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AI-Assisted Active Mixed Control for Performance Optimization of an On-Grid PMSG-Based Wind Energy Conversion System

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Abstract

Objective: A The integration of wind energy into modern power grids is significantly challenged by the highly stochastic and nonlinear nature of wind speed variations.

Methodology: To address these issues, this paper proposes an artificial intelligence (AI)–assisted advanced active mixed control framework for the optimal operation of an on-grid Permanent Magnet Synchronous Generator (PMSG)–based Wind Energy Conversion System (WECS). The proposed control architecture combines a non-singular terminal sliding mode controller (NT-SMC) with a smooth switching active sliding mode observer (ASMO) to achieve robust regulation and intelligent state estimation under uncertain operating conditions. The NT-SMC is employed to ensure fast convergence and accurate tracking of system states, while the ASMO provides AI-assisted estimation of rotor speed and electromagnetic torque, thereby eliminating the need for physical sensors and reducing system complexity.

To ensure stable grid integration, a dedicated DC-link voltage management strategy is implemented, along with a feedback-based power control mechanism that regulates the active power injected into the utility grid.

Findings: The AI-enabled observer enhances disturbance rejection and adaptive decision-making by continuously learning system behavior in the presence of model uncertainties and external perturbations. MATLAB/Simulink-based simulation studies conducted under variable and rapidly changing wind conditions demonstrate that the proposed control strategy achieves superior set-point tracking, enhanced system stability, and strong robustness compared to conventional control schemes.

Novelty: The results confirm that the AI-assisted mixed controller provides an effective and reliable solution for intelligent, sensor-reduced, and grid-compliant wind energy conversion systems.

Keywords: permanent magnet synchronous generator (PMSG), sliding mode controller (SMC), active sliding mode observer (ASMO)

1. Introduction

The wind turbine proposed in this research is a permanent magnet synchronous generator, which has the advantages of varying speed and a low-frequency back-to-back converter. because the analysis lists substantial advantages [1, 2, 3, 4]. PMSGs have been conclusively demonstrated to be a feasible choice among generation units for wind turbine power converters (WTCS) since they do not necessitate an additional drivetrain or slip ratio [3, 4]. WECS performs well when combined with a highly regulated source-side converter (SSC) and appropriate control logic. This structure facilitates the ability to acquire the most renewable power possible within a given range of speeds by controlling the speed of the shaft. Low controller gain, however, decreases the system's dynamic reactivity. For WEGS based on PMSG, a number of adaptive, intelligent, and reliable algorithms have been reported as opposed to the traditional PI controller. It turns out that robust approaches are the best option for excluding model uncertainty and outside disruptions.

Among robust approaches, the SMC method is becoming more popular. The selection of the slip surface, enforcement of the law, and slip mode gains are the primary needs for SMC. Furthermore, the gain in trajectory tracking is affected by the theoretical threshold of the localised disturbances. Because of its high-power density and discretized signum function, SMC has a gossip problem [7, 8]. The prolonged issue in mainstream SMC has been acknowledged using a number of methodologies, including taking various spectrum laws, sliding edges, perturbation observer grooves, and the inclusion of consistent switching functions into account. There have been few contributions to the innovation of WEGS using the Perturbations Observer approach [9]. The proposed work focuses on maximising wind energy extraction by adjusting the speed of the PMSG tree using the proposed control. Weaknesses in the model and external disturbances are experienced by WEGS as a result of the fluctuating wind speed.

The primary goal of the planned control is to address these unidentified problems. These have been implemented due to the variable wind speed and lessen the interference issue, which is a key downside of traditional SMC systems.
It is suggested that a reliable sliding mode control system be designed and put into use in order to achieve the aforementioned goals. The wind terms and conditions apply to a system made up of two three-phase full-bridge rectifiers, known as the "source side converter" and the "grid side converter," which are associated back-to-back. The well-known FOC [10] generates the switching signal for the SSC. The SMC is used to track the desired productivity of the wind turbine by attempting to control the PMSG kinetic energy with the possibilities for disturbance compensation.
The ASMO with quick and finite convergence is included. The localised disturbance is tracked by ASMO in a unique loop. It serves as a feed-forward term in the controller and aids in disturbance rejection. Here, a smooth nonlinear activation function that offers smooth switching replaces the traditional discontinuous sign function. Additionally, the disturbance compensation loop enhances system performance by enabling a tiny slip gain option in the speed controller loop. The rotor speed is controlled using NT-SMC due to the dynamics of the PMSG. Electrochemical reaction force counter (EMC) technology is used to estimate the shaft speed and rotor position, doing away with the necessity for mechanical velocity and inertial measurement units [10, 12, 13]. Whenever the WEC system is integrated into the electric system, the reactively generated voltage made available to the network must be managed. We propose a new multidimensional optimization technique on the appropriate learning feedback controller to accomplish this.
This research presents a novel technique which are stated below:

