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Modeling and Comparative Study of Speed Sensor and Sensor-less based on TSR-MPPT Method for PMSG-WT Applications

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Abstract – *This paper aims to present a study and comparison between two approaches for maximizing the power delivered by the WT-S (wind turbine system) which is called (MPPT-Control) based on TSR method (tip-speed ratio): first method is based on MPC (maximum power control) with wind speed measurement (TSR-MPCWSM) and the second one based on MPC with wind speed estimation (TSR-MPCWSE). These methods are analytically compared to illustrate TSR-MPPT and power smoothing capability delivered by the aerodynamic turbine system. The dynamic performance, robustness and fast approximation of the optimal value are proved with the simulations (MATLAB/Simulink® software).*

Keywords: *Aerodynamic wind systems, MPCWSM, MPPT, MPCWSE, Tip-speed ratio (TSR), Proportional integral (PI), wind turbines systems (WT-S)*
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I. Introduction

Wind Turbines systems (WT-S) have been widely used both in autonomous systems for power supplying remote loads and in grid-connected applications. Although WT-S have a lower installation cost compared to photovoltaic, the overall system cost can be further reduced using high-efficiency power converters, controlled to obtain the optimum power according to current atmospheric conditions [1]. Aerodynamic wind systems based on variable-speed turbine have been used for many reasons. Among the WECS currently available, variable-speed based on aerodynamic wind systems are steadily increasing their market share, since changes in wind speed are followed by shaft speed control, which allows the turbine to function at its at maximum capacity regardless of wind speeds [2, 3].

One of the most major problems in aerodynamic wind systems is capturing as much aerodynamic wind power as possible in the shortest possible time, which can be achieved through different MPPT approaches [4]. In order to determine the optimal operating situation of the WT, it is essential to include a MPPT algorithm in the system. Much has been written about the subject of of MPPT algorithms [5], especially for aerodynamic wind systems. Many papers for MPPT technique have been presented, with different control schemes of WT-S to extract a maximum of power from wind speed variable, such as reference [6], which provided an analytical and critical study of several papers published in this area including [7, 8].

Wind turbines systems are controlled to operate only within a specified range of wind speeds value limited by by cut_in ($V_{cut\text{-}in}$) and cut out ($V_{cut\text{-}out}$) speeds. Beyond these bounds, the turbine must be shut down to protect both the generator and turbine. Figure. 1 shows the typical power curve of a WT (wind turbine) [9].

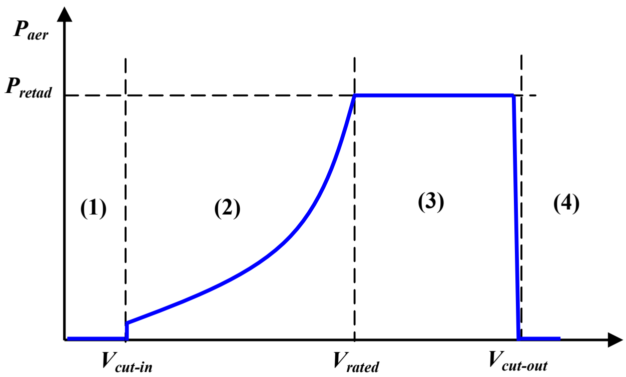

Figure 1. Areas of operation and control WECS

It can be seen from Figure 1 that there are three different operational regions. The first region is the low-wind-speed region, where the turbine should be stopped and dis-connected from the grid to prevent it from being driven by the generator [10]. The second region is the moderate-speed region which is limited by the cut_in wind speed at which the turbine begins to operate and the rated wind speed (V_{rated}), at which the turbine produces its nominal power. The WT produces maximum power in this region, because it is controlled to extract the available wind power. In the high speed region (i.e., between V_{rated} and $V_{cut\text{-}in}$), the turbine power is limited so that the turbine and generator are not over-loaded and dynamic loads do not cause mechanical failure [10, 11]. It should be noted that to protect the turbine against structural overload it should be stopped above the tripping speed (cut-out speed). This article focuses on the moderate-speed region, where the MPPT (Maximum Power Point Tracking) algorithm is required for optimal operation.

Although the speed of the WT can be fixed or variable, the maximization of the energy extracted can only be achievable with variable speed WT. Since these turbines may change their rotational speed to follow instantaneous changes in wind speed, they are able to maintain a constant rotational speed to wind speed ratio [11]. It can be noted that there is a specific ratio called the optimum TSR (TSR_opt) for each WT for which the extracted power is maximized [6, 11, 12].

