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Modeling and Adaptive Power Control-Designed based on Tip Speed Ratio method for Wind Turbines

***Abstract**. A simple and novel adaptive control method has been proposed to improve the efficiency of the maximum power control (MPC) technique. The proposed scheme is based on model reference adaptive power control approach using tip speed ratio method for wind turbines system (WT-s) applications to ensure the maximum energy production of a WT-s whatever the disturbances caused by variations in wind profile. The overall system model was implemented in MATLAB/Simulink® with three select mode of MPC (two conventional methods: (1) with wind speed measurement CMPCWSM and (2) with wind speed estimation CMPCWSE are compared with the proposed adaptive control method AMPC).The results demonstrate that AMPC is very effective in improving the power flow compared to the two other classical methods.*

Streszczenie.** Zaproponowano nową adaptacyjną metodę sterowania w celu poprawy techniki the maximum power control (MPC). Metoda bazuje na sterowaniu mocą na określaniu szczytowej prędkości turbiny w celu określenia produkcji maksimum energii przy uwzględnieniu zakłóceń powodowanych przez zmianę wiatru.* ***Modelowanie i projekt adaptacyjnego sterowania mocą bazującego na metodzie określania szczytowej prędkości turbiny wiatrowej

Keywords: Wind Turbines system (WT-s), Maximum Power Control (MPC), Tip Speed Ratio (TSR), Adaptive Power Control (AMPC).
Słowa kluczowe: turbiny wiatrowe, sterowanie maksymalną mocą MPC, system adaptacyjny.

Introduction

In the last decades, the WE (wind energy) is becoming one of the most promising renewable energy sources due to the experienced progress. WE is playing a key role in the effort to help and satisfy global energy demand, offering the greatest opportunity to unlock a new era of environmental protection with share of renewable energy sources in the world energy mix [1-3]. In this way, it can help to solve the world energy crises and global warming problem. Therefore, WT-s must operate in such a way as to optimize the kinetic energy of the wind for optimal electrical energy [4, 5]. 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 [5, 6]. 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 [7].

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 MPC approaches [8-10]. In order to determine the optimal operating situation of the WT-s, it is essential to include a MPPT (Maximum Power Point Tracking) algorithm in the system. Many papers for MPPT technique have been presented in the literature, with different control schemes of WT-s to extract a maximum of power from wind speed variable, such as reference [11], which provided an analytical and critical study of several papers published in this area including [12, 13]. To maximize and improve the quality and the quantity of energy in wind farms connected to the power grid, in [14], with the insertion of complex solution of small WT (wind turbine), the variation of the wind speed, rotational speed of rotor, active power with and without MPPT was examined. In [15], a comparative study is done between three estimators (the extended Kalman filter, the angle tracking observer and the synchronous reference frame phase locked loop) used in a sensor-less MPPT strategy for a wind energy conversion chain. In [16], an analytical study and comparison of two methods for MPPT and power smoothing in variable speed turbine is studied, based on OTC (optimal torque control) and TSR (tip speed ratio) methods, where the authors concluded that the TSR method required more improvement to achieve optimal operation of the WECS (wind energy conversion system).

In order to improve the efficiency of the TSR-MPPT approach in the WT-s, a non-linear TSR cascade control based on a backstepping approach is presented in [17]. A TSR-MPPT strategy based on FLC (fuzzy logic control) is performed in [18, 19]. In [20], integral SMC (sliding mode control) is used to improve the operation WECS. In [21], quantum neural network control for TSR-MPPT competence enhancement is investigated.

WT-s are controlled to operate only within a specified range of wind speeds value limited by cut-in ($V_{ws\text{-}in}$) and cut out ($V_{ws\text{-}out}$) speeds. Beyond these bounds, the turbine must be shut down to protect both the generator and turbine. Fig.1 shows the typical power curve of a WT [3].

