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Design and Simulation of a Sustainable Photovoltaic Electric Plug-In Boat.

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Abstract
The increase of energy prices and environmental catastrophes lead to a development of alternative and renewable energy systems. In this case transport. A high efficient electric engine with a variety of the source replaces the so far used internal combustion engine (ICE). A battery system with a renewable energy provider, like photovoltaic panels, affects promising results.
In the last few years the implementation of renewable energy sources, for example photovoltaic and wind energy in Hybrid Renewable Energy Systems (HRES) is becoming more popular. Those systems are very depending on seasonal impacts and that is the main disadvantage. The vehicles, which may be suitable, drive either on land or on water. On water the weight only plays an important role for small sail ships. But the energy consumption increases during the navigation with sail.
For those types of systems, which mix many power sources, mathematical simulation has become an object of study for electric battery vehicles and all kind of hybrid configurations and even specific software has been developed. However, there is almost no information about battery electric ship simulations and even less about renewable energy sources applied in these kinds of vehicles.
In this paper, a conceptual zero emission electric sailboat is created and simulated. Renewable solar energy and energy storage with batteries, in this case the charging energy is provided by the grid, is implemented. Subsequently independent modular models for each energy system will be development in Matlab®/Simulink® and embedded. All of these simulations are managed by a logic controller implemented in Matlab® as well.

Keywords: Simulation, Plug-In Hybrid boat, Renewable Energy.

1. Introduction

The aim of this work is the creation of an energy independent sailing boat with an electric engine. It contains a simulation and validation of a sailing boat with an integrated renewable energy system to create an emission and pollution free ship. Therefore the renewable energy technology, in this case photovoltaic panels, supplies the electrical energy for the engine, the electrical installation and the charging of the batteries. The target of this project is to create a sailboat for a river or a lake to work autonomously and ecologically. The main part is the simulation of the electrical installation with Matlab® and Simulink® to test the system under varying conditions.

2. Simulation Basis

The chosen sailboat is 4.80 m long and 1.55 m wide. Lithium-iron-phosphate batteries store provide the electrical energy. The engine and the usual electric installation

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for light and navigation all run on DC and the batteries are their power source.

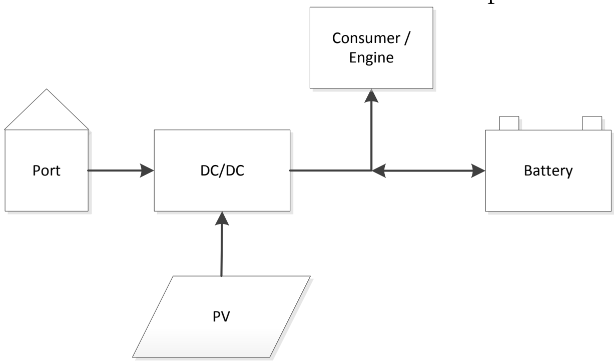

Figure 1: General electric system

On deck are 6 photovoltaic panels, which provide the energy for the consumers and for charging the batteries. Figure 1 shows the simulated system. Table 1 contents the geometric specifications of the ship. In Figure 2 it can be seen the side angle of the ship.

Table 1: Specifications of the geometric form.

Hull length	4.80 m
Length at water	4.07 m
Width	1.98 m
Hull draft	1.25 m
Max. draft	1.50 m
Weight	625 kg
Max. weight	2000 kg
Engine power	4 kW

Figure 2: Side angle of the ship

3. Energy consumption of the propulsion

First the boat is defined to calculate the required energy for cruising without sails. The design of the vessel is chosen by the usage of the boat for cruises on lakes and rivers. There are categories for each type of boat and their field of application. In this project a so-called "Centre Board Boat" delivers the ground structure.Once the type of ship is decided it is possible to calculate the resistance of the hull in the water. This resistance gives the minimum power requirement of the propulsion. Two different ways for the calculation are used. The free software FREE!Ship+ 3.4® [1] enables the creation and simulations of a 3D model. The already done model of the centre board boat is used from the freeship webpage and calculated in FREE!Ship+ 3.4®. The possibilities to calculate with this software are varying and the decision to use the method from van Oortmerssen(1971), which is for calculating the resistance of small ships by different speed, is made.