This paper presents the fundamentals of MPPT algorithms available for aerodynamic wind conversion system. In addition, a comparison of simulation results is made on the two selected MPPT approaches. Finally, a critical discussion is made and a conclusion is drawn.

II. Wind speed modeling

Wind speed generally has complex random variations, both deterministic effects (mean wind, tower shadow) and stochastic fluctuations over time due to turbulence. generally, the deterministic and stochastic components are superimposed to form the following wind profile model [13]:

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

Where: V_0, A_i, ω_i and φ_i are, respectively, the mean component, magnitude, pulsation and initial phase of each turbulence.

In this work we are interested only in much localized wind, the wind on the area swept by the rotor for a few seconds. In addition, to take into account the nature of wind turbulent, stochastic models are also used. The turbulence spectrum endorsed the distribution of turbulent fluctuations energy, whose integral is determined by the intensity of the turbulence. The intensity of the turbulence is the following ratio:

$$I = \frac{\sigma}{V_0} \quad \text{with the variance } \sigma^2 = \frac{1}{T}\int_0^T v(t)dt$$

A Gaussian process can generate a turbulent wind distribution. Therefore, the *V. Karman* spectrum and one *Kaimal* spectrum are the two models used, respecting the standards set by the IEC (International Electrotechnical Commission) [14]:

Von Karman spectrum: $\phi(\omega) = \dfrac{K}{(1+(T\omega)^2)^{5/6}}$

Kaimal spectrum: $\phi(\omega) = \dfrac{K}{\left|1+T\omega\right|^{5/3}}$

Where: K is a variable related to the change T, which determines the turbulence bandwidth. FAST simulator of the NREL (American National Renewable Energy Laboratory) considers these issues and is described in [15]. In fact, this concept will be used very much in the turbine modeling equations. These equations allow calculation of the average torque actually produced by the WT-S. The Danish Riso National Laboratory developed the wind model based Kaimal filter. This model is implemented in Matlab/Simulink®, as shown in Figure. 2.

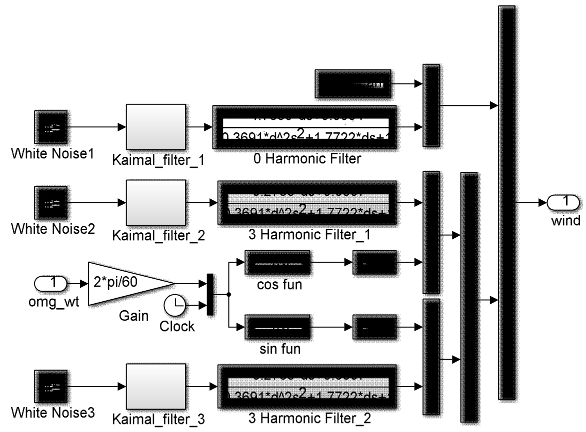

Figure 2. FAST Simulink implementation of aerodynamic wind speed model

III. Wind Turbine Modeling

According to aerodynamic characteristics of the WT-S, the amount of power captured by the WT-S delivered by the rotor is calculated by following formula [16]:

$$P_{aer} = \frac{1}{2} C_p(\lambda, \beta)\rho\pi R^2 V^3 \tag{2}$$

Where ρ is the air density, R is the blade length and V is the wind velocity.

The aerodynamic torque is is calculated by the ratio of the aerodynamic power P_{aer} to the shaft speed Ω_t :

$$T_{aer} = \frac{P_{aer}}{\Omega_t} \tag{3}$$

In WT-S, the turbine usually associated to the generator shaft through a gearbox whose gear ratio G is chosen to adjust the speed of the generator shaft to a desired speed range. Ignoring the transmission losses, the shaft speed and torque of the WT, referred to the gearbox on the generator side, are given by:

$$T_g = \frac{T_{aer}}{G}, \; \Omega_t = \frac{\Omega_g}{G} \tag{4}$$

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

Depending on the modeling turbine characteristics, the power coefficient C_p can be represented by the following expression [17]:

$$C_p(\lambda,\beta)=c_1\left(\frac{c_2}{\lambda_i}-c_3\beta-c_4\right)e^{\frac{c_5}{\lambda_i}}+c_6\lambda \tag{5}$$

Where $\frac{1}{\lambda_i}=\frac{1}{\lambda_i+0.08\beta}-\frac{0.035}{\beta^3+1}$

The power coefficient C_p depends on the pitch angle β and the ratio λ between linear speed at the tip of the blades and the wind speed [18]:

$$\lambda=\frac{\Omega_t\ R}{V} \tag{6}$$

The typical C_p versus curve for difference values of pitch angle β is shown in Figure.3. In a WT-S, there is an optimum value of TSR for which C_p is maximum and that maximizes the power for a certain wind speed.

