Harvesting wind gust energy with small and medium wind turbines using a bidirectional control strategy

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Abstract

Wind energy is an important renewable source with a stochastic nature. To capture this energy, variable speed generators are installed in wind towers and different Maximum Power Point (MPP) Tracking (MPPT) strategies have been developed in literature to maximize the output power. However, in gusty weather, wind turbines fail to track the optimum operating point due to their relatively high inertia. This paper proposes an innovative MPPT strategy to capture the energy of wind gusts. The developed controller consists of a conventional TSR control together with a bidirectional controller which takes over the control of the rectifier under varying wind condition. The simulation results show an overall efficiency improvement and more stability for the proposed strategy.

1 Introduction

Variable-speed wind generation systems have drawn enormous attention in the past decades because of their flexibility in harnessing wind energy and improved efficiency. To maximize the output power at various wind speeds, these systems have to adjust their rotational speed, to operate at the optimum point by maintaining the optimum Tip Speed Ratio (TSR) and maximize the aerodynamic power applied on the blades [1–3]. In this regard, various attempts have been made in literature to develop a fast MPPT strategy, to cope with the stochastic nature of wind energy and sluggish dynamic response of wind turbines [2] [3]. However, these strategies often fail to keep the track of the MPP when exposed to highly turbulent weather conditions [3] [4].

Previous research has focused on different MPPT strategies, namely TSR control, Power Signal Feedback (PSF), Hill Climbing (HC) and Optimal Torque (OT) or a combination of these methods [2,3,5]. More recent attempts have been mostly focusing on developing intelligent MPPT algorithm insensitive to uncertainties. Reference [2] indicates conventional HCs are only efficient if the turbine's inertia is negligible and has developed an advanced HC based algorithm. The author in [4] developed a variable perturbation-step HC algorithm using an optimum power-rotational speed curve to regulate next perturbation. The author in [3] suggests the similarity of PSF and OT methods and combines several improved OT algorithms with an effective tracking range with more emphasising on tracking higher wind velocities and discarding lower velocities and wind lulls.

Despite all the differences in aforementioned approaches they all have one point in common. All of these methods investigate a faster dynamics process for the MPPT and agree on the impact of the inertia on the performance of their proposed algorithm. In general, the dynamic of a MPPT algorithm for wind turbines depends on two different yet closely interlaced factors [3, 6]:

1. Mechanical inertia of the rotor and drive-train
2. Dynamic process of the MPPT algorithm

The first factor simply depends on the inertia of the turbine's drive-train. The higher the inertia is, the slower the turbine is. The second factor depends on how the controller calculates the optimum operating point. In sensorless control strategies such as HC, PSF and OT, the detection of the algorithm is based on the electrical power of the generator. This power is delayed from the actual aerodynamic power by the stored power of the inertia [2]. In other words, the electrical power does not represent the actual aerodynamic power applied on the blades. This leads to a slower MPPT process and causes other difficulties [4]. Equation 1 describes the impact of the inertia on the electrical output power, where η is the generator efficiency, T_f represents friction losses and P_g and P_t are the generator and turbine's aerodynamic power respectively. The targeted wind turbine for this paper is direct-drive and the friction losses are considered negligible.

$$P_\mathrm{g} = \frac{1}{\eta}\left\{P_\mathrm{t} - T_\mathrm{f}\Omega - \Omega J\frac{d\Omega}{dt}\right\} \tag{1}$$

On the contrary, in the TSR control strategy, the optimum operating point is derived from the wind speed value obtained by an anemometer and the rotors shaft speed encoder. Thus, the dynamic of the electrical power has no impact on the MPPT

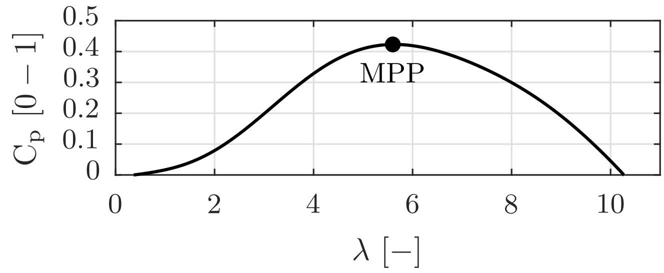

Fig. 1: Power coefficient versus tip-speed ratio

and it provides the fastest tracking comparing to other strategies [7]. In contrast with other approaches, additional sensors and experimental tests are required to obtain the optimum TSR for each turbine [2].