To calculate the total resistance of the ship the frictional and the residual resistance are added. The sailboats frictional resistance is achieved from the impacts of rudder, hull and keel in the water. The resulting experimental data gives a subject to statistical analysis of the residual resistance and expresses it as a polynomial function for a discrete value of the Froude number and the data of the hull geometry delivers the variables:

$$\frac{Rr}{\nabla_c g} = a_0 + a_1 C_p + a_2 LCB + a_3 \frac{\mathrm{Bwl}}{Tc} + a_4 \frac{Lwl}{\nabla^{1/3}} + a_5 Cp^2 + a_6 Cp \frac{Lwl}{\nabla^{1/3}} + a_7 (LCB)^2 + a_8 \left(\frac{Lwl}{\nabla^{1/3}}\right)^2 + a_9 \left(\frac{Lwl}{\nabla^{1/3}}\right)^3 \quad (1)$$

where:

Rr	Residual resistance	N
∇c	Weight	kg
ϱ	Density of water	kg/m^3
g	Acceleration due to gravity	m/s^2
Lwl	Floating line at length	m
Bwl	Floating line at width	m
LCB	Centre of weight	m
Tc	Draft of hull	m
Cp	Prismatic coefficient	-
a_n	DELFT coefficient	-

4. Discussion of Simulation Results

In Figure 3 the simulated resistance of the boat, depending on the maximum speed in knots, the hull geometry and the weight, shows a required engine power of 5 kW. Those dates come from the Free!Ship+ file and deliver the base for the calculations.

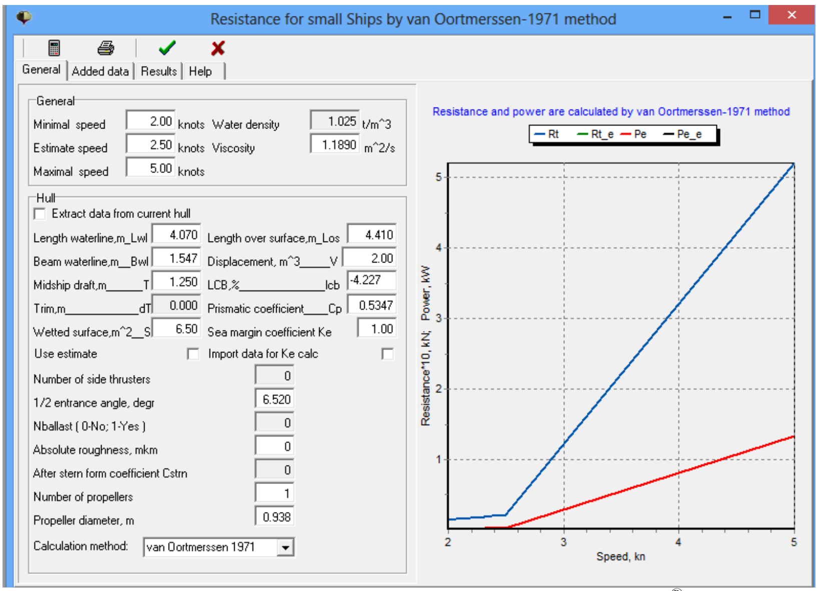

Figure 3: Resistance of the ship hull with FREE!Ship+ 3.4®.

The most important facts about the boat, the hydrostatic characteristics, to calculate the resistance and therefor the necessary power of the engine from Free!Ship+ are shown in Table 3.

Table 2: Hydrostatic characteristics

Hull length	4.80 m
Length at water	4.07 m
Width	1.98 m
Hull draft	1.25 m
Maximum draft	1.50 m
Water density	1025 kg/m^3
Displaced volume	1950 m^3
Width at water	1.55 m
Weight	625 kg
Maximum weight	2000 kg
Water plane coefficient	0.5347
Wetted surface	6.5 m^2

The second calculation of the resistance is made with Simulink®. The project Hydrovela,**Errore. L'origine riferimento non è stata trovata.**, gives the original simulation for this. The hydrostatic characteristic key dates from the ship are typed in and the simulation tells the minimal power for the engine required.

In Figure the resistance of the ship depending on the speed simulates the required energy of the engine. At a maximum speed of 5 knots the simulations shows a resistance of 4 kW. This result is used to calculate the total amount of needed electric energy and to calculate the amount of battery cells to fulfil the inquired time of cruising autarky.

