MODELING AND CONTROL OF WIND TURBINE GENERATOR CONNECTED TO INFINITE BUS

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Abstract

In this paper a wind turbine generator model is discussed. This model is obtained by using Park's equations of asynchronous generator and a wind turbine model. We are interested in the control strategy; so the electronic power converter is not taken into account. The objective is to operate and control a wind generator at variable speed in order to extract the maximum kinetic power of wind. Generally electromagnetic torque controls speed generator. As described in this paper, the useful torque allows controlling the speed of generator. So, useful torque feedback is needed to complete closed loop of torque regulation. Normally useful torque is not easily measurable or is very expensive to measure; it is equal to the sum of both electromagnetic and mechanical torques. This problem of useful torque measurement is resolved by using an estimator of torque signal. This paper provides a new approach to estimate the useful torque signal by a closed loop estimator. Such an estimator is based on the swing equation of the turning part of the wind generator and a Proportional Integral regulator. The results of simulation confirm the utility of this simple and useful approach.

Keywords: Wind turbine, Asynchronous generator, torque estimator.

Presenting Author's biography

Nesmat Abu-Tabak. He was born in Lattakia in Syria, on January 5, 1975. He received the Engineer degree in Electrical Engineering from the University of Damascus in Syria, Electric Power Department, in 1997. He worked as assistant of teaching at the University of Tishrine in Lattakia in Syria during two years. He actually prepares a thesis on modeling, simulation and control of electrical power systems and networks. He is also interested in modeling and control of wind generators.

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1 Introduction

In this paper the variable speed wind generator problem is treated. Modeling and control of a wind turbine and an asynchronous generator are discussed. A new approach to estimate the useful torque is presented. At the end of the paper, some results of simulation can show the utility of such approach. Wind speed continually varies and this influences power quality of generation. That affects users connected into distribution grid where wind generators are connected. Another problem, that can be interesting, is how to maximize the power extracted from wind. When the wind speed varies and the mechanical speed of generator remains constant the extracted power is not maximal. To obtain the maximum power, the generator must turn at a variable speed. We need the useful torque to control the speed of generator. The useful torque measurement is not technically possible or very expensive, so in this paper, we will try to apply a new estimator based on a virtual model controlled by a Proportional Integral corrector. The estimator's objective is to estimate the useful torque that is indispensable to control the generator speed.

In this work we suppose we don't have any noise which may influence the dynamic of the system.

2 Modeling

2.1 Wind generator description

Wind generator is mainly composed of wind turbine and synchronous or asynchronous machine. Other supplementary devices can be added as converter and transformer. The most common wind generator arrangement are shown in Fig.1

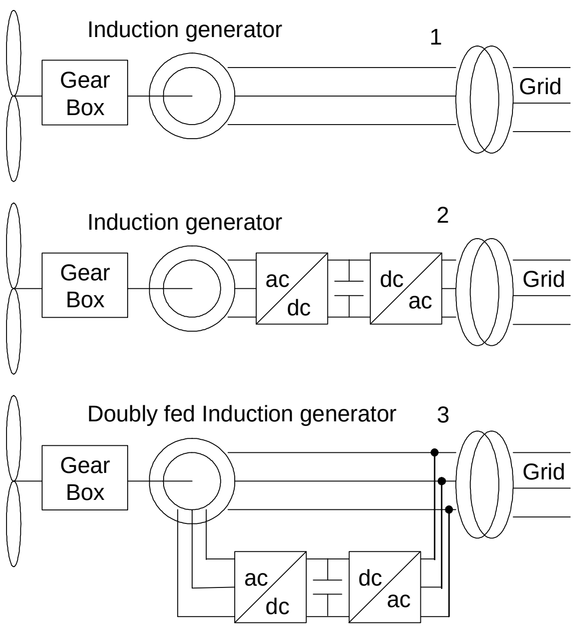

Fig.1 Example of wind generator configurations

2.2 Generator modeling

The squirrel cage induction generator is represented by Park's equations in the following form:

$$V_{sd} = R_s I_{sd} - \omega_s \varphi_{sq} + \frac{d\varphi_{sd}}{dt} \quad (1)$$

$$V_{sq} = R_s I_{sq} + \omega_s \varphi_{sd} + \frac{d\varphi_{sq}}{dt} \quad (2)$$

$$0 = R_r I_{rd} - (\omega_s - \omega_r)\varphi_{rq} + \frac{d\varphi_{rd}}{dt} \quad (3)$$

$$0 = R_r I_{rq} + (\omega_s - \omega_r)\varphi_{rd} + \frac{d\varphi_{rq}}{dt} \quad (4)$$

