Nonlinear Predictive Control of a Permanent Magnet Synchronous Generator Used in Wind Energy System

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Abstract **:** *In this paper, the output voltage of a permanent magnet synchronous generator (PMSG) connected to a PWM rectifier is controlled using a nonlinear predictive control. This device is intended for an application in wind energy conversion in the case of an isolated site. The simulation results of the whole conversion chain are presented to evaluate the performance of the proposed system.*

Keywords: *non-linear predictive control, wind turbine, permanent magnet synchronous generator (PMSG), PWM Rectifier.*

1. Introduction

Wind power is emerging as one of the fastest growing sustainable energy resources and technology in the world with the advantage of clean, inexhaustible, cost effective and eco friendly [1].

In the last two decades, various wind turbine concepts and high efficiency control schemes have been developed [2]. In the case of stand alone operating, induction generators are widely used due to their advantages of reduced unit cost and size, low maintenance and better transient performance [3]. Even so, permanent magnet synchronous generators (PMSG) are more and more preferred to induction machines because of their improved efficiency, direct drive operation and no need of excitation [4]. Based on a variable speed turbine, PMSG is then connected to a DC bus through a PWM power converter [5]. In such operating, as the rotational speed and the load are not fixed, the stator voltage can vary within wide limits. It is then necessary to use an appropriate control system to maintain the output voltage at a constant amplitude and frequency.

The predictive control aims to obtain certain desired performance in the presence of disturbances and internal variations. In a general way, the techniques of predictive control generated a great number of applications in various practical fields [6]. The extension of this technique to the control of nonlinear systems has recently been the subject of many research and several algorithms have been proposed [7].

The present paper focuses on the application of nonlinear model predictive control of wind energy conversion system with variable speed based on a PMSG. The overall scheme of the studied system is shown in figure 1.

2. Modeling of wind generator

A wind power system, with a variable speed turbine coupled directly to a PMSG connected to a DC bus through a PWM rectifier, is shown in Fig. 1

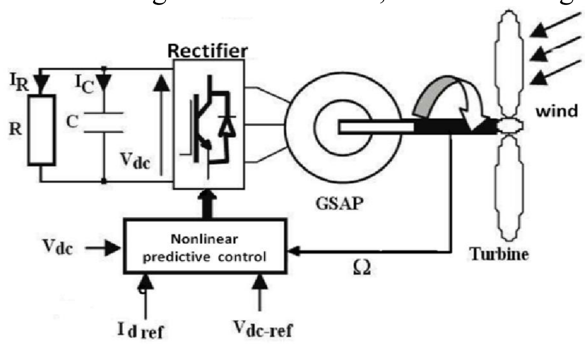

Fig. 1. Overall scheme of the studied system

2.1 Model turbine

Generally, the power of the air mass that passes through the surface $S_{turbine}$ of a horizontal axis turbine is given by [8,9]:

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

With

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

V_{wind} : The wind speed,

In the case of a vertical axis turbine with Savonius wing, $S_{turbine}$ is replaced by the surface S with the geometric dimensions of the wing shown in Figure 2:

$$S=2*R*H \qquad (2)$$

With

H : height of the turbine.

R : Radius of the turbine.

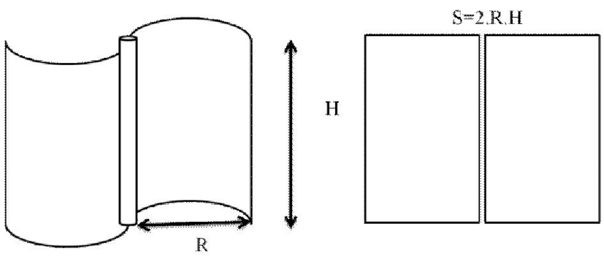

Fig. 2. Geometric Dimensioning Savonius wing

The power extracted by the wind, $P_{turbine}$, can be expressed using the power coefficient C_p such as:

$$P_{turbine} = C_p P_{wind} \qquad (3)$$

C_p is generally expressed with respects to the tip speed ratio λ :

$$\lambda = \frac{R.\Omega}{V_{wind}} \qquad (4)$$

R : The radius of the wind turbine blades,

Ω : The angular speed of the blades,

In the case of the Savonius system studied, the power coefficient $C_p(\lambda)$, derived from practical measures, is given by the following expression :

