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Modeling and influential factors of a horizontal axis tidal turbine

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Abstract: The conception and optimization of a tidal turbine require deep knowledge of its functioning. This paper develops a three-blade horizontal axis tidal turbine numerical model to determine its influential parameters. First, a tidal turbine simulation model equivalent to Ben-Eschenburg model is built in order to define its physical characteristics including produced mechanical power, load currents and stator voltages of the generator in the Prank frame. Second, sensitivity analysis FAST method is used to determine the influential parameters on the turbine and generator models. The designed tidal turbine numerical model displays qualitative results. In Prank frame, sensitivity analysis results show that gradually tidal currents speed, stator resistance and angular velocity have high influence on turbine power, voltage along d axis and voltage along q axis, respectively.

Keywords— Tidal turbine, Ben-Eschenburg model, Prank frame, Sensitivity analysis.

1. INTRODUCTION

After analyzing the potential of hydrokinetic turbines on the tides in Madagascar, it was found that the use of tidal turbine can be an important energy source. Although there are several studies on the subject, many physical phenomena still need to be studied in depth. Similar to wind turbine, tidal turbine power is governed by the Betz effect which limits extracted power less than 59.25% of available kinetic power. This study aims at predicting the evolution of the horizontal axis tidal turbine performance. The study focuses on improving tidal turbine power yield. First, tidal turbine numerical model is built. Model is based mainly on fluid kinetic energy conversion into electricity. Model simulations are useful to design new tidal turbine prototypes, to improve generated power or to control production chain. In addition, to optimize its performance properly, input parameters that influence the model output are investigated and identified. Sensitivity analysis is used to determine the influential factors on the model output.

2. EQUATION MODELING

The equation modeling of three-bladed horizontal axis tidal turbine system is linked to a Synchronous Electric Current Generator with Permanent Magnets (SCGPM). A gain multiplier adapts the slow rotation speed of the tidal turbine to the suitable speed of the generator. The three blades of the tidal turbine are fixed on a main shaft, which rotates at a nominal speed denoted Ω, (fig. 1).

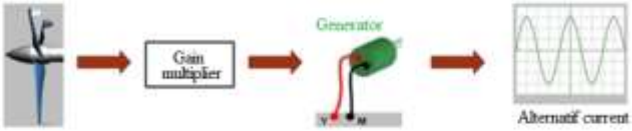

Fig. 1. *Tidal turbine model*

2.1 Hypotheses

The following hypotheses in modeling are adopted:

- notch effects and ferromagnetic losses are neglected,
- magnetic circuit saturation is neglected,
- skin effect influence and heating are neglected,
- stator conductors are parallel to the axis of the machine,
- current forms a balanced three-phase system,
- all resistances are constant.

2.2 Equivalent Ben-Eschenburg model

The generator model is a vector model in an *a*, *b*, *c* reference frame which is linked to the rotor. This matches to the equivalent Ben-Eschenburg model where each phase of the generator is presented in the diagram as shown in Fig. 2.

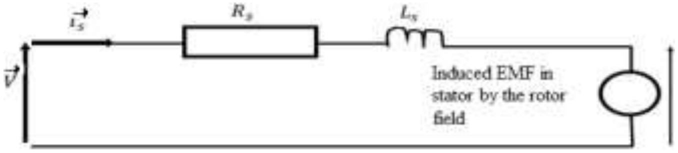

Fig. 2. *Generator model diagram*

2.3 Voltage vector in bound reference frame

In bound reference frame, voltage vector delivered by hydrolienne is given by generalized Ohm's law:

$$[\vec{V}] = R_s[\vec{I_s}] + L_s\frac{d[\vec{i_s}]}{dt} + \frac{d[\vec{\varphi_{fs}}]}{dt} \qquad (1)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}_s = R_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}_s + L_s \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}_s + \frac{d}{dt}\begin{bmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{bmatrix}_{fs} \qquad (2)$$

2.4 Electrical power of a permanent magnet synchronous machine

The electrical power of a permanent magnet synchronous machine can be expressed by voltage vector elements.

$$P_e = V_a i_a + V_b i_b + V_c i_c \qquad (3)$$

where each stator voltage vector elements V_a, V_b and V_c are transformed into voltages V_d, V_q in the Prank frame (Fig. 3) as follow,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4)$$