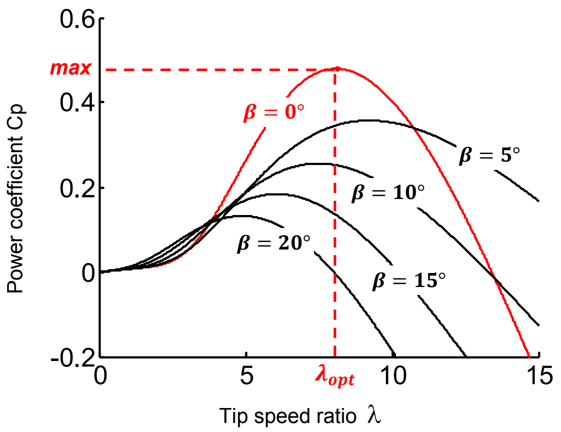

Figure 3. Power coefficient variation against TSR and deferent pitch angle

By using the Eq. (4), the dynamic mechanical equation of the PMSG shaft is given as follows [17]:

$$\frac{d\Omega_g}{dt}=\frac{1}{J}\left(T_g-T_{em}-f_v\Omega_g\right) \tag{7}$$

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

The typical characteristics giving the aerodynamic power of a WT-S, operating at variable speed, depending on the different values of wind speeds, are shown in Figure. 4. The maximum of energy efficiency is indicated in this figure, by connecting all the points of maximum power (MPP) of each power curve $P_{aer,opt}$ where the maximum power coefficient C_{p_max} is retained.

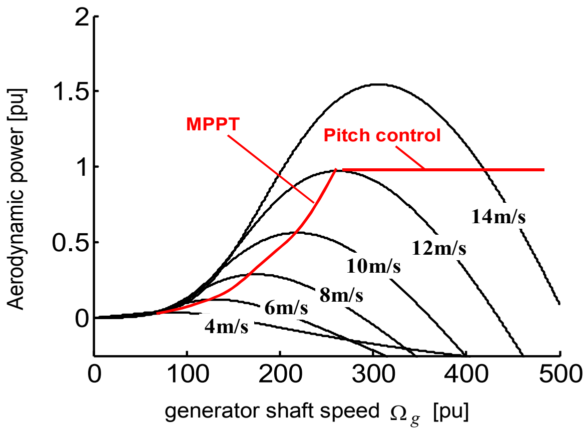

Figure 4. Aerodynamic powers various speed characteristics with tracking curve

IV. Maximum Power Tracking Control based on TSR method

Many techniques of MPPT algorithm have been studied in the literature [11, 13]. Control of the torque (thus of the power) is designed to extract the maximum possible power available from the wind by adjusting the generator shaft speed. To achieve this objective, the turbine TSR must be maintained at its optimum value ($\lambda=\lambda_{opt}$) despite wind variations, where maximum wind energy is captured by the turbine [18].

IV.1. Control with wind speed measurement TSR-MPCWSM

This first mode configuration consists in adjusting the torque appearing on the turbine shaft so as to fix its speed to a reference. In this context, it is considered that it is considered that the electromagnetic torque developed and its reference are equal at all times, assuming that the electric machine and its static converter are ideal.

$$T_{em}=T_{em}^{*} \tag{8}$$

From the Eq. (7) it is clear that the generator speed is governed by the action of two couples, the torque coming out of the gearbox T_g and the electromagnetic torque T_{em}.

This relation also shows that to have a reference torque, it's necessary to have a reference generator speed. To apply this control configuration, the speed must be enslaved by a Proportional-Integral (PI) regulator. As a result, the rotational of the reference speed generator Ω_g^*, which depends on the speed of the turbine, is obtained by Eq. (4) as follows:

$$\Omega_g^*=G\Omega_t^* \tag{9}$$

This method of the first mode is based on wind speed information. Therefore, an anemometer is required for measuring the wind speed on the wind turbine, supposing that the optimal value of the TSR λ_{opt} can be obtained from Figure.3, the optimal speed of the turbine can be determined from Equation. (6), as follows:

$$\Omega_{t,opt} = \frac{\lambda_{opt} V}{R} \tag{10}$$

We can easily deduce a diagram of this control configuration which presents the servo control of the speed for the maximization of the extracted aerodynamic power as show in Fig. 5 for the first mode.