This paper proposes a simple yet effective strategy to improve the dynamic response of the small and medium sized wind turbine. These applications have relatively lower hub heights and are more exposed to wind turbulences [8]. Concerning the impact of mechanical inertia on the dynamic of a MPPT algorithm, an innovative bidirectional control strategy is introduced to improve the efficiency of the conventional controllers and enhance the mechanical dynamic response of the turbine's rotor. In this basis, the TSR control strategy is chosen to ignore the impact of 'Dynamic process of the MPPT algorithm', to focus on the impact of the mechanical inertia and evaluate the effectiveness of the proposed strategy. In normal operation, a well-tuned TSR control keeps the track of optimum rotor speed by regulating the generator torque. The secondary controller is designed to imply a high positive or negative torque, by setting high generating or motoring current respectively, if there is a strong wind variation and the conventional controller is not able to track the optimum operating point. Thus, the generator assists tracking of MPP when the rotor is exposed to high wind variation. The effectiveness of the proposed strategy is validated numerically by implementing Fatigue, Aerodynamic, Structure and Turbulence (FAST) code in the Matlab/Simulink environment with a wind profile generated by TurbSim. The bidirectional control strategy may further be implemented on other MPPT strategies to improve their overall efficiency as well.

2 Model Description And Control Strategy

2.1 Wind Turbine Parameters

The rotor's blades can capture the kinetic energy of wind for wind velocities above the cut-in speed. The mechanical power applied to the rotor are given by

$$P_{\rm t} = \frac{1}{2}\rho A C_{\rm P}(\lambda, \beta) v^3 \tag{2}$$

where ρ is the air density, A represents the swept area by the rotor blades, $C_{\rm P}$ is the power coefficient of the turbine and v and Ω are respectively the wind velocity and rotational speed of the rotor.

$C_{\rm P}$ is defined as the ratio of the captured power to wind power and is a non-linear function of the parameters TSR (λ) and pitch angle β. The pitch angle is constant for small and medium sized without active pitch controller system. The λ is a dimensionless parameter and has an optimum value in which the $C_{\rm P}$ is maximized for any wind velocity. Fig. 1 shows the power coefficient curve versus the TSR for the implemented model. The parameter λ is given by

$$\lambda = \frac{R\,\Omega}{v} \tag{3}$$

where R and Ω are the radius of the blade and the turbine's rotational speed respectively.

2.2 FAST Model

Fatigue, Aerodynamics, Structure and Turbulence (FAST) is a multi-physics tool which uses the Blade Element Method (BEM) to simulate wind turbines [9]. This simulator is developed by the National Renewable Energy Laboratory (NREL) and is widely used to predict extreme and fatigue loads of Horizontal Axis Wind Turbines (HAWTs).

NREL has included a variety of wind turbines with different nominal powers and designs, enabling this tool to model a wide range of commercial wind turbines. To elaborate the concept study aimed at modelling small and medium sized HAWT, the smallest available model is selected and implemented in this simulation. This model is called through an s-function block in the Simulink environment and connected to the controller and Permanent Magnet Synchronous Generator (PMSG) model. Table 1 lists the specifications of the SWRT turbine.

