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.

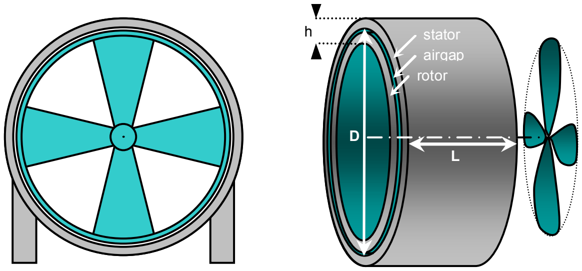

Fig. 1. Sketch of a ducted turbine surrounded by an electrical generator (left) and a radial flux electrical machine with an inner rotor (right)

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II. TECHNOLOGY DESCRIPTION

Compared with classical solutions, the proposed generator will be of direct-drive (DD) type. In addition, the active parts of the electrical machine will surrround the periphery of the blades (in a classical structure, they are placed on the axis of the turbine) and will be encapsulated into a protective duct.

This concept has already been studied and tested succesfully for marine propulsion [5], [6], [7], powers varying from a few hundreds of Watt up to several hundreds of kiloWatt. Some of those "rim-driven" propellers are already commercialized, mainly for bow thrusters or Autonomous Underwater Vehicules propulsion. Vessels propulsion (powers of several MW) has also been studied but it seems that only small scale prototypes have been developed for the moment. A similar machine, but used now as a generator, has been tested [8] on a small rating turbine (50W) with encouraging results.

In theory, this structure presents various benefits. First, the gearbox is suppressed. This element is generally made of up to three stages [4] and results in a rather complex, heavy and expensive structure. The DD solution, directly derived from wind turbines, leads to less failures and lower maintenance issues [9]. Secondly, we place the DD, high rated torque and low speed generator around the blades. It is quite advantageous compared with more classical DD machines that are usually heavier and less efficient than higher speed generators [10]. Finally, by housing the generator within a protective duct, it is well know that the hydrodynamic efficiency of the blades is improved [7]. In addition, ducts improve vibration and cavitation performances, as well as protection of blades.

As said above, it is interesting to put the active part of the generator around the blades as the gap diameter of the machine is increased, which results in a higher torque. Indeed, if we consider a turbine generating a power P with a rotor speed Ω, the torque *T* of the machine is deduced as follow

$$T = P.\Omega^{-1} \tag{1}$$

The electromagnetic (EM) interaction between rotor and stator occurs within the gap that separates them. Considering a classical value of tangential force density σ_t (N/m^2) in the gap, which depends mainly on the machine technology and cooling principle, the EM torque can be expressed as follow

$$T = \sigma_t .S.D / 2 \tag{2}$$

with D, the gap diameter (Fig. 1) and S the air gap surface. We understand now that, for a given performance (power and speed), it is interesting to increase the gap diameter D as it will decrease the required surface S, hence the size of the machine. In terms of volume and mass of active components, if we suppose the thickness h independent of the chosen diameter D (this 1st order assumption is realistic for a given rotation speed), we understand that the required active volume (approximately the surface S time the thickness h, i.e. the grey volume on Fig. 1, right side) shall decrease if D increases.

The generator is a synchronous permanent magnet (PM) radial flux machine. Compared with wounded rotors, the use of magnets suppresses the copper losses within the rotor and the efficiency is improved. Induction machines have not been considered. Indeed, with such dimensions (the propeller diameter is several meters long), the gap height shouldn't be compatible with the principle of induction machines that require very thin separations between rotor and stator in order to limit magnetizing currents and magnetic leakages.

The synchronous machine will be associated with a Pulse Width Modulation voltage converter that can control the current wave into the stator of the generator, so is the rotation speed. It is interfaced, via a DC bus, with an equivalent converter connected to the electrical grid (or directly to a load in the case of an isolated application). Ideally, the current on the distribution network shall be controlled in order to reduce the harmonics. The rating of the converters (choice of the voltage) is not discussed in detail as it represents a complex subject that requires the knowledge of turbines topology as well as grid characteristics.

This study is a challenge as it has to take into account different disciplines that cannot be studied separately (electricity, mechanics, hydrodynamics and thermal transfers). For instance, the choice of the minimum gap height, that ensures the separation between stator and rotor, must take into account various constraints. First the magnetic interaction between stator and rotor, secondly the fabrication tolerances, thirdly the distortion and movements of the rotor with respect to the stator due to the action of the very large mass of water flowing through the rotor. Appropriate studies (mechanical and hydrodynamic) must be performed to quantify those forces. On an electromagnetic point of view, a minimum gap is required as the radial induction of the magnets that reaches the stator surface is, on a first order, inverse proportional to the magnetic gap thickness.