IV.2. Control with wind speed estimations TSR-MPCWSE

The difficulty found in this first method is the wind speed measurements which use an additional anemometer. Consequently, another method can be conceived for the MPPT, without wind speed measurement and without controlling the generator shaft speed, as presented in the second mode.

In this case, from the dynamic equation of the turbine shaft, we obtain the static equation describing the steady state of the turbine:

$$\frac{d\Omega_g}{dt} = 0 = \left(T_g - T_{em} - f_v\, \Omega_g\right) \tag{11}$$

So, ignoring the effect of the viscous friction couple ($f_v\, \Omega_g = 0$), we obtain:

$$T_g = T_{em} \tag{12}$$

At the output of the gearbox, with an estimation of the turbine torque, it is easy to determine the reference electromagnetic torque [19]:

$$T_{em}^{*} = \frac{\hat{T}_{aer}}{G} \tag{13}$$

The objective of the control is to improve the capture wind energy by following the optimal torque $\hat{T}_{aer,opt}$ expressed in Eq.(3), using the above estimated wind speed:

$$\hat{T}_{aer,opt} = \frac{1}{2\Omega_t} C_p\, \rho S \hat{V}^3 \tag{14}$$

The generator shaft speed allows the estimation of the turbine speed $\hat{\Omega}_t$ from the following relation:

$$\hat{\Omega}_t = \frac{\Omega_g}{G} \tag{15}$$

Assuming that the pitch angle β remains constant, the wind speed can be estimated as follows:

$$\hat{V} = \frac{R\hat{\Omega}_t}{\lambda_{opt}} \tag{16}$$

By grouping the previous equations, we obtain a global relation of TSR-MPCWSE method configuration:

$$T_{em}^{*} = \frac{C_p}{\lambda^3} \frac{\rho \pi R^5}{2} \left(\frac{\Omega_g}{G}\right)^2 \tag{17}$$

This control block diagram of variable-speed fixed-pitch WECS in generally aims at regulating the power (thus the torque) harvested from wind by modifying the generator shaft speed.

The generation system operated well and achieved the MPPT curve during variation of generator shaft speed. The electromagnetic will be an input for the control loop described in section IV. It should be noted that this work focuses on the MPPT. Accordingly, the MPCWSE of our system is shown in Fig. 5 (second select mode).

This control block also proposes a select mode to choose the operating mode; the first select mode for the MPPT is based on wind speed measurement with a simple anemometer and speed control with a classical PI controller.

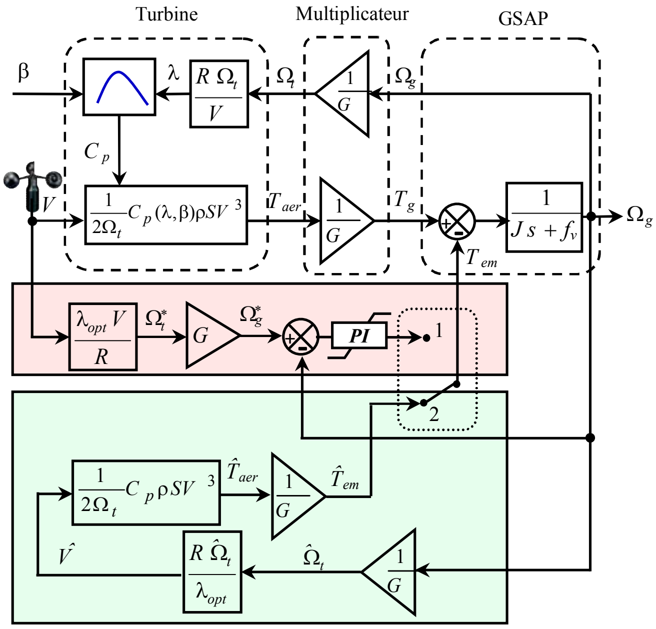

Figure 5. The schematic diagram of the MPPT control with select mode: 1. With wind speed measurement (TSR-MPCWSM), 2. with wind speed estimations (TSR-MPCWSE).

