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Linearizing control input-output of a wind turbine permanent magnet synchronous

Riad AISSOU[#1], Toufik REKIOUA[#2]

[1,2] *Laboratory of Industrial Technology and the Information « LT2I »,*

Faculty of Technology, University A. Mira, Targa Ouzemour, Bejaia, Algeria

[1] riadaissou@hotmail.com [2] to_reki@yahoo.fr

Abstract — **In this paper, we study the control voltage at the output of a permanent magnet synchronous generator (PMSG) connected to a PWM rectifier. The input-output linearizing control is tested for PMSG. This device is intended for an application of wind energy conversion in the case of an isolated site. The results of the different simulations of the entire chain conversion performed under MATLAB / Simulink, were used to evaluate the performance of the proposed system**.

Keywords— Linearizing control input-output; wind turbine; permanent magnet synchronous generator (PMSG); PWM Rectifier;

I. INTRODUCTION

The power generation sector is the largest consumer of primary energy and two-thirds of its sources are fossil fuels. It is technically and economically capable of making significant efforts to reduce violations of human activity on climate and the environment. One possibility is to increase the rate of production of electricity from resources of non-renewable fossil type and Today, renewable generation sources, including solar and wind energy, which are the growth rate is highest.

The wind power generator, which is based on a variable speed turbine and a synchronous permanent magnet generator is connected to a DC bus through a PWM power converter. [1] However, stand-alone operation, the rotational speed and the load is not fixed, the stator voltage can vary within wide limits. It then becomes necessary to use an appropriate control system to maintain the output voltage at a constant amplitude and frequency.

The input-output linearizing command is a command which generalizes the vector-ensuring decoupling and linearization of the relationship between inputs and outputs. Assuming that all of the state vector is measurable, it is possible to design a nonlinear state feedback which ensures the stability of the closed loop system [2].

This article focuses on the application of the input-output linearizing the wind energy conversion system control with a variable rate based on a permanent magnet synchronous generator. The overall plan of studies of the system is represented by the figure 1. Results of the simulation of the dynamic behavior of the studied system are presented. From these results, we can verify the effectiveness and reliability of the applied control.

II. MODELING OF WIND GENERATOR

The wind power generator, comprising a variable speed turbine coupled directly to a PMSG connected to a DC bus through a PWM power converter, is shown in Figure 1

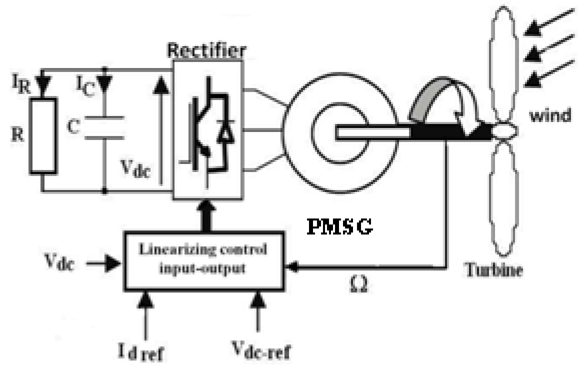

Fig. 1. Schematic diagram of the system studied.

II.1 MODEL TURBINE

The power of the air mass that passes through the surface of the turbine S is given by [3,4]:

$$p_{wind} = \frac{1}{2}\rho s_{turbine} V_{wind}^3 \qquad (1)$$

With

$s_{turbine}$: The effective area through which the wind,

ρ : The density of the air (1.25kg / m3),

V_{wind} : The wind speed,

We focus our work in the operation of a vertical axis turbine. The value of the active surface (S) was replaced by the geometric dimensions of the wing shown in Figure 2 where:

S=2*R*H (2)

With

H : height of the turbine.

R : The radius of the turbine.