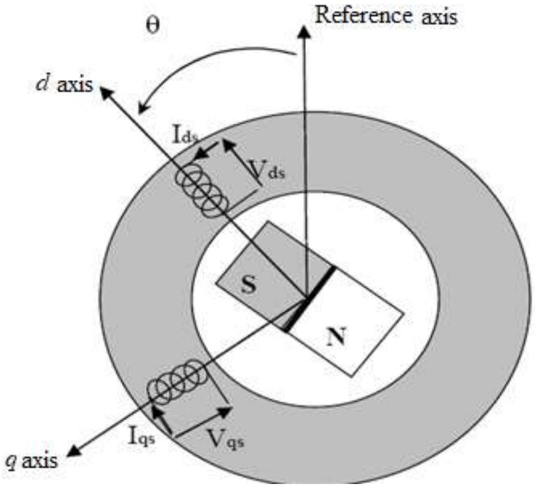

Fig. 3. *Prank frame*

Stator flux along the d and q axes are given by,

$$\begin{cases} \varphi_d = L_d i_d + \varphi_{fs} \\ \varphi_q = L_q i_q \end{cases} \quad (5)$$

Using equation (5), voltages V_d and V_q can be expressed by:

$$\begin{cases} V_d = R_s i_d - \omega\varphi_q + \frac{d\varphi_d}{dt} \\ V_q = R_s i_q + \omega\varphi_d + \frac{d\varphi_q}{dt} \end{cases} \quad (6)$$

Finaly, this yields,

$$\begin{cases} V_d = R_s i_d + L_d \frac{di_d}{dt} - L_q i_q \omega \\ V_q = R_s i_q + L_q \frac{di_q}{dt} - (L_d i_d + \varphi_s)\omega \end{cases} \quad (7)$$

2.5 Mechanic power

Mechanic power P includes Joule losses in the stator P_{Joules} electromagnetic power stored in the field $P_{strored}$ and transformed electrical power P_{tr} where,

$$P_{joules} = R_s i_d^2 + R_s i_d^2 + R_s i_q^2 \quad (8)$$

$$P_{stored} = L_d \frac{di_d}{dt} + L_q \frac{di_q}{dt} \quad (9)$$

$$P_{tr} = \frac{3}{2}\omega(L_d i_d i_q + \varphi_{fs} i_q - L_q i_d i_q) \quad (10)$$

and

$$P = [R_s i_d + L_d \frac{di_d}{dt} - L_q i_q \omega] i_d + [R_s i_q + L_q \frac{di_q}{dt} - (L_d i_d + \varphi_s)\omega] i_q \quad (11)$$

2.6 Electromagnetic torque

Knowing peer number, transversal and direct inductances, electromagnetic torque is done by,

$$T_{em} = \frac{3}{2} p[\varphi_{fs} i_q + (L_d - L_q) i_d i_q] \quad (12)$$

2.7 Power coefficient

Using specific speed, the Power coefficient $C_p(\lambda)$ is written as,

$$Cp(\lambda) = -3.89\ 10^{-8}\lambda^7 - 4.21\ 10^{-6}\lambda^6 + 2.1\ 10^{-4}\lambda^5 - 3.1\ 10^{-3}\lambda^4 + 1.64\ 10^{-2}\lambda^3 - 1.76\ 10^{-2}\lambda^2 + 1.74\ 10^{-2}\lambda - 1.93\ 10^{-3} \quad (13)$$

3. SIMULATIONS

The simulations used BERGEY XL.1 turbine model having mass 34kg, generating 600W power and made by 3-blades rotor of radius 1.25m with friction coefficient Cf=0.025N.m.s.rd^{-1}. Table 1 shows its characteristic parameters.

Table 1*:* Generator simulations parameter

Parameter	Value
Peer number	p=17
Stator resistance	R_s=1.137Ω
Direct inductance	L_d=2.7 10^{-3}H
Transversal inductance	L_q=2.7 10^{-3}H
Stator flux	$\phi_f=0.15$ *Wb*
Torque coefficient	$C_f= \phi_f P= 2.55$V s rd^{-1}
Viscos friction coefficient	f= 0.06N m s rd^{-1}
Engine inertia	J_m= 0.1kg m^2
Nominal voltage	U_n=90*V*
Nominal current	I_n=4.8*A*
Nominal power	P=600W

The turbine power coefficient is given by the equation (13) and its curve is displayed in Fig. 4 in which the specific speed nominal value $\lambda_{nom}=0.69$ for the maximum power coefficient $(C_p)_{max}=0.4421$.