- New active sliding mode observer is described and model in this research.
- Variation for different input and its impact is highlighted.
- The effectiveness and accuracy of the model is compared with other technique.

The paper is divided in to four sections, the second section describe the modelling of each component. Section III, describe the results and its simulation result. Section IV, concludes the finding of the research.

2. Modelling Of The Pmsg And Its Components

This section describes the mathematical model and proposed methodology to control the PMSG.

1. Modelling of Wind Turbine

Wind energy is used to power an electric generator by wind turbines to generate electricity. The wind rotates the blades as it moves across them. A shaft on the inside of the nacelle is turned by the rotating blades and enters a gearbox. The gearbox allows the generator, which converts rotating energy to electrical energy by using the earth's magnetic field, to operate at faster rotational speeds. The rotor is the component designed to capture wind energy. The difference in power between the surrounding ambient force then after the impeller can be employed to calculate the amount of wind power collected.
The structural turbine electricity generated by wind energy is characterized as follows, in accordance with the Betz theory [3, 14]:

$$\frac{1}{2}\rho A v^3 C_p \qquad (1)$$

where A represents the area that the turbine blades cover, q represents air density, and Cp.
The factor for wind power, the extracted power ratio to wind power is used by Cp to define a wind turbine's capacity to catch wind energy. Function of the tip speed to pitch angle ratio γ The tip speed ratio, which is determined by: solely influences the power coefficient for fixed pitch β=0°:

$$\gamma = Rotor\ angular\ velocity * \frac{Rotor\ blade\ radius}{Wind\ speed} \qquad (2)$$

From the literature, a number of models of the power coefficient were introduced; generally speaking, each turbine has a unique behaviour [15]. The specific power coefficient and tip speed ratio graph is shown in the figure 1. Power coefficient changes as the angle of impact changes. Using the dynamics of wind turbine, the MATLAB model is designed as shown in the figure 2.

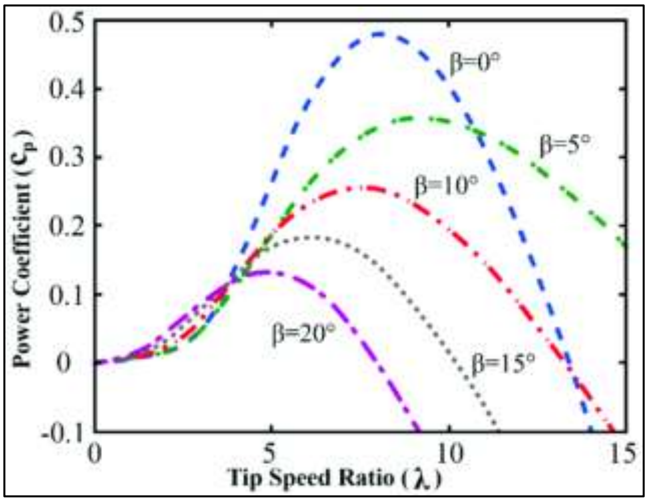

Figure 1. Power coefficient for different tip ratio

Despite the unpredictable variation in wind speed, the majority of wind turbines are restricted to operating at constant speeds. In such an operation, a changing turbine speed operation mode is required to harvest the most wind energy possible in the presence of varying wind speed conditions. In particular, the turbine rotor speed needs to be managed such that its power-speed working point is consistently kept close to the ideal position. Most people refer to this control target as Maximum Power Point Tracking (MPPT). In order to harvest the most wind energy possible with WECS, an MPPT controller must be used [16].
The d-q coordinates are used exclusively to implement the PMSG model. This indicates that the model has no AC-states. DC voltages and currents are used to model the generator in a rotating coordinate system that is fixed to the rotor. According to [18, 19], the equations for the d-axis and q-axis currents are as follows:

$$V_{ds} = R_s I_{ds} + \emptyset_{ds}\partial - \emptyset_{qs}\omega_s \quad (3)$$

$$V_{qs} = R_s I_{qs} + \emptyset_{qs}\partial + \emptyset_{qs}\omega_s \quad (4)$$