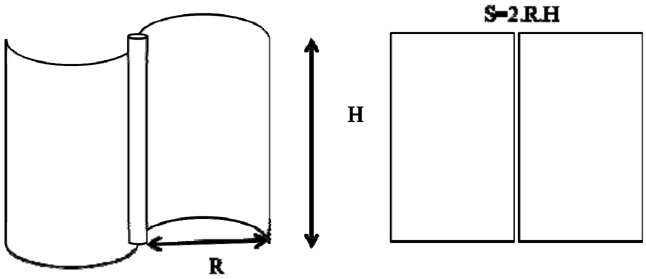

Fig. 2. Geometric Dimensioning Savonius wing

For describing the operating speed of a wind turbine, the low

speed (specific) λ is used, where :

$$\lambda = \frac{R.\Omega}{V_{wind}} \quad (3)$$

R : The radius of the wind turbine blades,

Ω : The angular speed of rotation of the blades,

V_{wind} : Wind speed..

Wind power and power extracted by the wind $p_{turbine}$ can be expressed in terms of the power coefficient c_p

$$P_{turbine} = CpP_{wind} \quad (4)$$

The power coefficient Cp is often derived from practical measures:

$$c_p(\lambda) = -0.2121 * \lambda^3 + 0.0856 * \lambda^2 + 0.2539 * \lambda \quad (5)$$

Figure 3 shows the power coefficient Cp

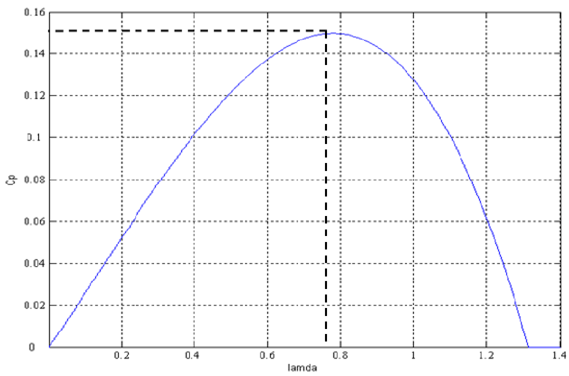

Fig. 3. Curve $c_p(\lambda)$ of the blade Savonius type studied

From this power, the wind torque is given by:

$$C_{eol} = \frac{P_{eol}}{\Omega} \quad (6)$$

By replacing the value of the power by the product (torque * speed)

$$C_{turbine} = \frac{C_p(\lambda)*\rho*R^2*H*V_{wind}^2}{\lambda} \quad (7)$$

II.2 MODELING OF THE SHAFT OF THE MACHINE

The differential equation that characterizes the mechanical behavior of the turbine and generator is given by [6].

$$(J_t + J_m) * \frac{d\Omega}{dt} = C_{turbine} - C_{em} - (f_m - f_t) * \Omega \quad (8)$$

where :

J_t et J_m : are the inertias of the turbine and of the machine respectively,

f_m et f_t : the coefficient of friction of the engine and of the blades respectively,

$C_{turbine}$: the static torque provided by the wind.

In our application, we consider that the friction associated with the generator (one the wing will not be taken into account), then:

$$C_{turbine} = J_t \frac{d\Omega}{dt} + C_{em} + f_m\Omega \quad (9)$$

II. 3 MODEL OF THE SYNCHRONOUS MACHINE

The equations for the PMSG, can be written in a reference linked to the rotor as follows: [7]

$$\begin{cases} V_{ds} = R_s I_{ds} + L_{ds}\frac{d}{dt}I_{ds} - p\omega_r L_{qs} I_{qs} \\ V_{qs} = R_s I_{qs} + L_{qs}\frac{d}{dt}I_{qs} + p\omega_r L_{ds}I_{ds} + p\omega_r \phi_f \end{cases} \quad (10)$$

with :

R_s : Resistance of the stator windings.

I_{ds}, I_{qs} : Currents in the stator mark Park.

V_{ds}, V_{qs} : Stator voltages in the benchmark Park.

L_{ds}, L_{qs} : Inductions in the stator cyclical mark park.

p : Number of pole pairs.

ω_r : The pulse voltages (rad/s).

ϕ_f : The flux created by the permanent magnet through the stator windings.