2.3 Model of PMSG

The generator efficiency has a determining impact on the harvested power of the gusts. Hence, it is critical to implement a

WIND TURBINE PARAMETERS	
Model Name	SWRT NREL
No. Blades	3
Rotor Radius	2.9 m
Rated Power	10 kW
Nominal Wind Speed	11.5 m/s
Gear Ratio G	1
Inertia	108.8 kg m^2
Air Density	1.225 kg/m^3

Table 1: Wind Turbine Specifications

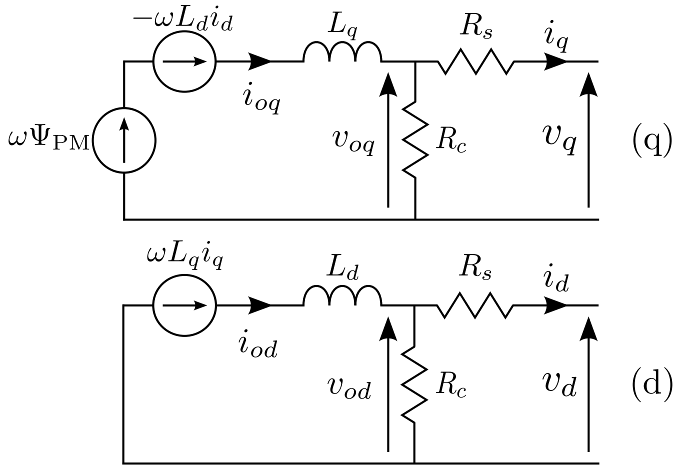

Fig. 2: PMSG d-q equivalent circuit

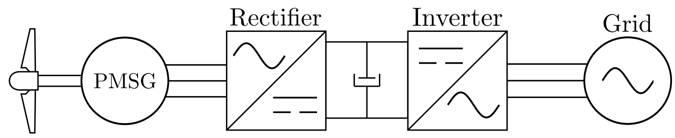

Fig. 3: Back To Back inverter topology

PMSG model, capable of precisely calculating generator losses and power. Figure 2 demonstrates a d-q axis equivalent circuit of the PMSG, which rotates with the angular velocity ω [1]. The copper and iron losses are modelled by R_{s} and R_{c} respectively. The generator power and torque are defined positive in generating mode and can be calculated as:

$$P_{\mathrm{e}} = \frac{3}{2}\left(V_{\mathrm{d}}\, I_{\mathrm{d}} + V_{\mathrm{q}}\, I_{\mathrm{q}}\right) \tag{4}$$

where P_{e} is the electrical power, $V_{\mathrm{d}}, V_{\mathrm{q}}$ are d- and q- axis voltages and $I_{\mathrm{d}}, I_{\mathrm{q}}$ are d- and q- axis currents respectively.

2.4 WECs Topology and control method

Considering Wind Energy Conversion systems (WECs), different possibilities have been compared in [5] and their pros and cons are widely discussed. Figure 3 depicts a back to back converter topology implemented in this study. The PMSG is directly coupled with the turbine rotor and the rectifier converts the wild ac current into a dc current. The grid side inverter injects power into the grid and regulates the dc voltage. In this configuration, the rectifier realizes the MPPT of the turbine. An active rectifier provides lower torque ripple, shorter reaction time and higher efficiency in comparison with the passive ones [5]. It also allows bidirectional power flow from the DC bus to the PMSG. This feature is used in this study to improve the TSR tracking of the controller by motoring the turbine when the controller lags behind the optimum operating point.

The suited control method for the active rectifier is field orientation control. Figure 4 illustrates the schematic of TSR controller together with field orientation control. The three phase stator current is converted to the d-q reference frame. The I_d current is generally set to zero, while I_q determines the generator torque. Therefore, the MPPT can be realized be regulating I_q. The PMSG torque can be calculated as:

$$T_{\mathrm{g}} = \frac{3}{2} N_p \Psi_{\mathrm{pm}} I_q \tag{5}$$

where N_p is the number of pole pairs and Ψ_{pm} is defined as the flux linkage of the permanent magnets.

