Adaptive Regulation methodology of large scale wind turbine

H. Lehouche [1] and S. Zadri[2] and B. Mendil[3]

[1] LTII of Bejaia university of Algeria, Email: lehouche2006@yahoo.fr
[2]LTII of Bejaia university of Algeria, Email: samirzadri@yahoo.fr
[3]LTII of Bejaia university of Algeria, Email: bmendil@yahoo.fr

***Abstract*−High performance and reliability are required for wind turbines to be competitive within the energy market To capture their nonlinear behavior, wind turbines are often modeled using highly nonlinear dynamics. The paper presents and illustrates the design of indirect adaptive regulation strategy. The main objective is the estimation of a linear reduced model which behaves like the real process and the online adjustment of R-S-T regulator parameters. The simulation results show the importance and the effectiveness of this controller in terms of performances in the exploitation of wind energy conversion.**

Key words: variable speed wind turbine, R-S-T controller, recursive least quart identification, adaptive control.

I. INTRODUCTION

The environmental concerns and the depletion of fossil fuels, motivate an increasing attention to wind energy which is one of the most promising sustainable energy sources. Recently, there has been a significant growth in wind turbine technology attributed because of its mature technology. The maturity of the technology can easily be observed by the increasing sizes of the new wind turbines with sophisticated wind turbine controls. Since size practically means more power extraction, new wind turbine sizes are seen to have increased from just 15m in diameter in the mid 1980s generating about 50kW to over 100m just after the turn of the century generating an average of 3MW [1, 2].

From a control point of view, a wind turbine is a challenging machine, since it is driven by a stochastic input, which is poorly known. Recent developments in the wind-turbine industry deploy different control strategies to maximize the energy capture by wind-turbine. Research indicates that a variable-speed operation gives more energy than the fixed wind-turbine, so further research has been focused on the variable-speed operation of wind-turbines [3]. A two mass nonlinear variable-speed wind-turbine is for controller synthesis in this paper [4, 5].

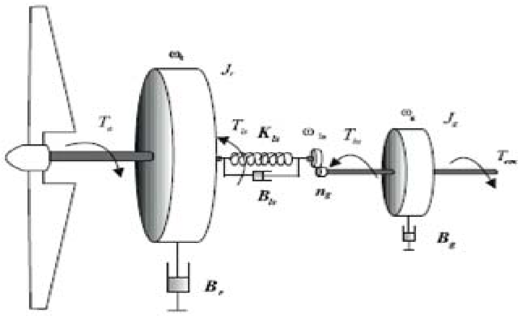
Wind turbines inherently exhibit nonlinear dynamics motivating the use of different advanced control techniques such as gain-scheduled control to continuously adapt to the dynamics of the plant, [3], LQG and nonlinear state feedback control [5], fault-tolerant control [6], and Digital robust control [7]. Although, many control algorithms are used for this application, the most obtained results are valid either in local operating regions or limited under some constraints. The difficulties to find an accurate model which approximates the nonlinear wind turbine system can be solved by using online estimation.

In this paper, an indirect adaptive regulation strategy is designed for controlling the speed of wind turbine. Unlike the research reported in the literature [8], where wind turbine models are obtained from linearization, in the proposed approach the linear model is estimated using online identification algorithm and the R-S-T regulator parameters are adjusted automatically.

The rest of the paper is organized as follows: Section 2 describes the modeling of two mass variable speed wind turbine process. Section 3 devoted to recall the methodology of indirect adaptive control algorithms Section 4 presents the application of this control approach to the process of section 2. Conclusions are drawn in the last section.

II. PROCESS MODELING

A two-mass model is well described in [4, 5], its scheme is described in Figure. 1.



Two-mass drive train scheme.

