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Modeling and Control Strategy for a Wind Turbine by an AG-SMC without Wind Speed Sensor

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Abstract

This work presents a control strategy for Wind Turbine (WT) power by using an algorithm of Indirect Maximum Power Control (IMPC). This algorithm is based on Tip Speed Ratio (TSR) approach, which is applied to control wind turbines. Indeed, the WT used in this study has a single mass brought back to the generator shaft. The main contribution of this study is to maximize the aerodynamic power delivered by the WT system. In fact, this maximization is carried out during partial load operation, without consideration of the disturbances caused by variations in the wind profile. In this context, the control strategy of the WT is performed by estimating the Wind Speed (WS) instead of using an anemometer. This estimation is handled by using an Adaptive Gain Sliding Mode Control (AG-SMC). For this control, the surface is chosen as an improved solution that carried out the adaptation for the sliding gain and the generator torque estimation. The results obtained in Matlab / Simulink software showed that the aerodynamic power maximum is achieved and the control algorithm IMPC is given a high efficiency in the WS estimation.

Keywords: Adaptive Gain Sliding Mode Control, Indirect Maximum Power Control, Direct Maximum Power, control WT.

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1. Introduction

Recently, the Renewable Energy Sources (RESs) have attracted more and more worldwide attention. These RESs present advantages in the environment because it is free and clean. Moreover, RESs don't contribute to the emissions of gaseous pollutants. Thus, RESs are considered to be a natural alternative to electricity generation [1]. Among all RESs, wind energy technology is the fastest growing.

The WT is a device to produce electricity from the wind. This WT transforms the kinetic energy of the wind into mechanical energy, and thus into electrical energy through a generator [2]. Indeed, the WTs are based on variable speed systems that can be used to achieve maximum power extraction, lower mechanical stress, and less fluctuation in aerodynamic energy [3]. The use of strategies based on maximum power control (MPC) algorithms is necessary in order to determine the optimal operating state of the WT [3]. The MPC algorithms are required to calculate the optimum generator speed input from the control system as a reference speed. Due to the large importance of maximum aerodynamic power extraction, many different approaches have been proposed to provide MPC. In [4], a comprehensive overview of conventional and advanced control algorithms to maximize the aerodynamic power extracted by the WT. Generally, MPC algorithms are divided into two main categories, as shown in Fig. 1.

Typically, in wind systems, the WS is measured by an anemometer placed on top of the nacelle. Obtaining an accurate and efficient value of the rotor WS is difficult. Since the WS varies spatially over the swept area of the rotor. Therefore, the measured WS is not present the effective WS of the rotor since it is impossible to represent the WS by a single measurement. In [5], used the algorithm of Newton- Rafsont to estimate the WS and applies on the turbine a single mass. In [6] also used the algorithm of Newton- Rafsont to estimate the WS and applied the two-mass turbine.

This work presents the IMPC configuration based on the TSR approach. In addition, it is also presented a variable structure control by using the Lyapunov theory that used AG-SMC controller to obtain MPC. This proposed theory was discussed in [7]. The AG-SMC and an estimate of the generator torque have been proposed in [8]. In this study, the main objective of this control is to follow the variable speed characteristics, which allows searching for maximum aerodynamic power conversion operation of the WT below the rated WS. The AG-SMC with generator torque estimation proposed an efficient solution for aerodynamic power conversion optimization while reducing mechanical fatigue and improving energy efficiency. In addition, the estimated generator torque helped to estimate the WS.

This paper is organized as follows. Section 2, modeling of the wind speed. Section 3, the elements forming the WT is modeled. Section 4, proposed a control structure based on IMPC strategy with the design of AG-SMC. The method of WS estimation via the generator torque estimated is presented in section 5. Section 6, some simulation results are performed in view of the AG-SMC in responses IMPC. Finally, we end this work with a conclusion.