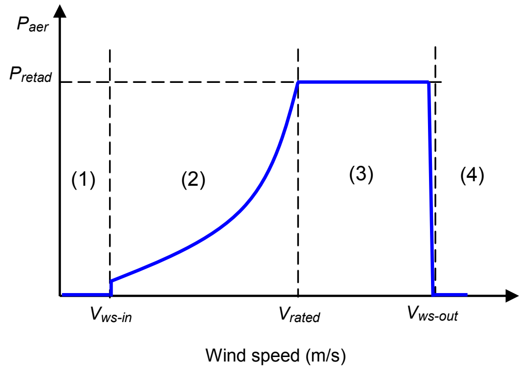

Fig.1. Areas of operation and control WECS

It can be seen from Fig.1 that there are four different operational regions. The first region is the low-wind-speed region ($V < V_{ws\text{-}in}$), where the turbine should be stopped and dis-connected from the grid to prevent it from being driven by the generator [22]. 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 ($V_{ws\text{-}in} \leq V < V_{rated}$). 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_{ws-in}), the turbine power is limited so that the turbine and generator are not over-loaded and dynamic loads do not cause mechanical failure [9]. It should be noted that to protect the turbine against structural overload it should be stopped above the trip-ping speed (V_{ws-out}). This paper focuses on the moderate-speed-region, where the MPPT algorithm is required for optimal operation.

Although there are various types of WT, relying upon fixed or variable wind speed, the maximum energy can be extracted only by VSWT (variable speed wind turbines). Since these can vary their rotational speed to follow the instantaneous variation in wind speed [9]. It can be noted that there is a specific ratio called the optimum TSR (λ_{opt}) for each WT for which the extracted power is maximized [8, 11].

This paper can be seen as a continuation of the above-mentioned works. First a detailed model for representation of WT-s dynamics simulations and the two conventional methods of TSR-MPPT (CMPCWSM and CMPCWSE) are described. Then, this study focuses attention on improving a method to allow better performances of the whole system in question, using adaptive control theory. The proposed control objective is to follow the variable speed characteristics, which makes it possible to search for maximum power conversion operation of the turbine below the rated wind speed. Instead of the conventional TSR-MPPT methods referenced in [23, 24], a tip speed ratio method based on adaptive power control is used in this work, as an effective solution for optimizing power conversion while reducing mechanical fatigue and output vibrations on the driveline. The main contribution of this study is the application of the AMPC (Adaptive Maximum Power Control) technique to the maximization of power with two different wind speed models.

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 [9]:

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

where: V_0 – mean component, A_i – magnitude, ω_i – pulsation, φ_i – initial phase of each turbulence.

As part of 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:

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

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) [25]:

$$\text{V-Karman-spectrum: } \phi(\omega) = \frac{K}{(1+(T\omega)^2)^{5/6}}$$

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

where: K is a variable related to the variance T, which determines the turbulence bandwidth. FAST simulator of the NREL (American National Renewable Energy Laboratory) considers these issues and is described in [26]. In fact, this concept will be used very much in the turbine modeling equations, which will be determined later in this paper. These equations allow calculation of the average torque actually produced by the WT-s. The Danish Risø DTU national laboratory for sustainable energy developed the wind model based *Kaimal*-Filter. This model is implemented in MATLAB/Simulink®, as shown in Fig.2.

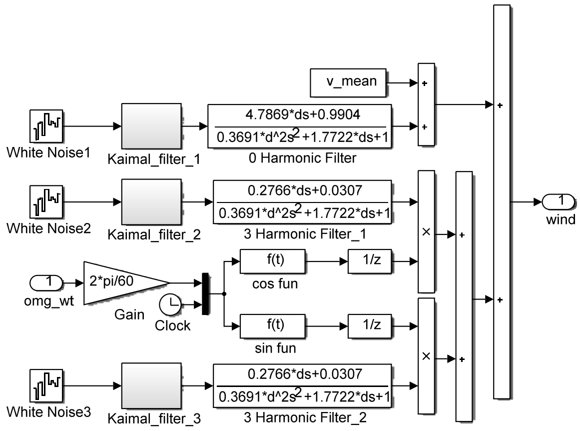

Fig.2. FAST Simulink implementation of aerodynamic wind speed model

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 [27]:

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

where: ρ– air density, R– blade length, V– wind velocity.