The flux is given by

$$\begin{pmatrix} \varphi_{sd} \\ \varphi_{rd} \end{pmatrix} = \begin{pmatrix} L_s & M \\ M & L_r \end{pmatrix} \begin{pmatrix} I_{sd} \\ I_{rd} \end{pmatrix} \quad (5)$$

$$\begin{pmatrix} \varphi_{sq} \\ \varphi_{rq} \end{pmatrix} = \begin{pmatrix} L_s & M \\ M & L_r \end{pmatrix} \begin{pmatrix} I_{sq} \\ I_{rq} \end{pmatrix} \quad (6)$$

And the electromagnetic torque is given by

$$T_e = P \frac{M}{L_r} (I_{sq}\varphi_{rd} - I_{sd}\varphi_{rq}) \quad (7)$$

The motion equation is written as:

$$\frac{d\omega_{mec}}{dt} = \frac{1}{J}(T_{mec} - T_e - f\omega_{mec}) \quad (8)$$

Where V_{sd} and V_{sq} are the d - and q -axis stator voltages, I_{sd} and I_{sq} are the d - and q -axis stator currents, φ_{sd} and φ_{sq} are the d - and q -axis stator flux linkages, I_{rd} and I_{rq} are the d - and q -axis rotor currents, φ_{rd} and φ_{rq} are the d - and q -axis rotor flux linkages, R_s, R_r are the stator and the rotor resistances, L_s, L_r are the stator and the rotor inductances, and M is the mutual inductance. ω_s is the speed of rotation of dq frame, and ω_r is the rotor electrical angular velocity. $\omega_r = P\omega_{mec}$ where ω_{mec} is the mechanical speed and P is the pairs of poles number. T_e is the electromagnetic torque and T_{mec} is the mechanical torque. J is the polar moment of inertia of the machine and turbine referred to the induction machine shaft. f is the friction factor. t is the time.

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2.3 Turbine modeling

Wind turbine transforms kinetic power of wind into mechanical power given by Eq. (9):

$$P_t = 0.5 C_p \rho A V^3 \tag{9}$$

Where

ρ is the air density $\left(Kg/m^3\right)$

A is the cross sectional area of the turbine $\left(m^2\right)$

V is the wind velocity $\left(m/s\right)$

Although this equation seems simple C_p is dependent on the ratio between the turbine's angular velocity ω_t and the wind speed V. This ratio, called the tip speed ratio λ and given by Eq. (10):

$$\lambda = \frac{\omega_t R}{V} \tag{10}$$

R is the radius of the turbine.

$\omega_t = \dfrac{1}{G}\omega_{mec}$ and G Gear box ratio.

Wind turbines are characterized by non-dimensional curves of power coefficient as a function of tip speed ratio for various blade pitch angles β. From [4], the following relationships Eq. (11) and Eq. (12) give the curves illustrated in Fig. 2.

$c_1 = 0.511, c_2 = 116, c_3 = 0.4, c_4 = 5, c_5 = 21,$
$c_6 = 0.0068$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{11}$$

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{12}$$

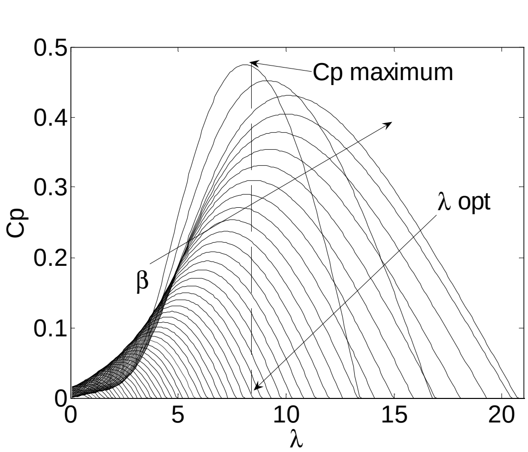

Fig. 2 Wind turbine characteristic curves

In the literature, some authors proposed several models to have the power coefficient like [1, 2, 3]. Look at Fig. 3.

