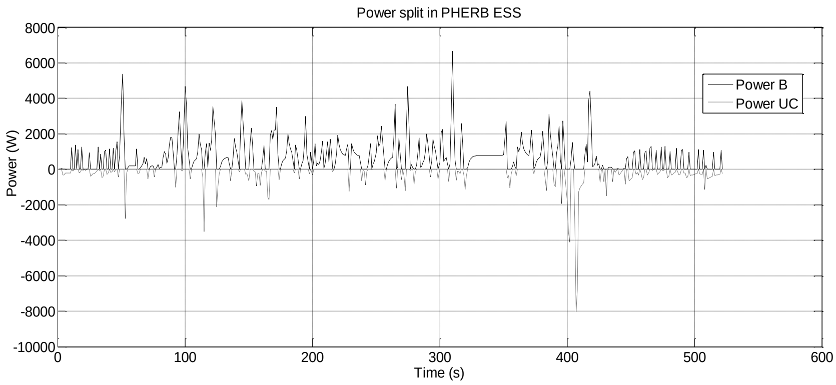
(b) PHERB.

Fig. 14. The different power of ESS in PHEV and PHERB using KT driving cycle.

This analysis explicated the underlying principle behind boat power and energy management strategy of the PHERB powertrain. This split power occurs in PHERB is presented in Fig. 15 based on KT river and ST river driving cycle. Based on the simulation results in Figs. 12 to 15 of the power of ESS requirements between the battery and ultracapacitor in the PHERB powertrain, it can be concluded that different drive cycles have different driving style characteristics according to the acceleration and deceleration events during the driving schedule. This is because ultracapacitor can capture and provide quick bursts of energy as it has high power density. Hence, battery- ultracapacitor combination as an energy storage system for PHERB is one of the best solution. By using this combination, the battery peak current reduces as during high power demand, the average power is provided by battery and peak power demand by ultracapacitor. Using the optimal combination of both the battery stress is reduced and provide from damage. Besides that, an effective EMS, which controls the power balance between components in the PHERB powertrain is really important in order to improve the PHERB all-electric drive performance and energy efficiency.



(a) KT river.



(b) ST river.

Fig. 15. Power split in ESS of PHERB using KT river and ST river driving cycle.

4.2. Fuel economy and emission analysis

This study compares the Fuel Economy (FE) and emissions of PHERB model configuration for different ESS, which is used battery only and combination battery-ultracapacitor shown in Table 1 such as hydrocarbon (HC), carbon monoxide (CO) and nitrogen dioxide (NOx) for the KT and ST drive cycles. Norbakyah et al. [4], Abdul Rahman et al. [15-16] and Norbakyah et al., [16], where *D* is a distance in miles and V fuel is volume of fuel in consumed in gallons.

$$\text{FE (mpg)} = D/V\ \text{fuel} \tag{7}$$

The PHERB model is simulated using a specially developed EMS. SOC is an important part in EMS although not related to the component sizing it gives the impact in FE and emission. The FE and emissions for different drive cycles are given in Table 4.

Table 4. FE and emission analysis.

Driving cycle	ESS	Fuel economy (mpg)	Emission (grams/mile)		
			HC	CO	NOx
KT river	Battery pack	157.2	0.655	0.322	0.102
	Battery-ultracapacitor	184.6	0.558	0.285	0.000
ST river	Battery pack	246.0	1.526	0.954	0.058
	Battery-ultracapacitor	282.5	1.060	0.525	0.000

5. Conclusions

Based on the simulation results between the battery and battery-ultracapacitor in ESS for PHERB powertrain, it can be concluded that battery-ultracapacitor give the higher output for power, current and voltage while for SOC battery-ultracapacitor decrease slower than SOC battery. From this analysis, battery-ultracapacitor in ESS can give the maximum power to components in the boat powertrain. While in fuel economy and emission analysis has shown that using battery-ultracapacitor produced high fuel economy and low emission. As a conclusion, battery-ultracapacitor in ESS for new invention PHERB powertrain is really important in order to improve the boat all-electric drive performance, energy efficiency and the result can be used to build ESS PHERB prototype.

Nomenclatures

C	Usable capacity
Iout	Output of current
η	Efficiency of charging and discharging
$P_{battery}$	Power of battery
P_{ESS}	Power of energy system storage
Pout	Output power
P_{UC}	Power of ultracapacitor
R	Internal resistance
SOC_0	Initial value of SOC
V_{min}	Minimum voltage
V_{max}	Maximum voltage
Voc	Open circuit voltage of battery

Abbreviations

EM	Electric Machine
EMS	Energy Management Strategy
ESS	Energy System Storage
FE	Fuel Economy
ICE	Internal Combustion Engine
PHERB	Plug-in Hybrid Electric Recreational Boat
SOC	State of Charge

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