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The Utilization of a TSR-MPPT-Based Backstepping Controller and Speed Estimator Across Varying Intensities of Wind Speed Turbulence

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ABSTRACT

Because wind systems are so prevalent in the electrical grid, an innovative control method can significantly increase the productivity of permanent magnet synchronous generators (PMSG). A wind power generation system's maximal power point (MPP) tracking control approach is presented in this paper. The nonlinear backstepping controller, which is robust to parameter uncertainty, is used in this work to enhance the tip speed ratio approach. To lower the system's equipment and maintenance costs, we suggested utilizing a speed estimator. As a novel addition to the backstepping controller development, the suggested estimator is a component of the backstepping controller development. The control and system organization approaches are presented. Lyapunov analysis is used to guarantee the stability of the controller. To assess the suggested approach, step change and varying wind speed turbulence intensities are employed. The results expose the great efficiency of the proposed method in both tracking MPP and calculating generator speed. The proposed control strategy and structure are validated by MATLAB simulations.

1. Introduction

Energy is an essential requirement for achieving sustainable economic and social development, as providing and securing access to its sources is essential [1]-[3]. Power generation and economic development are both significantly accelerated by energy [4], [5]. Fossil fuels have historically been essential to meeting the world's energy needs, but their limited and diminishing supplies, along with harmful environmental effects like the release of carbon monoxide, hydrocarbons, and ionizing radiation, highlight the need for a paradigm change [6], [7]. Global interest has now increased in diversifying and renewing energy sources, especially renewable sources, to reduce dependence on traditional energy sources, which are threatened with disappearance, and to confront environmental threats and economic developments that are increasing day after day [8]-[10]. Investment in the field of renewable energies (REs) has become necessary, and this is what has been activated. There is a lot of scientific research in the field of REs with huge budgets [11]-[13]. In this regard, efficiently utilizing RE sources and coordinating prudent energy resource management becomes an essential task [14], [15]. A paradigm shift known as the "energy revolution" has taken place in the current energy landscape, promoting sustainable development at all levels of human existence. Countries are developing strategic plans to move away from these traditional sources and toward more general environmental goals as they become aware of the negative environmental effects of using fossil fuels [16], [17]. Particularly notable is the rise of RE sources, which are motivated by their promise to achieve near-zero emissions and meet environmental demands [18].

Wind energy (WE) stands out as the most popular and economically feasible RE source in the universe, with broad public support [19]. Its ability to meet significant energy demands in a variety of contexts, whether close or far away, grid-tied or lonely, demonstrates its adaptability [20]. The rapid adoption of WE in systems is evidence of its growing popularity as the environmental fees and environmental damage of other energy sources become intolerable [21]. Numerous wind turbines (WTs) use induction machines of different kinds, with the doubly fed induction generator being the most widely used variety. The most widely used kind of electric generators are permanent magnet synchronous generators (PMSGs) due to their high efficiency, reliability, power density, gearless design, low weight, and self-excitation capabilities [22]-[25].

For several uses [18], such as optimizing WE output, designing and positioning WTs, and evaluating possible wind farm locations, accurate wind speed profile estimation is essential. Furthermore, knowing the wind speed profile is crucial for forecasting and controlling WE system performance and maintenance requirements, as well as for guaranteeing the effectiveness and safety of wind-related activities [26]. The integration of WE into the larger electrical grid and environmental impact assessments both heavily rely on this knowledge [27]. When assessing the WE potential of a particular location, the analysis and interpretation of wind velocity data are crucial. This examination plays a crucial role in thoroughly assessing the feasibility and effectiveness of using WTs to generate electricity [28]. It is clear from mathematics that WE and wind speed are directly correlated. In particular, WE get stronger as wind velocity cubed increases. As a result, WT produces more electric energy at higher wind speeds, which lowers the cost per kWh. Average wind velocity and wind dispersion are two important parameters that determine wind in a given area. Wind velocity is known to fluctuate and be unstable over time and in various places [28].

The direct operation of the WE system at constant speed involves a large loss of energy up to 40% [29]-[31], which is why the so-called variable speed WTs. The WE system now contains many components including the current and voltage sensors, the speed sensor, and the controlled power converter which is an essential part of this system, and it works to adapt the generator load so that we extract or operate the WE system at the maximal power point (MPP) [32]-[35].

Actually in [36], the WT system was operated at MPPT using a second-order sliding mode controller. To maximize sequence control, a nonlinear predictive controller was presented in [37] that uses output power estimations to gain power and reduce transient loads. The efficiency of backstepping control (BC) has been explained by a number of theories; in [38], a BC is created to regulate the stator output voltage while meeting demand energy changes and wind velocity effects. In [39], rotor currents govern the system's electrical and mechanical components. Ref. [40] simply applies the control methods to the generator side converter by merging two Takagi-suggest fuzzy systems with the feedback form of BC to regulate the mechanical portion. Ref. [41] compares the BC and PI controllers for independently managing the extracted active and reactive power to the grid.