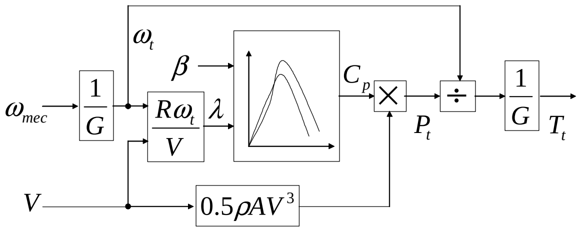

Fig. 3 Wind turbine model

3 Control strategy

The main idea is to change the turbine speed according to the wind speed variation. Let's take Fig. 4, it shows the power curves for two wind speeds. We can note that we can have the maximum power at point C if we change the mechanical speed when the wind speed changes.

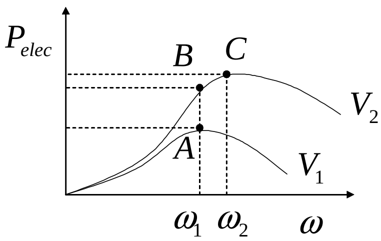

Fig. 4 Turbine power vs. speed

So, to extract the maximum power, the mechanical speed must be controlled. The wind generator speed can be controlled by acting on the electromagnetic torque of generator and on blade pitch angle. In this paper we are interested in acting on the electromagnetic torque to control the turbine speed. The wished characteristic of the electrical power versus the generator speed is represented in Fig. 5.

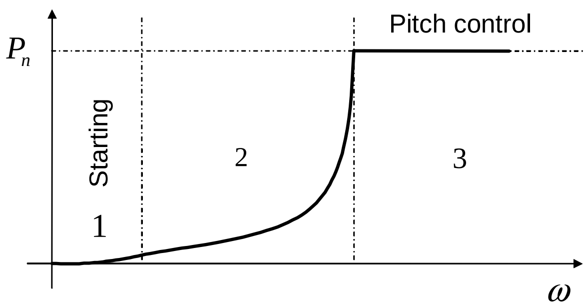

Fig. 5 Electrical power vs. generator speed

In fact, we are interested in zone 2 where we want to control the generator speed in order to extract the maximum of power or to keep the power coefficient at its maximum value.

3.1 Vector control by flux orientation

The principle here is to control an induction machine as a continuous current machine. That means the torque depends on one of the current components. The torque is controlled by acting on the stator currents [5].

From Eq. (7) we can orient the flux of the rotor such $\varphi_{rq} = 0$, so we can have Eq. (13)

$$T_e = P\frac{M}{L_r}(I_{sq}\varphi_{rd}) \tag{13}$$

If $(\varphi_{rd} = \varphi_{rd\_ref})$ is kept as constant, so, the torque can be controlled by acting on I_{sq}.

But we can note in Eq. (1, 2) that the stator current components are coupled, so they must be decoupled to avoid their interaction, see Fig. 6.

In Fig. 6, the current I_{sd} is kept constant at its nominal value, and the torque T_e is controlled by acting on I_{sq}. The PI controllers are used because the relationships between V_{sd1}, V_{sq1} and I_{sd}, I_{sq} respectively are of first order.

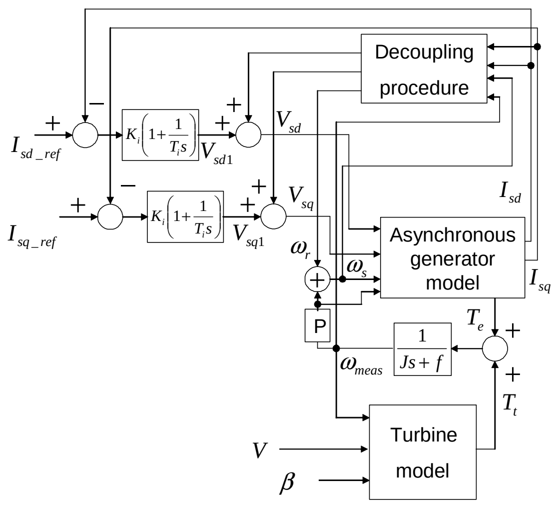

Fig. 6 Control block diagram

Speed is controlled as described in Fig. 7.