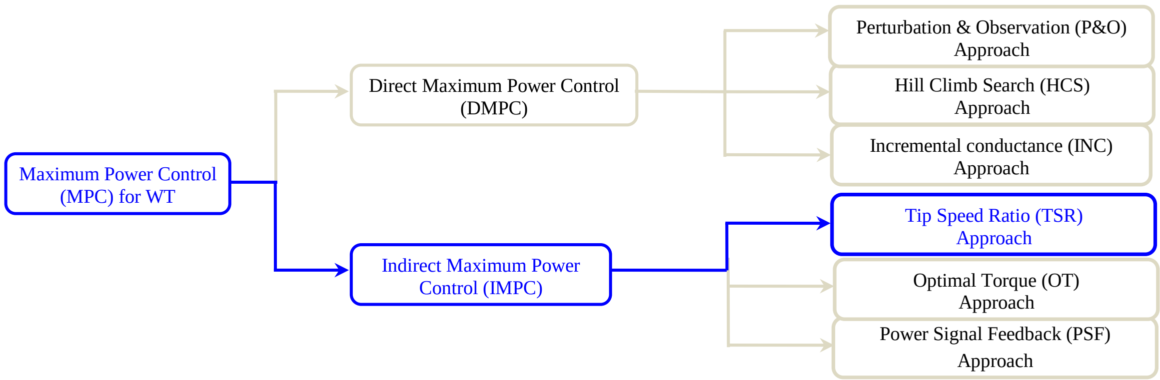

Fig 1. Maximum power control algorithms overview

2. Wind Speed Model

The wind speed model is given by the following equation [1]:

$$V(t) = V_0 + \sum_{i=1}^{n} A_i \sin(\omega_i t + \varphi_i) \tag{1}$$

Where, V_0 is the average component, A_i is the magnitude, ω_i is the pulsation and φ_i is the initial phase of each turbulence.

In this study, we will only focus on much localized wind, the wind over the area swept by the rotor for a few seconds. This model is detailed in [9].

3. Wind Turbine model

The aerodynamic power extracted by the wind system is given by the following equation [3]:

$$P_{aer} = 0.5 C_p(\lambda, \beta)\rho\pi R^2 V^3 \tag{2}$$

Where, V is the wind speed, R is the blade length, ρ is the air density and C_p is the power coefficient.

In general, the captured power coefficient (Betz factor) is a non-linear function of the TSR λ and pitch angle β, which can be expressed by the following formula [10] :

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{c_5}{\lambda_i}} + c_6\lambda \tag{3}$$

The parameter λ_i can be calculated as follows [10] :

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

The TSR is the ratio between the linear speed of the WT and the wind speed, its expression is given as follows:

$$\lambda = \Omega_t R V^{-1} \quad (5)$$

Where, Ω_t is the speed of the WT shaft.

From the above equations, the aerodynamic torque equation can be written as follows:

$$T_{aer} = P_{aer}\Omega_t^{-1} \quad (6)$$

Assume that the mechanical losses are negligible and that the ideal gearbox, the generator torque and the generator speed are modeled by the following equation [1]:

$$\begin{cases} T_g = G^{-1} T_{aer} \\ \Omega_g = G\Omega_t \end{cases} \quad (7)$$

Where, Ω_g is the speed on the generator shaft and T_g is the torque of the generator.

The dynamic mechanical equation is given by:

$$J\dot{\Omega}_g = T_g - T_{em} - f_v\Omega_g \quad (8)$$

Where, J is the total moment of inertia, T_{em} is the electromagnetic couple and f_v is the viscous coefficient of friction.

Figure 2, illustrates an example of the typical C_p curves of a WT as a function of TSR for different values of the blade orientation pitch angle β. In a wind system, there is an optimum value of TSR λ_{opt} for which $C_{p\max}$ is maximum and that maximizes aerodynamic power for a certain wind speed. Figure 3, illustrates an example of the power curves of a high-power WT. This figure shows the characteristics giving the power available as a function of the rotation speed of the generator for different wind speeds.