Figure.1: *Two-mass wind turbine process*

The aerodynamic power captured by the rotor is given by

$$P_a = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda, \beta) \qquad (1)$$

where P_a is the power caught by the turbine, ρ is the air density, R is the blade radius, v is the wind speed, and C_p is the power coefficient which depends, for a fixed blade geometry and material, on the blade pitch angle β and the tip speed ratio λ.

$$\lambda = \frac{R\omega_t}{v} \qquad (2)$$

where ω_t is the rotor speed. The aerodynamic torque is

$$T_a = \frac{P_a}{v} = \frac{1}{2}\rho\pi R^2 v^2 C_q(\lambda, \beta) \qquad (3)$$

where

$$C_q(\lambda, \beta) = \frac{C_p(\lambda, \beta)}{\lambda} \qquad (4)$$

C_q is the torque coefficient.

The rotor-side inertia J_r dynamics are given by this differential equation

$$J_r\dot{\omega}_t = T_a - T_{ls} - B_r\omega_t \quad (5)$$

where $\omega_t$is the rotor speed, B_r is the rotor external damping, and T_{ls} is the low speed shaft torque which acts as a braking torque on the rotor.

$$T_{ls} = K_{ls}(\theta_t - \theta_{ls}) + B_{ls}(\omega_t - \omega_{ls}) \quad (6)$$

The generator inertia J_g is driven by the high-speed shaft torque T_{hs} and braked by electromagnetic torque T_{em} that is develops, so that

$$J_g\dot{\omega}_g = T_{hs} - K_g\omega_g - T_{em} \quad (7)$$

The torque and speed of the shaft are transmitted via the gearbox with a rate ratio n_g. For an ideal gearbox, one has

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} = \frac{\theta_g}{\theta_{ls}} \quad (8)$$

The curve of the power coefficient C_p is presented in Figure. 2.

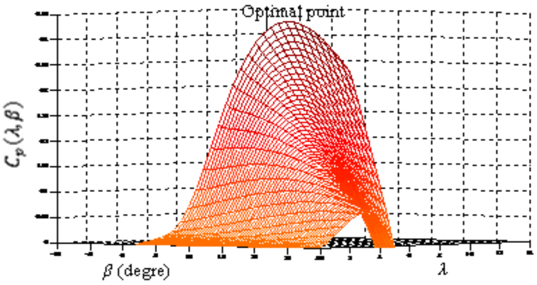


Figure.2: *power coefficient* $C_p(\beta,\lambda)$

Mainly, the control objectives are in one hand to maximize the captured wind power, in the other hand to minimize the transient of low-speed shaft load. We see from Fig. 2, the curve of $C_p(\beta,\lambda)$ has a unique maximum point that corresponds to an optimal one.

$$C_p(\beta_{opt},\lambda_{opt}) = C_{popt} \quad (9)$$

where

$$\lambda_{opt} = \frac{\omega_{topt}R}{v} \quad (10)$$

In order to maximize the wind power capture, the blade pitch angle β is fixed to its optimal value β_{opt} and in order to maintain λ at its optimal value. The rotor must be adjusted to track the optimal reference ω_{topt} found from (10), this reference has the same shape as the wind speed The equations (1)-(8) have been illustrated in the following bloc diagram, the values used for this application are given in table 1.

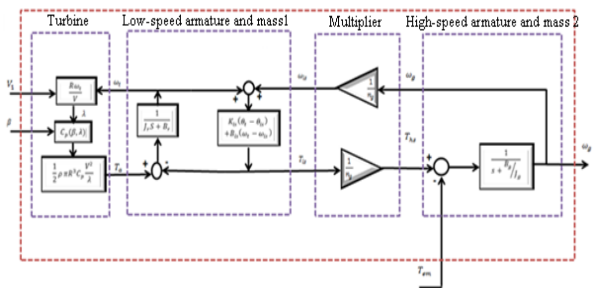


Figure.3: *Bloc diagram of two-mass turbine*

Parameter name	Description	value
R	Rotor radius	21.65 m
ρ	Air density	1 kg/m^3
J_r	Rotor inertia	3.25×10^5 kg m^2
J_g	Generator inertia	34.4 kg m^2
B_{ls}	Shaft damping coefficient	9500N m/rad/s
K_{ls}	Shaft stiffness coefficient	2.691×10^5 N m/rad
B_r	Rotor friction coefficient	27.36 N m/rad/s
B_g	Generator friction coefficient	0.2 N m/rad/s
n_g	Gear box ratio	43.165

Table.1: *characteristics of two-mass wind turbine*

We take also some other characteristics as hub height is 36.6m, generator system electrical power is 600kW and maximum torque is 162 kN m. The wind profile for 10 minutes is depicted in this figure, [4].