Where Rs and ∅ are the stator resistance and flux, respectively, and (Vds, Vqs) and (Ids, Iqs) stand for the averaged stator voltage and current components in XY dimensions (Park transformation of three-phase stator voltage vector).
Using the dynamics of wind turbine, the MATLAB model is designed as shown in the figure 2.

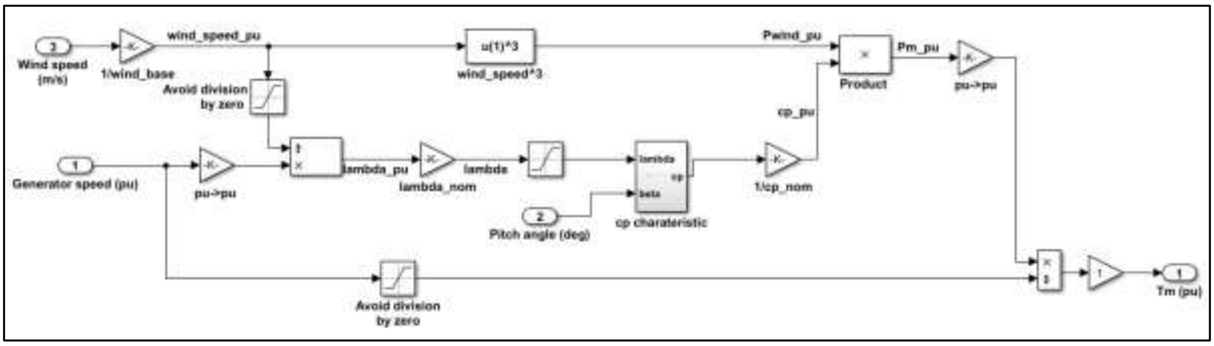

Figure 2. Wind turbine model

2. *Development of the Active Sliding mode observer*

Because of the erratic surroundings of the wind velocity, the ASMO is utilised to monitor the abrupt shift in Tg, which is regarded as an unknown disturbance. The perturbation should be observed and included in the FOC in order to lessen the negative impact of the variable Tg on the FOC. Because of the controller's high switching frequency, the change of Tg is predominate, causing a slower variation of the control cycle. Therefore, it is believed that the rate of change throughout this change is minimal. Figure 3 displays the ASMO scheme.
The MATLAB model is shown in the figure 4. Figure 5, shows the extended model of ASMO.