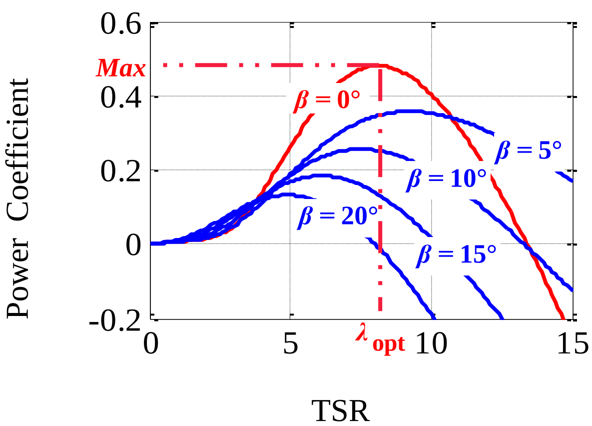

Fig 2. power coefficient versus TSR for different pitch angle value

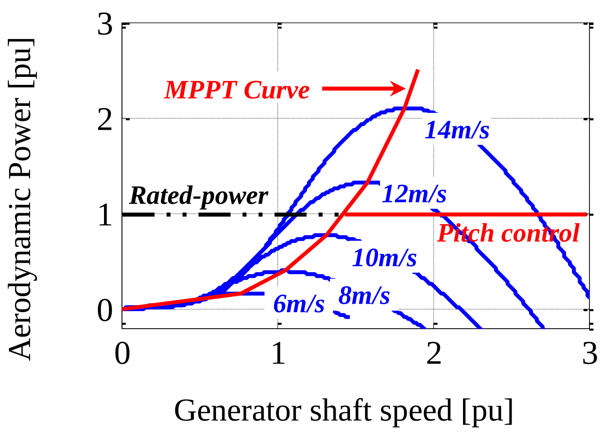

Fig 3. Power-speed characteristics for different wind speeds

4. IMPC Based on the TSR Approach

In references [1, 11, 12], the IMPC algorithm based on the TSR approach was investigated. By controlling the speed of the generator shaft, the optimum torque reference curve is obtained and from which the maximum aerodynamic power is extracted. To achieve this objective, the TSR must be kept at its optimum value. In order to maximize the power extracted by the WT in the Maximum Power Point Tracking region (Zone II), the TSR must always be at optimum value and the power coefficient at maximum when the angle of inclination of the blades is $\beta = 0^{\circ}$.

According to equation (5), the speed of rotation on the turbine shaft can be adjusted to maintain the optimum value:

$$\Omega_{t,opt} = \lambda_{opt} \cdot VR^{-1} \tag{9}$$

To obtain the reference electromagnetic torque, it is necessary to obtain a reference speed on the generator shaft, the reference generator shaft speed is given as follows:

$$\Omega_g^* = G\Omega_{t,opt} \tag{10}$$

4.1. Speed Control by Sliding Mode

This section is presented a variable structure control based on Lyapunov theory. This control is based on a robust and dynamic SMC. It has already been applied in the case of WTs [7, 12]. This control configuration consists of the following three main steps:

a) Sliding Surface

The first step is to determine the error. The sliding surface is the error dynamic of the generator shaft speed, the generator shaft speed tracking error can be expressed as:

$$S(\Omega_g) = e(\Omega_g) = \Omega_g - \Omega_g^* \tag{11}$$

From equation (8), the derivative of the sliding surface is obtained by the following expression:

$$\dot{S}(\Omega_g) = J^{-1}(T_g - T_{em} - f_v\Omega_g) - \dot{\Omega}_g^* \tag{12}$$

Equation (12) of the sliding surface derivative is rewritten in the form:

$$\dot{S}(\Omega_g) = F + DT_{em} \text{ Where, } F = J^{-1}(T_g - f_v\Omega_g) - \dot{\Omega}_g^*,\ D = -J^{-1} \tag{13}$$

b) Study of the Existence and the Convergence Condition

The second step is to ensure the stability of the system, the Lyapunov function is given by:

$$V = \frac{1}{2} S(\Omega_g)^2 \tag{14}$$

The derivative of the Lyapunov function is defined in the next expression:

$$\dot{V} = \dot{S}(\Omega_g) S(\Omega_g) < 0 \tag{15}$$

The torque control law has to ensure the stability condition and the convergence of the trajectories of the system on the sliding surface, $S(\Omega_g) = 0$, from:

If $S(\Omega_g) < 0$ and $\dot{S}(\Omega_g) > 0$, therefore $S(\Omega_g)$ will increase to zero.

If $S(\Omega_g) > 0$ and $\dot{S}(\Omega_g) < 0$, therefore $S(\Omega_g)$ will increase to zero.

c) Determination of the Control Law

The last step is to determine the control law. The equivalent control is found though $\dot{S}(\Omega_g) = 0$, from the Eq (13) the following equation is obtained:

$$T_{em,eq} = T_g - f_v \Omega_g - J\dot{\Omega}_g^* \tag{16}$$

By inserting the switching control, the control law becomes:

$$T_{em}^* = T_g - f_v \Omega_g - J\dot{\Omega}_g^* + JK_{\Omega g} sign(S(\Omega_g)) \tag{17}$$

