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Small nomadic counter-rotating wind turbine : Design and experimentation

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Abstract—Many studies show the efficiency of large-scale wind turbines in wind energy harvesting for collective applications. However, few examples relate to small one stage wind turbines (OSWT) for mobile and individual applications. This work details the modeling and the prototype realization of a 18 cm diameter wind turbine using counter-rotating propeller technology (CRWT). This device has been tested in a wind tunnel with wind velocities in the range of 3.5 to 8 m.s⁻¹. First experimental results with a wind of 4.2 m.s⁻¹ (which is the theoretical optimum wind velocity of the device) show that the wind turbine can provide a power of 0.6 W currently dissipated in a load resistance of 1.5 Ω. The power goes up to 2.8 W for a wind of 8 m.s⁻¹.

Keywords—Small-scale wind turbine, counter-rotating propeller, wind energy, nomadic power.

I. INTRODUCTION

The green sources of energy are a major concern and become even a necessity while we wish to deploy an activity in nomadic or isolated natural environment. The energy demand goes from some watts to recharge batteries of low capacity (smartphone, GPS, lamp...) to some hundred watts to feed isolated structures as a mountain refuge for example. The technologies usually used for these applications exploit the solar or wind energy. The power density supplied by the outdoor solar energy can be very important, 15 000 μW.cm⁻², but it decreases strongly in 150 μW.cm⁻² when weather conditions are degraded [1]. On the other hand, the power density supplied by a laminar airflow is stable is estimated at 380 μW.cm⁻³ for a wind velocity of 5 m.s⁻¹. The ubiquity of the natural wind in the relief or the sea regions favors the exploitation of this energy source. This natural wind velocity follows a Weibull distribution with average value is 3.94 m.s⁻¹ and the maximal is about 5 m.s⁻¹. The source of airflow can also come from human motions and thus capture relative flows. In these two cases, the harvesting energy depends strongly on the velocity of the source and less on the apparent surface.

Many studies show the efficiency of large-scale wind turbines in wind energy harvesting for collective applications. However, few examples [2] relate to small wind turbines for mobile and individual applications. This paper suggests a mechanical concept of counter-rotating propeller to a small-scale wind turbine (< 20 cm). The counter-rotating propeller solution is well known in the aviation to increase the thrust of aircrafts for the same initial mechanical power level. The efficiency of this propeller is improved by 30 % compared with a conventional propeller [3]. The integration of this structure type of large-

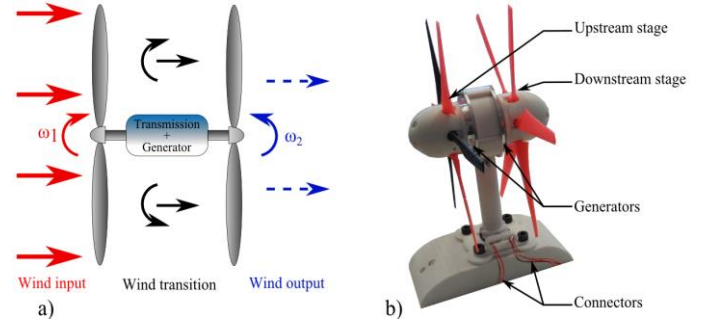


FIGURE 1. COUNTER-ROTATING WIND TURBINE CONCEPT AND PROTOTYPE

scale wind turbine was already realized to validate this theory [4-7]. However, the use of this technology on small-scale devices is a real innovation and allows envisaging an efficiency improvement of the same factor.

II. COUNTER-ROTATING WIND TURBINE

A. Counter-rotating wind turbine concept

The CRWT concept exploits a general technology adapted to propulsion propellers in aviation. In this paper, this structure is composed of two different and optimized propeller stages which rotate in the opposite direction (Figure 1a). The stages directly engrave the two independent generators. The incoming air flow is partially captured by the first propeller stage and is converted into mechanical energy by the shaft rotation. The outgoing airflow is deflected, creating a flow composed of an axial and tangential velocity. The second propeller stage is adapted to harvest this new form of wind field, but it turns in the opposite direction. The optimization of the geometry of the propeller blades maximizes the caption of wind kinetic energy. The maximum power is theoretically restricted by the Betz limit and it can be formulated from the following relation:

$$P_{max} = \frac{16}{27} P_{kinetic} = \frac{8}{27} \rho S v^3 \quad (1)$$

B. Propellers modelisation

The propellers geometries are optimized with Heliciel software. The latter proposes a reverse design of the blades in order to optimize the mechanical power according to a defined wind field (axial and tangential velocities). The characteristics of the upstream and downstream propeller stages are listed in Table 1. After the first stage incidence angle optimization, the airflow data output is injected in the second stage input data.