- Expression of the power and electromagnetic torque

The expression of electromagnetic torque in the repository Park

$$C_e = \frac{3}{2} P[(L_{ds} - L_{qs})I_{ds}I_{qs} + \phi_f I_{qs}] \quad (11)$$

II.4 Modeling Rectifier

Modeling of the rectifier is made by a set of switches ideals. These switches are complementary, their state is defined by the following function [8, 9]:

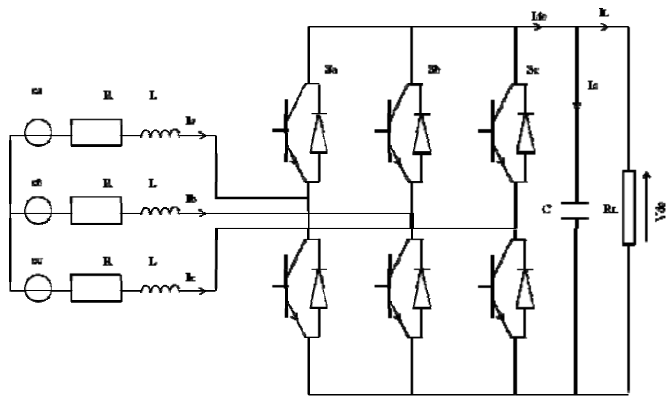

Fig. 4. Schema of association PMSG-PWM rectifier

$$s = \begin{cases} +1, \bar{s} = -I \\ -1, \bar{s} = +I \end{cases} \qquad \text{for s=a ,b ,c}$$

The input voltage and the output current phase can be written in terms of: Sj, and Vdc input currents ia, ib, ic.

$$i_a + i_b + i_c = 0 \qquad (12)$$

Input voltages between phases of the PWM rectifier can be described by:

$$\begin{cases} U_{sab} = (S_a - S_b)U_{dc} \\ U_{sbc} = (S_b - S_c)U_{dc} \\ U_{sca} = (S_c - S_a)U_{dc} \end{cases} \qquad (13)$$

The equations for the voltage phase balanced system without neutral connection can be written as:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{di}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} \qquad (14)$$

with :

$$\begin{cases} U_{sa} = \frac{2s_a - s_b - s_c}{3} . U_{dc} \\ U_{sb} = \frac{2s_b - s_a - s_c}{3} . U_{dc} \\ U_{sc} = \frac{2s_c - s_a - s_b}{3} . U_{dc} \end{cases} \qquad (15)$$

Finally, we deduce the equation coupling between AC and DC sides by:

$$c \frac{dU_{dc}}{dt} = s_a i_a + s_b i_b + s_c i_c - i_l \qquad (16)$$

The previous equations in synchronous dq coordinates are:

$$e_d = Ri_d + L \frac{di}{dt} - \omega L i_q + U_{sd} \qquad (17)$$

$$e_q = Ri_q + L \frac{di}{dt} + \omega L i_d + U_{sq} \qquad (18)$$

$$c \frac{dU_{dc}}{dt} = s_d i_d + s_q i_q - i_l \qquad (19)$$

with :

$$s_d = \frac{1}{\sqrt{6}}(2s_a - s_b - s_c).\cos(\omega t) + \frac{1}{\sqrt{2}}(s_b - s_c).\sin(\omega t)$$

$$s_q = \frac{1}{\sqrt{2}}(s_b - s_c).\cos(\omega t) - \frac{1}{\sqrt{6}}(2s_a - s_b - s_c).\sin(\omega t)$$

III. APPLICATION OF THE LINEARIZING CONTROL INPUT OUTPUT FOR PMSG

Our command is to control the stator current (I_d) and the rectified voltage V_{dc} of PMSG. For this we chose as the state vector $x = [I_d \;\; I_q \;\; V_{dc}]^T$, and as output y=$[V_{dc}\; I_d]^T$ and control vector $u = [V_d \;\; V_q]^T$.