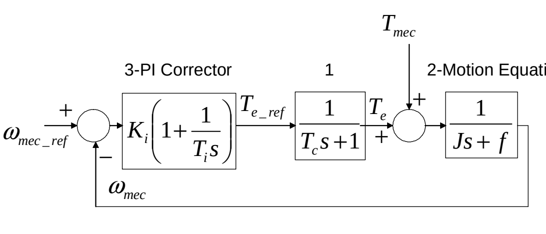

Fig. 7 Speed control

Because the mechanical time constant $T_m = J/f$ is greater than T_c, so the block 1 can be neglected; and we can use the PI corrector to control the speed. The mechanical torque is considered as perturbation.

On the other hand, we will propose this schema to illustrate our procedure of the speed control as shown in Fig. 8.

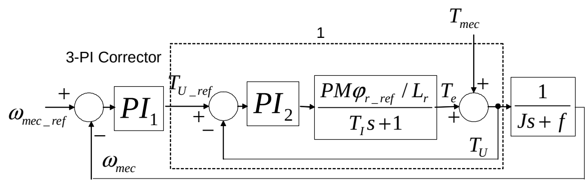

Fig. 8 Speed control

In fact, block 1 is neglected when we calculate PI_1. The objective of using the useful torque to feedback the torque loop is to make $|T_e + f\omega_{mec}| = |T_{mec}|$; so we can easily control the mechanical speed of generator. We have taken the absolute value of torques because both T_e and $f\omega_{mec}$ are with negative signs. With such configuration, the useful torque $T = T_e + T_{mec}$ must be accessible, but, this is not really our case. Therefore, the useful torque must be estimated.

3.2 Torque estimation

The problem, here, is that the useful torque isn't easily measurable and it is often very expensive to measure. In the literature some authors as [6, 7], proposed open loop observers to have the mechanical torque signal. In our work, here, we will propose an original estimator of the useful torque and not of the mechanical one. It is based on a virtual model of the motion equation. A closed loop system is made through a PI corrector as shown in Fig. 9.

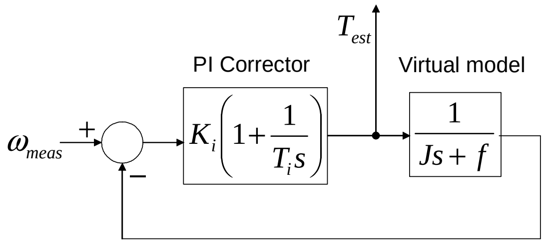

Fig. 9 Useful torque estimator

The idea is simple; we can have the torque signal as output of the PI corrector when we have the measured speed as consign to follow. The torque T_{est} must feedback the torque loop to complete the control loop of our system as shown in Fig. 10.

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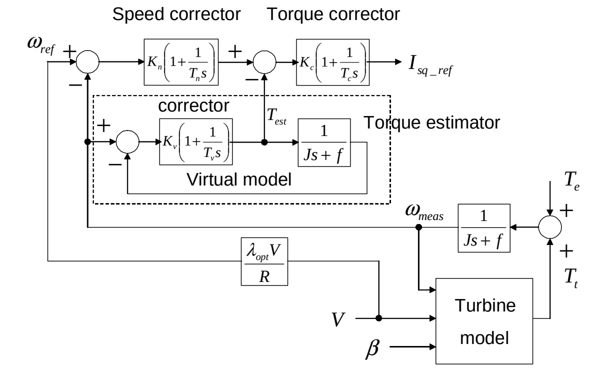

Fig. 10 Useful torque estimator

To operate correctly, the estimator dynamic must be faster than other loop dynamics in this system.

Now, to have the speed consign we can take Eq. (10) and write Eq. (14) as following

$$\omega_{ref} = \frac{\lambda_{opt} V}{R} \tag{14}$$

Why don't we use state observer?

State observer normally is used to obtain some unknown state variables when other one is known. But here, because the useful torque isn't a state variable and it is an input of subsystem so we can't use any state observer to observe it. That is why we don't use state observer here.

In addition, we find that the useful torque estimation is easier and less complex than the one of the mechanical and the electromagnetic torques. That is why we have proposed this simple estimator.

The complete control configuration is shown in Fig. 11.