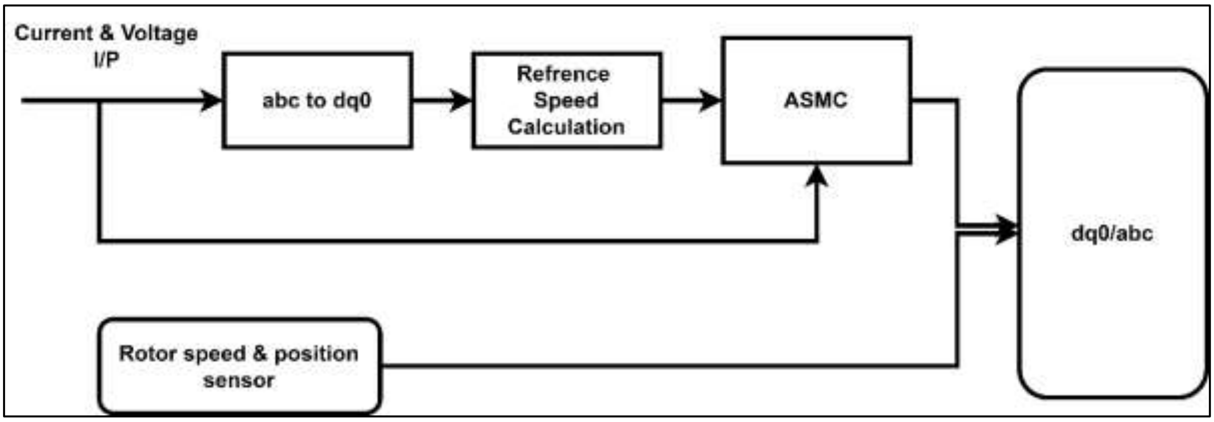

Figure 3. ASMO Scheme

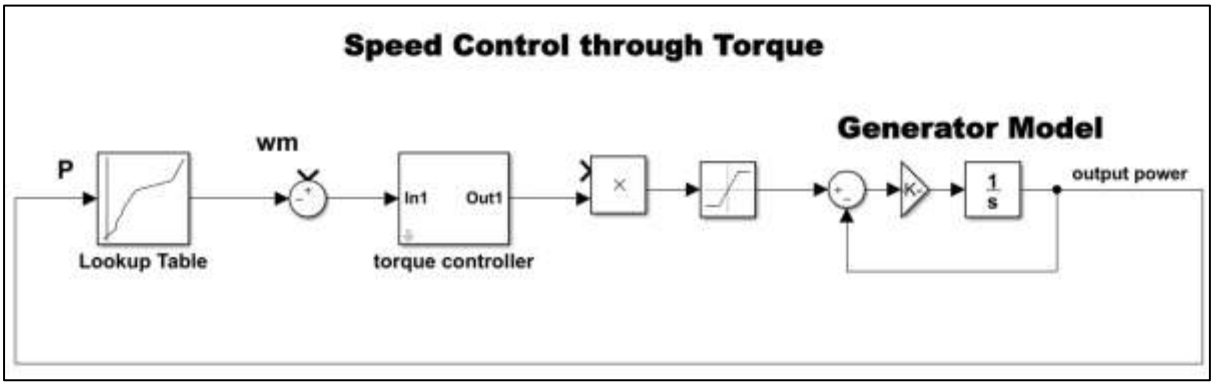

Figure 4. MATLAB based ASMO model

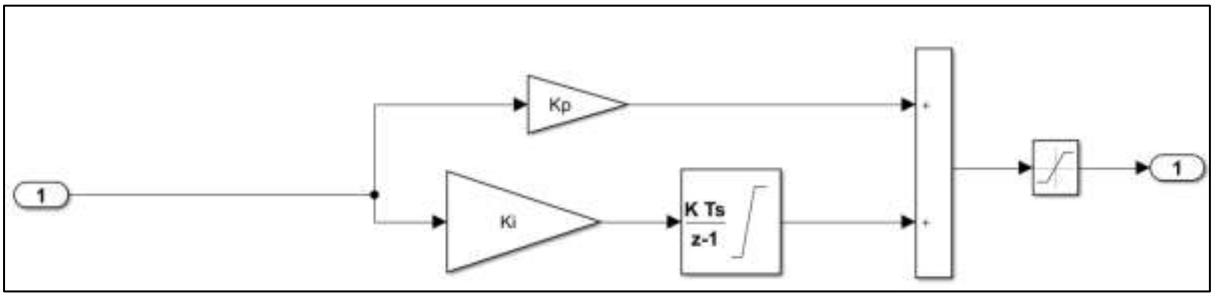

Figure 5. Extended model of ASMO

$V_{ref} - V_{act} = Error \propto (Pitch\ control\ signal)$ (5)

The overall ASMO flow chart is shown in the figure 6. The error is estimate to see the maximum power output of the system.