V. SIMULATION RESULTS AND DISCUSSION

Some results of the simulation of the two mode of control were carried out on the MATLAB/Simulink® platform. In this simulation, we are required to represent most the simulation figures that allow us to evaluate the performances provided by the control system. The parameters of the WECS are reported in the Appendix.

The proposed profile of the wind speed using FAST model is given in Fig. 6.

The MPC (maximum power control) is then applied by the conditions given from Fig. 2, the maximum values of power coefficient $C_{p\_\max}$ and the optimum speed ratio λ_{opt} for the curve associated to the fixed pitch angle $\beta = 0°$. The pitch angle is maintained at its fixed value, without power limitation below the rated wind speed.

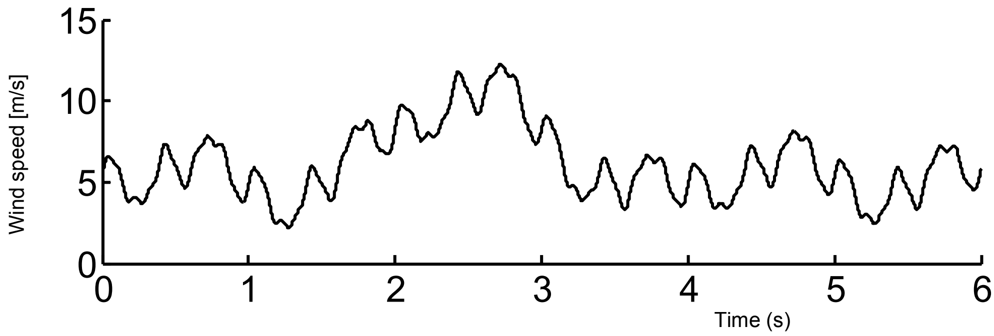

Figure 6. Wind speed profile using FAST model

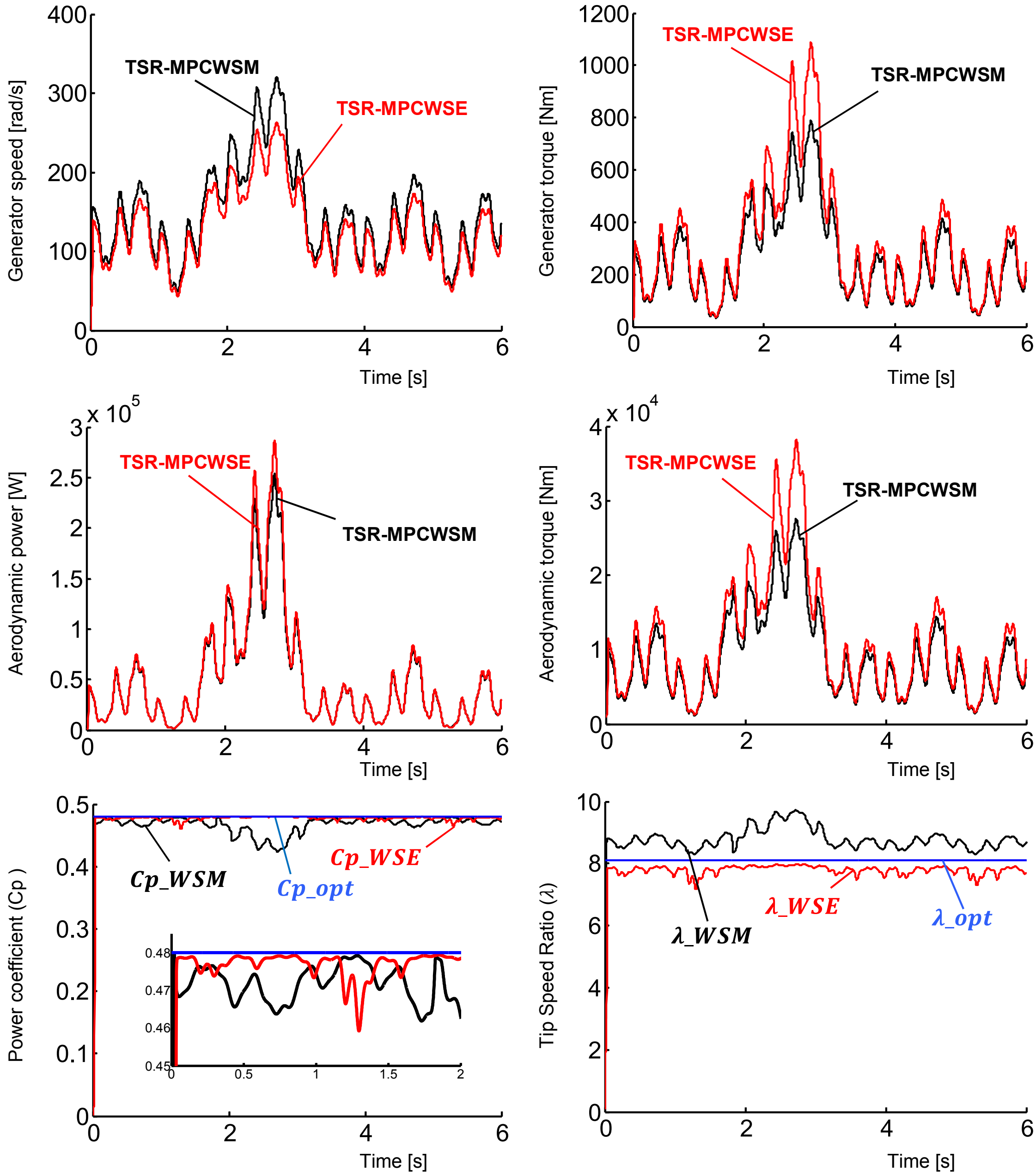

Figure 7. Reponses of WECS: (a) Generator speed, (b) Aerodynamic torque, (c) Aerodynamic power, (d) generator torque, (e) Power coefficient, (f) Tip Speed Ratio.

The following simulation results are performed to compare the two modes of control, namely, control with wind speed estimations (TSR-MPCWSE) and control with wind speed measurement (TSR-MPCWSM) algorithm (see Fig. 5).

Fig. 7(a) shows the mechanical speed of the PMSG shaft obtained by using two different models.

Fig. 7(b), Fig. 7(c), Fig. 7(d) shows the dynamic behavior of WECS such as aerodynamic power, aerodynamic and generator torque using TSR-MPCWSM/MPCWSE approach.

It can be seen from Fig. 7(e) that the MPPT technique ensures the tracking of the optimum power points, by maintaining the power coefficient around its maximum value $C_{p\_\max} \approx 0{,}479$.

It is also shown from Fig. 7(f) that the tip speed ratio is around its optimum value $\lambda_{opt} \approx 8$.

Based on the response of the techniques described above, comparisons are made between the two methods:

