Study of an innovative electrical machine fitted to marine current turbines

L. Drouen, J.F. Charpentier, E. Semail and S. Clenet

Abstract—**This paper is included into the theme "challenges for marine renewable energy". It discusses an innovative concept of electrical machine that should be particularly fitted to marine current turbine generators. Our investigations focus on permanent magnet direct-driven synchronous generators connected to a variable speed power electronic drive. Original and conventional solutions are compared in terms of mass and cost for a common set of specifications of a realistic application.**

Index Terms—**marine current turbine, electrical generator, direct drive, synchronous, permanent magnets, rim driven.**

I. Introduction

THE concept of power generation converting the kinetic energy of tidal streams into electricity is not new as some experimental works already started in the 1970s [1]. Nevertheless, the amount of academic and industrial studies has significantly increased in the last years, essentially due to new environmental constraints on power generation technologies. Let's remind that the countries that ratified the Kyoto protocol committed to reduce their global greenhouse gas emissions below their 1990 levels by 2008-2012.

Several studies on European waters indicate that the tidal streams could represent a significant amount of future electricity needs [2]. Even if estimated amounts are based on rough methodologies, the available power should be of the order of several thousands of MegaWatt only for Europe (mainly for the United Kingdom, Ireland, France and Portugal). Moreover, compared with wind resource, one main advantage of tidal energy is that, due to its astronomic nature, it is predictable and, as a consequence, it should be integrated more easily on an electrical network [3].

Several studies have been carried out since the late 1990s and some prototypes have been installed and tested. One of the most famous project is the "Seaflow" installed in 2003 on the North Devon coast of England by MCT Ltd [4]. It consists in a horizontal-axis turbine with 2 blades, has a 11 meter diameter rotor and looks like a wind turbine. The rotor has a speed around 15-17 rpm and is connected onto the shaft of a speed-increasing 3 stages gearbox which, in turn, drives a 1000 rpm asynchronous generator. It yields a maximum power of 300kW with favorable conditions (a current speed of about 2.5m/s). This project has proven that electrical power can be extracted from a horizontal axis turbine. Another project, called E-Tide, has been developed by Hammerfest Strøm (Norway): it consists in a 300kW horizontal-axis turbine with a 15-16m diameter rotor connected to a multi-stage gearbox and an electrical generator. The electromechanical conversion technologies of both projects are very similar.

Those technologies are based on the association of an axial flow turbine with an "on the shelf" electrical generator, directly inspired from the wind turbine conversion systems. The connection is made via a gearbox that adapts the speed of the rotor (typically 10 to 20 rpm) to the speed of a conventional electrical machine (generally above 500 rpm). However, those solutions might not be ideal in terms of complexity, failure rate, efficiency, maintenance cost. As some investors plan to develop tidal turbines on a large scale [4], it looks relevant to study some innovative solutions that won't necessarily look like an immersed wind turbine and will be fitted to the tidal energy extraction.

In this paper, we present the design of a radial magnetic flux electrical generator that will be put on the periphery of the blades of a horizontal-axis tidal turbine (Fig. 1). The benefits and drawbacks of such a structure are highlighted. Only electromechanical aspects are discussed in detail, whereas hydrodynamics concepts are only mentioned. The paper starts with a description of the proposed technology. Then, it explains the analytical model that will be used to estimate the main characteristics of the generator for typical specifications. Finally, the results are compared with more classical solutions.

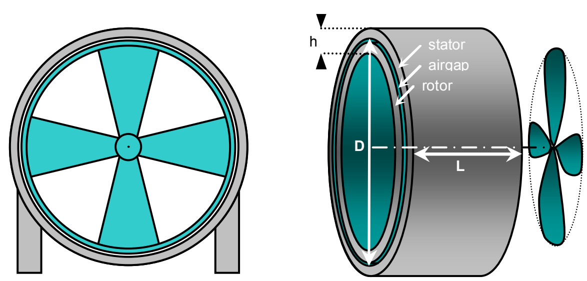

Fig. 1. Sketch of a ducted turbine surrounded by an electrical generator (left) and a radial flux electrical machine with an inner rotor (right)

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thin and proper mechanical studies will be necessary to confirm the influence of mechanical constraints on the stator and rotor housing design. Additionally, a 3D FE EM analysis seems relevant to evaluate the end effects on such a short machine (4cm of active axial length). At the same time, the short length favours the integration of the machine into a nozzle with good hydrodynamic performances. For instance, a ratio R=L/d close to 3 (Fig. 7) leads to good hydrodynamic performances in terms of pressure and friction drag.

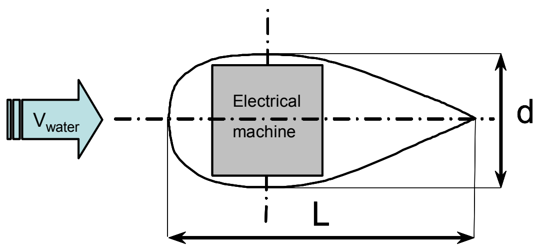

Fig. 7. Integration of the electrical machine section into a nozzle

The electrical and thermal results are summarized in table III. It shows the influence of the high value of the cyclic reactance (0.61 pu) on the machine performance. This value is typical of high diameter machines [10]. A high reactance implies a low power factor (around 0.7) which leads to an oversized converter. In the other hand, it results in a high electrical time constant which tends to reduce the constraints for the choice of the converter switching frequency.

TABLE III
ELECTRICAL AND THERMAL CHARACTERISTICS

Number of turns par coil	n_s	6	turns
EMF (rms)	E	236	Vrms
Line current (rms)	I	423	Arms
Voltage (rms)	V	344	Vrms
Cyclic reactance	$L\omega$	0.61	p.u.
Phase resistance	R	0.10	p.u.
Electrical time constant	τ	0.014	s
Copper losses in the slots	P_{Cus}	7570	W
Copper losses in th end windings	P_{Cueww}	30706	W
Iron losses	P_{Fe}	7987	W
Efficiency	η	86.6	%
Conductor temperature	T_{cond}	93.7	°C

On a thermal point of view, the highest temperature level (in the conductors) should be less than 100°C, that is in accordance with classical electrical machine materials specifications. The thermal study shows that around 1/3 of the heat flux is evacuated through the gap, confirming the benefice of the water sea in the gap. The main part of the copper losses is related to the end-windings. The efficiency of the machine can probably be increased by using non conventional winding technologies as concentrated windings that lead to smaller end-windings.

B. Elements of comparison with more classical machines

Regarding the mass and cost, the proposed machine seems to be competitive compared with more classical technologies. If we consider a more conventional DD PM generator driven by the axis with D=1.5m, using the same set of specifications but with a lower gap (h_g=3mm), then the multi-physics model results in an active mass of 4934 kg and a cost of 23.4k€.

Now, considering a solution combining a gearbox and a classical speed machine (500-1500rpm), the cost of a 300kW three levels gearbox should be close to 20k€ (the value of 80K€/MW is often proposed). Additionally, the active mass of the generator/gearbox association should exceed 4000kg.

Both comparisons confirm that the structure should be highly competitive in terms of active mass and cost compared with more classical solutions.

V. CONCLUSION

In this study, an innovative concept of tidal current turbine electrical generator is presented. This concept is based on the integration of a PM synchronous machine in the nozzle of a ducted turbine. This application has non conventional dimensions, and an appropriate multi-physic electromechanical model is developed and validated. The main physical characteristics of the active part as well as their cost are roughly estimated. Results are encouraging as, on an electromechanical point of view, this gearless technology is feasible and competitive in terms of cost, mass and volume in comparison with more conventional technologies.

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