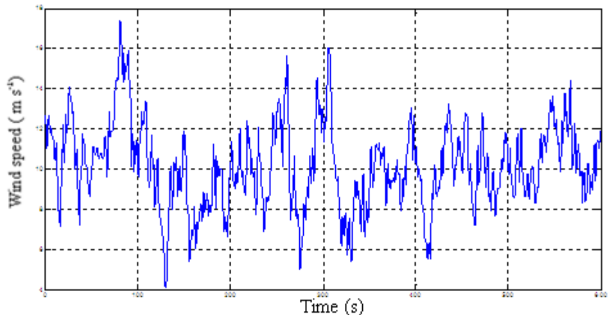


Figure.4: *wind profile for a mean speed of 10 ms^{-1}*

Simulation of the process in open loop

By considering $\beta = 2$, $\lambda_{opt} = 10$, and $T_{em} = 750\ Nm$ the simulation results in open loop are given in the following figures.

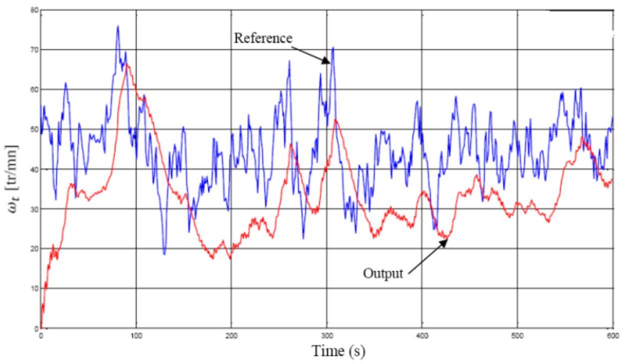


Figure.5: *evaluation of the rotor rotational speed*

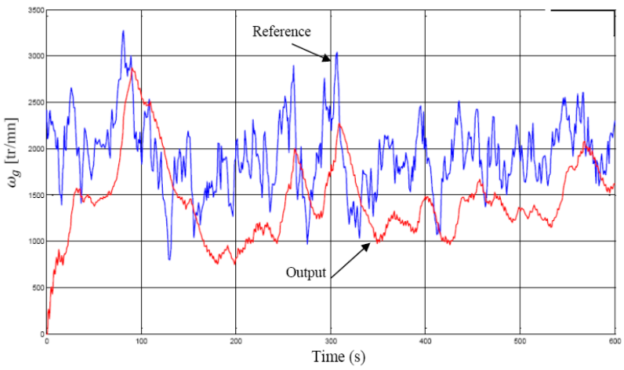


Figure.6: *evaluation of mechanical speed*

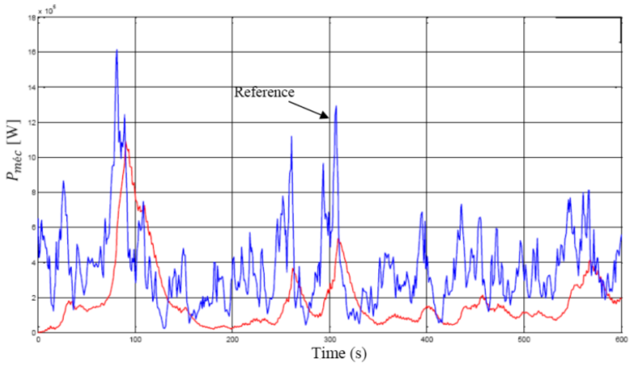


Figure.7: *evaluation of mechanical power*

Results discussion

We can see from Fig. 6 that the mechanical speed is greater than the nominal speed, which may cause damage for the generator. The error between the turbine and reference power is considerable (see Fig. 7), which let us to think about a control strategy that can maximize the power and to stabilize the process for a certain profile of wind.