To operate the system at the MPP, we need control methods, and there are many proposed control methods, [42]-[48], where we find the perturb and observe (P&O) MPPT control it is a method that hinges on perturb in the voltage by changing the duty cycle of the power converter and observing the direction of the power change [49], [50]. It is a method It is easy to use and inexpensive, however, the important drawback is the value of the duty cycle if it is very large, it guarantees a fast response and instability at the MPP, and if it is small, the response is slow, especially since the wind speed changes greatly [51]. To improve the behavior of the P&O control, we find a P&O with a variable duty cycle depending on the wind speed proposed in [52], which showed high efficiency in tracking MPPs.

The optimal torque control (OTC) method depends on the characteristics of the WE system, where we can define the value of the OT of each wind speed and force the generator to follow the OT by the action on the current imposed by the load through the power converter to extract the maximum of available power [53]. To enhance MPPT efficiency, some improved OT controls have been proposed [54]. Modification of torque curve gain is proposed by [55]. Compensation of generator torque, such as inertia compensation control (ICC) proposed in [56]. The power signal feedback (PSF) control method depends on the characteristic curve of the WT system, as the correct definition of the system leads to good and reliable control. One of the most important defects in this control is the presence of a speed sensor [57]. According to [50], the PSF control has the same performance as OTC.

Tip speed ratio (TSR) MPPT control is a method based on comparing two speeds, the generator speed and an optimal speed that depends on the wind speed and WT parameters. Making the generator speed follow the optimal speed means that the WT system is operating at the MPP [58], [59]. To achieve this, we need a good regulator and knowledge of the generator speed and wind speed, which means the presence of a sensor. The speed of the wind (anemometer) and the speed of the generator, which leads to an increase in the cost, is considered one of the most prominent disadvantages of TSR [60], where we find much research on control without a speed sensor, [61] used a speed sensor based on electromagnetic force induced and a rotor flux observer to estimate the speed generator. Reference [62] proposed the speed observer based on the MRAS method with the classical PI mechanism, to improve the performance of the MRAS observer they used an adaptation mechanism based on a predictive regulator. Also, [63], [64] used the speed observer based on the MRAS method based on the stator currents with the PI controller with adaptive gains as an adaptive mechanism. In [65], the authors used the MRAS method based on rotor flux, the flux was estimated by the fourth-order Kalman filter and the neural network was cast for the speed estimate.

Unexpected changes in atmospheric conditions can affect a PMSG system, and monitoring the MPP continuously is essential to increasing the operative effectiveness of the PMSG. As previously indicated, a variety of MPPT approaches have been documented in the literature. Nevertheless, these methods lack adequate robustness and have some issues, including oscillation about the MPP. Nonlinear control is a crucial control solution to ensure an optimal and reliable PMSG system, given the nonlinear nature of the PMSG system. To address the issue of sensors in the MPPT technique, we proposed the backstepping controller in the TSR-MPPT control method for the speed sensor. To estimate the generator speed and reach the MPP, the backstepping controller is utilized. Using Lyapunov theory, the controller's stability has been confirmed. The higher performance of the suggested method has been demonstrated through, robust tests and simulations.

To accomplish this goal, this paper is structured as follows: The literature review for the most recent publications, which concentrate on sensor control techniques in WTs, is presented in the first section. Modeling the WT system is covered in the second section. The applied controller and the suggested MPPT approach are shown in Section 3. The results and their discussions are shown in Section 4. The work is concluded in the final portion.

2. Structure and Modeling of Studied WEGS

The structure of the investigated system is shown in Fig. 1. The generator and grid-side converters are employed to regulate the PMSG velocity with MPPT, to control the DC-link voltage, and to regulate the power factor [66]. The object is to harvest the MPP at various wind speeds by using the BC in the TSR-MPPT control method without the speed sensor and by using the backstopping algorithm to estimate speed.

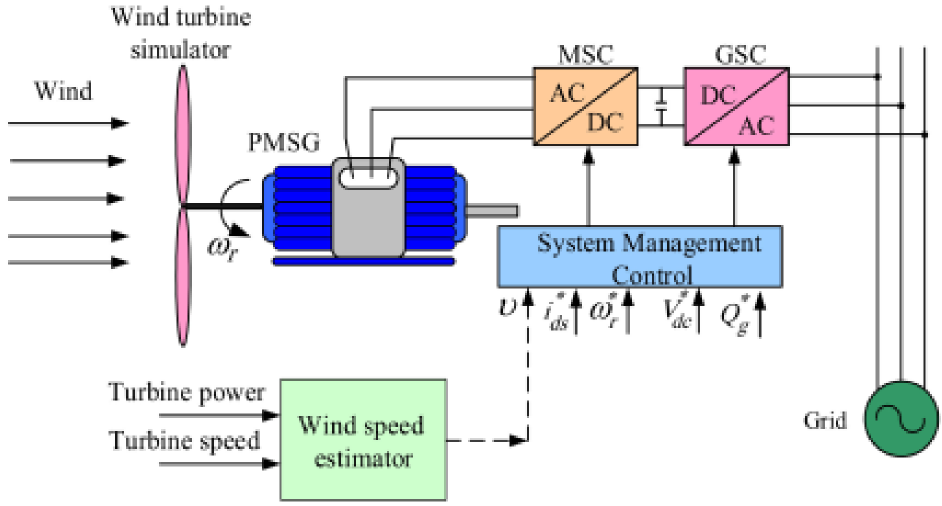

Fig. 1. Arrangement of a grid-linked PMSG

The WT, PMSG, and their control system models are shown in detail in [14], [67], [68].