The aerodynamic torque T_{aer} 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:

$$\begin{cases} T_g = T_{aer}/G \\ \Omega_t = \Omega_g/G \end{cases} \tag{4}$$

where: Ω_g – generator shaft speed, T_g – torque of the generator.

Depending on the modeling turbine characteristics, the power coefficient C_P (Betz's factor) can be represented by the following expression [28]:

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

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:

(6) $\lambda = \dfrac{\Omega_t \ R}{V}$

The typical C_P versus curve for difference values of pitch angle β is shown in Fig.3. In a WT-s, there is an optimum value of λ for which C_P is maximum and that maximizes the power for a certain wind speed ($C_{p,max} \approx 0.479$, $\lambda_{\text{opt}} \approx 8.1$).

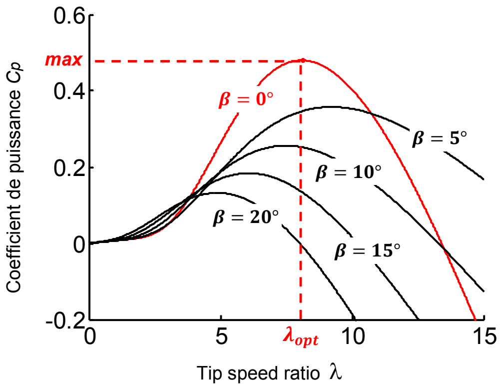

Fig.3. Power coefficient variation against TSR and deferent pitch angle

By using the Eq. (4), the dynamic mechanical equation of the PMSG shaft is given as follows [28]:

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

Where: T_{em} – electromagnetic torque, J– total moment of inertia, f_v– 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 Fig. 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.

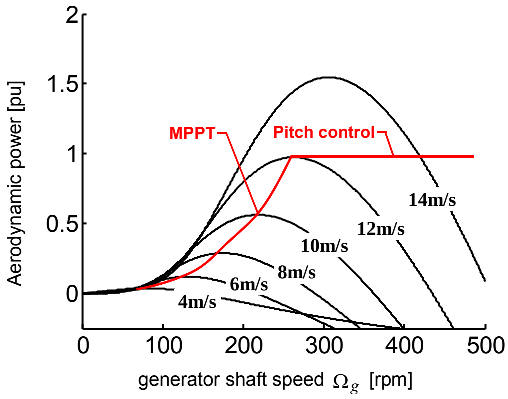

Fig.4. Aerodynamic powers various speed characteristics with tracking curve

MPC based on TSR method

As described in [23, 24], 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 ($\lambda = \lambda_{\text{opt}}$) despite wind variations, where maximum wind energy is captured by the turbine [29].

Conventional MPCWSM

This first mode configuration consists in adjusting the torque appearing on the turbine shaft so as to fix its speed to a reference [30]. In this context, 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 [24]:

(8) $T_{em} = T_{em}^*$

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, The rotational of the reference speed generator Ω_g^*, which depends on the speed of the turbine, is obtained by Eq. (4) as follows:

(9) $\Omega_g^* = G\,\Omega_t^*$

This method of the first select mode is based on wind speed information. Supposing that the optimal value of the TSR λ_{opt} can be obtained from Fig.3, the optimal speed of the turbine can be determined from Eq. (6), as follows:

(10) $\Omega_{t,opt} = \dfrac{\lambda_{opt}\,V}{R}$

With a change in wind speed, reference rotor speed is change. To apply this control configuration, the speed must be enslaved by a Proportional-Integral (PI) regulator. In order to rack reference rotor speed, servo speed control using reference electromagnetic torque T_{em}^* is used:

(11) $T_{em}^* = \left(\Omega_g^* - \Omega_g\right)\left[K_p + \dfrac{K_i}{s}\right]$

The block diagram of CMPCWSM strategy is shown in Fig.5. In this control strategy, an anemometer is required for measuring the wind speed on the wind turbine, this technique is also called by the anemometer control scheme.

