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A Systemic Design Methodology of PM Generators for Fixed-Pitch Marine Current Turbines

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***Abstract*—This paper deals with the systemic design of permanent magnet (PM) generator associated with fixed-pitch turbine for tidal energy generation. The main problem with marine current turbines systems are the maintenance requirements of the drive-train. It is known that the blade pitch system increases the complexity, cost, and the maintenance requirements of the drive-train. In offshore energy generation, the maintenance should be minimized as much as possible. For that purpose direct-drive permanent-magnet machines associated with fixed-pitch marine turbines can be an attractive solution. The main challenge with fixed-pitch blades is to ensure the power limitation of the turbine at high speed without using variable pitch system. As solution, we propose a systemic design approach of the generator that takes into account the power limitation requirement. In addition, this methodology takes into account the tidal site energy potential, the turbine characteristic, the control strategy, the generator specifications and the power converter constraints. The obtained results show the feasibility of our approach to satisfy the control strategy requirements.**

Keywords—Marine current turbine, fixed-pitch turbine, direct-drive, permanent magnet generator, systemic design.

I. Introduction

Tidal energy is a renewable source of energy; its potential is easily predictable many years in advance. This energy is generated by the ocean current that results from the contribution of the gravitational forces of the moon and the sun on the oceans (tides) [1]. The total potential of this energy resource is estimated to 450TWh/year, with about 24TWh/year on the European coasts. This resource is distributed mainly among UK with 48 %, France 42% and Ireland 8% of the European potential [2]. Therefore, it constitutes a good alternative to complete the other renewable energy resources for power generation. In addition, the predictable nature of this energy resource is highly interesting for electrical grid connection of marine current turbines. This aspect facilitates the management of the produced electricity. Other advantages can make this energy resource interesting to be exploited, such as reduced environmental impact, low visual pollution and noise exposure for the population [3].

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Marine current turbines (MCTs) are submerged under seawater and intended to produce energy from tidal currents [1]. The MCTs systems can be similar in principle to the drive-train systems used in wind turbines generation, it can include the following elements: *1)* The turbine: According to [4], horizontal axis turbines where mainly used for the first industrial MCT prototypes. It can include variable or fixed-pitch blades. The blades orientation mechanism allows the control of the turbine power by varying the blades pitch angle. However, this mechanical control system increases the complexity of the tidal generation system and increases the MCTs failure probability. It should be noted that for an offshore application and particularly for tidal power generation, enhancing reliability and reducing maintenance are key futures for sustainable and cost-attractive exploitation of marine currents [3]. *2)* The gearbox: it can be used to increase the drive speed of the generator. Nonetheless, this element causes a major part of failures and maintenance needs. In the case of a direct-drive system, the generator is directly driven by the turbine without using gearbox. *3)* The generator: it is an important element in the drive-train as it realizes the energy conversion from mechanical to electrical energy. In direct-drive drive-train, low speed permanent-magnet (PM) machines are mainly used. In this case, the rotational generator speed is typically below 50 rpm for high power turbines (MCTs). *4)* The power converter: it allows the control of the generator and the power regulation before its injection into the electrical grid. Several architectures of power converters are possible for MCTs [5]. A Back-to-back double-bridge IGBT converter is considered in this work. *6)* The storage system: it can be used in particular configurations for smoothing the electrical power before being injected into the electrical grid [6].

Referring to [7], the gearbox and the blades variable pitch systems are the main sources of failure and maintenance in wind turbine applications. With tidal power generation the maintenance is a key future because it is really difficult to ensure maintenance operations on immersed seawater MCTs. In addition the maintenance adds significant additional costs. In order to reduce maintenance requirements, a simple architecture of the drive-train is proposed in this study (Fig. 1). A direct-drive PM generator is considered for a fixed-pitch blade turbine.

Power limitation strategy is interesting to a cost-attractive sizing of electrical energy conversion chain.

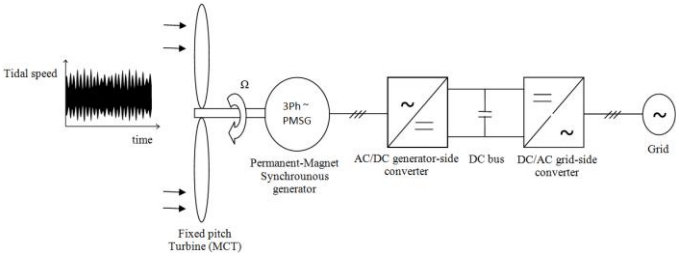


Fig. 1. Marine current turbine drive-train, with direct-drive generator and fixed-pitch blades.

