



A comprehensive energy analysis of a hybrid motorization for small/medium boats

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Abstract.

Small/Medium boats are considered as favourite maritime transportation, and they are mostly propelled by Outboard Motors. Boats are designed for recreative, fishing and surveillance purposes, however in tropical undeveloped countries boats are employed for different applications such as passenger and goods transportation fairly away from nominal power engine, which lies from 8 to 12% engine efficiency. The present survey aims to develop a novel navigation perspective in a power and efficiency analysis of Plug-in Hybrid Electric Ship (PHES)¹. An internal combustion engine (ICE) is converted in hybrid propulsion system (HPS) coupling an electric motor powered by batteries through an electric DC bus device in a parallel configuration system, in order to increasing the traveled distance to fuel consumption ratio. Parameters such as boat size, engine hybrid configuration, were simulated on a schematic model system following an actual navigation route drawn, improving a 25-30% overall system efficiency respect nominal engine performance.

Key words

Plug-in Hybrid Electric Ship (PHES), Marine Transportation, Outboard Engines.

1. Introduction

Colombia has more than 11593 km navigable river [1] and about 6% of total products manufactured and fifth of entire population moves in low weight river transportation per year, employing commercial exchange and transportation [2]. However engine power requirements for small and medium boats are designed for recreative transportation, and short operating distances [3-4] not for passengers or products transportation as mentioned before, meaning different loads requirements and fuel consumption respect to its original design.

Outboard and Inboard engines are meanly carried for fluvial transportation and employed during long operating periods with different load requirements [4]. This fact

represents costly fuel consumption and environmental problems because of low efficiency at different power boat range from nominal power engine range [4].

Several attempts have been done with the aim to improve the performance of combustion engines for boats of different sizes [3-4] but results were not encouraging enough, so hybrid systems has turned up as alternatives to improve fueling consumption [5]. Hybrid systems have been originally conceived for stand-alone electric power generation and automotive applications, none developments for fluvial transport schemes are presented in technical literature [6-7], converting this research an original work and an innovative solution for fluvial application.

2. Problem Statement

Small and medium boats are designed for recreative, fishing and surveillance purposes; but in developing countries boats are employed for different applications such as passengers and products transportation at low speed and fairly away from nominal (and optimal) power ranges. This fact can be analyzed in the following engine power and effective power of a small conventional boat (Fig. 1) and its fuel consumption performance (Fig. 2) at nominal and maximum velocity.

On Fig. 2, a wide gap between Engine Offered Power and Boat Required Power can be seen, leading to a low efficiency of the engine at low speeds, because most of the energy offered by the engine in this region its not used. Furthermore boats moves away of nominal power and nominal velocity and because of this, they handle high fuel consumption per mile. This makes a complete hybrid system a solution in order to lead the ICE power offer to a high performance operation condition powering up batteries and making that an EM satisfies the boat power requirements. However there are several technical limitations compared to land vehicles such as general size, engine-transmission configuration, that can even

being a challenge to adapt hybrid land vehicles technologies to maritime boat configuration.

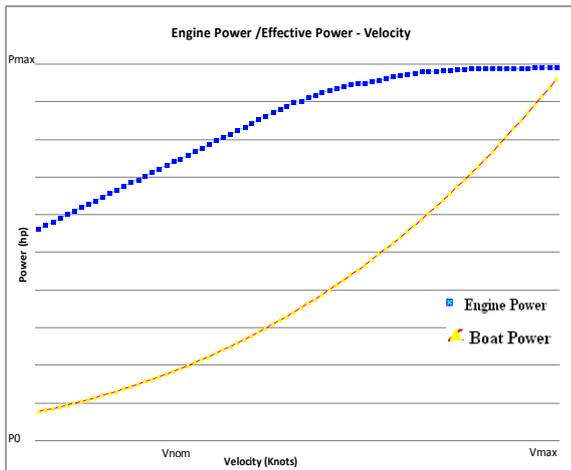


Fig. 1. Power engine and effective curves compared to boat velocity.