Another challenge will be the immersion of the gap. As already done for some rim-driven applications [6], [7], we propose to let the water flow through the gap. Thus, it minimizes the sealing problems (classical hub systems need a rotating seal). Moreover, it improves the thermal performances of the machine. However, since most of the active elements are corrosive, they will be covered with corrosion-resistant paint or fiber glass plus epoxy coating. Moreover, specific hydrodynamic studies have to be performed as it is well known that some phenomena like turbulent Taylor vortices may occur between two immersed moving cylinders [11]. The probability of occurrence tends to increase for low clearance ratios (ratio of gap thickness to gap radius D/2).

III. ANALYTICAL MODEL

A. Principle

For this study, we developed some analytical tools supported by 2D finite difference (FD) simulations. They are based on models of different types: electromagnetic, electrical, losses, thermal and financial (Fig. 2). Some of them are commonly used in the design of machines whereas others have been especially developed for this particular generator and represent one of the contributions of this paper

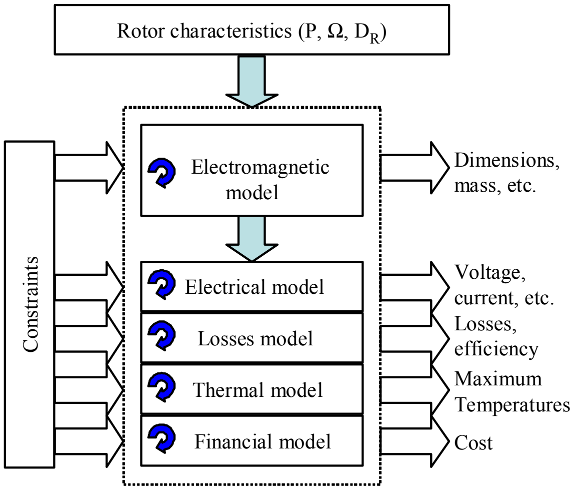

Fig. 2. General principle of the analytical model

Each model input data is a combination of specification data and output data issued from other models. The specifications include the generator power P, the rotor speed Ω and diameter D_R that are deduced from a specific hydrodynamic study. They also include constraints related to thickness, length, efficiency, network voltage. The output data is representative of the perfomances of the machine (dimensions, mass, cost, efficiency,..) and is compared to the specification constraints.

On a mathematical point of view, some internal parameters (current density, poles number, etc) are fixed to relevant values such that the equations can be solved. They may vary on a specific range of values in a process of optimization.

B. Electromagnetic model

This model aims at determining the main physical characteristics of the machine. The most representative parameter is the electromagnetic torque T that is calculated with (1) if we ignore the mechanical losses. With a purely sinusoïdal current in the stator, T can also be expressed as a function of electromagnetic parameters

$$T = k_{b1} \sqrt{2} A_L B_1 (\pi D^2 L / 4) \cos \psi \tag{3}$$

where A_L (A/m) is the stator rms current loading, B_1 (T) is the peak value of the fundamental of the flux density at the stator surface, k_{b1} is the winding factor and ψ is the angle between the stator current and the induced EM Force. If A_L, B_1, k_{b1} and ψ are fixed to classical values of low speed and high torque machines, then (3) is useful to get an idea of the size of the generator active part. For this study, the angle is fixed to zero in order to minimize the size. It tends to increase the converter size and cost [12] but, for this immersed application, it seems relevant to favour first the machine.

The flux density B_1 depends mainly on the type of magnet, the gap thickness, and also on dimensional or financial constraints. The magnets are surface mounted on the rotor and have uniform radial magnetization (Fig. 3). Unfortunately, a simple analytical expression of B_1 functions of dimensions and magnets characteristics is not simple due to the particular features of the machine. The large airgap to short pole pitch ratio results in an abnormal proportion of leakage flux from one magnet to the next [5]. Classical assumptions with a purely radial flux density give inaccurate results. In order to take into account those leakages, our calculations are based on the 2D model proposed by Zhu et al. [13] that solves the governing field equations by separating the polar variables. It predicts the open-circuit field distribution anywhere in the airgap of a slotless surface mounted PM machine. For our study, it is applied to an equivalent slotless machine and an expression of B_1 is derived and simplified assuming a large rotor diameter compared with the machine thickness and a high pole number.