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

Whose waveform is shown in Figure 3:

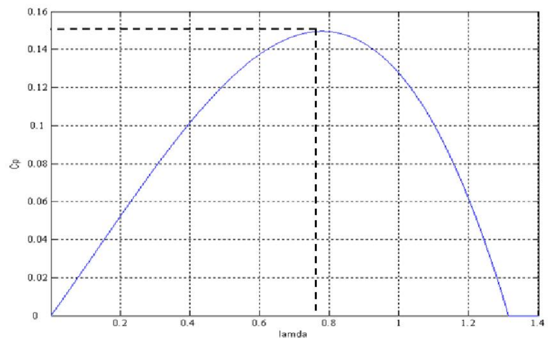

Fig. 3. Waveform of C_p (λ), of the blade Savonius studied

From this power, the turbine torque can be expressed by:

$$C_{turbine} = \frac{P_{turbine}}{\Omega} \qquad (6)$$

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

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

2.2 Model of the shaft of the machine

The differential equation that characterizes the mechanical behavior of the turbine and generator is given by [11].

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

where :

J_t, J_m : are the moments of inertia of the turbine and of the machine respectively,

f_m , f_t : the friction coefficients 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 coefficient is associated to the generator only (the one relative to the wing is not taken into account), then:

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

2. 3 Model of the synchronous machine

The equations of the PMSG, can be written in a reference linked to the rotor as follows: [12]

$$\begin{cases} V_d = RI_d + L_d \frac{d}{dt} I_d - \omega L_q I_q \\ V_q = RI_q + L_q \frac{d}{dt} I_q + \omega L_d I_d + \omega \phi_f \end{cases} \qquad (10)$$

with :

R : Resistance of the stator windings.

I_d, I_q : Stator currents in the Park rotating frame.

V_d, V_q : Stator voltages in the Park rotating frame.

L_d, L_q : Inductances along the direct and quadrature axes which are differents in the general case.

$\omega = p.\Omega$: The voltage pulsation (rad/s).

p : Number of pole pairs.

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

The expression of the electromagnetic torque in the rotating frame is given by:

$$C_{em} = \frac{3}{2} P[(L_d - L_q)I_d I_q + \phi_f I_q] \qquad (11)$$

2.4 Rectifier modeling

The model of the rectifier (Fig. 4) is made by a set of ideal switches. The latter are complementary; their states are defined by the following function [13, 14]:

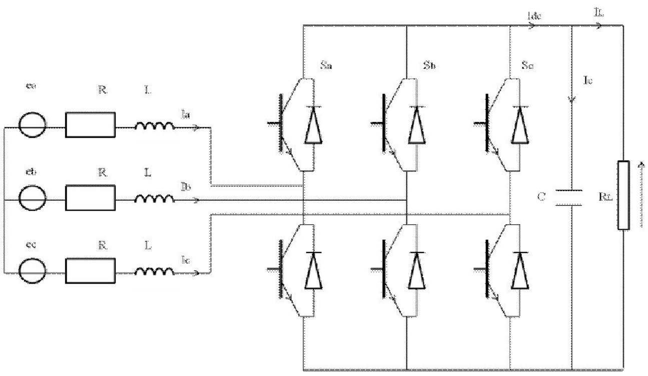

Fig. 4. Scheme of the PMSG and PWM rectifier

$$Sj = \begin{cases} +1, \bar{s} & = -I \\ -1, \bar{s} & = +I \end{cases} \qquad \text{for j=a, b, c} \qquad (12)$$