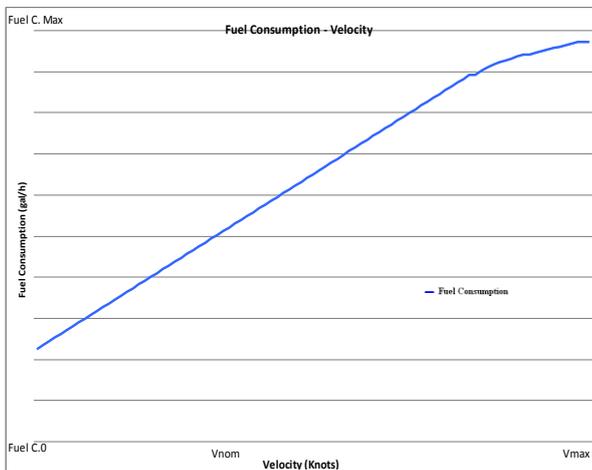


Fig. 2. Fuel consumption compared to boat velocity.

A. Problem Statement Analysis

Analysis began from a small boat specifications data and fluid properties in following Tables. The following equations were used in the simulation of the ship behavior when shipping.

Table I. - Boat Data Specifications

Boat Data	Nomenclature	Unit
Length	L	Long
Wet Length	Lw	Long.
Perpendicular Length	Lpp	Long.
Beam	B	Long.
Depth	P	Long.
Displacement	D	Weight
Boat Weight	W	ton
Max. Power	Pw	Power
Velocity	V	Long./time
Nom. Velocity	Vnom	knots
Max. Velocity	Vmax	knots
Rotational speed engine	rpm	Rev/time.

Table II. – Fluid Parameters

Fluid Data	Nomenclature	Unit
Cinematic viscosity	ν	Long ² /time
Water density	ρ	Weight/Volume

Table III. – Hydrodynamics properties for boats and forces on boats

Wet area	$S = (1.7 * Lpp * P) ((D / 1026) / P)$
Reynolds Number	$R = \frac{V * 0.514 * L}{\nu}$
Frictional coefficient	$Cf = \frac{0.075}{(\log R - 2)^2}$
Frictional Resistance	$\frac{(0.5 * 104.44 * Cf * Ah * (V * 0.514)^2 * 9.81)}{1000}$
Wave resistance	$Rw = \frac{(0.06 * ((D / 1000)^2 / 3)) * (V)^4}{L}$
Whirlpool resistance	$Rwl = 0.08Rf$
Trailer resistance	$Rtr = Rw + Rf$
Air resistance	$Ra = 0.5Rtr$
Propulsion resistance	$Rp = 0.15Rr$
Total resistance	$Rt = Rtr + Rp + Ra$
Effective Power (Boat Power)	$Pe = 1.34(0.514Rt * V)$

The effective power curve behavior can be shown on Fig. 1; the engine power behavior is from a conventional engine and fuel consumption from power effective ranges.

B. Hybrid Propulsion System (PHS)

HPS offer a sustainable mobility with a great improvement of the quality of life in highly populated cities. Within this universal trend, the automotive market is continuously supplied by new hybrid vehicles. Some of them are already popular worldwide.

There are 3 major topics when we're Referring to the published material and to the manufactured concepts [8]:

1. The Series Hybrid.
2. The Parallel hybrid.
3. The Series/parallel hybrid.

Parallel HPS concerns, both the ICE and the electric motor drive the wheels with appropriate power ratios. The battery pack is recharged by switching the motor to act as a generator. In spite of its simplicity, the parallel HPS cannot drive the charge from the electric motor while simultaneously charging the battery pack [8].

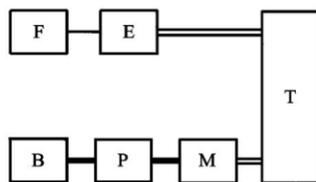


Fig. 3. Parallel HPS block diagram.

C. Structure of the Hybrid Boat

Considering standards, properties, advantages and disadvantages of different technologies in market for a specific function, a comprehensive analysis of Novel Hybrid Motorization of Small/medium Boats for sustainable transportation is exposed. This boat will work with an energy management array obtained from gasoline and electric energy.

A Parallel HPS (Fig. 3) was selected to be implemented into the boat due to the flexibility power generation it presents, the superior ability to handle changes in charge, constructive simplicity, in addition to the smaller engines robustness requirement for a specific application when it's compared to a single Series or Series/parallel HPS. The selection a Parallel HPS configuration implies a more difficult global transmission gear design, superior building complexity and more complex control strategy than a series HPS one.