Conventional MPCWSE

This second mode configuration consists in adjusting the torque appearing on the turbine shaft without wind speed measurement and without controlling the generator shaft speed [24, 30]. This method is based on the assumption that wind speed varies very little in steady state. In this case, from the dynamic equation of the turbine shaft, we obtain the static equation describing the steady state of the turbine:

(12) $\dfrac{d\Omega_g}{dt} = 0 = T_g - T_{em} - f_v\ \Omega_g$

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

(13) $T_g = T_{em}$

At the output of the gearbox, with an estimation of the turbine torque, it is easy to determine the reference electromagnetic torque [30]:

(14) $T_{em}^* = \dfrac{\hat{T}_{aer}}{G}$

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:

(15) $\hat{T}_{aer,opt} = \dfrac{1}{2\Omega_t} C_{p,\max}\,\rho\,S\,\hat{V}^3$

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

(16) $\hat{\Omega}_t = \dfrac{\Omega_g}{G}$

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

$$\hat{V} = \frac{R\,\hat{\Omega}_t}{\lambda_{opt}} \tag{17}$$

By grouping the previous equations, we obtain a global relation of CMPCWSE method configuration:

$$T_{em}^{*} = \frac{C_{p,\max}}{\lambda_{opt}^{3}} \frac{\rho\,\pi\,R^{5}}{2} \left(\frac{\Omega_g}{G}\right)^{2} \tag{18}$$

Proposed AMPC method

In the same operating principle as the MRAC approach (Model reference adaptive control), the AMPC (Adaptive Maximum Power Control) is a kind of control methods that follows the response signal at the output of the reference model. It has simple, fast and stable structure advantages. The general idea of the AMPC technique is to incorporate a reference model to acquire the preferred closed-loop reactions. AMPC designs the Adaptation mechanism and adjustments technique to drive the desired trajectories for the system to track the reference model output. The block diagram of the AMPC is shown in Fig. 5. As seen from the figure, the AMPC technique consists of two independent models for estimating the same parameter (generator torque). One is called the reference model, and this model does not include an estimated parameter, and the other is called an adjustable model, which depends entirely on the estimated parameter.

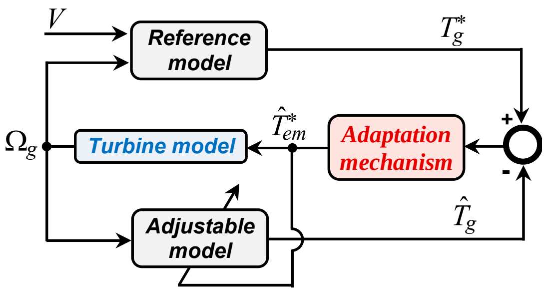

Fig.5. Proposed Adaptive Maximum Power Control scheme.

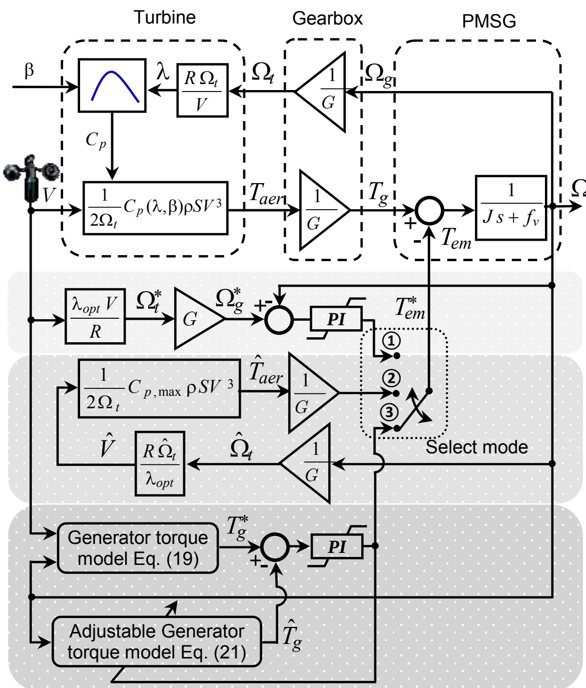

Fig.6. WT-s model and control structure with select mode:
1. CMPCWSM, 2. CMPCWSE, 3. AMPC