• *TSR-MPCWSM*: This method is characterized by a good and rapid response. As the technique uses the actual wind speed for the purpose of measuring the optimum rotational speed, the ability to track this controller is very good. However, the exact measurement of wind speed is a daunting task, especially in the case of large-scale wind turbines.

• *TSR-MPCWSE*: This method is characterized by a rather slow response, as shown in Fig. 7. The control strategy for this part is easy and simple to implement as there is no need to measure wind speed (anemometer). The two previous methods are compared in Table I.

It can be seen, that during of WECS operation, the control policy with TSR-MPCWSE has a good performance against variations in wind profile and the difference between the measured value and its reference is significantly reduced compared to the TSR-MPCWSM.

TABLE 1. Comparison of control methods

Techniques	Power coefficient Error value	Tip Speed Ratio Error value	complexity	Convergence speed	Wind speed measurement
MPCWSM	High	High	High	Fast	Yes
MPCWSE	Low	Low	Low	Slow	No

VI. CONCLUSION

In this paper, the modeling and control strategy of a Wind Energy Conversion System (WECS) based on PM generator is presented. The randomly varying wind speeds and modeling uncertainties can affect the WECS' efficiency and lead to drive train mechanical stresses.

The overall system is simulated for two different approach, control with wind speed measurement TSR-MPCWSM and control with wind speed estimations TSR-MPCWSE. The results of the simulation showed the possibility of extracting the maximum power of energy for different wind speeds values.

APPENDIX

In this part, simulations are investigated with a 1.5MW generator wind turbine [13]. The parameters of our system are presented below:

Parameters				Value	
Turbine					
Air density:				$\rho = 1.22 Kg/m^3$	
Wind turbine blade radius:				$R = 35.25m$	
Pitch angle:				$\beta = 0\deg$	
Gearbox ratio:				$G = 30$	
Cp Parameters					
C_1	C_2	C_3	C_4	C_5	C_6
0.5176	116	0.4	5	21	0.0068

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