It avoids a significant oversizing of the electrical elements. When the turbine has variable-pitch blades, the power limitation strategy is achieved mechanically by varying the blades pitch angle. For fixed-pitch turbines, the power limitation control can be electrically carried out by torque and speed control of the generator considering over speed flux-weakening operations [8]. In this paper, we propose a specific design methodology of a Radial Flux Permanent Magnet (RFPM) generator to perform power limitation control strategy only through the RFPM generator control. For that purpose, a systemic design approach of the PM generator is proposed. It takes into account the control strategy, the generator specifications, the energy resource characteristic, the turbine power coefficient (C_p) law and the converter voltage and current constraints. This systemic design methodology is described in the second part of the paper. In the third part, a design is achieved according to the given methodology and the results are discussed.

II. Design Methodology

A. Tidal Resource Modeling and Analysis

In this study, Raz de Sein tidal site, France, is considered thanks to its high tidal current velocity and favorable location near the coasts. The GPS coordinates of the studied site are (φ_B = 48°02'42'', G_B=4°45'45''). The used data consist of the velocity values for each hour during a tidal period of 8424hours [1]. The tidal velocity is here varying between -2.75m/s to 3.63m/s. Figure 2 show the velocity variation during the considered period.

If the tidal speed range is divided by n interval and the speed in the ith interval is v_i, Fig. 3 represents the occurrences OCC_i (number of hours) corresponding to the ith tidal speed interval in the considered tidal period. OCC_i corresponds to the number of hours in the ith tidal interval around the speed v_i.

Knowing the occurrence of the tidal velocity, it is possible to calculate the corresponding energy potential density (Wh/m^2) by the following formula.

$$E_p^i(v_i) = \frac{1}{2}\rho_{water}\left|v_i^3\right| \times OCC_i(v_i) \quad (1)$$

Where E_p^i is the energy potential given in (Wh/m^2), ρ_{water} is the water density, v_i is the tidal speed ,and OCC_i is the occurrences at speed v_i.

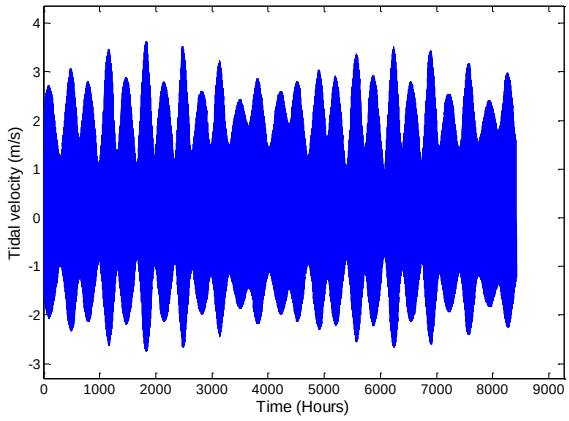


Fig. 2. Tidal velocity in Raz de Sein site, France.

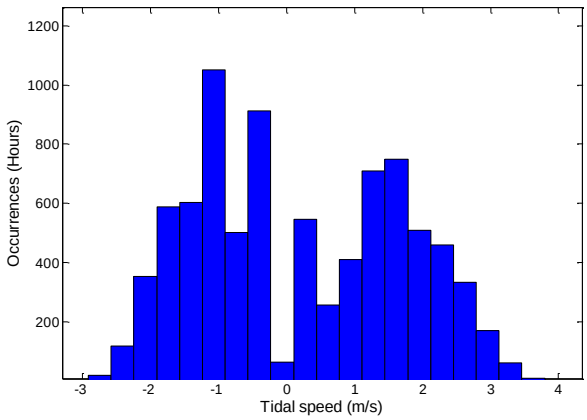


Fig. 3. Occurrences (OCC_i) versus tidal velocity (v_i).