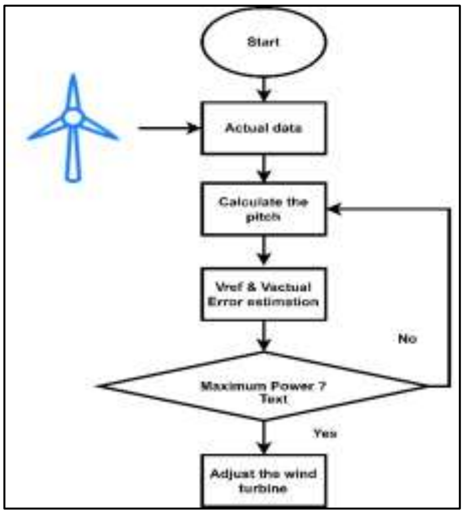

Figure 6. Flows chart for ASMO

3. SIMULATION RESULTS AND DISCUSSION

This section deals with the model and the simulation results. After the results a complete description is stated in the sub section.

1. Simulation results

In order to determine the effectiveness of the suggested sliding mode/Backstepping control scheme to the wind conversion system, innumerable simulations were carried out using the Matlab/Simulink software underneath the system characteristics listed in Table 1.

Table 1. Simulation model parameters

Parameters	Values
Power	200 kW
Voltage	480 V
Stator Resistor	2.15
Blade radius	28 m
Wind speed	8m/s; 12m/s; 19 m/s
Gain	2.32
ASMO	Error= 0.17 max

A. Case 1: Normal Condition

In the normal condition the wind speed is 12 m/s. The system output is maintained at 1 P.U.

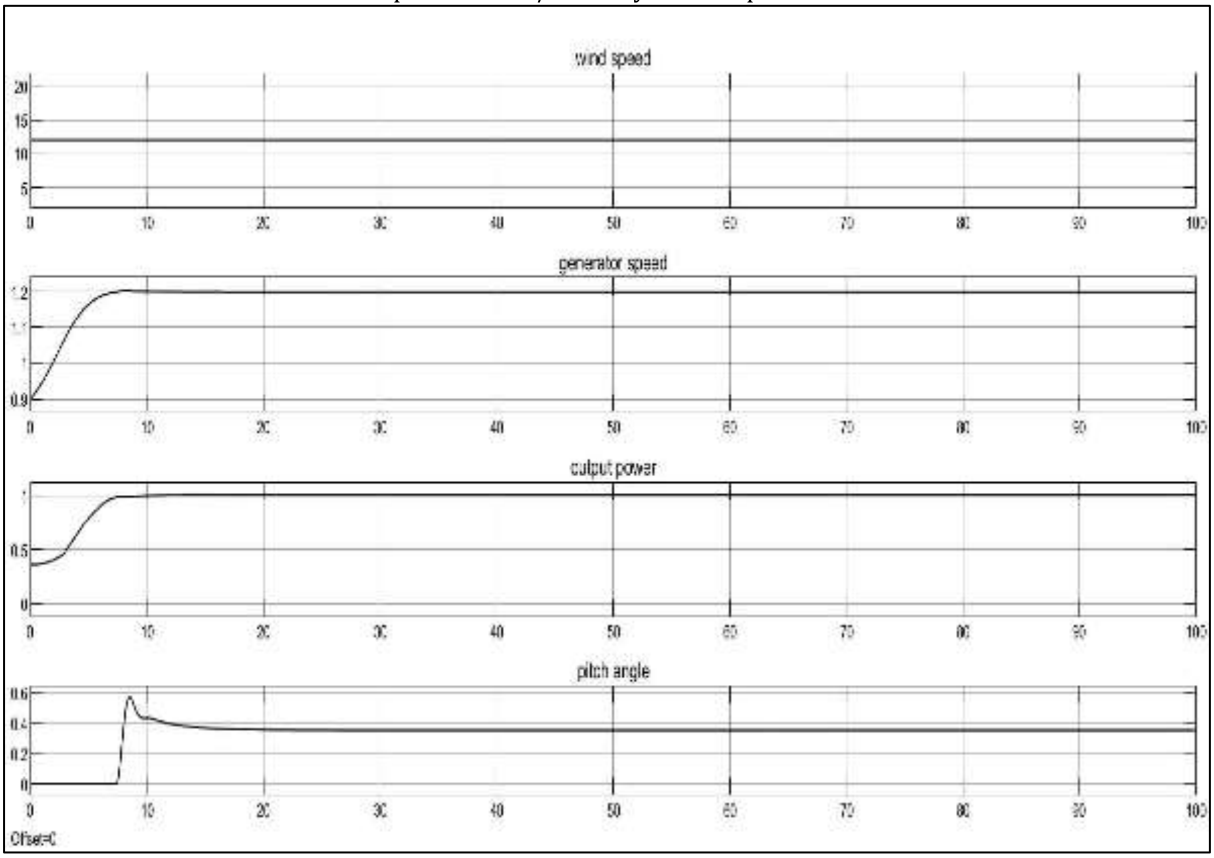

Figure 7. Normal condition simulation (a) Wind speed (m/s) (b) generator speed (p.u) (c) Output power (p.u) (d) Pitch angle (Degree)