The aerodynamic power is given by:

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

where V is the wind speed, ρ air density, R is the radius of WT, C_p is the power coefficient, β is the pitch angle and λ is the TSR.

The $C_p(\lambda, \beta)$ is signified as:

$$C_p(\lambda, \beta) = 0.22 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{-12.5}{\lambda_i}}$$
$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{2}$$

$$\lambda = \frac{R\Omega_t}{V} \tag{3}$$

where $\Omega_t$is the WT speed

The WT torque is given by:

$$T_{aer} = \frac{T_{aer}}{\Omega_t} = \frac{1}{2\lambda} C_p(\lambda, \beta) \rho \pi R^3 V^2 \tag{4}$$

The mechanical equation is given as:

$$j \frac{d\Omega_g}{dt} = T_g - T_{em} - f_c \Omega_g \tag{5}$$

where T_{em} is the electromagnetic torque, j is the total moment of inertia, f_c is the coefficient of viscous friction, Ω_g is the generator shaft speed, and T_g is the generator torque.

$$T_g = \frac{T_{aer}}{G}$$
$$\Omega_g = G\Omega_t \tag{6}$$

From Fig. 2 we can realize that at $\beta = 0°$ the MPP is characterized by the $\lambda_{opt} = 0.48$ and the $C_p^{opt} = 8.1$.

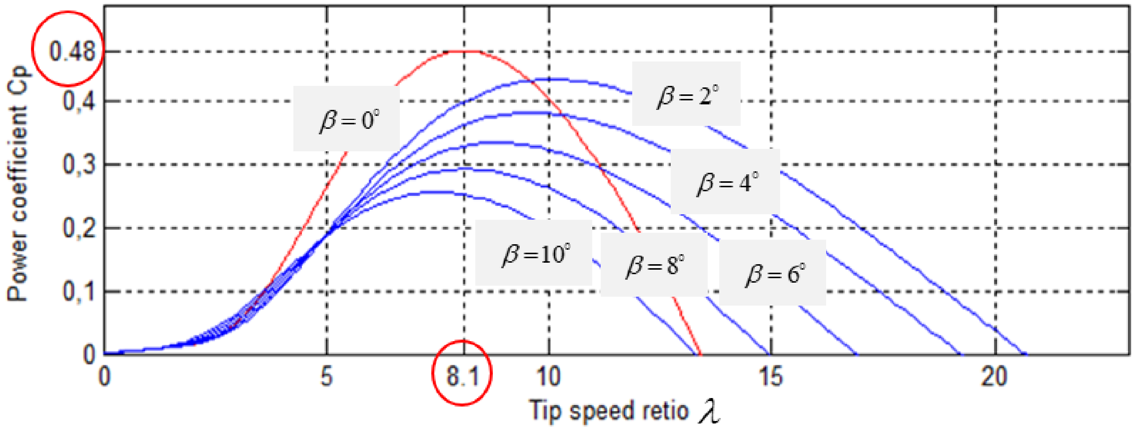

Fig. 2. C_p - λ characteristic at different pitch angles

From Fig. 3, we can perceive that for each wind speed, there is one MPP. This point is characterized by $\lambda_{opt} = 0.48$ and the $C_p^{opt} = 8.1$.