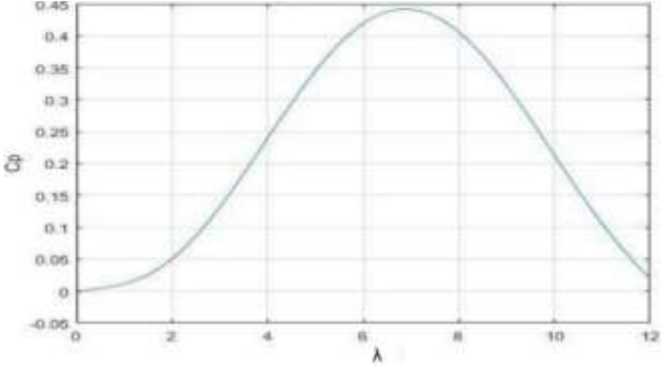

Fig. 4. *Turbine power coefficient*

4. SENSITIVITY ANALYSIS: FAST METHOD

Based on the operating principle of sensitivity analysis (Fig. 5), the parameter x_i in Fast method varies with the frequency f_i according to the equation,

$$x_i = F[\sin(f_i\ s)] \tag{14}$$

where s varies from 0 to 2π with $2\pi/N$ step and N the number of simulations defined by Shannon's relation

$$N \geq 2\ M\ f_{max} + 1 \tag{15}$$

in which M indicates the interference order ($M \leq 6$). In all simulations M is fixed at 5.

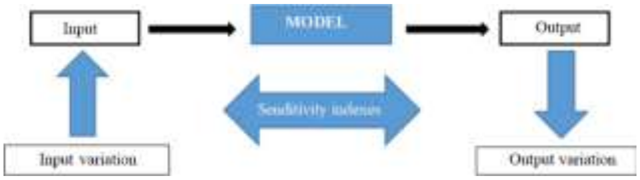

Fig. 5. *Sensitivity analysis fonctionning*

The sensitivity analysis model is expressed by,

$$Y(s) = \sum[A_i\ \cos(f_i\ s) + B_i\ \sin(f_i\ s)] \tag{16}$$

where the main effect S_i is given by,

$$S_i = \frac{V[E(Y/X_i)]}{V(Y)} \tag{17}$$

5. RESULTS

A conclusion section must be included and should indicate clearly the advantages, limitations, and possible applications of the paper. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

5.1 Turbine and mechanic power

According to the simulation model results, the turbine power increases along the rotor radius and the tidal speed (Fig. 6). The mechanical power varies with the rotational speed of the rotor (Fig. 7).

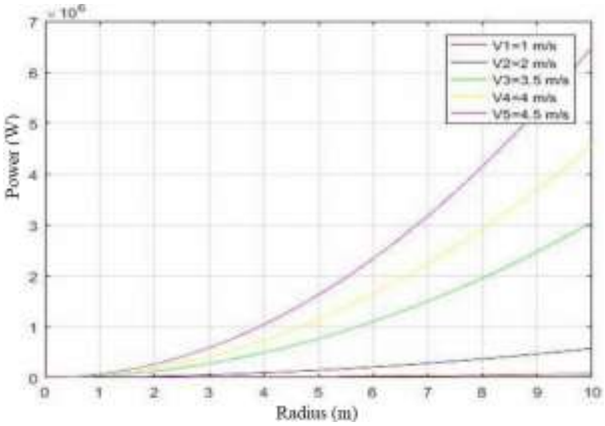

Fig. 6. *Variation of turbine power with rotor radius*

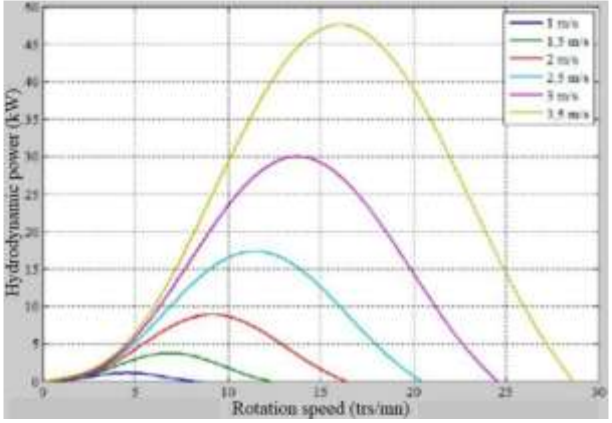

Fig. 7. *Variation of mechanical power with rotational speed*

5.2 Influence on the turbine

The power of the turbine P (18) is transformed into a model Y (19) where the parameter ρ for example becomes X_1 and is associated with the frequency f_1. The frequencies associated with parameters X_1 to X_4 are 11, 21, 27 and 85 respectively.

$$P = \frac{1}{2} Q\ Cp\ S\ v^3 \tag{18}$$

$$Y(X_i) = \frac{1}{2} X_1 X_2 X_3 X_4^3 \tag{19}$$

To evaluate the influence of the power on the turbine, simulation number N has been fixed at 352. Fig. 8 shows that the influence of tidal current speed S_4=0.2963 contributes three times greater than the other parameters.