2.5 Wind Gust Detector and Secondary Controller

As mentioned earlier, in the TSR control strategy, the turbine's TSR is calculated by the values obtained from an anemometer and the shaft speed encoder. This value is compared with the optimum TSR and the error regulates the PMSG torque. In the proposed strategy, the wind measurement and TSR error are also used to detect the wind gust. Fig. 5 depicts the decision tree for the controller. The discrete wind speed value from the FAST s-function block is given to a low-pass filter to smooth out higher frequencies and the derivator block extracts the variations of the wind profile. If the derivative exceeds κ_1 the second step is activated. The second condition is made because different driving torque captured by the rotor render to different tracking behaviour [3]. Every time a high derivative in wind measurement is detected, the detector block perceives the TSR error to inspect if the conventional controller is unable to follow the optimum TSR. If the TSR error is higher than the value κ_2, the bidirectional controller takes over and sets the I_{q} to $-I_{\mathrm{q,nom}}$ and 2 $I_{\mathrm{q,nom}}$ for a positive and negative derivative respectively. The reason for choosing these currents is the fact that, in positive derivative the PMSG motoring torque and aerodynamic torque cooperate to accelerate the rotational speed. However for a negative derivative, only the generator torque decelerates the rotational speed. The bidirectional controller switches off when the turbine's TSR verges on the optimum value and the conventional controller carries on the MPPT. The criteria of tuning the value κ_2 is dependent on the moment of inertia of the wind turbine's rotor, the efficiency of the generator and the $C_{\mathrm{p}} - \lambda$ curve of the turbine and varies for different applications. If the harvested energy of the gust is higher than the energy losses in PMSG, a higher efficiency is achieved by the proposed control strategy.

3 Simulation Results

In order to verify the effectiveness of the proposed controller, the module is tested under two different wind profiles.

3.1 Uniform Wind Profile

In the first simulation a uniform wind profile with an average velocity of 4 m/s and smooth fluctuation is implemented.