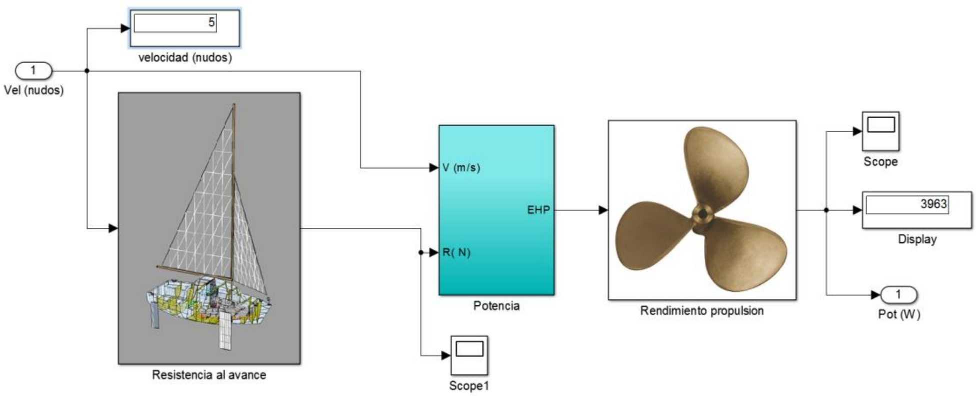

Figure 4: Calculated energy required by the motor in Simulink®

5. Engine

The electric engine is the main part of the consumer site. There are certain requirements coming from the resistance and the generated energy from the photovoltaic panels. The calculated resistance is 4 kW. Therefore an engine with a voltage of 48 V and a power of 4 kW and a power consumption of 5 kW will provide the propulsion. An internet research brings up many possibilities and the decision on the

ACAV 4,0 from Kräutler Electrical Engines was made.Beside the engine a sailboat has other electrical energy consumers for navigation, safety and physical wellbeing. This electrical system runs on 12 V and consumes energy every time the ship is in use. The following table shows a list of the auxiliary components. The energy consumptions were estimated Larminie (2012).The base of a photovoltaic system is the operation of a photovoltaic panel. Those panels are photosensitive devices, which generate electricity by using the photovoltaic effect. This effect describes the transformation of solar radiation into electrical power. The modelling of this system is used to give a forecast of the energy, generated by the integrated photovoltaic panels. The calculation requires an amount of variables, which are not public available but the de Soto model only uses five inputs, to find in every datasheet of a photovoltaic panel de Soto (2006).

6. Lithium-iron-phosphate battery

The battery is used as storage for electrical power from the plug or generated by the photovoltaic panels on deck of the sailboat and to provide it for the use of the engine and other consumers. It is an accumulator, which stores the energy electrochemically. Each battery from the type SP-LFP60AHA-S from SinoPoly provides up to 3,2 V with a capacity of 60 Ah. Charging and discharging at the same time is possible and furthermore the weight causes stability for the boat. In Simulink® a discharge simulation is created to show the performance of the battery.

7. Simulation

The target of the simulation is to find the amount of cells to cruise for at least threehours with 4.5 knots without using the sails in terms of weather conditions without sun. The radiation dates are on a daily base, which means they are the same for a time period less than 24 hours. The calculationsshow the amount of cells needed, parallel and serial, to deliver and store the required energy by the engine and the auxiliary consumers. The calculated cells are than simulated for different time periods in Simulink®. Three types of simulations are made:

Case 1: cruising without sun to simulate the total dependence on the batteries and to find out how long the ship could go without wind at different speeds.

Case 2: sailing without engine and the solar panels charge the batteries to find out how long it takes for a total charge.

Case 3: the engine uses and the photovoltaic panels generate electricity at the same time, so the control panel finds out if the generated energy could cover the consumption. If more energy is provided than used the battery is charged and if more energy is consumed than generated the battery is discharged.

8. Results

Case 1): In the case 1, the dependence on the batteries is total.

Case 1a) 5 hours at 5.5 kn.In **Errore. L'origine riferimento non è stata**

trovata.5 the battery is discharged from the engine and the auxiliaries for 5 hours (18200 seconds) with 9975 W. The result is a total discharge of the battery, DoD = 1, after 4500 seconds, about 1h 30 mins. This is the highest possible speed to return in case of an emergency.

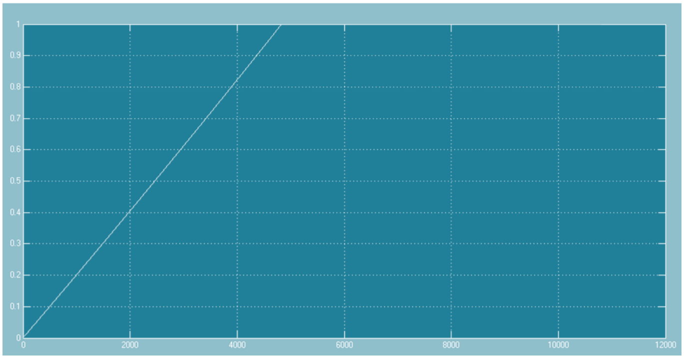

Figure 5: DoD at discharging with 5,5 kn with x-axis = Time (sec); y-axis = DoD (-)

Case 1b) 5 hours at 5 knInfigure 6, the battery has to provide the power for the engine and the auxiliaries for three hours, or 18.000 seconds. The scope diagram shows a linear discharge in the range of the capacity.