The Parallel HPS selected above will be electrically powered by batteries. An important fact is the availability to recharge the Batteries at harbor, taking advantage in the common periods that boats are inactive, i.e. when loading the cargo, by plugging the ship connector to national power grid. At low power demand the ship will be totally powered by the EM taking advantages of its high efficiency at low loads. While traveling when the power demand reaches a high efficiency state for ICE it is activated for, not only supply the energy requirements for transportation, but also recharge the battery pack. A DC/DC Converter is coupled to the EM/GE in order to rectify the voltage signal needed according to the operational mode selected. The different electric devices are interconnected through a DC bus; this DC bus allows adapting and exchanging energy between the different components.

Fig. 3 shows the block diagram of the components that constitute the generation system and power management for boat Parallel HPS. Fig. 4 shows the layout of the most relevant equipment in the structure of fuel boat parallel HPS.

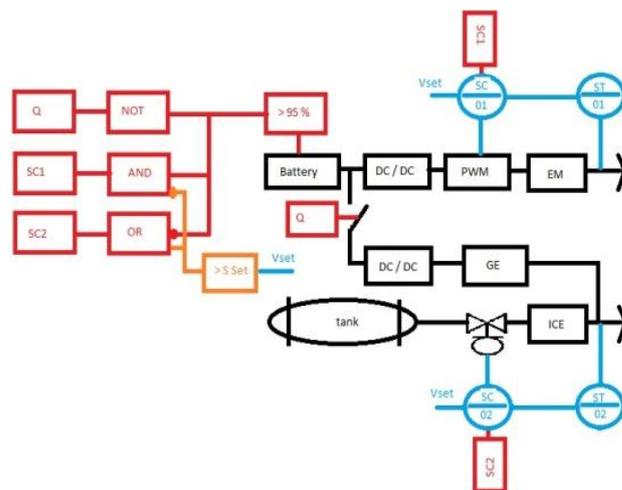


Fig. 4. Boat Parallel HPS Schematic diagram.

3. Description of Components

In this section the components of the HPS proposed will be discussed. The effectiveness of the hybrid configuration will depend on the state of the art of all of the following components. Some of them like batteries and electric motors put a technological limitation to a better performance.

A. The Hull

A conscious Cost-Benefit relation must to take place. While a Semicircular Shape for building the hull implies a very good deal between ICE fuel consumption and power required from driving system, it's also represent higher manufacturing costs, higher qualification from designers and machine operators, and high-tech instruments when its compared to V-shape. The U-shape is usually preferred by important ship manufacturers worldwide due to its relatively easy fabrication requirement commitments and technology applied.

According to topics developed above, and aiming to generate a practical solution to undeveloped countries just like Colombia, a hull U-shape was selected to design the boat. This boat has been designed with 6m Length, 2m beam, 0.83m Depth, 0.7m Draft, 1,5 tons weight and displacement of 1.5 tons according to Pedro Vite -1991 & Antoni Cànaves et al – 2011. [21,22].

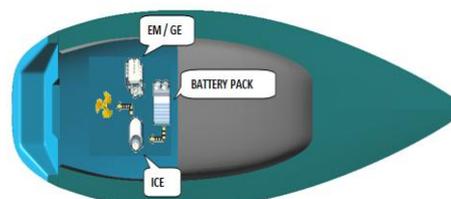


Fig. 5. Boat Components Layout.

B. Internal Combustion Engine (ICE)

A complete understanding of machine performance and technological problems of ICE are very good explained in literature nowadays, in order to review this specific issue the reference [23] it's recommended. The efficiency of the ICE was modeled by using a regression model approximation shown in Prediction of Energy efficiency in gasoline Engines under Partial Load Performance (In Spanish) [24], obtaining the following polynomial expression:

$$EE = 0.0346 + 1.1825T + 2.27 \times 10^{-6}n - 1.67 \times 10^{-5}Tn - 1.5969T^2 - 4.79 \times 10^{-9}n^2 - 8.53 \times 10^{-9}Tn^2 + 0.66T^3 + 5.56 \times 10^{-13}n^3 + 6.86 \times 10^{-5}T^2n$$

This expression gives the ICE engine efficiency as a function of the partial load (required torque to maximum one) and the speed regime in revolutions per minute.

C. Motor/Generator Pack

According to electrical motors concern, a Couple Brushless DC motor/generator was selected. Several products in market are good enough to reach the standards we need for this application. Chapman S. et al has been well studied Electric machines, so it's used as reference for simulation models [25].

D. Electric Motor (EM)

Utilization of DC motors makes easier the design process and reduces in complexity the HPS required to fluvial applications because of capacitors, Electrolizers and DC/AC converters become unnecessary [26]. Electrical motor behavior at changing loads has been well analyzed by Ogata et al [27].