The model of PMSG, expressed in the rotor reference frame related to the form of equation of state:

$$\begin{cases} \dot{X} = f(x) + G(x).U(t) \\ y = H(x) \end{cases} \qquad (20)$$

with :

$$y(t) = \begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix} = \begin{bmatrix} x_3 \\ x_1 \end{bmatrix} = \begin{bmatrix} V_{dc} \\ I_d \end{bmatrix};$$

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} I_d \\ I_q \\ V_{dc} \end{bmatrix}; U = \begin{bmatrix} V_d \\ V_q \end{bmatrix}; G(x) = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \end{bmatrix} =$$

$$\begin{bmatrix} g_1 & 0 \\ 0 & g_2 \\ 0 & 0 \end{bmatrix}; f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{bmatrix} = \begin{bmatrix} a_1x_1 + a_2x_2 \\ b_1x_2 + b_2x_1 + b_3 \\ c_1\frac{x_2}{x_3} + c_2 \end{bmatrix}$$

where :

$$a_1 = -\frac{R_s}{L_d};\; a_2 = \frac{\omega_r L_q}{L_d};\; b_1 = -\frac{R_s}{L_q};\; b_2 = -\frac{L_d\omega_r}{L_q};$$

$$b_3 = -\frac{\omega_r \phi_f}{L_q};\; c_1 = \frac{2*E}{2*C};\; c_2 = \frac{-IL}{C}.$$

The linearization condition to check if a nonlinear system admits a linearization input - output is the order of the relative degree of the system.

The following notation is used for the Lie derivative of the function $h_j(x)$ along a vector field $f(x) = (f_1(x) \ldots f_n(x))$ [11].

- $L_f h_j = \sum_{i=1}^{n} \frac{\partial h_j}{\partial x_i} f_i(x) = \frac{\partial h_j}{\partial X} f(x)$
- $L_f^k h_j = L_f(L_f^{(k-1)} h_j)$ (21)
- $L_g L_f h_g = \frac{\partial L_f h_j}{\partial X} G(x).$
- degree relative

The relative degree of output is the number of times that is needed to derive the output to bring up the input U. The future output y(t+ τ) is calculated by:

- Relative degree of the rectified voltage

$$\dot{y}_1(t) = \dot{h}_1(x) = L_f h_1(x) + L_g h_1(x).U = f_3(x) \qquad (22)$$

$$\ddot{y}_1(t) = \ddot{h}_1(x) = L_f^2 h_1(x) + L_g L_f h_1(x).U \qquad (23)$$

with *:*

$$L_f h_1(x) = f_3(x)$$

$$L_g h_1(x) = 0$$

$$L_f^2 h_1(x) = \frac{c_1}{x_3} f_2(x) - \frac{c_1 x_2}{x_3^2} f_3(x)$$

$$L_g L_f h_1(x) = \begin{bmatrix} 0 & \frac{c_1}{x_3} g_2 \end{bmatrix}$$

Relative degree of $y_1(t)$ is $r_1 = 2$

- Relative degree of the current

$$\dot{y}_2(t) = \dot{h}_2(x) = L_f h_2(x) + L_g h_2(x).U \qquad (24)$$

With :

$$L_f h_2(x) = f_1(x)$$

$$L_g h_2 = [g_1 \quad 0]$$

The matrix defining the relationship between the physical inputs (U) and the derivatives of the outputs (y (x)) is given by the following expression :

$$\begin{pmatrix} \dot{y}_1(t) \\ \ddot{y}_2(t) \end{pmatrix} = \begin{pmatrix} \frac{d}{dt} I_d \\ \frac{d^2}{dt^2} V_{dc} \end{pmatrix} = A(x) + D(x) \begin{pmatrix} V_d \\ V_q \end{pmatrix} \qquad (25)$$

With :

$$A(x) = \begin{pmatrix} f_1(x) \\ \frac{c_1}{c_3} f_2(x) - \frac{c_1 x_2}{x_3^2} f_3(x) \end{pmatrix}$$

$$D(x) = \begin{pmatrix} g_1 & 0 \\ 0 & \frac{c_1}{x_3} g_2 \end{pmatrix}$$

To linearize the input-output behavior of the generator in a closed loop non-linear state feedback is applied according to [24]

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = D^{-1}(x) \left[-A(x) + \begin{pmatrix} V_1 \\ V_2 \end{pmatrix} \right] \qquad (26)$$

The determinant of the matrix decoupling D (x) is not null

$$D^{-1}(x) = \begin{pmatrix} \frac{1}{g_1} & 0 \\ 0 & \frac{x_3}{c_1 g_2} \end{pmatrix} \qquad (27)$$