$$B_1 = \frac{2 B_r k_\beta {R_{sm}}^p (1 - x^2 + 2x / p)}{(\mu_r + 1)({R_{sm}}^{2p} - x^2) - (\mu_r - 1)(1 - x^2 {R_{sm}}^{2p})} \tag{4}$$

$$x = \left(1 - h_m / (0.5 D_R - h_g)\right)^p \tag{5}$$

$$k_\beta = (4 / \pi) \sin\left(\beta\pi / 2\right) \tag{6}$$

where B_r is the remanent flux density of the magnets, β is the magnet width l_m to pole width l_{pole} ratio (Fig. 3), R_{sm} is the airgap diameter D to magnet outer diameter D_m ratio, p is the number of pole pairs, μ_r is the magnets relative recoil permeability, h_m and h_g are the magnet and airgap heights. The equivalent slotless machine is obtained by using the classical Carter factor [13] that accounts for the slotting effect on the airgap flux. Now, if B_1, p and R_{sm} are given, then h_m is the only unknown parameter of (4). It can be easily solved and the required magnet height deduced.

For a given current loading A_L, the slot height h_s is calculated as [12]

$$h_s = A_L (J k_f k_s)^{-1} \tag{7}$$

with J (A/m), the rms current density in the slot conductors, k_f, the slot fill factor and k_s the ratio l_s on l_{t+s} (shown on Fig.3) J depends mainly on the thermal performances that should be improved for this specific application thanks to the water all around the stator. Thus, it tends to reduce the overall thickness of the machine.

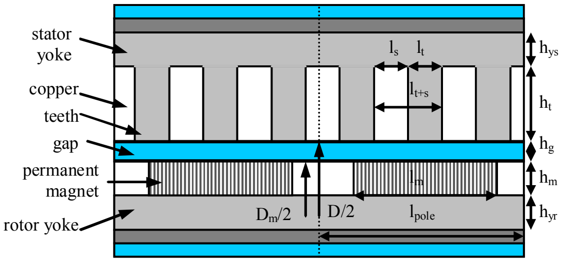

Fig. 3. Sketch of a cross section of 2 poles of the electrical machine

The rotor and stator yoke heights are chosen such that the iron is never saturated. Normal electric steels have a saturation flux density B_{sat} around 1.7T [12] but we propose to use B_{sat}=1.4T for the moment in order to limit the iron losses. The values of flux densities produced by both the magnets and coils are estimated following classical methodologies [10]. However, 2D FD simulations reveal that those equations underestimate the dimensions because of large airgap to short pole pitch ratios. The large proportion of leakage flux between magnets and between coils increases the mean value of the flux density into the yokes. Thereby, thanks to an iterative process, the yoke heights h_{yr} and h_{ys} are readjusted. However, the yokes remain thin and, actually, mechanical constraints for structural integrity might be the main rating factor. A proper study has to be launched to confirm this point. Following the same principle, the tooth width l_t to slot pitch l_{t+s} ratio is estimated such that the teeth don't saturate and their shape remains realistic.

Once the magnet and rotor yoke heights are calculated, we can deduce the airgap diameter D (the rotor diameter D_R and the gap h_g being fixed) and, from (3), the active length L.

Additional considerations are briefly mentioned. First, in order to limit the iron losses, the electrical frequency will be limited to a maximum value f_{max}. Thus, it imposes a maximum number of poles that cannot be exceeded. Secondly, the magnets have to be protected against demagnetization, especially if low B_1 values are specified. It imposes that the magnetic field in any point of the magnet cannot exceed its coercive field. Thus, it imposes a minimum number of poles. Finally, we recommend limiting the number of poles as a high number of poles tends to increase the proportion of magnetic leakages, useless for the rotor to stator EM interaction.

C. *Electrical model*

The study includes an electrical model linked to the EM model presented in the previous section. The aim of this model is to link the generator voltage and current levels to its design parameters (machine dimensions and coils characteristics).