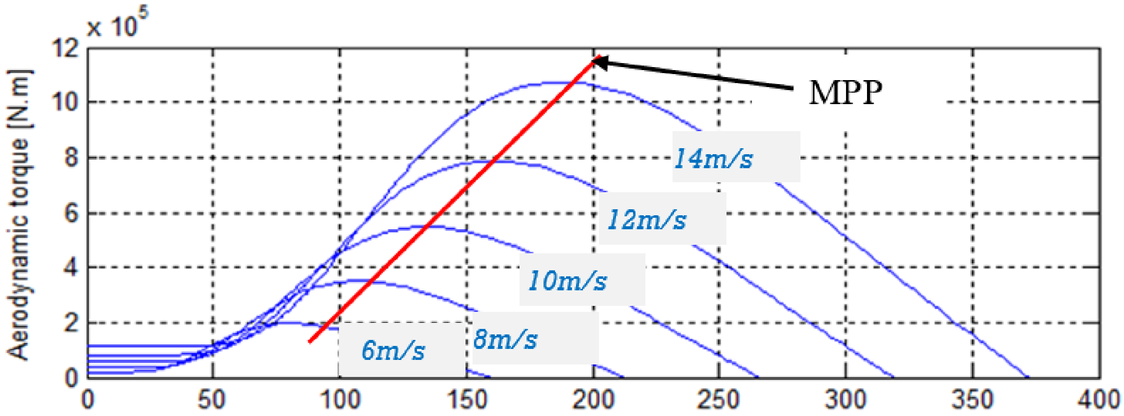

Fig. 3. Aerodynamic torque for different generator speeds

3. Investigated MPPT Method

Fig. 4 represents an organization chart that represents the different control strategies of WEGSs. Many studies have dealt with methods of searching for the MPP. Sources [69]-[71], have touched on direct methods, including P&O, incremental conductance, and hill climb search approach, while indirect methods OTC, PSF, and TSR approach have been discussed in sources [72]-[76].

3.1. TSR Approach

The TSR approach uses physical parameters to predict V, or it uses sensors to continuously measure them [69], [77]. For the system to function at its MPP, this strategy aims to keep it operating at the optimal value of TSR during variations in V. Although MPP requires ongoing understanding, its efficiency and quickness can be commended. This method's drawback is the requirement for a V sensor, which could raise the system's cost [78].

3.2. Design of the Proposed Backstepping Controller and Estimator Speed Proposed Approach

The BC approach is one of the nonlinear controllers used for the nonlinear system [79]-[81]. In the TSR-MPPT control technical, we used the BC to maintain the WE system in the MPP and estimate the generator speed. The BC is based on defining the positive Lyapunov function; if the system is stable, the Lyapunov function must be negative. The TSR-based MPPT technical method is based on making the generator speed follow the optimal generator speed or reference speed, which is defined as:

$$\Omega_g^* = \frac{V\lambda_{opt}}{R} \tag{7}$$

Step 1
The speed error (SE) is defined as:

$$e_1 = \Omega_g^* - \Omega_g \tag{8}$$

The dynamic of the SE can be defined as:

$$\dot{e}_1 = \dot{\Omega}_g^* - \dot{\Omega}_g \tag{9}$$

$$\dot{e}_1 = \frac{\lambda_{opt}\dot{V}}{R} - \frac{1}{j}\left(T_g - T_{em} - f_c\Omega_g\right) \tag{10}$$

To estimate the generator speed (GS), the SE can be defined as:

$$\Omega_g = \hat{\Omega}_g - \tilde{\Omega}_g \tag{11}$$

The dynamic error of speed is defined as:

$$\dot{e}_1 = \frac{\lambda_{opt}\dot{V}}{R} - \frac{1}{j}\left(T_g - T_{em} - f_c\left(\hat{\Omega}_g - \tilde{\Omega}_g\right)\right) \tag{12}$$

To ensure the stability of SE and to estimate the GS in Lyapunov condition stability, the proposed Lyapunov function is defined as:

$$V = \frac{1}{2}e_1^2 + \frac{1}{n}\tilde{\Omega}_g^2 \tag{13}$$

$$\dot{V} = e_1\dot{e}_1 + \frac{1}{n}\tilde{\Omega}_g\dot{\tilde{\Omega}}_g \tag{14}$$

From the equation (12) and (14) the dynamic Lyapunov function can be written as:

$$\dot{V} = e_1\left[\frac{\lambda_{opt}\dot{V}}{R} - \frac{1}{j}\left(T_g - T_{em} - f_c\left(\hat{\Omega}_g - \tilde{\Omega}_g\right)\right)\right] + \frac{1}{n}\tilde{\Omega}_g\dot{\tilde{\Omega}}_g \tag{15}$$

To ensure the stability of the Lyapunov dynamic function, the electromagnetic torque control and the estimated SE are defined as:

$$\begin{cases} T_{em} = -\dfrac{j\lambda_{opt}\dot{V}}{R} + T_g - f_c\hat{\Omega}_g + Ke_1 \\ \tilde{\Omega}_g = \displaystyle\int n\frac{f_c}{j}e_1 \end{cases} \tag{16}$$

where K and n are the constant positive gain.

To justify the system's stability according to the Lyapunov theorem, the dynamic of the Lyapunov function must be negative. If we replaced the equation (16) into (15), we have:

$$\dot{V} - Ke_1^2 \leq 0 \tag{17}$$

From equation (17), we can say that the system is stable.

Fig. 5 represents the proposed controller.