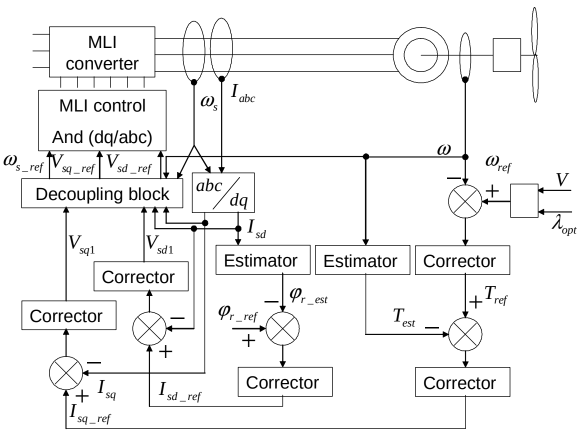

Fig. 11 Control block diagram

4 Numerical application

Let's take, for example, a variable speed wind turbine asynchronous generator of 300 (Kw) as shown in Fig. 12. The data of the wind generator are given below.

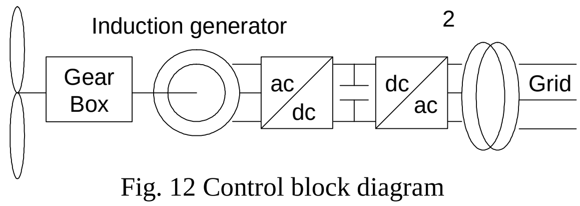

Fig. 12 Control block diagram

The squirrel generator data:

$R_s = 0.0063(\Omega)$, $R_r = 0.0048(\Omega)$.
$L_s = 0.0118(H)$, $L_r = 0.0116(H)$, $M = 0.0116(H)$
$\omega_{mec\_nom} = 1515(r.p.m)$, $P = 2$

The turbine data:

$J = 50(Kg.m^2)$, $f = 0.358(Kg.m^2/s)$
$R = 14(m)$, $V_{nom} = 12(m/s)$ $\rho = 1.22(Kg/m^3)$,
$\lambda_{opt} = 8.1, C_{p\max} = 0.475$

The gear box ratio:

$G = 23$

5 Simulation results

For the following simulation, wind is supposed having a variable speed as shown in Fig. 13. The speed of generator is controlled to extract the maximum of power from wind. The following figures show the speed variation, the torque variations and the power variation.

5.1 With torque estimator

The wind speed profile is shown in Fig. 13. The simulation starts with some initial conditions of speed and flux. The wind speed values are supposed under the nominal wind speed that is equal to 12 (m/s).

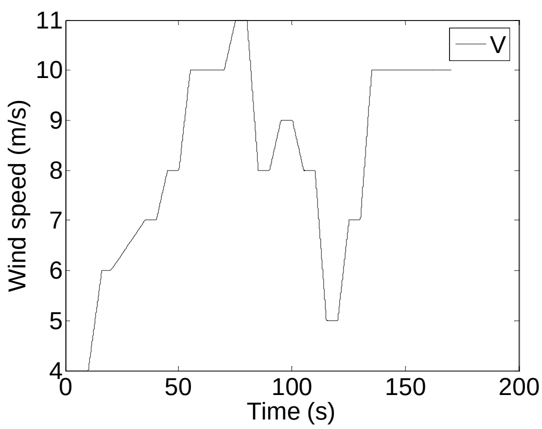

Fig. 13 Wind speed variation

In Fig. 14 we note that the mechanical speed is perfectly controlled and it follows the speed reference.

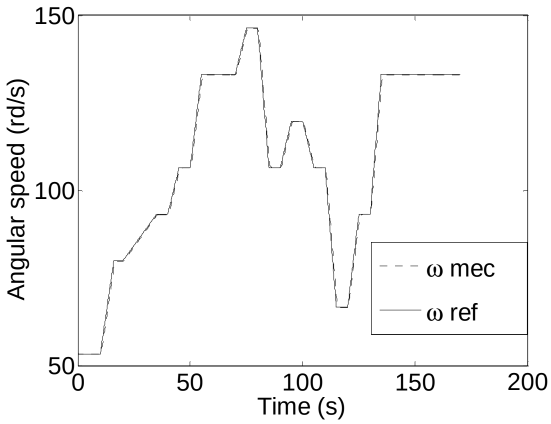

Fig. 14 Mechanical speed variation

We can note in Fig. 15 that there is a difference between the mechanical and the electromagnetic torques in steady state because the friction torque $f\omega_{mec}$. There are some transient states indispensable to change the mechanical speed.