Figure 4 illustrates the energy density potential distribution deduced from (1). It can observe that the energy potential distribution at Raz de Sein tidal site follows a Gaussian law distribution. This law is constituted by two normal laws, one for the positive values of tidal speed and the other one for the negative values. This analytical interpolation law can be modeled by

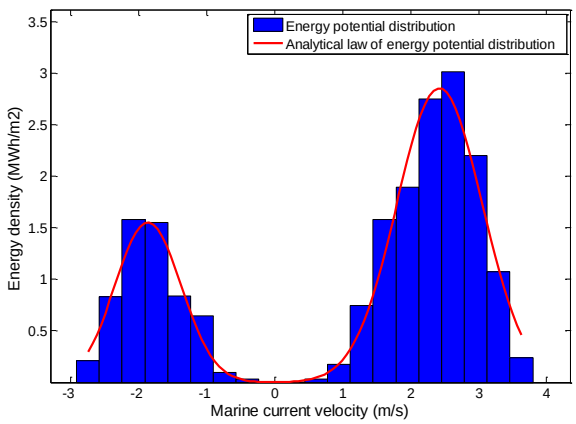


Fig. 4. Energy potential distribution in Raz de Sein site, France.

$$E_p^i(\nu_i) = \frac{1}{n}\left(57.09e^{-\left(\frac{\nu_i - 2.426}{0.8915}\right)^2} + 31.068e^{-\left(\frac{\nu_i + 1.862}{0.6888}\right)^2}\right) \quad (2)$$

Where n is the sample number of tidal velocity.

If the energy potential of the tidal site is known for each speed value, it is possible to calculate the turbine extractable energy by

$$E^i(\nu_i) = E_p^i(\nu_i) \times S_{turbine} \times C_p(\lambda(\nu_i)) \quad (3)$$

Where $S_{turbine} = \pi D_{turbine}^2 / 4$ is the turbine blade swept area and C_p ($\lambda(v_i)$) is the power coefficient given for a Tip-Speed-Ratio (TSR) $\lambda(v_i)$ which is determined for each speed value v_i.

B. Turbine Modeling

The turbine is characterized by the C_p (power coefficient) law. For a fixed-pitch turbine this factor is given as a function of λ. The TSR is defined as the ratio between the blades peripheral speed to the tidal current speed.

$$\lambda = \frac{\Omega \times (D_{turbine}/2)}{|\nu|} \quad (4)$$

Where Ω (rad/s) is the generator rotational speed, $D_{turbine}$ (m) is the turbine diameter and v (m/s) is the tidal current speed. In this study, C_p data of an experimental underwater turbine prototype is used [9]. These experimental data are fitted by an analytical law as

$$\begin{cases} C_p(\lambda) = 0.0195\lambda^2\left(1.3172e^{(-0.3958\lambda + 1.539)} - 0.0867\cos(0.4019\lambda - 5.6931)\right) \\ \lambda \in [0 \quad 11.8] \end{cases} \quad (5)$$

As shown in Fig. 5, the C_p curve calculated with the proposed analytical law matches the experimental one given in [9].

We assume in this work that the considered turbine has a diameter of 12m and it operates at a tidal speed of 1m/s. It has a $C_{pmax} = C_p(\lambda_{opt}) \approx 0.46$ for $\lambda_{opt} \approx 6$.

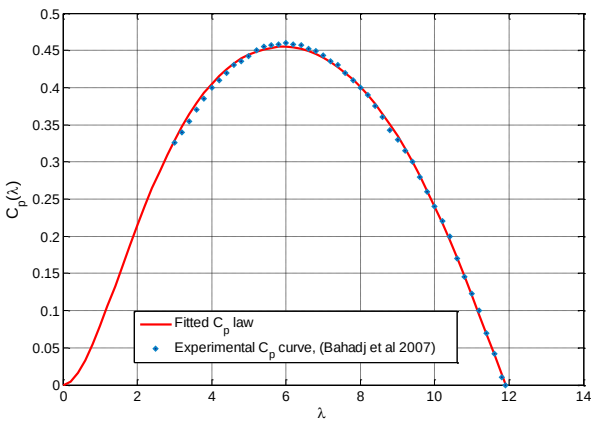


Fig. 5. *Cp* law of the considered turbine.

