Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 75 (2015) 1901 – 1906
Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Design considerations of a solar racing boat: propeller design parameters as a result of PV system power

Tim Gorter*

NHL University of Applied Sciences, Rengerslaan 10, 8921HN, Leeuwarden, The Netherlands

Abstract

In order to optimize a PV-powered racing boat, we researched the relationship between the power generated with PV modules and the design of the propeller for the boat during a race. Research on solar-powered boats show optimization of sub-components, but do not consider the interaction of the complete set of components and the optimization thereof.

We made a set of equations describing the energy generated while sailing a distance, and a model for a permanent magnet DC motor. Furthermore, we considered the power flows from PV module hull resistance in the water. Considering the available amount of power and the hull's resistance for various speeds, we were able to determine optimum efficiencies of the electrical engine to determine design parameters for the boat's propeller. We compared monitoring data from a race for PV-powered boats from 2012 with a similar race in 2014. As a result, we noticed an increase of 15% in efficiency. With these equations, we prove that considering the available amount of solar energy can help optimize the propulsion system for PV-powered boats.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: Solar boats, PV-powered boats, PV system, propulsion optimization

1. Introduction

In the past years, several studies focused on sub-components of (partly) solar-powered boats and the optimization thereof [4-8]. However, it is important to create synergy between the sub-components in order to let them operate optimally as a whole. The aim of this paper is to contribute to the knowledge of solar boat design.

* Corresponding author. Tel.: +31 58 251 2575
E-mail address: t.gorter@nhl.nl.

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.179

In 2006, the Dong Energy Solar Challenge (DSC) was initiated in Friesland. Participants in the race have to sail a 220 km trajectory with several legs on solar energy only. Leg distances vary between 5 km (sprint) and 56 km (endurance). The onboard electrical system's voltage may not exceed 52 V. Typical power consumption for an A-class boat is 1.2 kW for long distances and 5 kW for sprints [1].

NHL University of Applied Sciences (NHL) participated in the DSC with a solar-powered racing boat, see Fig 1 [2,3]. We optimized the propeller design and compared monitoring data from the race in 2012 with a new challenge in 2014 to determine the increase in efficiency.

Fig 1. NHL PV-powered racing boat

2. Research methodology

In order to optimize the working of sub-components in our race boat, we analyzed the power flows from the photovoltaic (PV) system to the propeller while taking the hull resistance in consideration. We mapped the components in the system and how they are related to each other, see Fig. 2. This shows that the hull resistance has influence on the dimensioning of the PV system, since the power generated by the PV system is an indicator for the amount of thrust the propeller can deliver, considering the distance of sailing and time of the day.

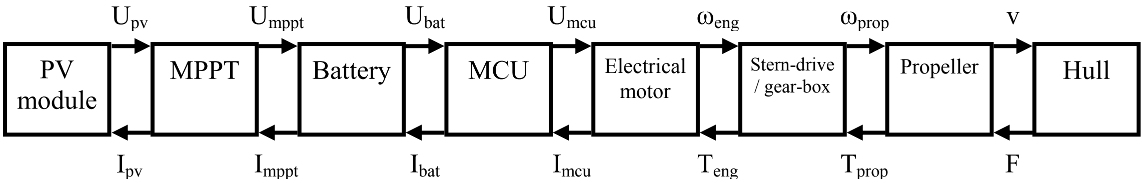

Fig. 2. Overview of components which influence the performance of a PV boat. Wiring is not included in this overview, but should not be neglected as a possible source of losses if high currents are involved.

A PV boat can be divided into a mechanical and an electrical domain. The electrical domain consists out of the PV system, the battery and the motor controller unit (MCU). The mechanical domain consists out of the electrical motor, gear box and propeller. The link between these domains is the electrical motor.

The PV modules provide a voltage U_{pv}, which is transformed by MPPTs to a voltage U_{mppt} to charge the battery. The battery provides the voltage U_{bat} which is transformed by the MCU to apply a voltage U_{mcu} accross the electrical engine. The electrical engine has an angular velocity ω_{eng} according to the voltage U_{mcu}, in the ratio 1:K. K is a constant do describe this ratio as shown in section 3.3. Connected with axles and/or a gearbox, a propeller starts rotating with an angular velocity ω_{prop} to give the hull a certain speed.

Depending on the speed v of the hull, a resistance F is seen by the hull. This resistance F translates into a torque T_{prop} from the propeller. The torque from the propeller results in a torque T_{eng} from the engine which results in a current I_{mcu} from the MCU. The energy needed is withdrawn from the battery, and is balanced with a well-dimensioned PV system.

We used a displacement hull and the relationship between the power and the speed can be empirically determined, see equation 1 [10]. We characterized the hull with drag tests. Then, we characterized the electrical engine and we determined the relationships between the electrical power and the mechanical power of the drive train. Finally, we estimated the available energy under various sailing scenarios to find optimal parameters for propeller design.