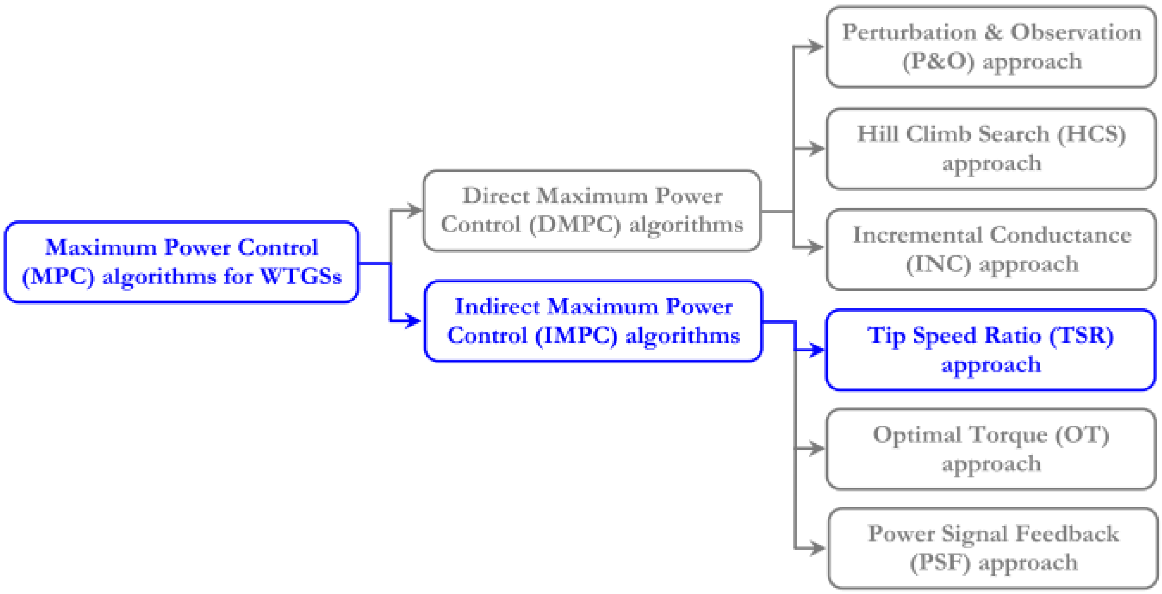

Fig. 4. Different MPPT control strategies of WECS

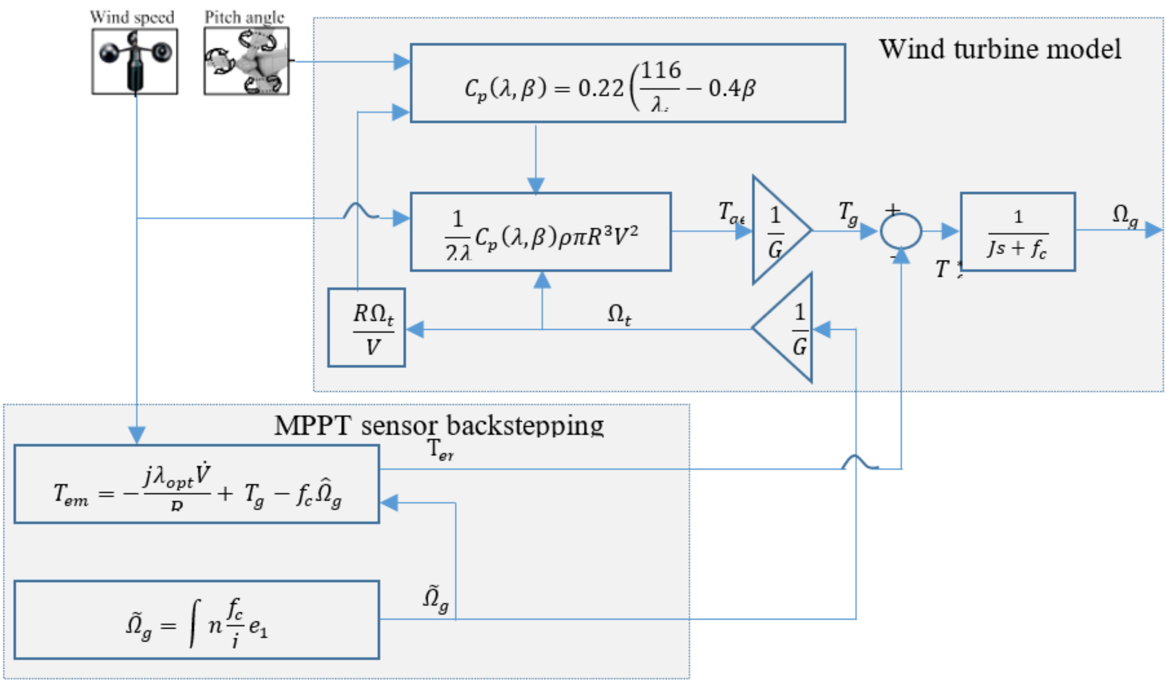

Fig. 5. Structure of TSR MPPT control method based BC and proposed speed estimator

4. Simulation Results and Discussion

4.1. Case I: A Step Change in Wind Speed

To verify the effectiveness of the proposed controller, we tested it with different V. In this case, we checked the system at the V shown in Fig. 6. Through our observation of Fig. 7, we conclude that the proposed controller made the system operate at the MPP, where we notice that λ and C_p reached their optimal values of 8.1 and 0.48, with a time response of 5.5 s and 1.8 s, respectively, and through a figure that shows GS and estimated speed, we conclude that the proposed speed estimator tracks the generator speed well with a very small error rate.