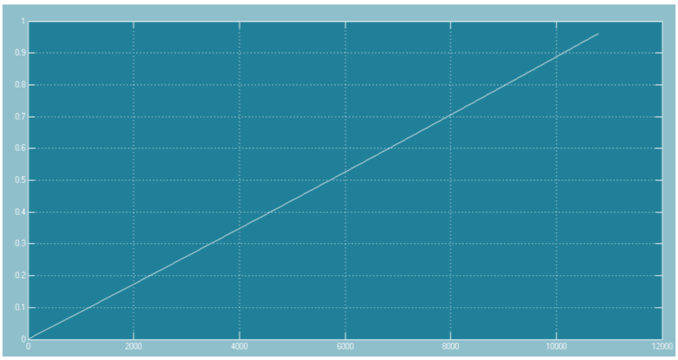

Figure 62: DoD at discharging with 5 kn with x-axis = Time (sec); y-axis = DoD (-)

Case 1c) 10 hours at 4.5 kn.

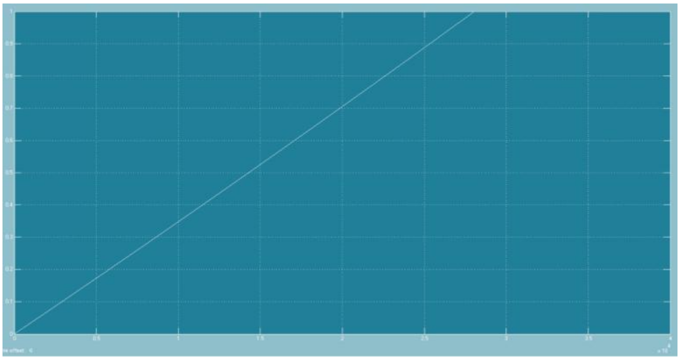

Figure 7: DoD at discharging with 4.5 kn with x-axis = Time (sec); y-axis = DoD **(-)**

In **Errore. L'origine riferimento non è stata trovata.** the battery delivers energy to the engine at 4.5 kn for a time of 10 hours. At 27500 seconds,about 7.5 hours, the DoD is one, which means the battery is totally discharged.

Case 2): In case 2 the battery is charged by the solar panels. There is no power discharged from the engine or the auxiliary consumers. The following diagrams show the time of three and ten hours to charge the battery. The charging is very slow because of the small amount of installed photovoltaic power caused by the limited space on deck of the ship.

Case 2a). See Figure 8.

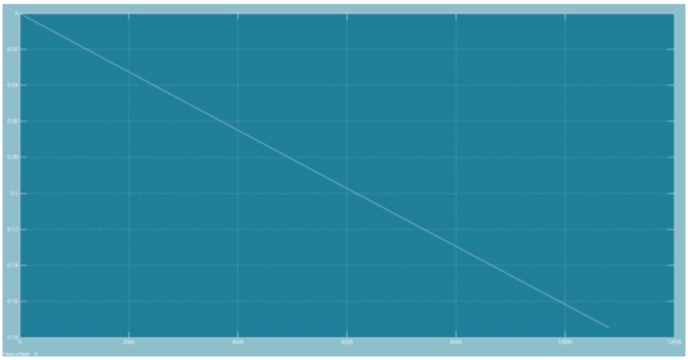

Figure 8: Charging of the battery by solar power in 3 h with x-axis = Time (sec); y-axis = DoD (-)

Case 2b is show in figure 9.

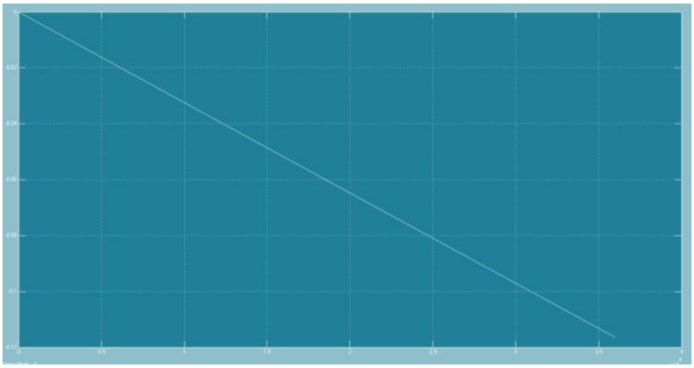

Figure 9: Charging of the battery by solar power in 10 h with x-axis = Time (sec); y-axis = DoD (-)

After ten hours there is only a tenth of the battery recharged. The amount is very small and the conclusion is, that the time to charge the battery fully will be 9 days with each ten hours of solar radiation. In praxis it is nearly impossible and therefore the battery needs to compensate the energy consumed.