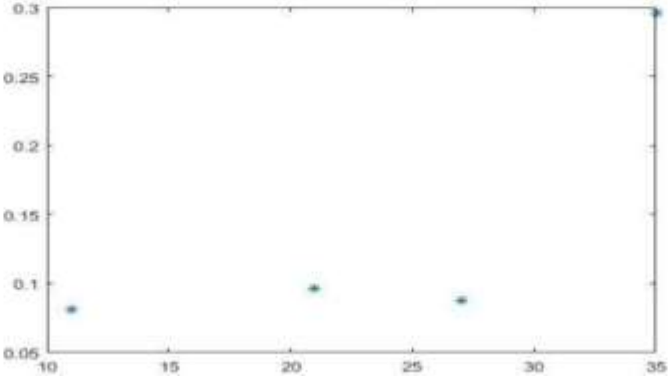

Fig. 8. *Power influential factors*

5.3 Influence on the generator

The stator voltages (8) along d and q axes are transformed into models Y_1 and Y_2 (20) respectively:

$$\begin{cases} Y_1(X_i) = X_1X_2 + X_3X_4 - X_5X_6X_7 \\ Y_2(X_i) = X_1X_2 + X_3X_4 + (X_5X_6 + X_7)X_8 \end{cases} \tag{20}$$

To evaluate the influence of the voltage on the generator in d axis (Y_1), the frequencies associated with parameters X_1, X_2 to X_7 are 17, 39, 59, 69, 75, 83 and 87 respectively. N fixed at 875, among these parameters, stator resistance S_1 shows the most influential (Fig. 9), and angular velocity S_7 the least influential.

For the stator voltage in the q axis (Y_2), the frequencies associated with parameters X_1 to X_8 are 23, 55, 77, 97, 107, 113, 121 and 125 respectively. With N=1260, it can be seen that the angular velocity (S_8) has a significant influence on the stator voltage along the q axis. The inductance and the intensity (S_5 and S_6) along d axis are less influential on the simulation model (Fig. 10).

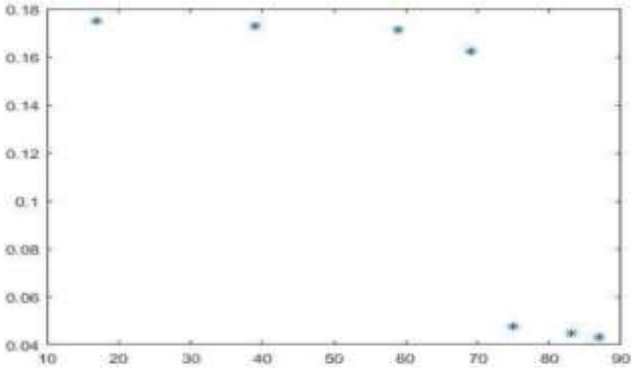

Fig. 9. *Influencial factors on the generator in d-axis*

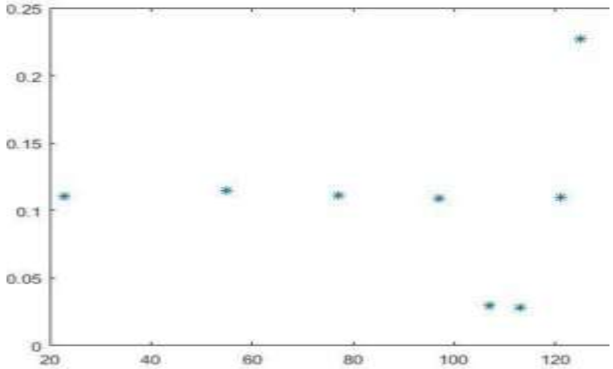

Fig. 10. *Influencial factors on the generator in q-axis*

6. CONCLUSION

The designed tidal turbine numerical model gives qualitative results. Using Prank frame associated with sensitivity analysis, results show that tidal currents speed highly contributes to the turbine power. In addition, stator resistance and angular velocity values should be well-defined to better scale the voltages along d axis and q axis respectively. Taking into account these outcomes in turbine structure, it substantially gives power enhancement from hydrokinetic energy.

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