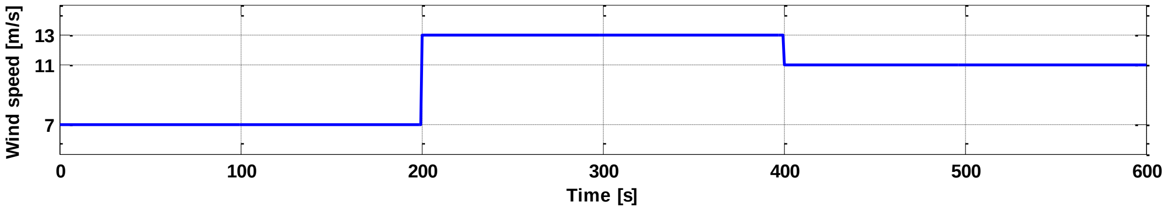

Fig. 6. Profile of V

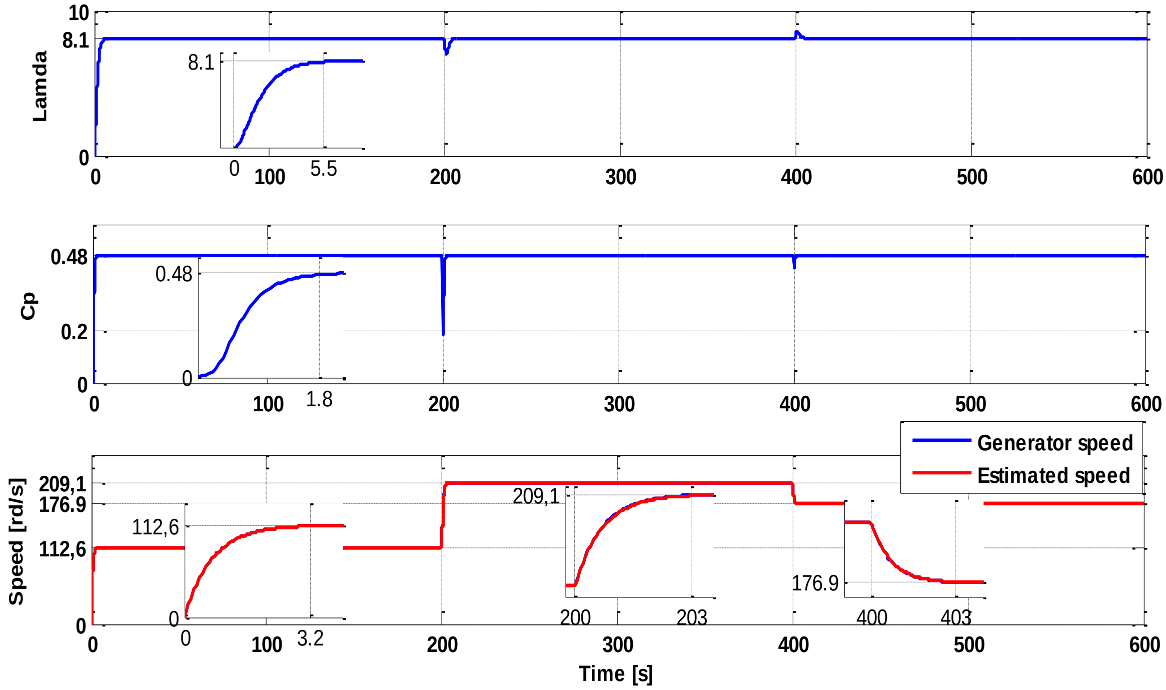

Fig. 7. Simulation results under-investigated V profile

4.2. Different Wind Speed Turbulence Intensities

In this case, we will examine the system through the V with the different V turbulence intensities: 10% as in Fig. 8 anf Fig. 9, 12% as in Fig. 10 and Fig. 11, and 14% as in Fig. 12 and Fig. 13. Through the all results in this case: we conclude that the system operates at the MPP, regardless of the V, and this is what is shown by the λ, and C_p curves, where λ takes the value 8.1 and C_p value is 0.48. As for the proposed speed estimator, through the curve that shows the GS and the estimated speed, we notice that the proposed estimator tracks the GS with very high accuracy and with a very weak error rate. It can be concluded that when the V turbulence intensities increased the ripples increased on the output signals λ, rotor speed, and C_p.