A PERM motor PMG132 Series was selected; Table IV shows relevant features for this motor.

Table IV. – Selected EM features

Armature Voltage (V)	Current (A)	Speed (rpm)	Torque (N.m)	Power (Hp / Kw)
72	110	3480	20	5,38 / 7,22
Resistance (OHM)	Mom. Inertia (Kg.m2)	Weight (Kg)	Efficiency (%)	Inductance (mH)
0,016	0,025	11	87	0,019

Complete technical features for PERM MOTOR PMG 132 Series motor are provided in Perm Motor brochure for PMG catalogue [28].

E. Generator

When the ship is traveling at plain charge the ICE recharge the batteries trough an alternator joined. A PSG 120 alternator Series by PERM MOTORS was selected, this element is specially manufactured for automotive

applications; Table V shows relevant features for this element.

Table V. - Main characteristics of PSG 120 alternator by PERM MOTORS.

ITEM	OUTLINE
Stator Outside Diameter	Ø 152 - 230
Lenght	114,7 - 159,7 (mm)
Output	2,2 - 7 (Kw)
Weight	12,3 (Kg)

Complete technical features for PSG 120 alternator Series motor are provided in PERM MOTORS technical brochure [29].

F. Batteries

Batteries selection means a break point into mechatronic designs because implies a great deal between weight and power, therefore a pack from Panasonic® was selected. These batteries belong to HHR450A series, the one specially designed for High power and Marine engine starting, getting 6.2Amp/h from every single element and rechargeable in only 12 minutes at 100Amps rate. Using batteries above mentioned the design equipment achieves only 0, 42% weight from total ship weight.

Batteries have been simulated by using the generic battery model in Simulink™, available at SympowerSystem pack. Complete technical features for Panasonic® HHR450A series are provided in technical brochure [30].

G. Electronic Converter

Boost and Buck-Boost power converters are used to adapt the different electrical signals to the HPS boat. Three DC/DC converters are needed:

- 1) The first converter is located between the EM and the DC bus. It is necessary because the voltage needed by the EM varies from 245 V up to 470 V. Is needed to increase the voltage, therefore is used a boost converter type.
- 2) The second converter is located between the EG and the DC bus. This is also a boost converter type to increase the output voltage of the generation system from 12V to 100 V.
- 3) The last converter is a bidirectional buck-boost, which manages power between the DC bus and the battery.

4. Model Validation

A. Control Considerations

As discussed above, if fuel energy is not optimized during shipping, Control scheme proposed reaches ICE operational point to its maximum efficiency and recharge batteries. The control logic it's presented in Table VI.

Table VI. - HPS logic for driving system selection.

Operational Condition					
Desired speed	Condition	Nom. speed	SOC	Drv. Selection	
Vd	<=	Vnom	>80%	EM	Optimum
Vd	<=	Vnom	<20%	ICE	Waste
Vd	>	Vnom	>80%	ICE	Optimum
Vd	>	Vnom	<20%	ICE	Recharge

According to EM and ICE response to incoming signals, PI and P controllers were implemented in the simulation in order to maintain a desired output speed value. Table VII shows principal characteristics of controllers implemented.

Table VII. – Tuning parameters of Controllers

5% overshoot		PI
Kc	0,042155	
Tc	0,35686	
Td	NA	
5% overshoot		P
Kc	1	

With this, the final PHES's Simulink model it's presented on Fig 6.

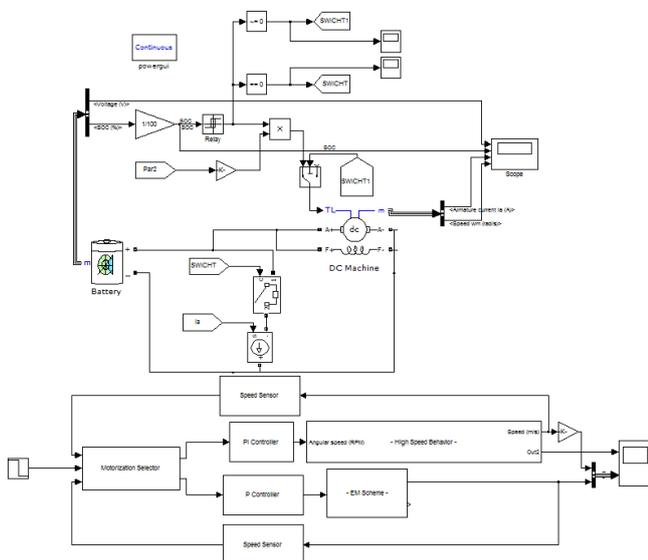


Fig. 6. Simulink model of the PHES.