C. Control Strategy Description

In this section, we define the turbine control strategy from the tidal speed characteristic and the turbine specifications. For a given value of Ω and v the turbine extracted power is calculated by (Fig. 6)

$$P_{turbine} = \frac{\pi}{8}\rho_{water} D_{turbine}^2 C_p(\lambda)\left|\nu^3\right| \quad (6)$$

In Fig. 4, it can be seen that the tidal current energy potential is very low at high tidal speed. It is then obvious that the limitation power strategy is interesting to avoid a power oversizing of the electrical conversion chain. Figure 6, particularly illustrates P^* that denotes the turbine reference operating power (control strategy). It is calculated by

$$P^* = \begin{cases} \frac{\pi}{8}\rho_{water} D_{turbine}^2 C_{pmax}\left|\nu^3\right| & \text{if } |\nu| \le \nu_{Lim} \\ P_{Lim} & \text{if } |\nu| > \nu_{Lim} \end{cases} \quad (7)$$

P_{Lim} is the limitation value of the turbine power. If P_{Lim} is known, it is obviously possible to determine the limit tidal speed v_{Lim} where the limitation power strategy is applied. It is calculated by

$$\nu_{Lim} = \sqrt[3]{\frac{P_{Lim}}{\left(\frac{\pi}{8}\rho_{water} D_{turbine}^2 C_{pmax}\right)}} \quad (8)$$

The base rotation speed Ω_b (rad/s) of the generator is then deduced as below

$$\Omega_b = \frac{\lambda_{opt}\nu_{Lim}}{(D_{turbine}/2)} \quad (9)$$

Then the base rotational speed in rpm is:

$$N_b = \Omega_b \times \frac{60}{2\pi} \quad (10)$$

The maximal speed (given at the limit operating point of Fig. 6) is defined by

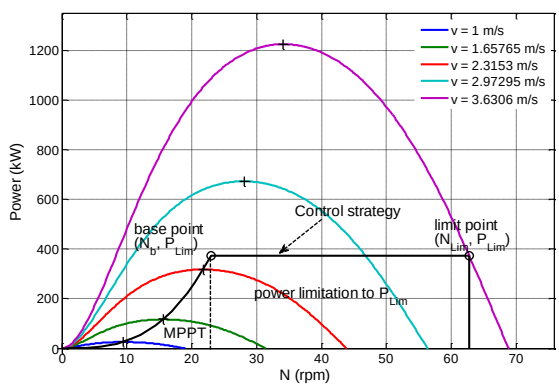


Fig. 6. Extracted power and used control strategy.

$$\Omega_{Lim} = \frac{\lambda_{Lim} v_{Lim}}{\left(D_{turbine}/2\right)} \tag{11}$$

and

$$N_{Lim} = \Omega_{Lim} \times \frac{60}{2\pi} \tag{12}$$

Where λ_{Lim} is calculated by solving the following equation.

$$C_p(\lambda) - \frac{P_{Lim}}{\left(\frac{\pi}{8}\rho_{water} D_{turbine}^2 \left|v_{max}^3\right|\right)} = 0 \tag{13}$$

Equation (14) gives the extracted energy by the turbine considering the chosen tidal site and adopting the described limitation power strategy.

$$E_{extracted} = \sum_{i=1}^{n} P^*(v_i) \times OCC_i(v_i) \tag{14}$$

Figure 7 gives the extracted energy when the limitation power rate is varying. P_{Lim} is varying from 5% to 100% of the maximum power that can be extracted by the considered turbine ($P_{max} = P(C_{pmax}, v_{max})$ = 1245kW in the studied case). It clearly shows that limiting the power at high tidal speed to 30% of the maximum turbine power is enough to extract 87.5% of the total extractible energy. Then the limitation power is set to P_{Lim} = 374kW. According to this control strategy the turbine operates until 7864hours with MPPT control and 560hours in power limitation mode. Therefore 75% (656MWh) from the total extracted energy (884MWh) is extracted during the MPPT control mode and 25% (228MWh) during the limitation power mode.

The torque setpoint characteristic that the generator-drive should develop during an operating rotational speed cycle is deduced from

$$\Gamma^* = \frac{P^*}{N \times (2\pi/60)} \tag{15}$$

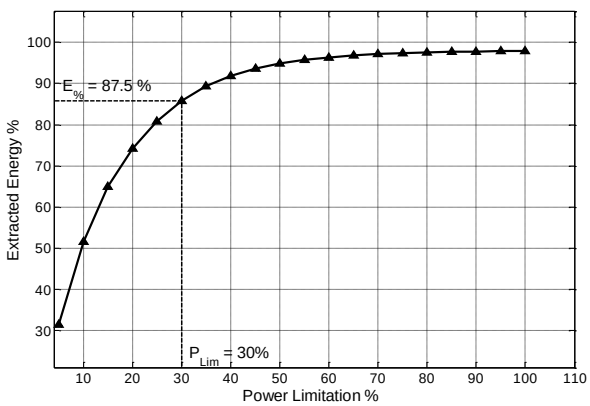


Fig. 7. Extracted energy rate versus power limitation rate.