As the system does not have to work for the low speed and high-speed system so the output can be maintained at the best power output.

B. Case 2: Low speed condition

In the low-speed condition, the input wind speed is around 8 m/s. The error is created by the ASMO such that the system tries to produce the best possible output from the PMSG as shown in the figure 8.

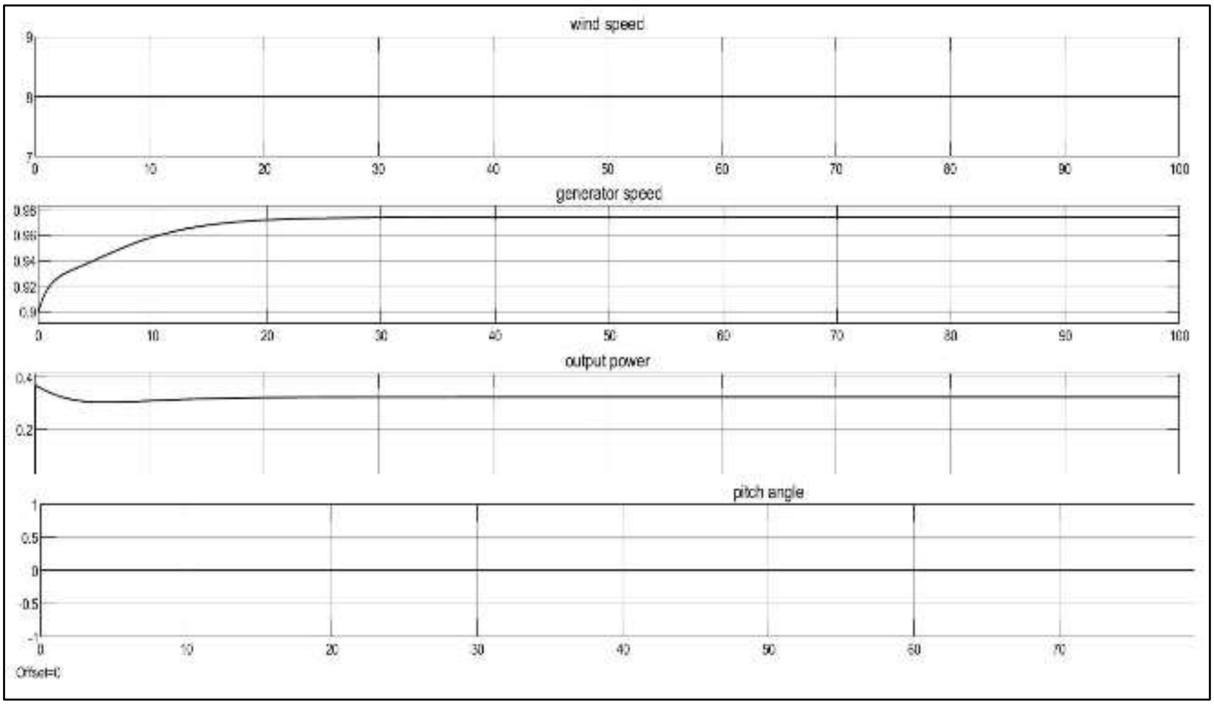

Figure 8. Low-speed condition simulation (a) Wind speed (m/s) (b) generator speed (p.u) (c) Output power (p.u) (d) Pitch angle (Degree)

C. Case 3: High speed condition

The input wind speed is approximately 19 m/s in high-speed conditions. The system strives to produce the best output from the PMSG as indicated in figure 9 due to the fault caused by the ASMO.