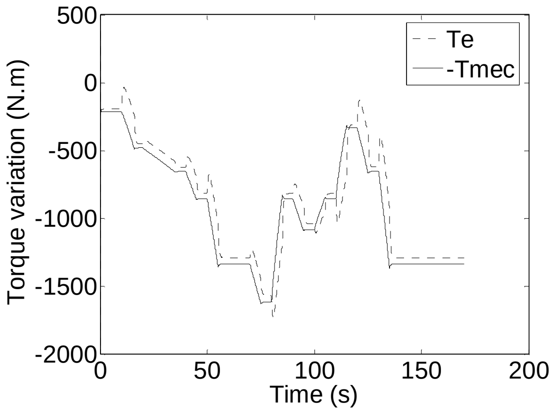

Fig. 15 Torque variation

In Fig. 16 the electrical power is negative so it is produced by the generator.

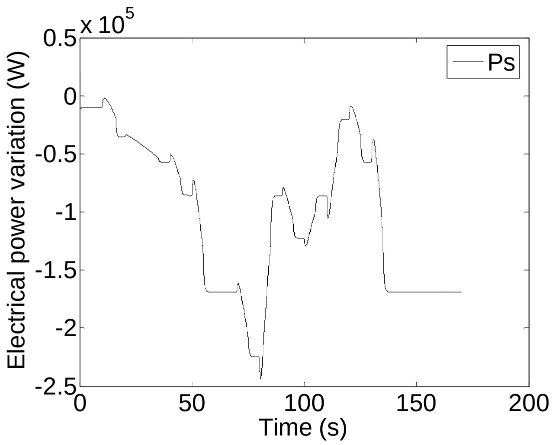

Fig. 16 Electrical power variation

We can note the fluctuation of the power according to the wind speed variations. The transient states correspond to those of the electromagnetic torque. This means the wind generator injects or absorbs an electrical power when the generator speed changes. If wind generator is connected to an infinite grid there is no problem, but if the grid is local there is a problem of power quality for users' grid.

Now, let us suppose we have access to the useful torque (that is equal to the sum of torques as $T = T_e + T_{mec}$), let's compare T with the estimated torque T_{est} as shown in Fig. 17.

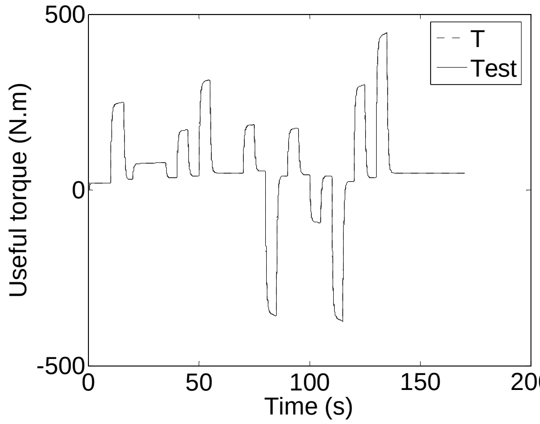

Fig. 17 Useful torque variation

We can note that the dynamic behaviors of T and T_{est} are almost similar. In fact there is a small invisible difference.

In the following figure, Fig. 18, we can note that the power coefficient is kept constant around its maximum value. For the transient states, it changes but in steady states this coefficient is maximal.

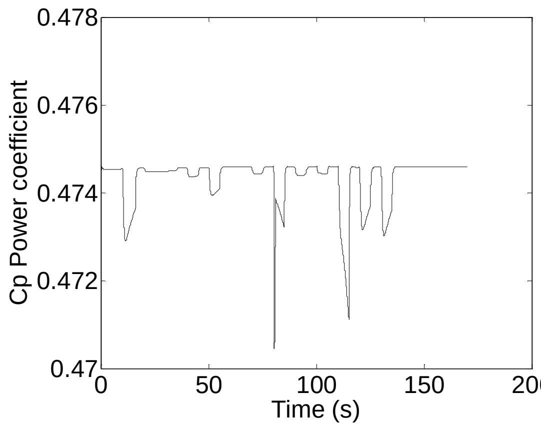

Fig. 18 Power coefficient Cp

When the mechanical and the wind speeds vary the tip speed ratio (λ) varies too. The variations of (λ) are around its optimal value as shown in Fig. 19.