Reference Model: From Equations (3) and (4), the generator torque model is:

$$T_g^{*} = \frac{P_{aer,opt}}{\Omega_g} \tag{19}$$

Equations (2) and (5) can be used to express the reference generator torque model as:

$$T_g^{*} = C_{p,\max}\left(\lambda_{opt},\beta\right)\frac{\rho\,\pi\,R^{2}\,V^{3}}{2\Omega_g} \tag{20}$$

Adjustable Model: According to dynamic Equations (7), the adjustable generator torque model is expressed by:

$$T_g^{*} = J\frac{d\Omega_g}{dt} + f_v\Omega_g + \hat{T}_{em} \tag{21}$$

The adaptation algorithm (PI controller) is chosen so as to converge the adjustable model to the reference model by minimizing the error and having a stability of the system.

The WT-s operated well and achieved the MPPT curve during variation of generator shaft speed. The electromagnetic torque will be an input for the control loop described in this section. It should be noted that this work focuses on the MPPT. Accordingly, the AMPC of our system is shown in Fig. 6 (third select mode).

Simulation Results and Discussion

Some results of the simulation of the three select mode of power control were carried out on the MATLAB/Simulink® platform. In practice, the parameters are never determined according to inequalities. Therefore, the appropriate technique is to adapt the controller parameters during computer simulations. The parameters of the WT-s are reported in the Appendix. All simulations have developed with a fixed-step size of 0.1 [ms] with a view to digital implementation in future works.

The first wind speed profile used in this simulation, shown in Fig. 7, is based on Eq. (1). Although it is not typically the case in reality, this form is very frequently used in simulations, because it is easy to use and shows the worst case. In addition, the second wind speed profile based on the FAST model is shown in Fig. 9. The MPC is then applied by the operating conditions given in Fig. 2, the $C_{P,max}$ (maximum values of power coefficient) and the λ_{opt} (optimum tip speed ratio) for the curve associated to the fixed pitch angle β=0°. The pitch angle is maintained at its fixed value, with no power limitation lower than the rated wind speed. The following simulation results are performed to compare the three select mode control, namely, the classical methods (CMPCWSM and CMPCWSE) and the proposed Adaptive Maximum Power Control (AMPC) algorithm (see Fig. 6).

In order to demonstrate the robustness and to verify the effectiveness of our proposed approach, a step-noise of magnitude 25, uncertainties in the WT-s are under the influence of a white noise added to the turbine torque. These types of noise can include unmodeled quantities, parametric uncertainties and external disturbances.

Fig. 8 illustrates the dynamic performance of the WT-s based on wind speed using the Eq. (1), while, Fig. 10 shows the performance of the our system under the same conditions based on wind speed using FAST model.

The generator shaft speed using the three select mode control for the two wind profiles used, are shown in Fig. 8(a) and Fig. 10(a), which is proportional to the wind speed curve. It can be seen from these figures that the proposed control configuration curve mediates the curves of the conventional configurations, this proposed AMPC strategy has better response characteristics in settling time and overshoot as compared with both CMPCWSM and CMPCWSE.

Fig. 8(b), Fig. 10(b), Fig. 8(d), Fig. 10(d) show, respectively, the generator torque and aerodynamic torque obtained by using two different models, as indicated in Eq. (4), it can be seen that the generator torque variations are perfectly adapted to the aerodynamic torque variation.