Where, $K_{\Omega g}$ is the sliding gain and the function $sign(S(\Omega_g))$ is defined as follows:

$$sign(S(\Omega_g)) = \begin{cases} 1 \ \ si \ \ S(\Omega_g) > 0 \\ 0 \ \ si \ \ S(\Omega_g) = 0 \\ -1 \ \ si \ \ S(\Omega_g) < 0 \end{cases} \tag{18}$$

By replacing the control law (17) in the resulting mechanical equation in the generator shaft (8), the dynamic of the closed-loop system is given as follows:

$$\dot{S}(\Omega_g) = -K_{\Omega g} sign(S(\Omega_g)) \tag{19}$$

4.1.1. AG-SMC

The adaptation of the time sliding gain $K_{\Omega g}(t)$ is used, in order to improve the response of the system. Then, the control law becomes:

$$T_{em}(t) = T_g(t) - f_v \Omega_g(t) - J\dot{\Omega}_g^*(t) + JK_{\Omega g}(t) sign(S(\Omega_g)) \tag{20}$$

The sliding gain is expressed as follows:

$$\dot{K}_{\Omega g}(t) = -\alpha S(\Omega_g) \frac{\partial}{\partial K_{\Omega g}} \dot{S}(\Omega_g) \tag{21}$$

Where, α is the positive scalar.

By replacing equation (19), in (21), the derivative of the sliding gain is given as follows:

$$\dot{K}_{\Omega g}(t) = \alpha S(\Omega_g) sign(S(\Omega_g)) \tag{22}$$

The sliding gain adaptation is settled as follows:

$$K_{\Omega g}(t) = \int \alpha S(\Omega_g) sign(S(\Omega_g)) dt \tag{23}$$

4.1.2. Generator Torque Estimation

In this part, the control configuration will not depend on the torque measurement of the generator, which is considered unknown by the controller. The control law (22) has the following formula:

$$T_{em}^{*}(t) = \hat{T}_g(t) - f_v\Omega_g(t) - J\dot{\Omega}_g^{*}(t) + JK_{\Omega g}\,sign\left(S(\Omega_g)\right) \tag{24}$$

Where, $\hat{T}_g$ is an estimate of the generator torque.

The dynamics of the closed-loop system are settled as follows:

$$\dot{S}(\Omega g) = -K_{\Omega g}\,sign\left(S(\Omega g)\right) + J^{-1}\tilde{T}_g \tag{25}$$

Where, $\tilde{T}_g = \hat{T}_g - T_g$ is the generator torque error.

Using the adaptive torqueT_g estimator, then the closed-loop dynamics (25) is analogous to (17). The first-order dynamics of the generator torque error is imposed as:

$$\dot{\tilde{T}}_g + a_0\tilde{T}_g = 0, a_0 > 0 \tag{26}$$

Using the expression T_g of from (8) and variation in the electrical dynamics of the generator is therefore very fast compared to the mechanic dynamics; the equation (27) is rearranged as:

$$\dot{\hat{T}}_g = a_0\left(T_g - \hat{T}_g\right) = a_0\left(f_v\Omega_g + J\dot{\Omega}_g^{*} + T_{em}\right) - a_0\hat{T}_g \tag{27}$$

From the substitution of the control law from (20) to (27), the estimated generator torque becomes:

$$\hat{T}_g(t) = a_0 JS(\Omega_g) + a_0 J\int K_{\Omega g}(t)\,sign\left(S(\Omega_g)\right)dt \tag{28}$$

5. Estimated of the Wind Speed

Using equation (28), the estimated WS is obtained. Before estimating the WS, it is necessary to estimate the aerodynamic torque, because the estimation of the WS is related to the estimation of the aerodynamic torqueT_{aer}. The aerodynamic torque is estimated as follows:

$$\hat{T}_{aer} = G\hat{T}_g \tag{29}$$

The estimated wind is expressed as follows:

$$\hat{V} = \sqrt{\frac{\hat{T}_{aer}\cdot\lambda}{0.5C_p(\lambda,\beta)\rho RS}} \tag{30}$$

The wind speed estimation scheme is shown in Fig. 4.

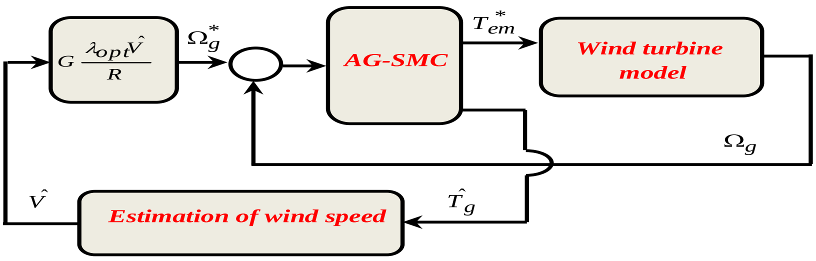

Fig 4. The wind speed estimation scheme

Fig. 5 shows the WT system model and control structure by the IMPC algorithm using the TSR approach with wind speed estimation and AG-SMC generator speed control.