The input voltage between phases can be written in terms of Sj and Udc, knowing that the sum of the input currents ia, ib, ic is nil, such as:

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

Thus, the equations of the balanced phase voltage system, without neutral connection, can be written as:

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

with :

$$\begin{cases} U_{SA} = \frac{2S_A - S_B - S_C}{3}.U_{DC} \\ U_{SB} = \frac{2S_B - S_A - S_C}{3}.U_{DC} \\ U_{SC} = \frac{2S_C - S_A - S_B}{3}.U_{DC} \end{cases}$$

(15)

Finally, we deduce the coupling equation 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, expressed in the synchronous a, b, c coordinates, become:

$$0 = Ri_d + L_d\frac{di_d}{dt} - \omega L_q i_q + V_d \qquad (17)$$

$$e_q = Ri_q + L_q\frac{di_q}{dt} + \omega L_d i_d + V_q \qquad (18)$$

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

with :

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

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

3. Application of the nonlinear predictive control to the PMSG model

The goal of the proposed study is to control the stator current I_d and I_q and the rectified voltage U_{DC} of the PMSG. Hence, we chose as state vector $x = [I_d \;\; I_q \;\; U_{DC}]^T$, as output $y=[U_{DC}\; I_d\,]^T$ and as control vector $U = [V_d \;\; V_q]^T$.

The model of the PMSG, expressed in the rotor reference frame under a state equation form is given below:

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

with :

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

$$\dot{X}=\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}=\begin{bmatrix}I_d\\I_q\\U_{DC}\end{bmatrix};U=\begin{bmatrix}V_d\\V_q\end{bmatrix};$$

$$G(x)=\begin{bmatrix}\frac{1}{L_d}&0\\0&\frac{1}{L_q}\\0&0\end{bmatrix}=\begin{bmatrix}g_1&0\\0&g_2\\0&0\end{bmatrix};$$

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

The objective of the predictive control is that the future process output $y(t+\tau)$ is controlled near $y_r(t+\tau)$. This task is accomplished by minimizing $\mathfrak{J}$ [15]. The cost function is given by the following relationship:

$$\mathfrak{J}(X,U)=\frac{1}{2}\int_0^{\tau_r}(y(t+\tau)-y_r(t+\tau))^T(y(t+\tau)-y_r(t+\tau))d\tau \quad (21)$$

with :

τ_r : The prediction time.

$y_r(t+\tau)$: The reference trajectory for the future.

$y(t+\tau)$: The prediction step τ of the system output

The prediction of outputs is calculated from the Taylor serie expansion

$$y_i(t+\tau)=h_i(X)+\tau L_f h_i(X)+\frac{\tau^2}{2!}L_f^2 h_i(X)+\cdots++\frac{\tau^{r_i}}{r_i!}L_g L_f^{((r)_i-1)}h_i(X)U(t) \quad (22)$$

With :

r_i he relative degree of each output $y_i(t)$.

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

- $L_f h_j=\sum_{i=1}^{n}\frac{\partial h_j}{\partial x_i}f_i(x)=\frac{\partial h_j}{\partial X}f(x)$
- $L_f^k h_j=L_f(L_f^{(k-1)}h_j)$ (23)
- $L_g L_f h_g=\frac{\partial L_f h_j}{\partial X}G(x)$.