From an energy point of view for the two wind speed profiles used, Fig. 8(c) and Fig. 10(c) show the aerodynamic power obtained by the three control methods. These results show the predominance of energy production by using the proposed AMPC method over the classical CMPCWSM and CMPCWSE methods.

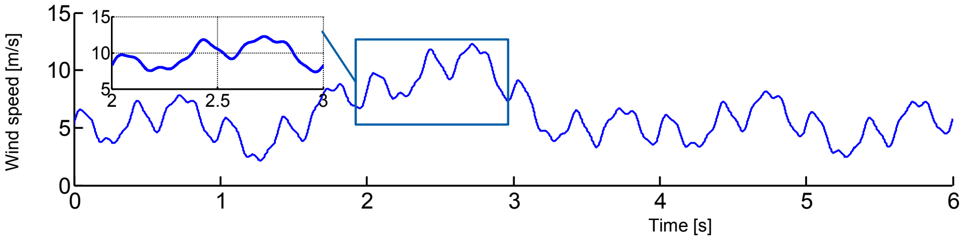

Fig.7. Wind speed profile using Eq. (1)

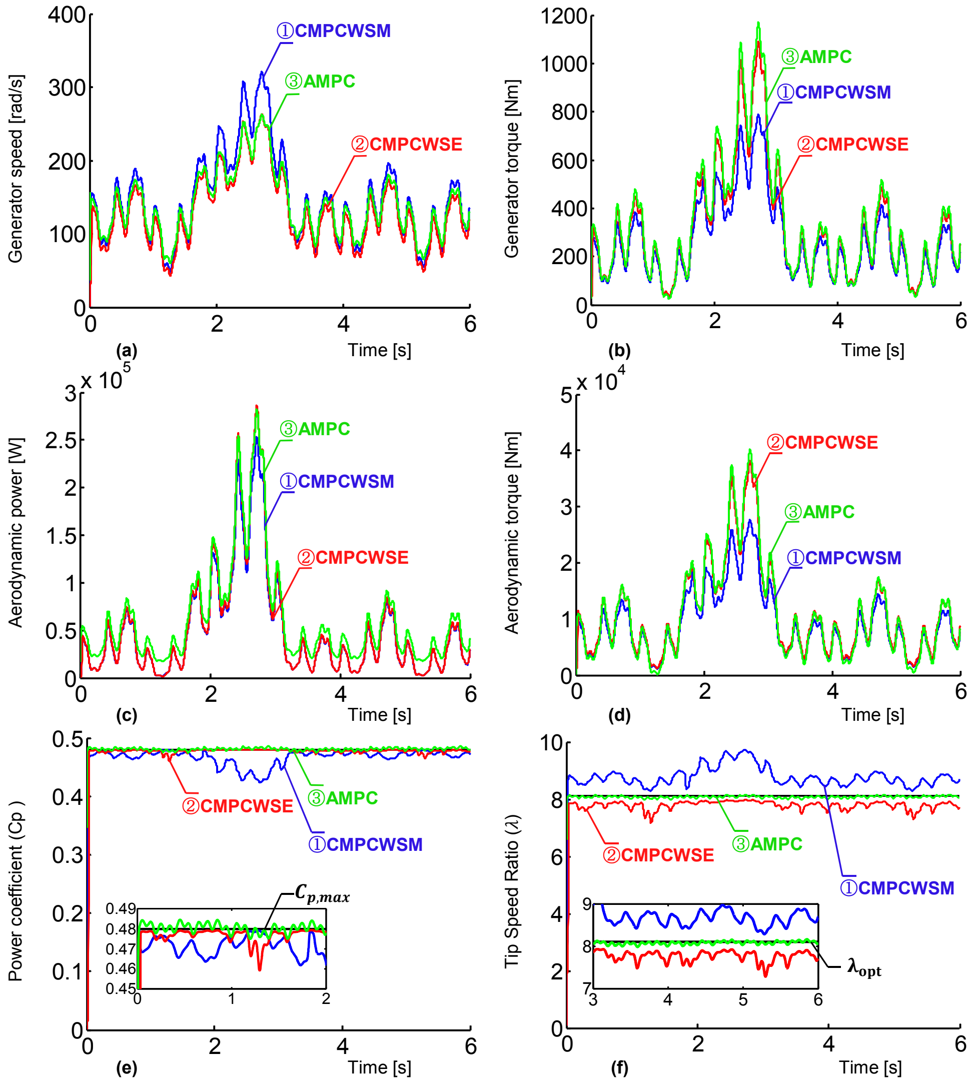

Fig.8. WT-s performance based on wind speed using Eq. (1)

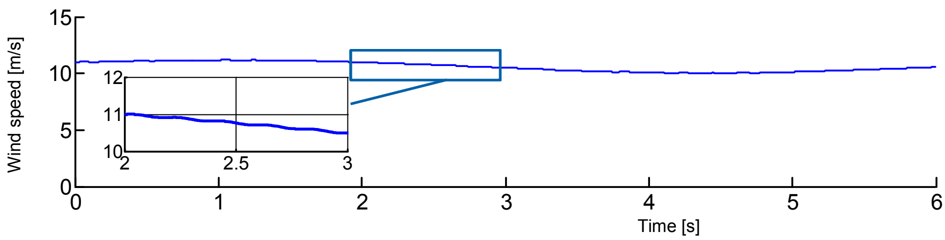

Fig.9. Wind speed profile using FAST model.