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} \dot{y}_1(t) \\ \ddot{y}_2(t) \end{pmatrix} = \begin{pmatrix} \frac{d}{dt} I_d \\ \frac{d^2}{dt^2} V_{dc} \end{pmatrix} \qquad (28)$$

Substituting (27), (28) into (26) we have:

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \begin{pmatrix} \frac{1}{g_1}(V_1 - f_1(x)) \\ \frac{x_3}{c_1 g_2}\left(-\frac{c_1}{x_3} f_2(x) + \frac{c_1}{x_3^2} x_2 f_3(x) + V_2\right) \end{pmatrix}$$

Entries ($V_1 \quad V_2$) are calculated by imposing a static regime ($I_{dref} = I_d$ et $V_{dcref} = V_{dc}$) and the dynamic error.

$$\begin{cases} \frac{d}{dt} e_1 + K_{11} e_1 = 0 \\ \frac{d^2}{dt^2} e_2 + K_{21} \frac{d}{dt} e_2 + K_{22} e_2 = 0 \end{cases} \qquad (29)$$

Internal inputs ($V_1 \quad V_2$) are defined as follows:

$$\begin{cases} V_1 = K_{11}(I_{dref} - I_d) + \frac{d}{dt} I_{dref} \\ V_2 = K_{21}\left(\frac{d}{dt} V_{dcref} - \frac{d}{dt} V_{dc}\right) + K_{22}(V_{dcref} - V_{dc}) + \frac{d^2}{dt^2} V_{dcref} \end{cases} \qquad (30)$$

$$I_{dref} = \dot{V}_{dcref} = \ddot{V}_{dcref} = 0 \qquad (31)$$

The coefficients (K_{11}, K_{21}, K_{22}) are selected so that equation (30) is a polynomial HURWITZ [11].

$$\begin{cases} s + K_{11} = 0 \\ s^2 + K_{21} s + K_{22} = 0 \end{cases} \qquad (32)$$

IV. SIMULATION RESULTS

Full operation of the device was simulated in the Matlab Simulink . In this control strategy, the reference voltage at the output of the rectifier is taken equal to Vdc−ref = 40 V and the variation of the wind speed is shown in Figure 5. In what follows, we present simulation results.

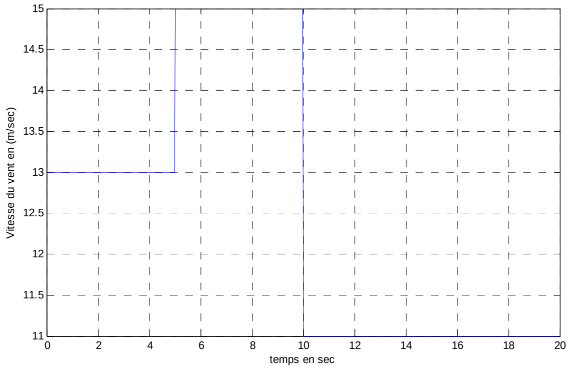

Fig. 5. Wind speed

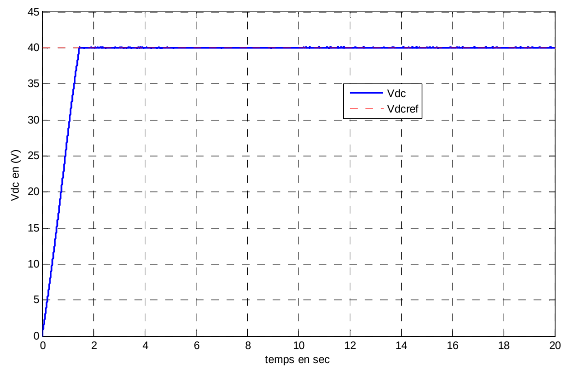

Fig. 6. Rectified voltage

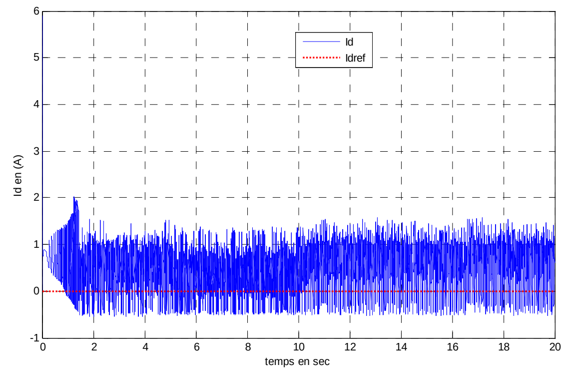

Fig. 7. Direct current

Wind speed show in Figure 8 is modeled as a sum of deterministic several harmonics [11] :