III. INDIRECT ADAPTIVE CONTROLLER

The indirect adaptive controller can be viewed as a combination of two algorithms, the first is the one used for online identification of the model parameters using parameter adaptive algorithm (PAA), and the second one is used for online adjustment of the controller coefficients at each sampling time by using minimum-degree pole placement method (MDPP), [8, 9]. This algorithm is given by these steps.

1) The specifications are given by the desired behavior described by the transfer operator $G_m(q^{-1})$ and the observable polynomial $A_0(q^{-1})$, which are;

$$G_m(q^{-1}) = \frac{B_m(q^{-1})}{A_m(q^{-1})} \tag{11}$$

where

$$A_m(q^{-1}) = 1 + a_{m1}q^{-1} + a_{m2}q^{-2} + \cdots + a_{mn}q^{-n}$$
$$B_m(q^{-1}) = b_{m1}q^{-1} + b_{m2}q^{-2} + \cdots + b_{mn}q^{-n}$$
$$A_0(q^{-1}) = (1 - a_0 q^{-1})^{\gamma}$$
$$0.005 \leq a_0 \leq 0.5 \tag{12}$$

2) The plant is parameterized by the transfer operator $G(q^{-1})$ and the degrees of its numerator and denominator are known.

$$G(q^{-1}) = \frac{B(q^{-1})}{A(q^{-1})} \tag{13}$$

where

$$A(q^{-1}) = 1 + a_1 q^{-1} + \cdots + a_n q^{-n}$$
$$B(q^{-1}) = b_1 q^{-1} + b_2 q^{-2} + \cdots + b_n q^{-n}$$

Therefore, the estimated output of the model can be written as

$$\hat{y}(k) \;=\; \beta(k-1)^T \hat{\vartheta}(k) \tag{14}$$

where

$$\beta(k-1)^T = [a_1(k-1), a_2\,(k-1), \ldots, a_n(k-1), b_1(k-1), b_2(k-1), \ldots, b_n(k-1)]$$

$$\hat{\vartheta}(k)^T = [-\hat{y}(k-1), -\hat{y}(k-2), \ldots, -\hat{y}(k-n), u(k-1), u(k-2), \ldots, u(k-n)]$$

where $\beta(k)$ and $\hat{\vartheta}(k)$ are the vectors of parameters and regression respectively. For identifying the parameters of the model and calculating the coefficients of RST controller at each sampling instant, three sub-steps are performed.

a) The PAA algorithm is used to estimate the parameters vector $\beta(k)$ of the model, which was described in [10]. This algorithm can be stated as follows

$$P(k) = \frac{1}{\lambda_1}\left[P(k-1) - \frac{P(k-1)\hat{\vartheta}(k)\hat{\vartheta}(k)^T P(k-1)}{\frac{\lambda_1}{\lambda_2} + \hat{\vartheta}(k)^T P(k-1)\hat{\vartheta}(k)}\right] \tag{15}$$

$$0 < \lambda_1 \leq 1 \qquad 0 \leq \lambda_2 < 2$$

$$e_i(k) = y(k) - \beta(k-1)^T \hat{\vartheta}(k) \tag{16}$$

$$\beta(k) = \beta(k-1) + P(k)\hat{\vartheta}(k)e_{cl}(k) \tag{17}$$

$$P(0) = \alpha I;\ \alpha > 0$$
$$P^{-1}(k) > \eta P^{-1}(0);\ 0 < \eta < \infty$$