Figure 8 gives the torque characteristic that the generator should be able to develop. This characteristic is then introduced as a specification to design the PM generator. It can be observed from this figure that the design torque characteristic can be introduced as two design points. The first one is the base point where the machine must develop the base torque Γ_b (it corresponds to the maximum torque) at base speed N_b. The second one is an over speed limit point, this point is introduced as a constraints in the generator design specifications. It traduces the torque Γ_{Lim} that the generator should be able to produce at the maximum rotational speed N_{Lim} of the turbine during an operating cycle.

D. Power Converter Limits

In our methodology the power converter constraints are taken into account. The converter is considered as a double bridge IGBT back-to-back one [5]. The grid side converter voltage is set to V_{grid} = 690V (rms). This voltage corresponds to a typical output voltage of offshore wind turbines [10]. Then the maximum generator phase voltage allowed by the power converter is here set to $V_{max} = V_{grid}$. V_{max} corresponds to the power converter input voltage.

E. Generator Calculation

1) Generator modeling. The generator is a radial flux permanent magnet machine and it is modeled considering the geometry illustrated in Fig. 9. The used models consist mainly on electromagnetic model coupled with a thermal one as described in [11-12]. These models allow calculating the electromagnetic torque, the electrical power, the electrical losses and the thermal behavior over the speed range operating cycle.

2) Optimization problem formulation. The generator design is formulated as an optimization problem that consists on minimizing the active parts costs function $C(\mathbf{x})$ under linear and nonlinear constraints. This mono-objective function takes into account the magnets, copper, and iron sheets costs. $\mathbf{x}$ is here the geometry variables. The constraints consist of:

– Equality constraint on the generator torque at the base speed $\Gamma_b(\mathbf{x},\Omega_b)$.

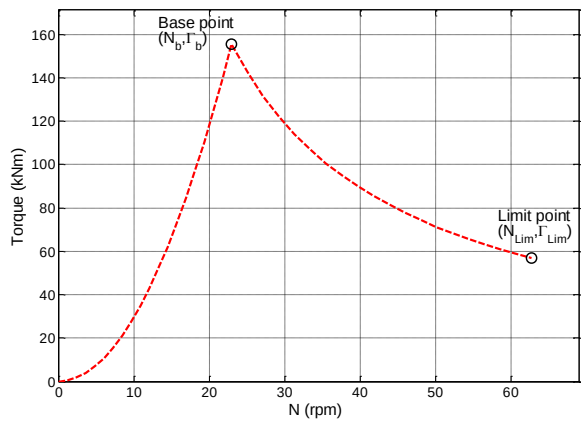


Fig. 8. Generator torque setpoint specification.

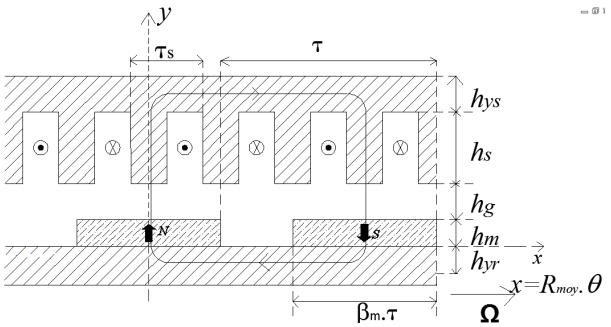


Fig. 9. Geometry of the RFPM generator: h_{yr} is the rotor yoke height, h_m is the magnet height, h_g is the air gap height, h_s is the slot height, h_{ys} is the stator yoke height, β_m is the magnet-to-pole width ratio, τ_s is the slot pitch width, β_t is the tooth-to-slot width ratio.