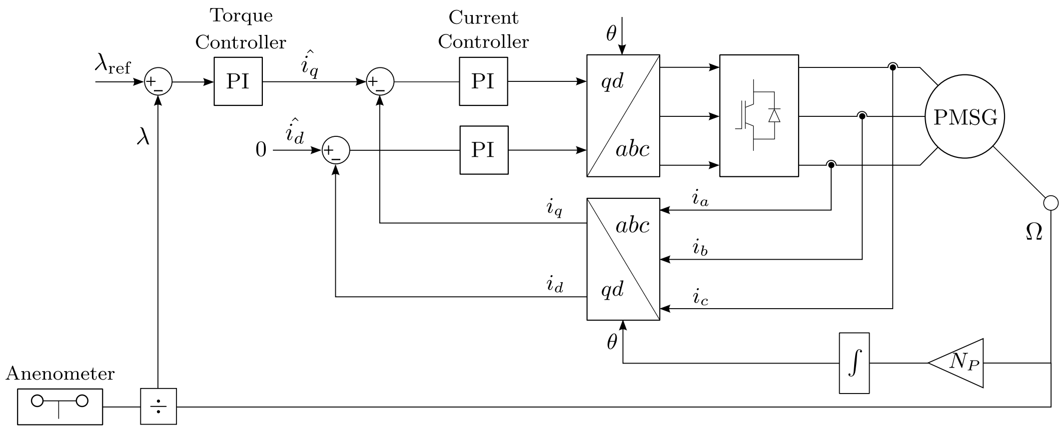

Fig. 4: TSR Controller Strategy using Field Orientation Control

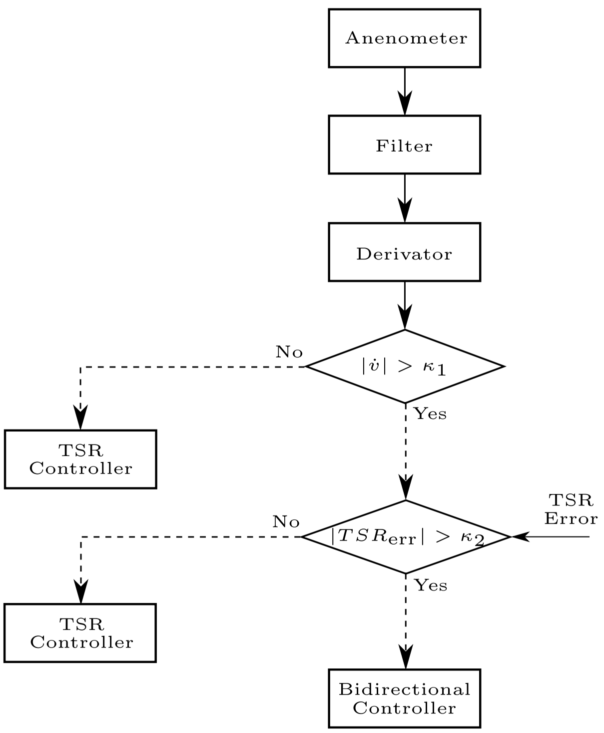

Fig. 5: Decision Tree of the controller

The turbine is exposed to one wind gust with a peak of 3 m/s. The low-pass filter effectively moderates the wind measurement and extracts the high derivatives in the wind profile. Fig 6 demonstrates the wind profile, wind derivative and the controller mode. In normal condition the controller mode is set to zero and the TSR controller regulates the turbine's torque. The moment a wind gust is detected, the controller mode sets to -1 to track the optimum operating point. The aerodynamic force and PMSG motoring torque cooperate to accelerate the rotor. Then, the controller mode goes back to normal operation when the TSR error is below the value κ_2. If the wind speed derivative is negative, the controller mode is set to 1 and the rectifier imposes a high positive torque to decelerate the rotor. The secondary controller switches off when the TSR error becomes lower than κ_2 value. The values κ_1 and κ_2 vary for different applications and have to be tuned and optimized to maximize the improvement of the proposed strategy.

Fig. 7 demonstrates the performance of the conventional and proposed controllers. From fig. 7 (a) it can be seen that the power coefficient curve is more stable and has less deviation regarding the optimum value in the proposed approach. It is worth noting that the conventional controller fails to track the optimum operating point not only during the wind gust, but also the following moments when the gust is over. As a consequence, the aerodynamic power captured by the turbine is higher in the proposed strategy. Although there is some energy losses in the PMSG, this loss is fully compensated by the difference of the captured power. The electrical power generation of the bidirectional controller has an improvement of 3.5% over a 50 seconds uniform wind profile with one gust.

The level of improvement for the proposed bidirectional strategy strongly depends on the characteristic of the application and the wind profile. Turbines with higher inertia have relatively slower dynamic and hardly react to wind variations. In the same way, in lower wind velocities, the driving torque needs more time to accelerate the rotor and follow the MPPT [3]. Thus, a higher efficiency improvement is expected in turbines with higher inertia or in lower wind velocities.

3.2 Stochastic Wind Profile

Under the second test condition, the SWRT is exposed to a stochastic wind profile generated by TurbSim with a mean value of 7 m/s. The IEC Kaimal model is used with the highest turbulence intensity defined by IEC-61400-1 standard. The hub height wind speed is shown in Fig. 8 (a) with a value lower than the nominal wind speed of the SWRT.