A factor α is chosen sufficiently large to ensure the convergence of the covariance matrix or the adaptation gain $P(k)$, but a forgetting factor $\lambda_1 \in]0, 1]$ prevents the convergence of $P(k)$ to zero. Decreasing λ_1 will result in an increased adaptation rate but also decreased robustness, and then the solution to this problem is to introduce a good excitation signal such as pseudo random binary sequence (PRBS) added to real input, but $\lambda_2 > 0$ tends to decrease this gain matrix, the bound $\lambda_2 < 2$ insure the stability.

b) By using the model polynomials $A(q^{-1}, k)$ and $B(q^{-1}, k)$ estimated in **(a)** by the algorithm defined by (15) to (17) at every instant k, and the desired polynomial $A_c(q^{-1}) = A_m(q^{-1})A_0(q^{-1})$, the coefficients of the polynomials $R(q^{-1}, k), S(q^{-1}, k)$ and $T(q^{-1}, k)$ of the controller are calculated online at the same instant according to the minimum-degree pole placement algorithm, this can be done by solving the following Diophantine equation [--]

$$\begin{aligned} A_c(q^{-1}) &= A(q^{-1}, k)R(q^{-1}, k) + \\ &+ B(q^{-1}, k)S(q^{-1}, k) \\ &= A_m(q^{-1})A_0(q^{-1}) \end{aligned} \tag{18}$$

$$T(q^{-1}, k) = \frac{A_m(1)}{B(1, k)} A_0(q^{-1}) \tag{19}$$

c) Computation of the control inputs of the real system $u(k)$ by using the RST polynomials found in (**b**).

$$R(q^{-1}, k)u(k) = T(q^{-1}, k)y_{sp}(k) - S(q^{-1}, k)y(k) \tag{20}$$

Causality of controller imposes

$$\deg\left(S(q^{-1})\right) \leq \deg\left(R(q^{-1})\right) \tag{21}$$

$$\deg\left(T(q^{-1})\right) \leq \deg\left(R(q^{-1})\right) \qquad (22)$$

$$\deg\left(A_0(q^{-1})\right) \geq 2\deg\left(A(q^{-1})\right) - \deg\left(B^{+}(q^{-1})\right) - \deg\left(A_m(q^{-1})\right) - 1 \qquad (23)$$

For minimum degree pole placement control, choose:

$$\deg\left(A(q^{-1})\right) = \deg\left(A_m(q^{-1})\right)$$

$$\deg\left(B(q^{-1})\right) = \deg\left(B_m(q^{-1})\right)$$

where $B = B^{-}B^{+}$ and B^{+} are the stable zeros and B^{+} are instable zeros.

IV. INDIRECT ADAPTIVE CONTROL STRATEGY OF TWO-MASS VARIABLE SPEED WIND TURBINE

The schematic diagram of this control strategy applied to two-mass variable speed wind turbine proposed here is depicted in Fig.8. The wind profile used in this case is indicated in Fig. 9.