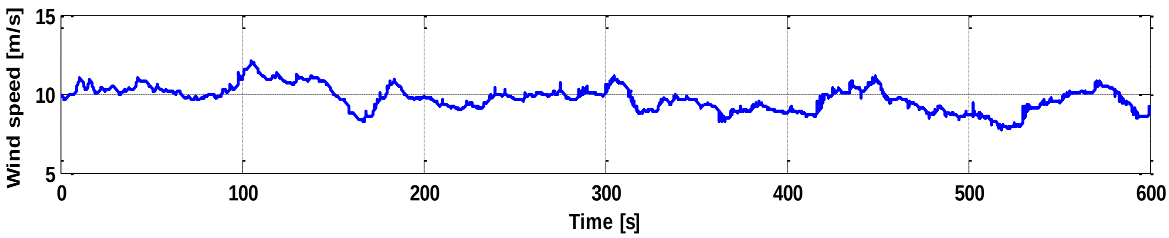

Fig. 8. V profile with 10% turbulence intensity

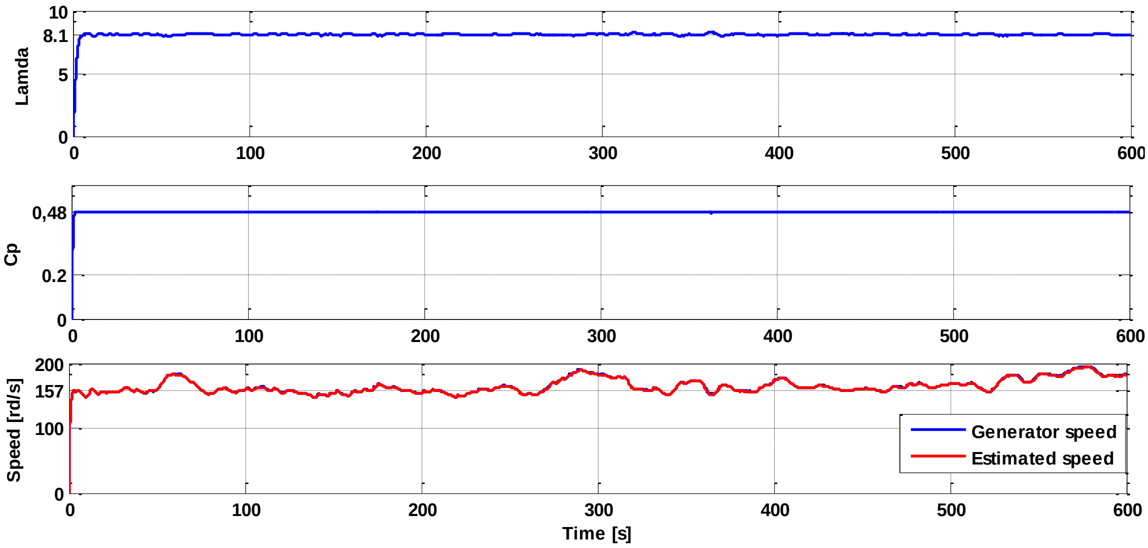

Fig. 9. Simulation results for V 10% turbulence intensity

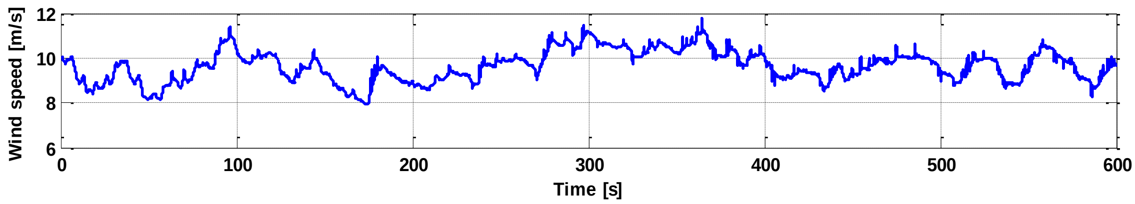

Fig. 10. V profile with 12% turbulence intensity

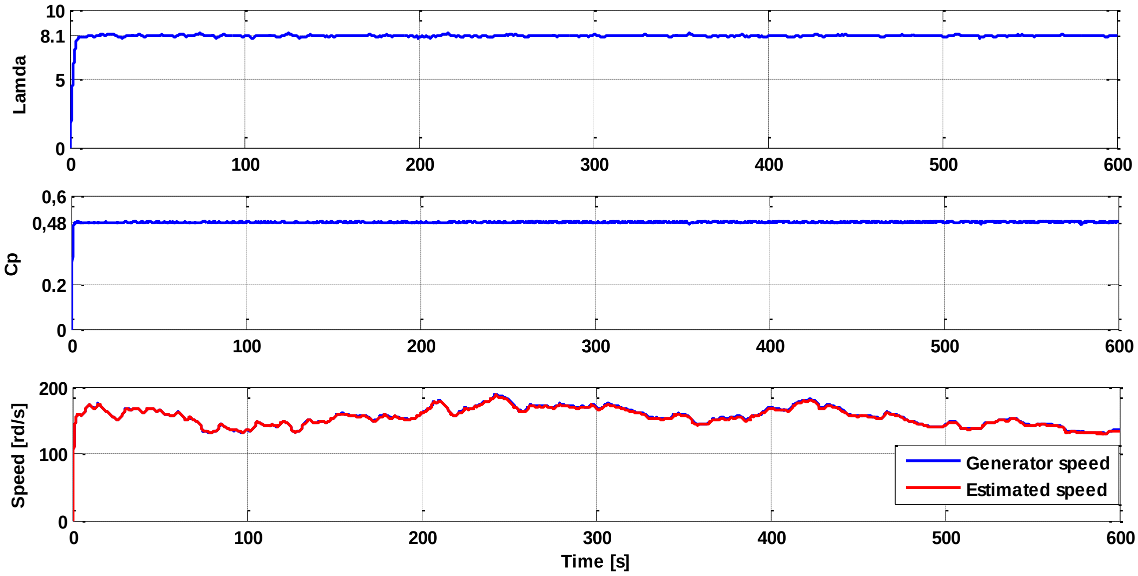

Fig. 11. Simulation results for V profile with 12% turbulence intensity

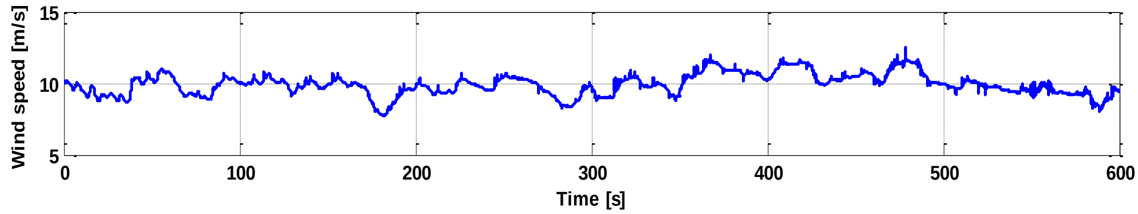

Fig. 12. V profile with 14% turbulence intensity

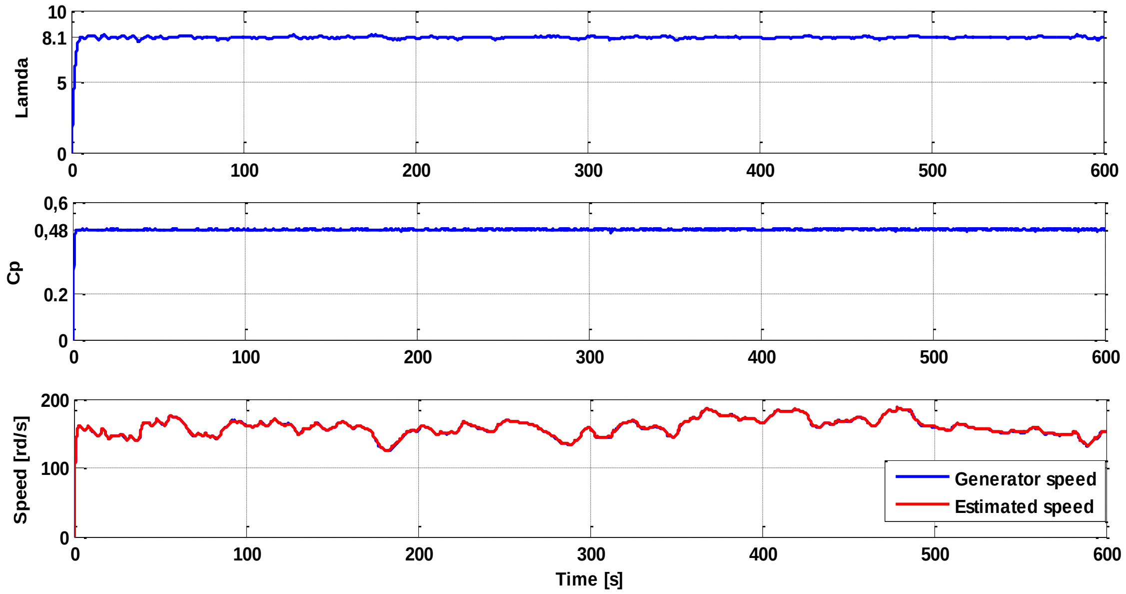

Fig. 13. Simulation results for V profile with 14% turbulence intensity

5. Conclusions

The primary goal of this research was to examine the efficiency and robustness of a TSR-MPPT-based BC and speed estimator for energy capture of a WT across a range of V turbulence intensities (10%, 12%, and 14%). MATLAB has been used to verify the dynamic model. The speed estimator with the BC is therefore regarded as being quite successful to a very significant extent based on the findings obtained. Lyapunov analysis is used to prove the accuracy of the BC. Robustness, aerodynamic efficiency, and tracking performance have all been used to assess the proposed method. The disturbances caused by sounds, measurement errors, and ambient conditions could all be rejected by the BC. To optimize the energy capture, they should also accurately track the intended rotor speed. The simulations have demonstrated a good tracking error for the system in which the BC, which is expected given its superior tracking, has demonstrated the most efficient fluctuations. Because of its low inherent switching control law, BC has displayed the highest control signal values. In the context of environmental uncertainties, the system's robust stability and performance have been examined. Simulation software was used to analyze the outcomes and demonstrate the effectiveness of BC in terms of resilience and efficiency.

Author Contributions: All authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Data Availability: The data used to support the findings of this study are available at reasonable request from the corresponding author.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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