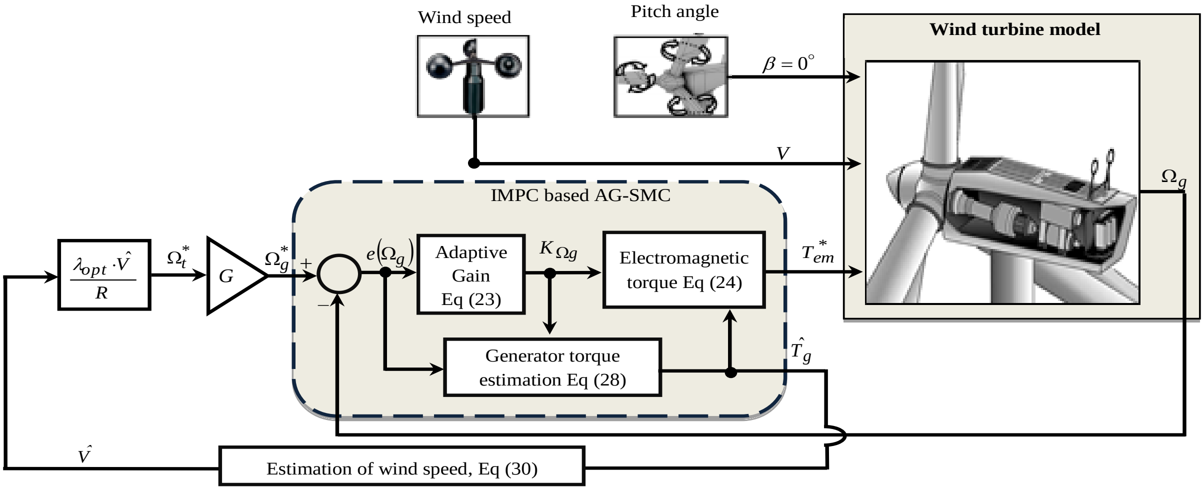

Fig 5. WT system model and AG-SMC control structure with wind speed estimation

6. Simulation Results and Discussion

The MPC simulation results were performed on the MATLAB / Simulink® platform. The simulations are studied with a wind power system at a nominal power of 1.5 MW [8]. The IMPC is applied by the conditions given from Fig. 2, the maximum values of $C_{p,\max}$, the optimum TSR λ_{opt} and fixed pitch angle $\beta = 0^\circ$.