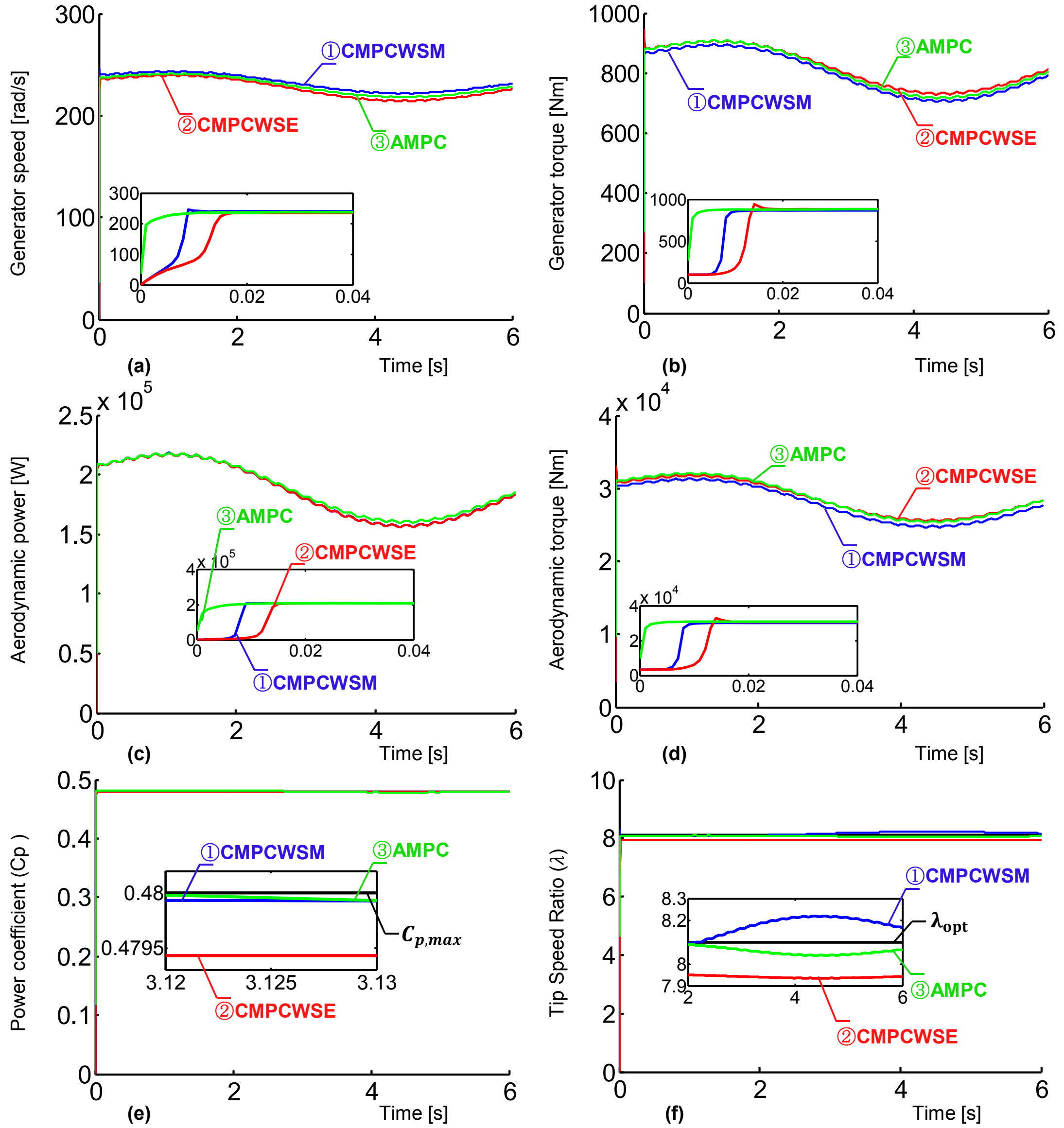

Fig.10. WT-s performance based on wind speed using FAST model

It can be seen from Fig. 8(e) and Fig. 10(e) that the proposed AMPC configuration is an efficient MPPT technique, tracking optimal power points, keeping the power coefficient around its maximum value ($C_{p,max} \approx 0.479$) with less oscillations. It is also shown in these figures that the tip speed ratio is around its optimum value ($\lambda_{opt} \approx 8.1$) with less oscillation. Therefore, this AMPC proposed technique is also considered a soft and robust control, which is proven in these figures, with an improvement in dynamic performance. Taking a comparative approach, it can be deduced from these simulation results that the oscillations in power coefficient and TSR are responsible for the mechanical stresses under the CMPCWSM and CMPCWSE methods.

Conclusions

In this paper, the proposed adaptive power control is designed for the WECS based on tip speed ratio (TSR) method in order to capture the maximum power of the wind. The randomly varying wind speeds and modeling uncertainties can affect the WT-s' efficiency and lead to drive train mechanical stresses. Hence, the control strategy of the wind turbine is required to guarantee robustness against this impact. The AMPC proposed algorithm is able to actively follow the generator shaft speed in quick dynamic changes under system