- Equality constraint on the generator phase voltage $V(\mathbf{x},\Omega_{Lim})$. This constraint is introduced by the power converter input voltage.
- Inequality constraint on the generator torque at the limit operating speed. Thereby the generator torque $\Gamma_{Lim}(\mathbf{x},\Omega_{Lim})$ at maximum speed Ω_{Lim} must be higher than the required torque at this speed.
- Inequality constraint on the power factor FP. The power factor $FP(\mathbf{x},\Omega_b)$ at base speed must be higher than a fixed minimal power factor value FP_{min} This constraint is introduced to avoid a very low power factor at low speed.
- Inequality constraint on the electrical efficiency. The generator electrical efficiency $\eta_{elec}(\mathbf{x},\Omega_b)$ must be higher than a minimal set value $\eta_{elec,min}$. This constraint is defined to avoid very low generator electrical efficiency.
- Inequality constraint on the maximum generator temperature. This constraint ensures the thermal feasibility of the generator. It is defined as the maximum temperature $T(\mathbf{x},\Omega_b)$ in conductors at base speed. The temperature $T(\mathbf{x},\Omega_b)$ should be lower than the maximum temperature T_{max} allowed by the conductors class thermal insulation.
- Inequality constraint on the maximum magnetic field $H_{max}(\mathbf{x})$ in the magnets. The magnetic field in magnets is calculated by considering the worst case where the field created by stator currents is in phase with the magnets field. Therefore to avoid the magnets demagnetization, the value of magnetic field should be lower than the magnets coercive field H_{cj}.
- Linear inequality constraints on the generator geometry variables. They are introduced in the optimization problem to ensure the a PM generator feasible geometry.

Then the optimization problem is summarized (16).

III. Design Results and Analysis

A. Electromagnetic Design and Analysis

The optimization process illustrated by (16) is performed under the Matlab® optimization toolbox with the *fmincon* algorithm. To achieve this optimization a set of constraint parameters used in this study are given in Table I. According to the described methodology the generator is designed and the obtained generator geometry parameters are given in Table II.

$$\mathbf{x}^* = \min_{\mathbf{x}\in\mathbf{X}} \left\| C(\mathbf{x}) \right\|$$
$$\begin{cases} \Gamma(\mathbf{x},\Omega_b) - \Gamma_b^* = 0 \\ V(\mathbf{x},\Omega_b) - V_{max} = 0 \\ -\Gamma(\mathbf{x},\Omega_{Lim}) + \Gamma_{\mathrm{Lim}}^* \le 0 \\ -PF(\mathbf{x},\Omega_b) + PF_{min} \le 0 \\ T(\mathbf{x},\Omega_b) - T_{max} \le 0 \\ \left|H_{max}(\mathbf{x},\Omega_b)\right| - \left|H_{cj}\right| \le 0 \\ -\eta_{elec}(\mathbf{x},\Omega_b) + \eta_{elec_{\min}} \le 0 \\ LB \le \mathbf{x} \le UB \end{cases} \tag{16}$$

Table III gives the electrical parameters and the main performances of the designed generator according to the developed methodology. The generator geometry is illustrated by Fig. 10.

B. Generator Ability in a Speed Cycle Range

Figures 11 and 12 show that the torque/speed and power/speed characteristics of the generator are over the specified torque/speed and power/speed characteristics (same curves as in Fig. 6 and 8).

TABLE I. Generator Specifications.

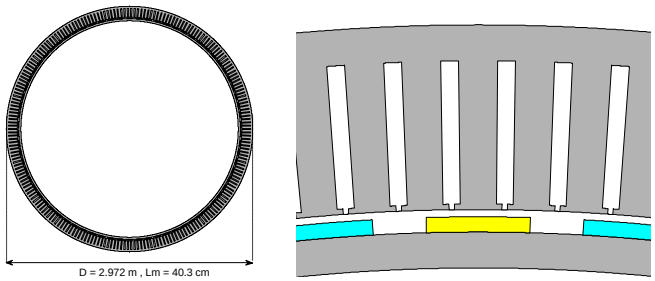
Generator external diameter	$D_{generator}$	3	m
Turbine torque at base speed	Γ_b	155.6	kNm
Turbine base speed	N_b	22.35	rpm
Turbine torque at maximum speed	Γ_{Lim}	57	kNm
Turbine limit speed	N_{Lim}	62.7	rpm
Tidal speed at base point	v_{Lim}	2.5	m/s
Power converter input voltage	V_{max}	690	V(rms)
Generator power factor at base speed	PF	0.82	-
Minimal generator electrical efficiency	$\eta_{elecmin}$	0.95	-
Maximum generator temperature	T_{max}	100	°C
Magnets coercive field	H_{cj}	10^6	A/m

TABLE II. Designed Generator.