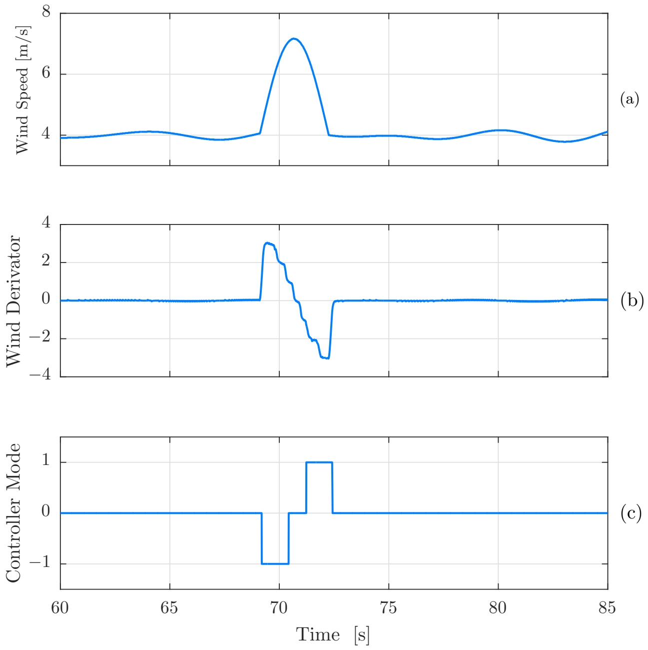

Fig. 6: a) Wind profile b) wind speed derivative c)controller mode

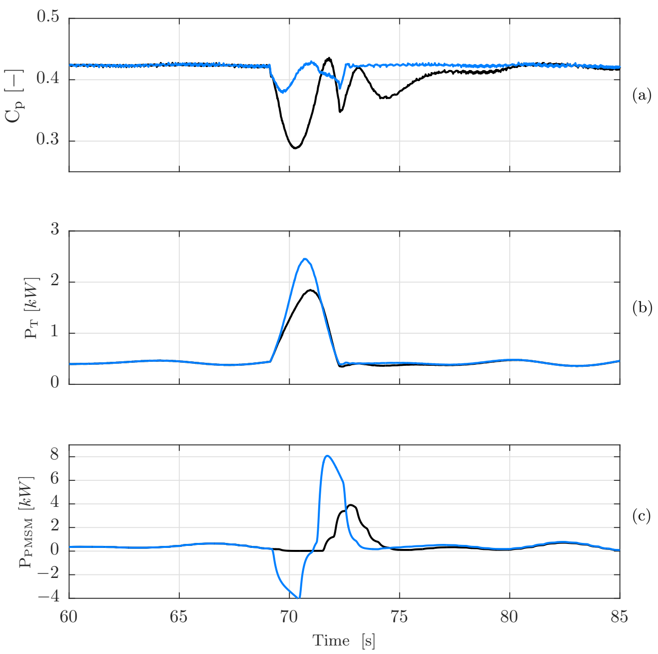

Fig. 7: a) Power coefficient b) Aerodynamic captured power c) PMSG Electrical power (▬ : Proposed controller, ▬ : Conventional controller)

The performance of the two controllers in tracking the optimum TSR are compared in Fig 8(b-d). It can be seen in Fig. 8(b) the proposed bidirectional has a better performance tracking the reference value 5.6. The allowed TSR error κ_2 for the conventional controller is set to 0.25. The power coefficient has the same value in TSR mode and higher values in wind turbulences (Fig. 8 (c)). The average C_p over this simulation is 0.422 for the proposed controller and 0.417 for the classic TSR control. Accordingly, a higher aerodynamic power is captured and higher efficiency is achieved, see Fig. 8 (d). The proposed strategy effectively boosts the performance of the TSR controller when exposed to a wind gust or wind drop. The generated electrical energy for the proposed controller has an improvement of 1.1% over this wind profile.

4 Conclusions

This paper introduces a simple yet effective strategy to improve the dynamic response of the small and medium sized wind turbines exposed to high wind variations. The secondary bidirectional controller is implemented with a conventional TSR control strategy. The bidirectional controller is aimed to detect wind gusts and wind lulls and imposes the necessary positive or negative torque to follow the MPPT. Validation of the proposed strategy is done using the FAST code in the Matlab/Simulink environment. The simulation results suggest a faster tracking for the proposed controller and a improved generated energy of 3.5% and 1.1% for uniform and stochastic wind profiles respectively.