$V_{vent}(t) = 10 + 0.2\sin(0.1047\,t) + 2(\sin 0.2665\,t) + \sin(1.2930\,t) + 0.2\sin(3.6645\,t)$ [36]

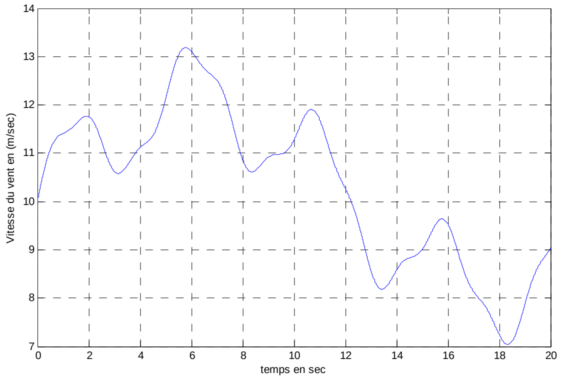

Fig. 8. Wind speed

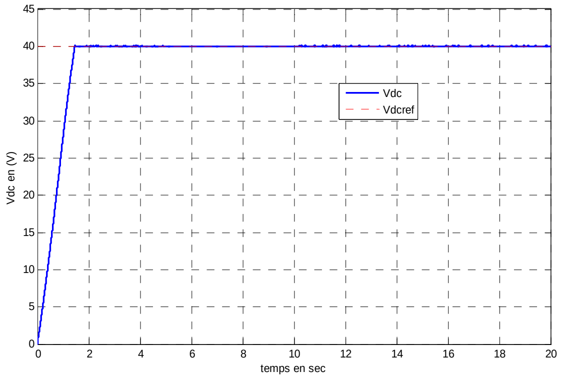

Fig. 9. Rectified voltage

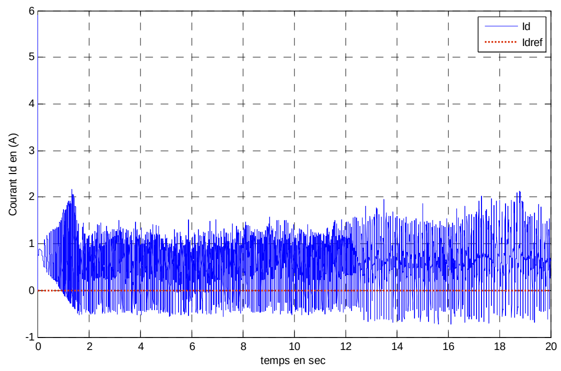

Fig. 10. Direct current

The response of the voltage at the output of the rectifier is given in Figures 6, 9. We can see that the voltage is well regulated. This is also the case of the current Id and the rejection of disturbances made in this case by changes in wind speed is ensured.

V. CONCLUSION

In this article, we presented the study of voltage control system consists of a permanent magnet synchronous generator feeding a PWM rectifier. The proposed control strategy is based on the input-output linearizing control to ensure good performance.

Law control system has been detailed. The results of different simulations were discussed and validated mathematical models of the system proposed wind.

ANNEXES

Désignation	**Valeur**
nominal voltage	Vn = 90 V
nominal current	In= 4.8 A
nominal power	Pn= 600 W
Number of pole pairs	2 p = 17
Winding resistance	Rs = 1,137 Ω
synchronous inductance	Ls = 2.7 mH
efficient flow	Φeff = 0.15 Wb
Coefficient of friction	f = 0,06 N.m.s/rad
Inertia of the GSAP	J = 0.1 N.m
Radius of the wing	R = 0.5 m
Height of the wing	H = 2 m
active surface	S = 2 ^{m2}
Inertia of the wing	J = 16 kg.m^2
Density of air	ρ = 1.2 kg/m^3

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