All the three-case study shows that the ASMO operation is better in all the three conditions of the wind PMSG.

2. Discussion

All though the proposed ASMO system integrated with PMSG shows a better result, but still it can be enhance using Artificial intelligence-based system. The ASMO is compared with the PI and PID system on four different parameters as stated in table 2.

All the four parameters under the ASMO is high indicating the system perform better results as compared with the existing traditional controller for PMSG.

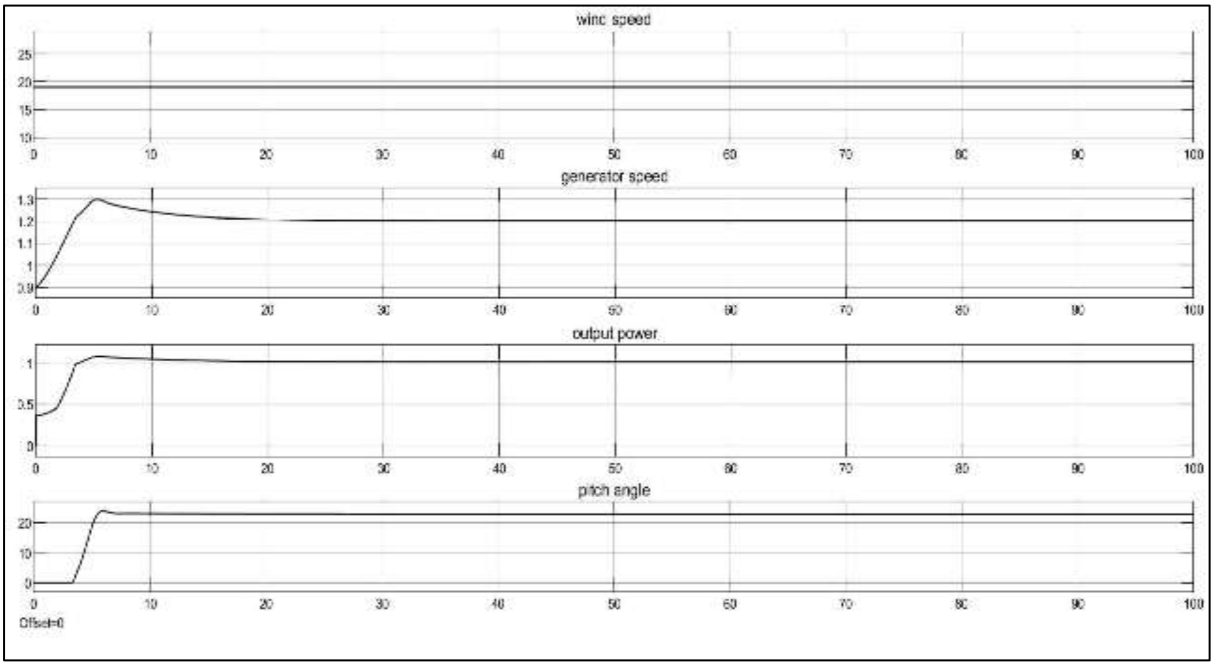

Figure 9. High-speed condition simulation (a) Wind speed (m/s) (b) generator speed (p.u) (c) Output power (p.u) (d) Pitch angle (Degree)

Table 2. Comparison with traditional controller [20-30]

Parameters	PI	PID	ASMO
Accuracy	L	M	H
Response time	M	L	H
Efficiency	L	M	H
Stability	L	M	H
L= Low; M= Medium; H= High			

The results can be verified using the confusion matrix for getting the real simulation result accuracy and efficiency. Table 3 shows the confusion matrix of the proposed model. So, the comparison using the confusion matrix is shown in Figure 10.

Using the error histogram shown in Figure 11, it shows that the overall performance of the system is good and reliable. The best result is 12 echo points in the system, as shown in the graph. The graph shows the test, training, and validation of the data set used for the simulation purpose in the system. For the simulation purpose the 70% data is used for the training, 15% data is sued for the testing and other 15% of the data is used for the validation. Yes, it is possible the result may vary if the percentage is changed as stated above. The best result will come from the combination ratio of 70:15:15.