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 $y(t+\tau)$ is calculated by:

$$y(t+\tau)=T(\tau)Y(t) \quad (24)$$

With :

$$Y(t)=\begin{bmatrix}y_1(t)\\y_2(t)\\\dot{y}_1(t)\\\dot{y}_2(t)\\\ddot{y}_1(t)\end{bmatrix}=\begin{bmatrix}h_1(X)\\h_2(X)\\L_f h_1(X)\\L_f h_2(X)\\L_f^2 h_1(x)\end{bmatrix}+\begin{bmatrix}0\\0\\0\\G_1(X)U(t)\end{bmatrix}$$

With :

$$G_1(X)=\begin{bmatrix}L_g h_2(X)\\L_g L_f h_1(x)\end{bmatrix},\ T(\tau)=\begin{bmatrix}1&0&\tau&0&\frac{\tau^2}{2}\\0&1&0&\tau&0\end{bmatrix}$$

If the reference to futur $y_r(t+\tau)$ is not predefined, a calculation similar to $y(t+\tau)$ used.

$$y_r(t+\tau)=T(\tau)\,Y_r(t). \quad (25)$$

Using (24), (25), the cost function can be expressed as:

$$\mathfrak{J}(X,U)=\frac{1}{2}(Y(t)-Y_r(t))^T\prod(Y(t)-Y_r(t)) \quad (26)$$

With :

$$\prod=\int_0^{\tau_r}T(\tau)^T T(\tau)d\tau=\begin{bmatrix}\tau&0&\frac{\tau^2}{2}&0&\frac{\tau^3}{6}\\0&\tau&0&\frac{\tau^2}{2}&0\\\frac{\tau^2}{2}&0&\frac{\tau^3}{3}&0&\frac{\tau^4}{8}\\0&\frac{\tau^2}{2}&0&\frac{\tau^3}{3}&0\\\frac{\tau^3}{6}&0&\frac{\tau^4}{8}&0&\frac{\tau^5}{20}\end{bmatrix}=\begin{bmatrix}\prod_1&\prod_2\\\prod_2^T&\prod_3\end{bmatrix}$$

$$Y(t)-Y_r(t)=M+\begin{bmatrix}0\\0\\0\\G_1(X)U(t)\end{bmatrix}$$

With:

$$M=\begin{bmatrix}M_1\\M_2\\M_3\\M_4\\M_5\end{bmatrix}=\begin{bmatrix}h_1(X)\\h_2(X)\\L_f h_1(X)\\L_f h_2(X)\\L_f^2 h_1(x)\end{bmatrix}-\begin{bmatrix}y_{r1}(t)\\y_{r2}(t)\\\dot{y}_{r1}(t)\\\dot{y}_{r2}(t)\\\ddot{y}_{r1}(t)\end{bmatrix}$$

To satisfy the necessary condition to have an optimal control is as follows:

$$\frac{\partial \mathfrak{I}}{\partial \mathbf{U}} = \mathbf{0} \qquad (27)$$

The non-linear control problem after the minimization of the cost function is given by:

$$\mathbf{U(t)} = -\mathbf{G_1(X)^{-1}}[\,\prod_3^{-1}\prod_2^{T} \quad \mathbf{I_{2*2}}]\,\mathbf{M} \qquad (28)$$

Where

$$\prod_3^{-1}\prod_2^{T} = \begin{bmatrix} 0 & \frac{3}{2\tau} & 0 \\ \frac{10}{3\tau^2} & 0 & \frac{5}{2\tau} \end{bmatrix}, \; G_1(X)^{-1} = \begin{bmatrix} \frac{1}{g_1} & 0 \\ 0 & \frac{x_3}{C_1 g_2} \end{bmatrix}$$

4. Simulation results

The operating of the studied system using the proposed control 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 waveform of the wind speed variation is shown in Figu 5. In th following, we present simulation results.