Case 3): the engine uses and the photovoltaic panels generate electricity at the same time

Case 3a) 3 hours at 5 kn and 200 W of solar power.

In Figure and Figure the DoD, depth of discharge, is increasing less than without solar power. The difference between maximum speed of 5 knots and the reduced speed at 4.5 knots is very clear visible. At the same time with the same solar radiation the DoD with 5 knots is three times the depth of discharge with 4.5 knots.

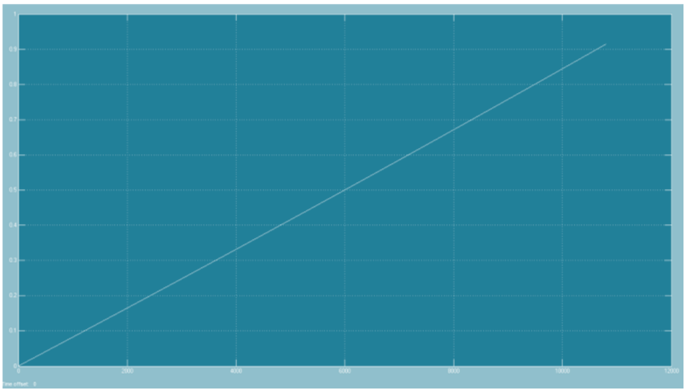

Figure 10: Simultaneous charge and discharge with x-axis = Time (sec); y-axis = DoD (-)

Case 3b) 3 hours at 4.5 kn and 200 W of solar power (Figure 11). Simultaneous charge and discharge with x-axis = Time (sec); y-axis = DoD (-). The DoD, depth of discharge, is increasing less than without solar power. The difference between maximum speed of 5 knots and the reduced speed at 4.5 knots is very clear visible. At the same time with the same solar radiation the DoD with 5 knots is three times the depth of discharge with 4.5 knots.

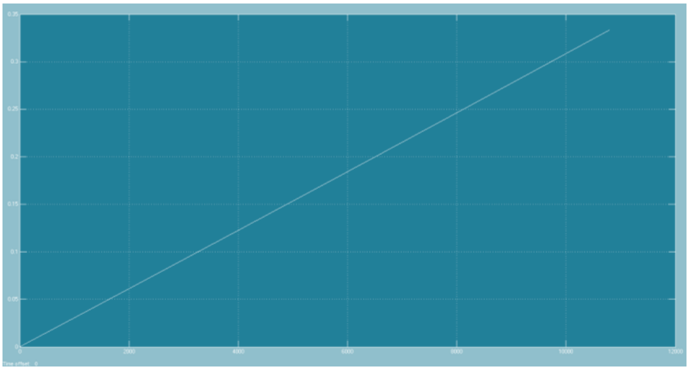

Figure 11: Simultaneous charge and discharge with x-axis = Time (sec); y-axis = DoD (-)

9. Conclusions

A zero emission and energy autarky sail ship is only possible if the space for solar panels is in this case about ten times higher. Another option would be to use other renewable energy systems to load the batteries, for example a wind or water generator. The simulated ship is possible to cruise 3 hours with a speed of 5 knots or 7.5 hours with 4.5 knots if only the energy of the battery is used. With the support of the solar panels the autarky time with 5 kn increases ten minutes and with 4.5 kn an hour. The ten mono-crystalline panels on deck perform only a hundred per cent without any gear causing shades. New technologies for flexible panels could change the performance of the solar generator. The photovoltaic could be placed and the whole ship surface and even the sails are generating power. The advantage is the amorphous technology, which is not temperamental to shade, but has lower efficiency. The main problem with the solar power is the seasonal dependence. In summer the radiation is highest but the wind to sail is on its minimum. To reach a higher period of autarky the battery stack could be enlarged. The 120 cells weight 216 kg and it is possible to load the boat with another 400 kg without affecting the safety. The batteries at the bottom of the ship give beside the power source an extra stability on water.

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