B. System Performance

In order to estimate the future performance of a prototype using the Novel hybrid system proposed, simulation of a variable speed set point is carried out. Fig. 5 shows the speed shape selected for simulating the future behavior, this speed shape comes out from a real trip from “Bocas de

Ceniza's Church” to “Islas del Rosario” in Cartagena Colombia.

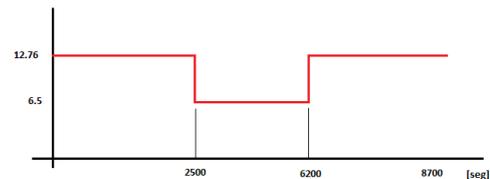


Fig. 7. Speed Shape [knots] required for the boat.

Electric components into PHES's behavior under simulation are presented in Fig. 8. Initial Value of 100% SOC was used as input for batteries state. It can be found that charge time is smaller than discharge time as desirable into a plug-in hybrid system.

From simulations are obtained an average charge time of 12.3 minutes, while the discharge time depends on the cruising speed selected. In addition, armature current into alternator strongly depends on ICE speed joined, under simulation conditions 60 Amps current value predicted are suitable for the application designed.

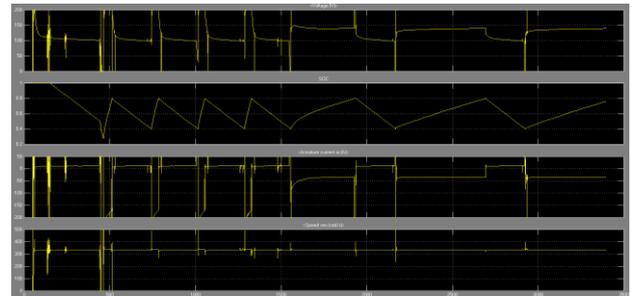


Fig. 8. Electric components behavior under speed shape.

What's energy efficiency concern, Fig. 9 a) presents the ICE performance during shipping under speed shape above. From Fig.9 a) can be found that efficiency operation curve for ICE remains constant at a high value, also a very low efficiency zone while traveling at low speed is presented, this low zone is resulting from polynomial array for making calculations and it's not recommended to take it into account because it's in this region where the EM it's working.

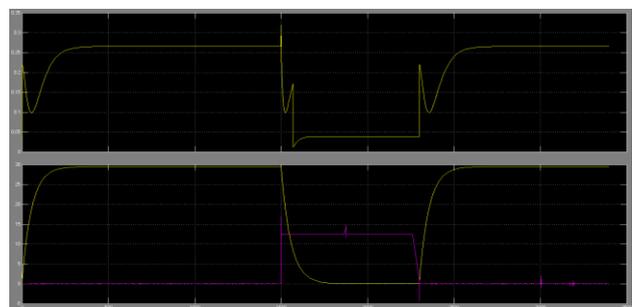


Fig. 9. A) Fuel Consumption B) Speed under PHES scheme.

Fuel Consumption savings come through while electric motorization scheme is activated, Fig.9 b) show switching behavior as continuous lines to achieve the

speed shape desired, boat speed while powered by EM is represented as a purple line. In this case, the energy obtained from the ICE it's used to recharge batteries in order to replenish the energy that now it's using the EM. As a result, adequate power driving system selection is made according to desired cruising speed, and with this a energy saving it's achieved meanwhile the power requirement it's fulfilled.

5. Conclusions and Remarks

A Novel HPS application has been introduced, the PEHS. This application was strongly build-in viability analyzed and simulated under Simulink for three different states with a typical speed curve shape. Majority of component was modeled using first principal models where ever possible and validated using data from a physical system. According to simulation developed on PHES under a typical trip shape selected: discharge time strongly depends on cruising speed desired, 12.3 minutes average recharge time was estimated leading to an efficiency increment of 29.41% is found. A lot of work is needed in order to build boats under PHES technology. In field tests are strongly recommended. According results obtained from simulation and considering that this simulation was done using commercial devices we conclude the PHES has a great potential for develop into real world.

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