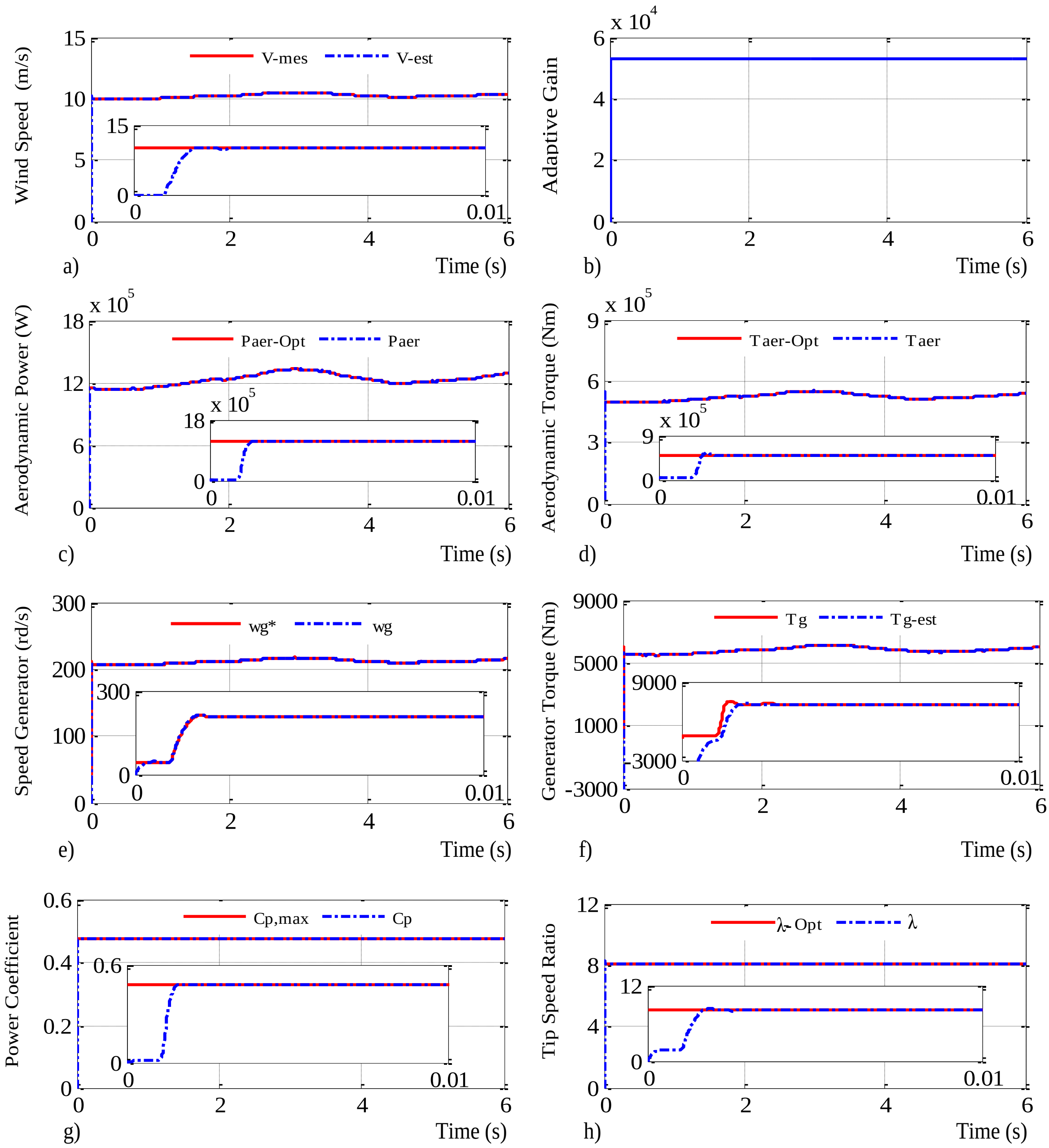

Fig 6. WT system performances with AG-SMC

It is noticed from fig (6-a) that the estimated wind speed perfectly follows the measured wind speed (using RISØ model turbulence intensity characteristics 14%). In fig (6-b), we show the adaptation of the sliding gain as a function of time. From an energetic point of view, fig (6-c) shows the aerodynamic power obtained from the control of WT by the method proposed. We notice that this power follows the maximum power extracted actively and quickly. Fig (6-d) shows the aerodynamic torque that follows the optimum aerodynamic torque satisfactorily. In fig (6-e), the convergence of the generator rotation speed to its reference speed is proportional to the wind speed curve. However, the proposed control configuration with AG-SMC is, therefore, able to actively and quickly track the generator rotation speed despite dynamic and rapid changes under system uncertainties. In fig (6-f), the estimated generator torque follows excellently the real torque. This estimation makes for performance improvement in terms of speed tracking. From fig (6-g), we notice that the proposed control configuration of the AG-SMC with wind speed estimation is an effective maximum power point tracking technique, ensuring the tracking of the optimum power points, keeping the power coefficient around its maximum value with fewer oscillations. In fig (6-h), it is shown clearly that TSR is around its optimum value with fewer oscillations. According to the results, it can be deduced that the oscillations in power coefficient and TSR are responsible for the mechanical stresses.

7. Conclusion

In this work, the mechanical model of a WT system is detailed. In addition, the indirect control strategy model of the maximum power is performed. Indeed, the TSR approach, without measuring the wind speed, is used to develop the indirect control model. In this context, we preferred to estimate the wind speed instead of using the wind sensor. This choice is due to the measurements obtained by the wind sensor cannot represent exactly the wind speed values. For this study, the IMPC is validated by a simulation with MATLAB® / Simulink® software. Through the simulation results, the AG-SMC control can be considered as a flexible and robust controller that can improve the WT system. This control achieved high efficiency in the case of wind speed estimation. In fact, the control system efficiency can reduce mechanical stress and can increase the performance and the mechanical working life of the WT.

8. References

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