The back EM Force E in each phase is classicaly derived from EM results as $d\phi/dt$ with ϕ the magnetic flux in one phase winding. The current level I is deduced from the EM torque

$$T = EI\Omega^{-1}\cos\psi \tag{8}$$

The magnetizing and slot leakage inductances are calculated following classical equations [9,10]. The phase resistance R is also calculated [9] taking into account the endwindings geometry (each endwinding is considered as a half circle with a diameter equal to the pole pitch). The copper conductivity value used for the calculation of R is related to the nominal temperature (in relation with the thermal model). Then, the output voltage V is deduced as well as the power factor for each operating point (Fig. 4). Current and voltage levels have to be chosen carefully as they are directly related to the design of the electronic drive and the electrical network. In addition, the time constant of the machine is determined. It is mainly related to the choice of the converter switching frequency.

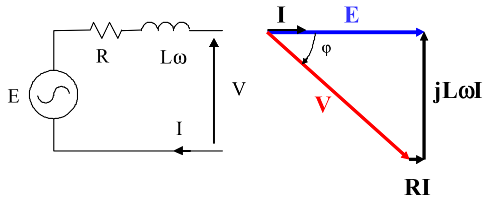

Fig. 4. Electrical model and phasor diagram at ψ=0 (one phase)

D. *Losses and efficiency model.*

In this model, the losses and efficiency of the machine are roughly estimated. Two kinds of losses are calculated: copper and iron losses. The copper losses are calculated in relation with the coil resistance value

$$P_{Cu} = 3RI^2 \tag{9}$$

This equation includes the contribution of both the active part and the endwindings. It must be noted that, for a large diameter and a small axial length, the proprtion of endwinding losses may increase significantly and become predominant. Iron losses are calculated using classical estimations of losses per unit mass in each part of the stator magnetic circuit

$$P_{Fe} = P_{Fe_o}\left(f.f_o^{-1}\right)^b\left(B_{max}B_{max_o}^{-1}\right)^c \tag{10}$$

with f, the frequency of the field in the iron, P_{Feo}, the iron losses per unit mass at the given frequency f_o and flux density B_{maxo}, b=1.5 and c=2.2, using typical high quality Fe-Si laminated steel datasheets.

Our model does not include the mechanical losses of the machine that could be estimated in a complementary study. They depend on the choice of the axial bearing technology used to compensate the axial drag of the turbine and to maintain a constant gap between the stator and the rotor. The choice of the bearings technology (mechanical, hydraulical or magnetic) is complex and won't be discussed in detail. It will take into account the reactive forces of the water flow through the turbine as well as cost, reliability and maintenance aspects.

E. *Thermal model*

The thermal model estimates roughly the temperatures in the different parts of the structure thanks to the dimensions and losses evaluated previously. It is based on a simple steady state thermal resistance network directly derived from the heat transfer equations under steady-state conditions. An equivalent but more general model can be found in [10]. For this study, only radial heat transfers are considered: it represents a strong hypothesis that tends to overestimate the temperatures but it simplifies a lot the analytical model. In addition, transfers in the rotor are ignored as rotor losses are negligible and also because the water flows through the gap represent a better path for the heat transfer. Two modes of transfer are considered: conduction that occurs in the solid parts of the machine and convection that appears between the stator internal and external surfaces and the sea water. One originality of the study is the heat transfer through the gap that is often ignored in more classical structures with air. Heat transfer by radiation is not considered as often insignificant in electrical machines.

For the conduction mode, an elementary volume is studied (Fig. 5, left side). It has an angular width, inner and outer radius and an axial length which are respectively α, R_i, R_o and l. The relationship between the temperatures at the inner and outer surfaces T_i and T_o, the inner flux ϕ_i, the volume losses P and the thermal resistances R_1 and R_2 is

$$T_i - T_o = R_1\phi_i + R_2 P \tag{11}$$

With a large diameter, R_1 and R_2 can be expressed as follow

$$R_1 = (R_o - R_i)(\lambda R_i \alpha l)^{-1} \tag{12}$$

$$R2 = (R_o - R_i)(2\lambda(R_o + R_i)\alpha l)^{-1} \tag{13}$$

Equation (11) corresponds to the elementary electrical network represented on the right side of figure 5.

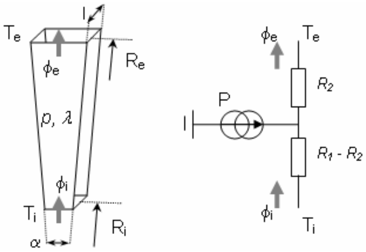

Fig. 5. Elementary volume and equivalent thermal network.