uncertainties, the proposed method is effective for real-time electromagnetic torque control under severe randomly varying wind speed and disturbance rejection. This approach was compared with two conventional CMPCWSM and CMPCWSE methods and validated by simulation. For some simulation results, the proposed AMPC is an improvement over conventional methods, demonstrating high robustness, accuracy of tracking the maximum conversion efficiency and ability to reduce mechanical stresses. Therefore, the mechanical working life is extended without significantly increasing the complexity of the control.

Appendix A

The controllers used in the simulations are of type Proportional-Integral (PI). Using the parameters listed in Appendix A and the pole-assignment technique, the parameters of the controllers are:

Controller parameters	K_p	K_i
CMPCWSM method	2.40	326.89
AMPC method	7.90	121.47

Appendix B

In this part, simulations are investigated with a 1.5MW generator WT-s [30]. The parameters of our system are presented below:

Parameters				Value	
Turbine					
Air density				$\rho = 1.22\ Kg\ /\ m^3$	
Wind turbine blade radius				$R = 35.25\ m$	
Pitch angle				$\beta = 0\ \deg$	
Gearbox ratio				$G = 90$	
(PMSG+Turbine)					
Inertia				$J = 1000\ kg.m^2$	
Friction factor				$f_v = 0.0024\ kg.m\ /\ s$	
C*p* 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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