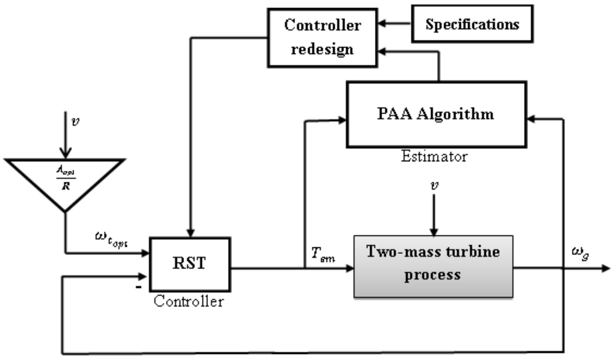


Figure.8: *Indirect adaptive control of two-mass variable speed wind turbine*

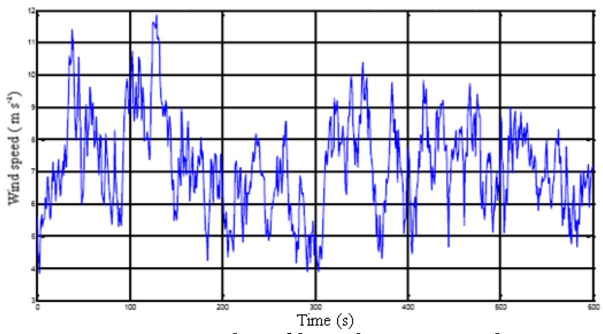


Figure.9: *Wind profile with mean speed* 7m/s

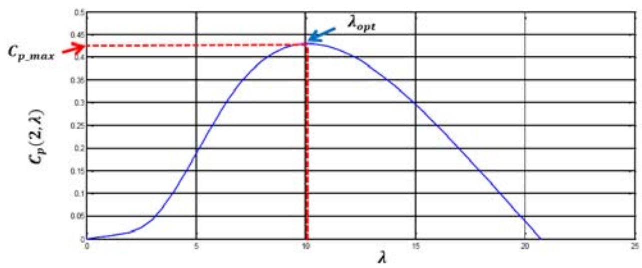


Figure.10: *optimal function of the turbine for fixed* $\beta = 2$

From Fig. 10, we can see that the optimal value of λ_{opt} equals 10 and the reference speed is

$$\omega_{t_{opt}} = \frac{\lambda_{opt} v_{wind}}{R} \qquad (24)$$

Simulation results

For controlling the speed of the process and identifying the corresponding linear model these steps should be accomplished;

- The model parameters are estimated and achieve constant values at steady state response.
- The mechanical speed tracks the reference signal.
- The turbine torque attenuated to avoid the effect of disturbance.

In this application, the model used for identification is a second order one, which is

$$G(q^{-1},k) = \frac{b_1(k)q^{-1} + b_2(k)q^{-2}}{1 + a_1(k)q^{-1} + a_2(k)q^{-2}} \qquad (25)$$

The reference model taken as

$$G_m(q^{-1}) = \frac{-0.0284q^{-1} - 0.0284q^{-2}}{1 - 1.5605q^{-1} + 0.6096q^{-2}} \qquad (26)$$

$$A_0(q^{-1}) = (1 - a_0 q^{-1})^3$$

The polynomials of RST controller are

$$R(q^{-1},k) = 1 + r_1(k)q^{-1} + r_2(k)q^{-2}$$
$$S(q^{-1},k) = s_0(k) + s_1(k)q^{-1} + s_2(k)q^{-2}$$

$$T(q^{-1},k) = \frac{A_0(q^{-1})A_m(1)}{B(1,k)}$$

The estimated parameters $a_1(k), a_2(k), b_1(k)$ *and* $b_2(k)$ are shown in Fig. 11. The simulation for different signals is given by;