TABLE 1. PROPELLERS CHARACTERISTICS

PARAMETERS	ROPELLER STAGE	
	UPSTREAM	DOWNSTREAM
BLADE NUMBER	6	6
PROFIL	NACA1412	NACA6412
BLADE FOOT / HEAD DIAMETER	40 mm / 180 mm	
BLADE FOOT / HEAD WIDTH	17 mm / 7 mm	17 mm / 17 mm
THEORETICAL MAXIMUM POWER	0.8 W	2.2 W
THEORETICAL ROTATION VELOCITY	2800 rpm	6000 rpm

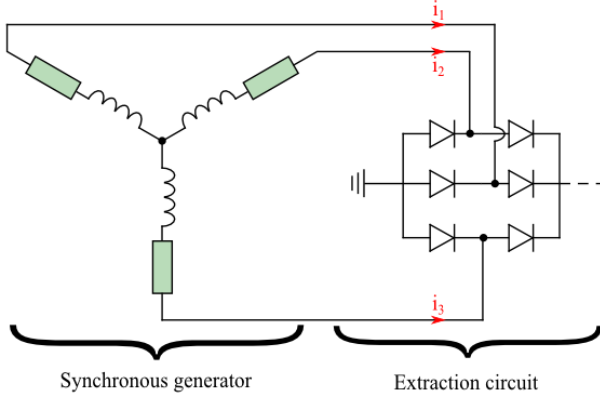


FIGURE 2. WIND TURBINE ELECTRICAL SCHEMATISATION

The axial velocity component is greatly reduced compared to the source. The global geometrical parameters listed in the Table 1 are determined using the design of experiments method (DOE).

C. Electromechanical conversion

For electromechanical conversion, two independent permanent magnet synchronous generators with an optimal rotation velocity of 7200 rpm are used. The frequency of the electrical signals informs directly about the rotation velocity of the propellers. The generator is modeled (Figure 2) by three coils in series with three resistors. To harvest the electrical energy produced, a passive extraction circuit composed of a diode bridge suitable for synchronous generators is envisaged. But actually, the electrical voltages at the coil terminals are too low to pass the threshold diode voltage. The power is measured on an optimum load resistance of 1.5 Ω in parallel with each coil.

III. EXPERIMENTAL RESULTS

The tests are carried out in a wind tunnel with an air stream of 23 \times 23 cm². An OSWT and a CRWT (Figure 1b) prototype were subjected to a wind source ranging from 3.5 m.s⁻¹ to 8 m.s⁻¹. The Figure 3 shows the produced electrical power by the OSWT and the optimized CRWT and the maximum recoverable power P_{max} (Equation 1) as a function of the wind velocity. The classical wind turbine starts at 4.6 m.s⁻¹ and it produce 0.01 W. The counter-rotating starts around 4.2 m.s⁻¹ with small difference between the two stages. This device produces 0.6 W which corresponds to the maximum efficiency of 85 %. At 8 m.s⁻¹, the OSWT produces 1.3 W and the counter-rotating produces 2.8 W.

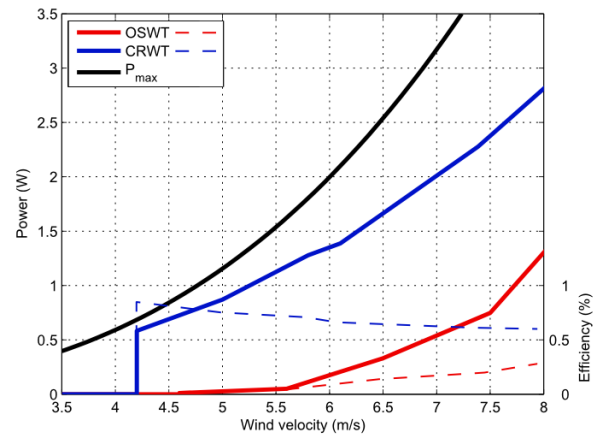


FIGURE 3. EXPERIMENTAL POWER RESULTS

IV. CONCLUSIONS AND PROSPECTS

A prototype of a counter-rotating wind turbine was realized and tested. The latter is above all a means of observing and measuring the effects of the airflow on the two stages independently. The first experimental test show promising results with an electrical power of 0.6 W for a wind velocity of 4.2 m.s⁻¹ and a maximum power of 2.8 W at the maximum test velocity. The optimum efficiency is 85 %. A semi-analytical model integrating the optimized propellers theoretical data is under development, in order to design a new small dimension counter-rotating wind turbine. These first results also show the need to integrate an intermediate transmission composed of a mechanical amplifier and a mechanical differential to couple both stages. This step will be included in the next prototype in order to exploit optimally a single generator while dissociating the propeller stages.

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