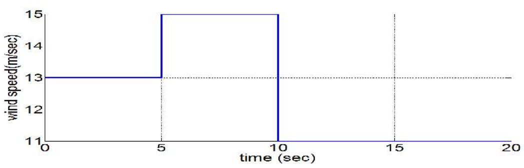

Fig. 5. Wind speed

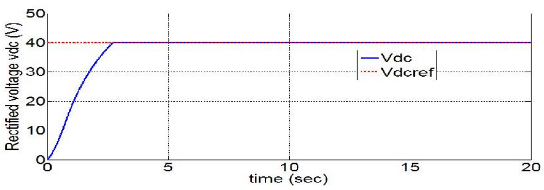

Fig. 6. Rectified voltage

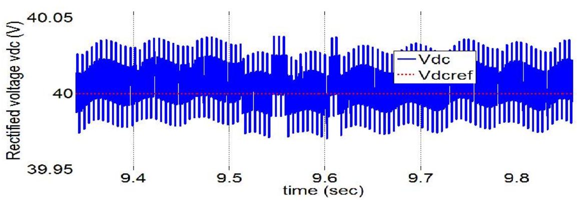

Fig. 7. zoom of Rectified voltage

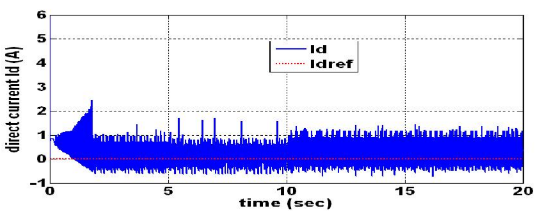

Fig. 8. Direct current

The waveform of the wind speed shown in Figure 10 is modeled as a sum of deterministic several harmonics [16]:

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

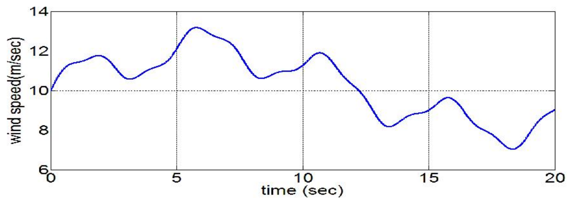

Fig. 9. Wind speed

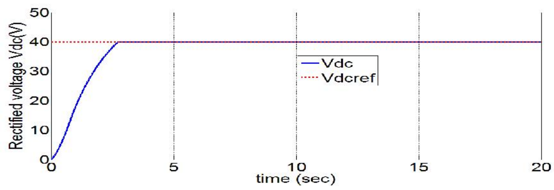

Fig. 10. Rectified voltage

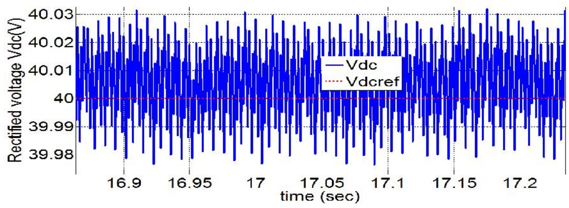

Fig. 11. zoom of Rectified voltage

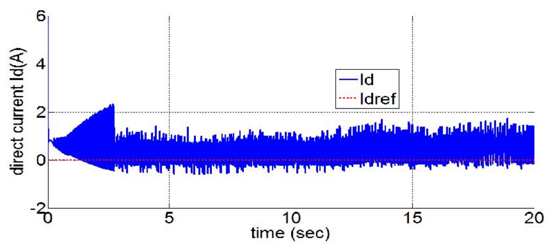

Fig. 12. Direct current

The response of the voltage at the output of the rectifier is given in Figures 8, 11. 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.

5. Conclusion

The study of voltage control system constituted of a permanent magnet synchronous generator feeding a PWM rectifier is presented. The proposed control strategy is based on non-linear predictive control to ensure good performance.

Law control system has been detailed. Simulations results were given and discussed. They show the interest and the validity of the proposed control strategy for this stand alone wind energy conversion system.

Annexes

nominal voltage	Vn = 50 V
nominal current	In= 4.8 A
nominal power	Pn= 300 W
Number of pole pairs	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 PMSG	J = 0.1 kg.m^2
Radius of a wing	R = 0.5 m
Height of a wing	H = 2 m
active surface	S = 2 m^2
Inertia of the wing	J = 16 kg.m^2
Density of air	$\rho = 1.2$ kg/m^3

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