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Preliminary study of sailing wind turbines for the harvesting of the far-offshore wind energy resource

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1 Introduction

According to [1], the far offshore technical wind energy potential is 9 times the 2050 global energy demand. However, the deployment of offshore wind turbines is limited by the increase in the grid-connection cost, moorings and installation cost and maintenance cost, when increasing the distance form shore. Therefore, to harness this humongous wind energy potential, innovative ideas were suggested. Among which, the energy ship concept patented in 1982 by Salomon [2] and the sailing wind turbine concept patented in 1983 by Vidal [3]. The focus of this study is the sailing wind turbine concept. It is a non moored floating wind turbine. Being mobile, it must be equipped with an on-board energy storage system (e.g. batteries, electrolyzers for hydrogen production and storage, etc.).

The sailing wind turbine is moving with a velocity $\vec{U}$ in a true wind speed $\vec{W}$. The apparent wind speed $\vec{V}$ is the velocity that spins the rotor of the wind turbine, which then produces electricity. The thrust $\vec{P}$ of the equal sized propellers allow the forward motion. The propellers use part of the energy generated by the wind turbine. The keel generates a hydrodynamic force $\vec{K}$ that may reduce the drift of the platform. $\vec{P}$ and $\vec{K}$ counteract the water resistance $\vec{R_w}$ and the thrust on the wind turbine $\vec{T}$. During this study, a Velocity and Power Prediction Program (VPPP) was developed. The VPPP evaluates the velocities of the platform (forward and drift) as well as the power generated by the wind turbine, the power consumed by the propellers and the net power, by solving the equation of motion described by Newton's first law. Note that the input to the VPPP are the environmental conditions and the dimensions and characteristics of the design. The dimensions of the design are as follows: 40 m × 40 m square barge platform of height 10 m, its draft is 7.5 m, the wind turbine has a rated power of 2 MW (corresponding to a diameter of 78 m), the nacelle height is 90 m, the propellers have a diameter of 6 m each, and the keel surface area is 15 m^2.

2 Performance of the sailing wind turbine

It has been shown that there exist two distinct operating regimes; the sailing and the drifting regimes. In order to better understand their characteristics, the following environmental conditions are considered: a true wind angle of 30° and a true wind speed of 11 m/s at 10 m of altitude. Figure 1 shows the turbine power, the propellers consumed power and the net power **(a)** the platform velocities **(b)** and the velocity made good V_{mg} **(c)** as function of the propellers' rotational velocity (in rpm). The velocity made good is a concept used in sailing. It corresponds to the velocity towards the direction of the wind when sailing upwind.

First, it can be noted that the power generated by the wind turbine is equal to the rated power. The reason is that in this RPM range, $V_{rated} < V < V_{cut-out}$. As expected, the power consumed by

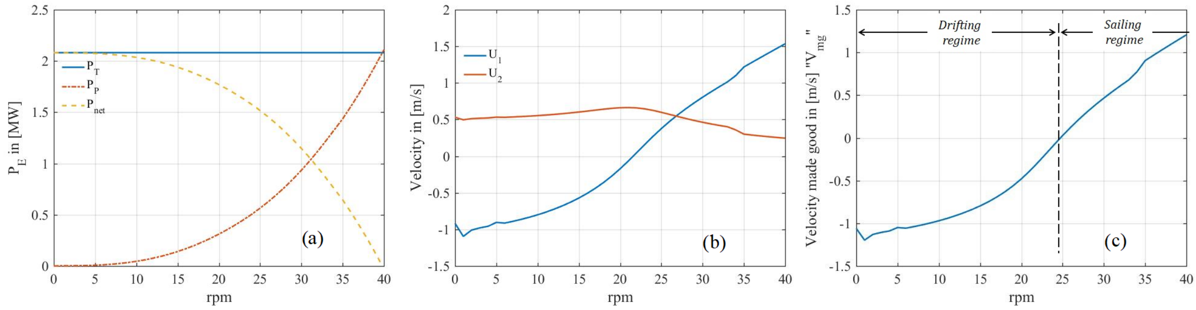

Figure 1: **(a)** Wind turbine generated power $\mathscr{P}_T$, propellers consumed power $\mathscr{P}_P$ and net power $\mathscr{P}_{net}$ as function of the propellers' RPM for TWA = 30° and TWS = 11 m/s. **(b)** Platform velocities U_1 (forward velocity) and U_2 (drift velocity) as function of the propellers' RPM for TWA = 30° and TWS = 11 m/s. **(c)** Velocity made good V_{mg} as function of the propellers' RPM for TWA = 30° and TWS = 11 m/s.

the propellers increases when increasing the RPM. Thus it reaches a value of 2 MW at an RPM of 40, resulting in a 0 net power production.

According to the platform velocities, as expected, U_1 (forward velocity) increases when increasing the RPM. For propellers' rotational velocity less than 22, the platform is moving backward. The reason is that for this range of RPM, the wind turbine thrust is greater than the propellers thrust. Above 22 rpm, the opposite is true, where U_1 becomes positive. As for the drift velocity U_2, it take values between 0.2 and 0.6 m/s. In addition, one can notice that in the range of [33-35] rpm, there exist a steep decrease in U_2, because the water flow attaches to the keel in such a way of having an angle of attack smaller than 15°. This configuration generates a lift force which counteracts the thrust on the wind turbine in the drift direction, reducing the drift motion. Accordingly, the forward velocity U_1 increases.

Looking at the velocity made good graph, one can notice that in the range [0-25] rpm, V_{mg} is negative, which means that the platform is drifting in the wind direction, hence the drifting regime. However, above 25 rpm, V_{mg} is positive, meaning that the platform is sailing upwind. Thus, this range is denoted as the sailing regime. Note that, unlike the drifting regime, the sailing regime is characterize by the ability to control the location of the platform in the seas.

In addition, the sensitivity of the net power to the propellers, keel and wind turbine dimensions was studied for both drifting and sailing regimes. As expected, it was shown that in the drifting regime, the propellers diameter has no major effects on the net power production. However, when increasing the wind turbine's diameter and the keel's area, $\mathscr{P}_{net}$ increases too. Indeed, in the sailing regime, the results show more complexity. For instance, increasing the diameter of the wind turbine increases its thrust. Therefore, to overcome this addition, greater power should be consumed by the propellers. Hence, $\mathscr{P}_{net}$ declines. Moreover, increasing the propellers' diameter rises their efficiency, which reduces $\mathscr{P}_P$ and maximizes $\mathscr{P}_{net}$. Whereas, by increasing the area of the keel, the skin friction increases too. Thus, more power is required to overcome the additional resistance. This, results in a smaller net power.

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