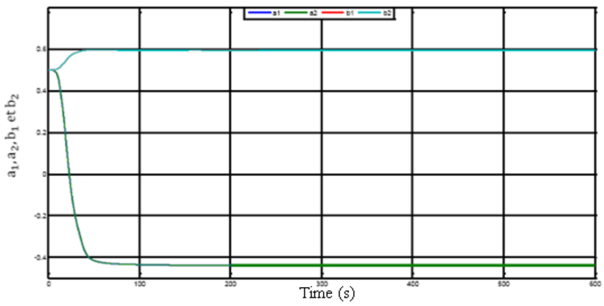


Figure.11: *Estimation of the model parameters*

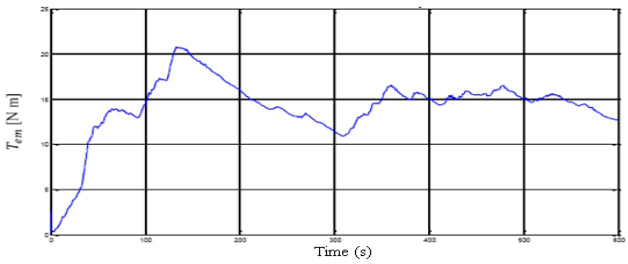


Figure.12: *Control signal*

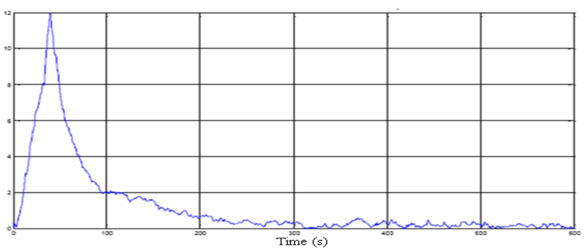


Figure.13: *Error between the output of the model and the one of the process*

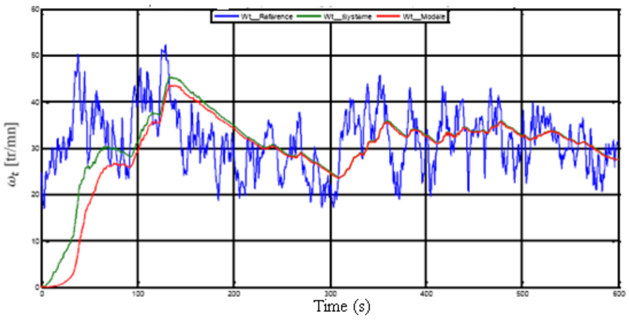


Figure.14: *The rotational speed of the rotor*

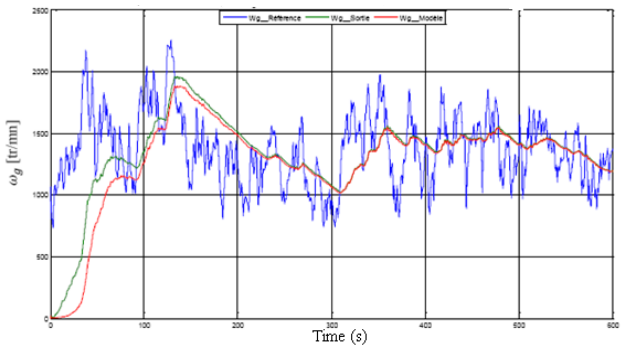


Figure.15: *The evaluation of mechanical speed*

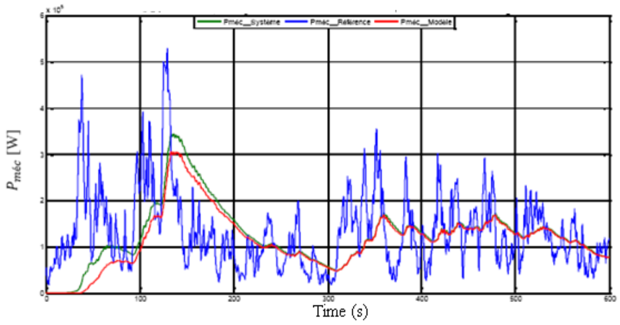


Figure.16: *the evaluation of mechanical power*

Results discussion

▪ From Fig. 12 we can observe that, the variation of control signal which represents the generator electromagnetic torque follows the same variation of the output.

▪ The estimated model is validated by the convergence of the model parameters after *t*=150s and the decreasing of the identification error to zero (see Fig. 11 and Fig. 13).

▪ We see from Fig. 14, 15 and 16 that each output or state follows its reference signal.

▪ We have observed from Fig. 15, that the mechanical speed is between 1200 and 2000 tr/min after 50s which is the good operational interval of the turbine. The power efficiency of the turbine is 94.49%.

V. CONCLUSIONS AND PRESPECTIVES

An indirect adaptive control methodology of two-mass variable speed wind turbine process was proposed for wind power capture maximization objective. In the first step a good model which approximates the real process is estimated using identification recursive method and in the same time at each instant, the coefficients of RST controller polynomials were calculated.

From the simulation results the stability and good performance are eventually achieved and satisfied in view of the capability of this linear control approach. The future work will focus on the application of more advanced robust control strategies to deal with the influence of different perturbations.

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