3. Results

The boat characteristics determine the power need to propel the boat, see equation 1.

$$P \mathrel{\widehat{=}} c \cdot v^3 \tag{1}$$

with:
P = power [W]
c = constant describing the hull's resistance [-]
v = speed [m/s]

The drive train consists out of a motor controller unit, an electrical motor, stern drive and a propeller. The power (or thrust) of a propeller is dependent on the angular velocity and torque.

$$P = \omega \cdot T \tag{2}$$

with:
ω = angular velocity [rad/s]
T = torque [Nm]

The efficiency for the motor with an arbitrary voltage and current can be found with equation 3. The voltage over an electrical engine determines the angular velocity of the engine, which will be proved in equations 4 to 7. With these motor variables (angular velocity and efficiency), the corresponding current which is needed, can be found. As a result of that, angular velocity and torque of the propeller can be determined.

$$\eta_{motor} = (\omega \cdot T) / (U \cdot I) \tag{3}$$

with:
U = voltage [V]
I = current [A]

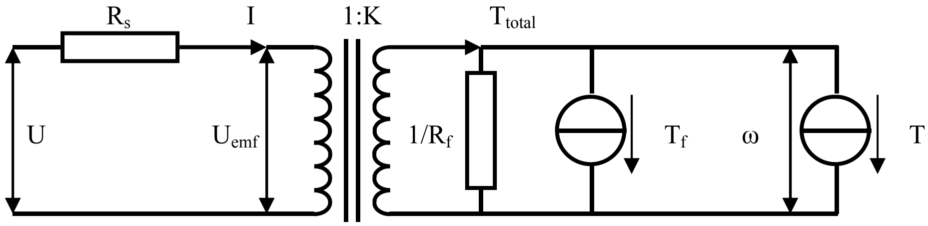

Fig 3. Typical schematic of an electrical motor model for a permanent magnet DC motor

When considering the motor model as shown in Fig. 3, the optimum efficiency for a certain voltage and current can be found. The motor can be characterized with four parameters, which are K, R_s, R_f and T_f, where K is a constant which describes the conversion from the electrical domain to the mechanical domain. R_s is the series resistance of the electrical components from battery to electrical engine. R_f is the viscous friction of bearings in the electrical motor and gearboxes or axle supports. T_f is the static friction [11]. From the schematic shown in Fig. 3, the equations 4 to 7 can be formulated:

$$U - U_{emf} = I \cdot R_s \tag{4}$$

$$T_{total} = T_f + \frac{\omega}{R_f} + T \tag{5}$$

$$U_{emf} = K \cdot \omega \tag{6}$$

$$T_{total} = K \cdot I \tag{7}$$

with:
U_{emf} = back EMF voltage dependent on angular velocity [V]
T_{total} = Torque measured at the axle [Nm]

By rewriting equations 4 to 7, the following relationships can be found:

$$\omega = \frac{U \cdot K}{K^2 + \frac{R_S}{R_f}} - \frac{R_S}{K^2 + \frac{R_S}{R_f}} \cdot \left(R_s + T_f\right) \tag{8}$$

$$I = \frac{T + T_f + \frac{\omega}{R_f}}{K} \tag{9}$$

With equations 3 to 9, the efficiency of the electrical motor for an arbitrary angular velocity and corresponding torque value can be determined. As a result, the corresponding voltage and current can be found. In order to determine the optimum efficiency of an electrical motor, the values of several variables need to be determined, which are 1) the intended distance D for the boat to sail, 2) the intended speed v and 3) the irradiation I during the time of sailing. Then the available energy E during a period t of sailing can be determined with equation 10. Equation 10 is adapted from [12] and completed with equation 1.

$$v = \sqrt[3]{E} \cdot \sqrt[3]{1/t} \cdot 1/\sqrt[3]{c} \tag{10}$$

with:
v = speed [m/s]

t = time of sailing [s]
E = available energy [Wh]

The available energy E consists out of the battery energy and PV energy. When considering equations 10 to 12, for an arbitrary distance, energy availability and boat speed, an optimum can be found for the average, and thus most efficient, sailing speed.

$$t = D/v \quad (11)$$

$$P = E/t \quad (12)$$

with:
D = distance of sailing [m]

For a certain distance D and speed v, this results in the power available during the sailing time t (equation 10 and 11). The optimum motor efficiency for a certain torque and angular velocity can be determined. Finally, optimal parameters for a propeller can be determined for a narrow power range which the PV boat will need for a certain distance and speed with equations 3 to 9.