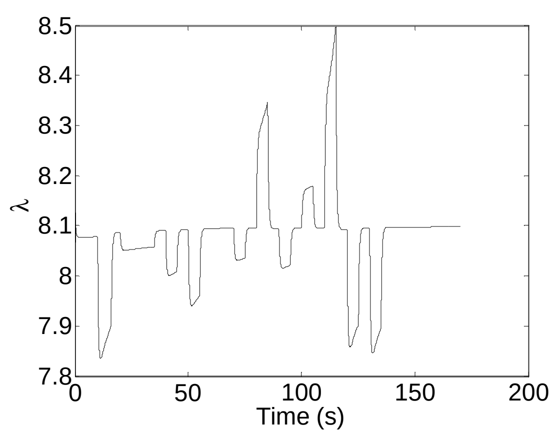

Fig. 19 Tip speed ratio λ

In the previous section, a torque estimator was used to estimate the useful torque. Now, let's try to do the simulation without an estimator and let's compare the simulation results.

5.2 Without torque estimator

If we suppose we have access to the useful torque, the results of simulation are those illustrated in the following figures Fig. (20, 21, 22).

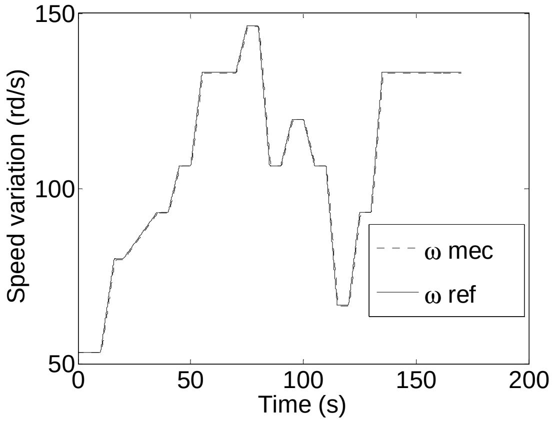

Fig. 20 Mechanical speed variation

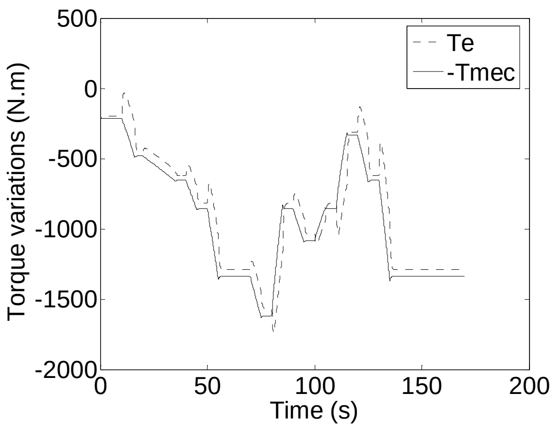

Fig. 21 Torque variation

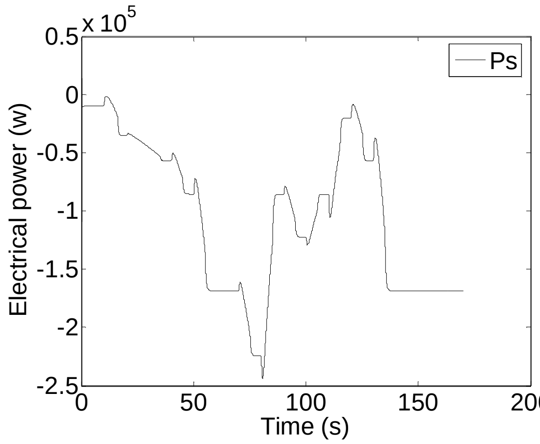

Fig. 22 Electrical power variation

We can note that the simulation results are similar with and without the torque estimator. That can confirm by simulation the efficiency of the proposed estimator to obtain the useful torque signal.

6 Conclusion

In this paper, the problem of a variable speed wind generator was discussed. Modeling and control of a wind generator was treated, and a new estimation approach of the useful torque was presented. The simulation results showed the utility of such approach to estimate the torque which is indispensable to complete the loop control of speed. This estimator was validated by simulation but not by physical application. This problem of validation may be a perspective of this work. In this paper, the blade angle control wasn't treated and the system was considered without noise, these may be also perspectives.

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