J	Current density	3.38	A/mm^2
A_L	Electrical load	52735	A/m
B_1	First harmonic of the Air gap flux density	0.89	T
p	Pair pole number	39	-
ncd	Number of conductors in series per slot per phase	9	-
m	Phase number	3	-
S_{pp}	Slot number per pole per phase	1	-
k_f	Slot fill factor	0.5	-
k_{b1}	Winding coefficient given at first harmonic	1	-
R_i	Inner radius	1.32	m
R_e	Outer radius	1.486	m
R_s	Stator bore radius	1.362	m
L_m	Active length	40.3	cm
β_m	Magnet to pole width ratio	66	%
β_t	Teeth pitch ratio	68.5	%
h_{ys}	Stator yoke thickness	2.5	cm
h_{yr}	Rotor yoke thickness	2.5	cm
h_s	Slot height	10	cm
h_m	Magnet height	1.15	cm
h_g	Air-gap thickness	5.28	mm

TABLE III. GENERATOR CHARACTERISTICS.

E_1	Phase electromotive force (emf)	582	V (rms)
V	Phase voltage	690	V (rms)
X_s	Synchronous reactance	1.9	Ω
rs	Phase resistance	0.107	Ω
$Cos\varphi$	Power factor at base speed	0.82	-
η_{elec}	Generator efficiency	95.3	%
T_{coils}	Maximum temperature in coils	54	°C
H_{max}	Maximum magnetic field in magnets	0.47	MA/m
P_j	Joule losses at base speed	15.4	kW
P_{fer}	Iron losses at base speed	2.04	kW



(b) (b)

Fig. 10. View of the generator active parts section (a), Zoom on the generator active parts (b).

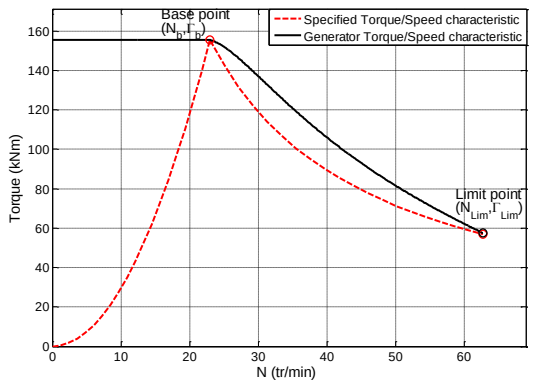


Fig. 11. Required torque/speed specification and generator torque/speed characteristic.

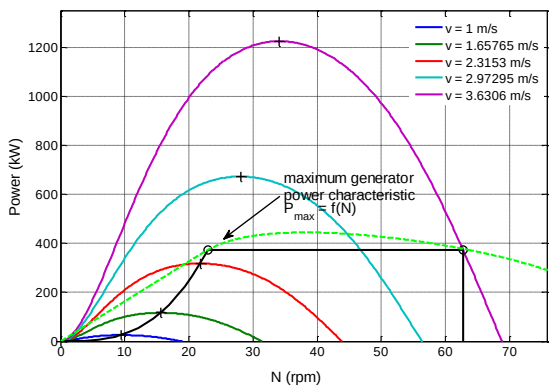


Fig. 12. Power control strategy and developable generator power.

This result implies that the electrical power limitation strategy at high tidal speed can be performed only by controlling the designed generator according to the developed methodology.

IV. CONCLUSION

In this paper a systemic design methodology of direct-drive permanent magnet generator associated with a fixed-pitch turbine for tidal generation has been proposed. The used control strategy is based on the power limitation at high tidal currents speed without blade pitching. This strategy is only based on the generator control adopting a flux weakening approach. The developed design methodology takes into account the main elements of the conversion chain as the resource characteristic, the turbine law, the generator specifications, the control strategy and the converter constraints. It allows determining the torque/speed characteristic as a design specification of the generator. The obtained results show that the designed generator fulfills the required torque characteristic over the speed range that confirms the relevance of our methodology. Therefore the limitation power at high tidal speed can be achieved without using variable pitch system.

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