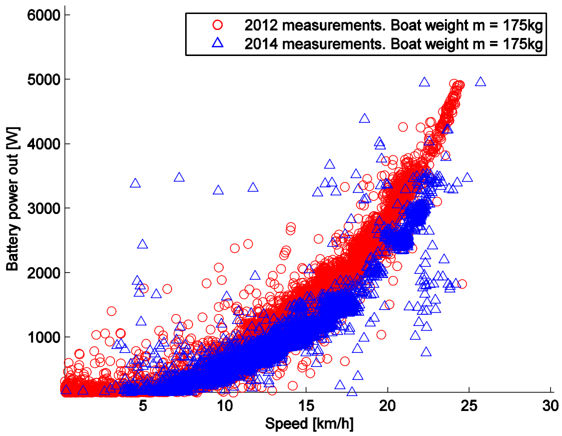

Fig. 4. Improvement in speed-power relations after optimizing the propeller for our PV-powered racing boat by considering the available energy from the PV system.

We applied the approach described in this paper to our solar boat and we determined the power-speed ratio before and after we optimized the propeller with data from the PV system. As can be seen in Fig. 4, the power need to reach a certain speed is lower for the 2014 boat compared to the 2012 boat. On average, the efficiency improved by 15% and sometimes showing over 20% increased efficiency. Since in our case the voltage increased to drive the engine more efficiently, the voltage ceiling is reached earlier, resulting in a lower top speed.

4. Discussion and Conclusions

We calculated parameters to design a new propeller for a PV-powered racing boat considering the available energy from the PV system during races. This resulted in a 15% efficiency increase.

When the hull's resistance constant, the intended distance to sail and the intended speed are known, the optimal configuration for the electrical motor and the propeller can be made when the solar irradiation and thus the available energy is estimated.

The optimal working point for an electrical motor and a propeller is narrow. This means that with different powers, thus different torques and revolutions, the engine might not work optimally. As a result, it can be difficult to design a drive train for a PV boat with a broad range, especially considering PV boats intended for racing purposes with high variations like cruise speed (endurance) and top speed (sprint). In such cases the designer can consider designing two or more propellers for different workloads of the engine, to reach optimum efficiency.

Some MCUs cannot boost the battery voltage, therefore it is important to consider the maximum voltage of the battery in relation to the maximum angular velocity of the engine. Another important consideration is the choice of battery. Certain battery technologies have a high internal resistance which on loads with high currents can make the voltage drop considerably, resulting in poor performance and a decreased maximum angular velocity of the engine and thus the propeller, which subsequently results in a lower top speed of the boat.

References

[1] DONG Energy Solar Challenge, www.dongenergysolarchallenge.nl, 2014

[2] Joore, P., Wachter, A., Frisian Solar boat design: A multi-level innovation analysis, *Proceedings of the 34th photovoltaic specialists conerence*, Philadelphia, USA, 2009

[3] Gorter, T., Joore, P., Reinders, A., Van Houten, F., Scenario-Based simulation of PV boats in an early design stage, *Proceedings of the 38th photovoltaic specialists conference*, Tampa, USA, 2013

[4] Gilbert C. D. Sousa, Domingos S. L. Simonetti, Ever E. C. Norena, J. Rey, Efficiency Optimization of a Solar Boat Induction Motor Drive, *Industry Applications Conference*, Conference Record of the 2000 IEEE , Vol 3, 2000, Pages 1424-1430

[5] Park, J., Katagi, T., Yamamoto, S., Hashimoto, T., Operation control of photovoltaic/diesel hybrid generating system considering fluctuation of solar radiation, *Solar Energy Materials and Solar Cells*, Vol 67, Issues 1-4, 2001, Pages 535-542

[6] Loois, G., Van der Weiden, T.C.J., Hoekstra, K.J., Technical set-up and use of PV diesel systems for houseboats and barges, *Solar Energy Materials and Solar Cells*, Vol 35, 1994, Pages 487-496

[7] Baggio, N., Bianucci, M., De Rosa, F., Petrone G., Sacchetti, A., Spagnuolo, G., Distributed Control of Photovoltaic Modules for Sailing Applications and for Sustainable Mobility, *24th European Photovoltaic Solar Energy Conference*, 2009, Hamburg, Germany

[8] Gorter, T., Reinders, A.H.M.E., A comparison of 15 polymers for application in photovoltaic modules in PV-powered boats, *Applied Energy*, Vol 92, 2012, Pages 286-297

[9] Kooistra, G. Optimization of the drive-train of a solar boat, Graduation Report, 2014 (available in Dutch)

[10] Gorter, T. Performance Evaluation of Photovoltaic Boats in an early design stage, 2014.

[11] Hendershot, J.R., Miller, T.J.E. Design of Brushless Permanent-Magnet Machines, 2010.

[12] Ageev, M.D, Blidberg, D.R., Jalbert, J., Melchin, C.J., Troop, D.P. Results of the evaluation and testing of the solar-powered AUV and its subsystems. In: 11th International Symposium on Unmanned Untethered Submersible Technology, 1999

Biography

Tim Gorter, PhD is associate professor at the department of solar power and mobility at NHL University of Applied Sciences in Leeuwarden, The Netherlands. He participated three times in the DONG Energy Solar Challenge and has participated in the building of 5 solar boats.