The convective heat exchanges are modeled with a surface resistance

$$R_{cv} = (hS)^{-1} \tag{14}$$

with S, the heat exchange surface and h the convective transfer coefficient. The convective coefficients at the stator external surface and in the air gap are evaluated using classical test case of fluid mechanics (flow along a plane surface and forced flow in an annular space).

F. Cost model

In order to optimize the design of the machine, the cost of the various active parts is evaluated, based on typical material mass cost values. It must be noted that the evaluated cost corresponds only to the cost of the active part of the electrical machine. Structure costs as well as converter and network connection costs were not evaluated.

IV. RESULTS

A. RIM generator design

Using the multi-physic model presented in the previous sections we have determined a rough design of a 3 phases rim generator for realistic specifications. They correspond to those of the MCT "seaflow" turbine [4]. It is characterized for its nominal operating point by the following data: the blade diameter is D=11m, the mechanical power is 300KW, the turbine speed is 15rpm and the fluid velocity is 2.5m/s. Table I summarizes the parameters that are fixed into the model.

They are typical design specifications of high diameter machines using conventional materials (NdFeB magnets and FeSi laminations). The air gap is thicker than in a classical machine because of the specific mechanical constraints related to the water flow in the air gap and the very high diameter. The chosen value of the rotoric flux density is lower than usual (0.6T) as higher values would impose abnormal quantities of magnets due to leakage fluxes. The windings are very common: one slot per pole and per phase.

TABLE I
DESIGN SPECIFICATIONS

Rotor diameter	D_R	11	m
Power	P	300	kW
Turbine speed	Ω	15	rpm
Air gap	h_g	0.02	m
Magnet remanent flux density (NdFeB)	B_r	1.2	T
Magnet width l_m to pole pitch l_{pole} ratio	β	0.70	
Current loading (stator)	A_L	60	kA/m
Current density	J	4	A/mm^2
Peak value of the 1^{st} harmonic rotoric	B_1	0.6	T
Maximum field in the iron magnetic	B_{sat}	1.4	T
Maximum electrical frequency	f_{max}	70	Hz
Slots per pole and per phase	s_{pp}	1.0	slot/p/ph
Winding coefficient	k_{b1}	0.95	
Maximum ratio h_t/l_t	R_{max}	10	
Slot filling factor	k_f	0.75	

The chosen design objective is the cost minimization. The main design results (dimensions and cost) are given in table II.

TABLE II
DIMENSIONS AND COST

Tooth l_t to slot pitch l_{t+s} ratio	k_t	0.65	
Optimal number of pole pairs	p	138	pairs
Magnet height	h_m	0.022	m
Slot depth	h_s	0.057	m
Stator and rotor yoke height	h_y	0.024	m
Housing thickness	h_h	0.010	m
Gap diameter	D	11.151	m
Machine thickness	h	0.167	m
Iron axial length	L	0.040	m
End winding axial length (one side)	L_{ew}	0.063	m
Total active axial length L +2L_{ew}	L_{machh}	0.167	m
Active part mass	M	2117	kg
Active part cost	C	20.4	k€

These results are validated by a 2D FD code which confirms the flux density, inductance, EMF levels (Fig. 6 shows the flux densities level in the machine at the nominal operating point).

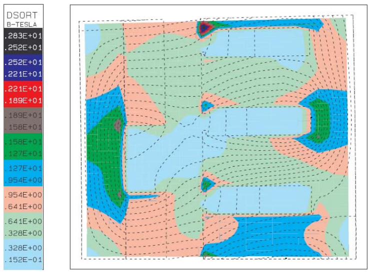

Fig. 6. Magnetic flux density levels in a section of the machine (one pole)

It must be noted that the rotor mass is only 455 kg for a global mass of 2117 kg due to a low magnet height and a large proportion of end-windings in the stator coils. This end windings volume should be reduced by the use of original concentrated fractional slot winding strategies. The structure is 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.

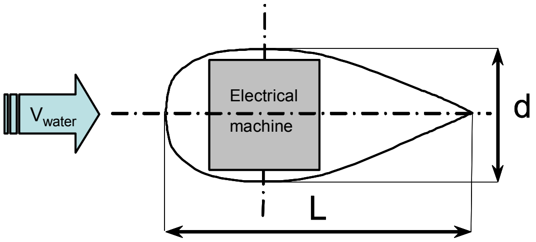

Fig. 7. Integration of the electrical machine section into a nozzle

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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