Acknowledgment

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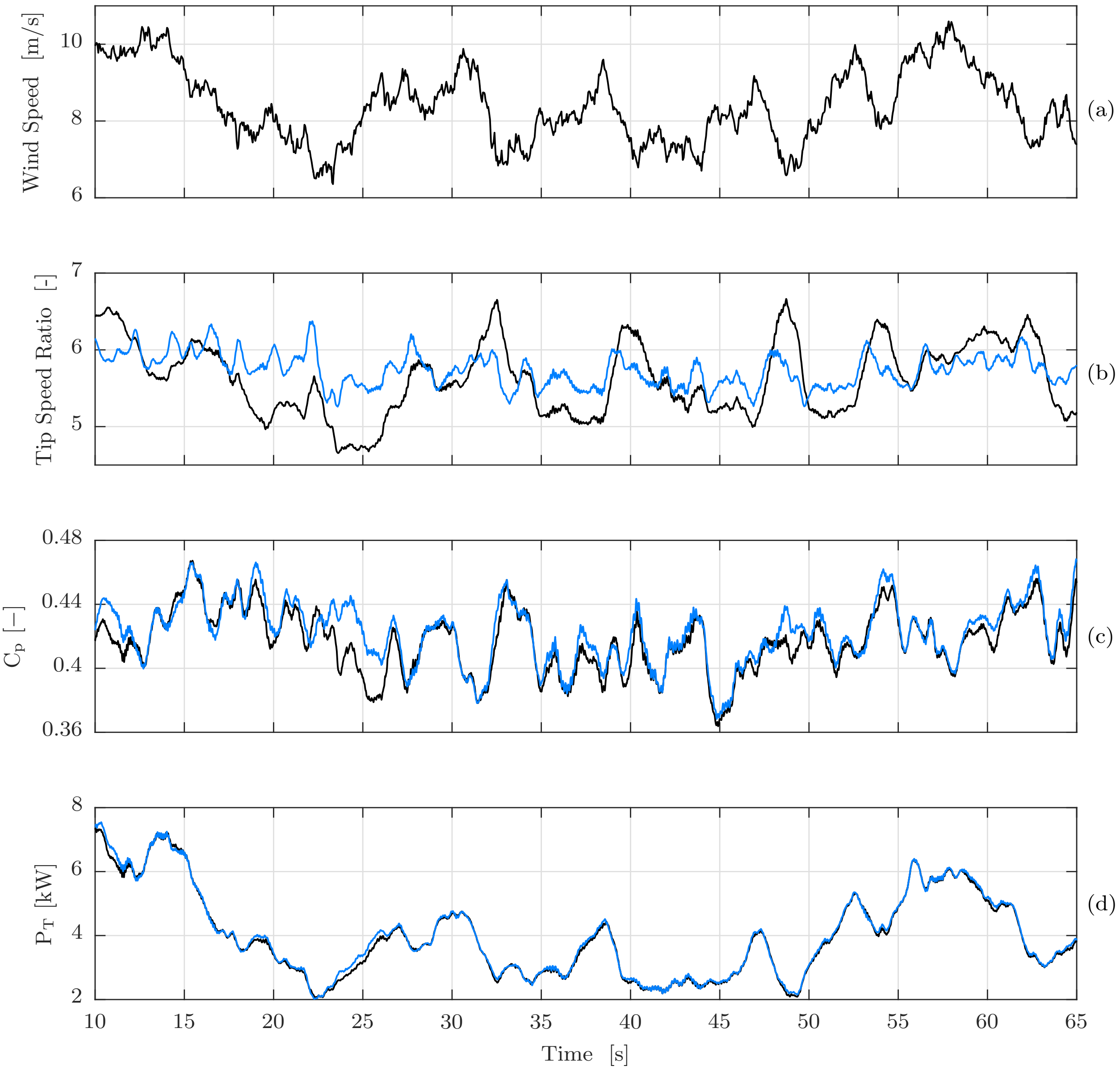

Fig. 8: a) Wind Profile b) Tip Speed Ratio c) Power Coefficient d) Aerodynamic Power (▬ : Proposed controller, ▬ : Conventional controller)

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