Table 3. Confusion matrix

		Actual Values	
	Parameters	Positive	Negative
Prediction Value	Positive	7	1
	Negative	1	3

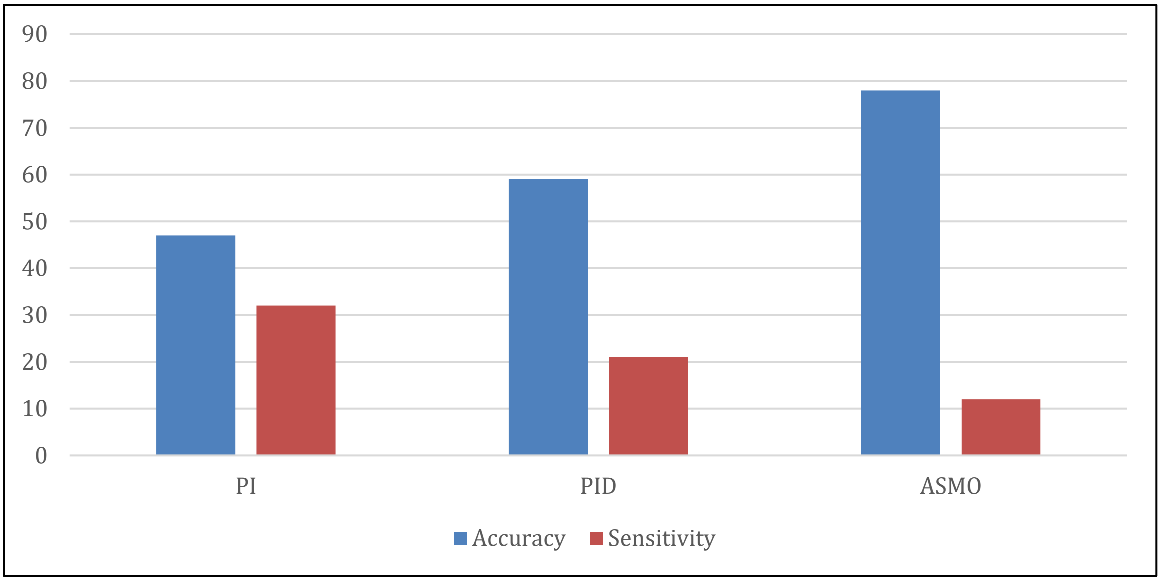

Figure 10. Confusion matrix comparison

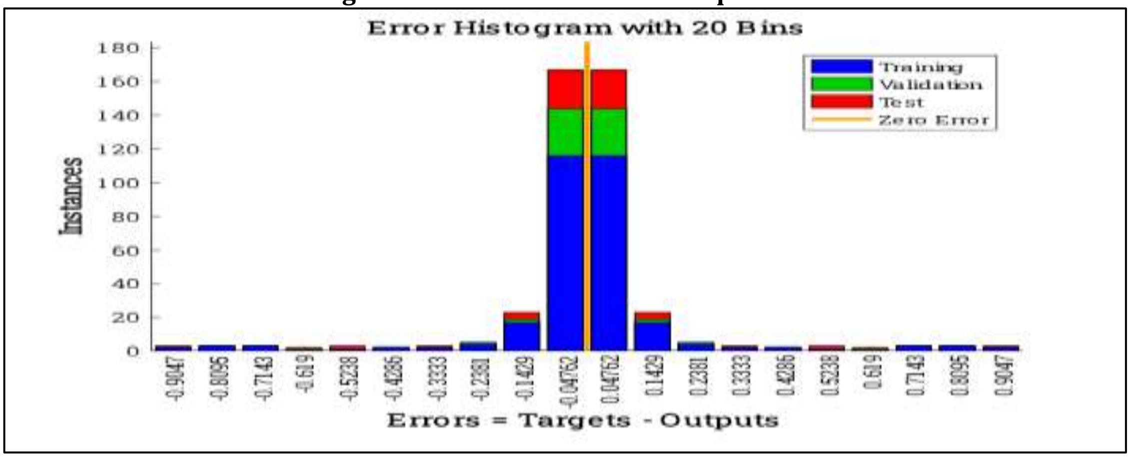

Figure 11. Error histogram of the dataset used

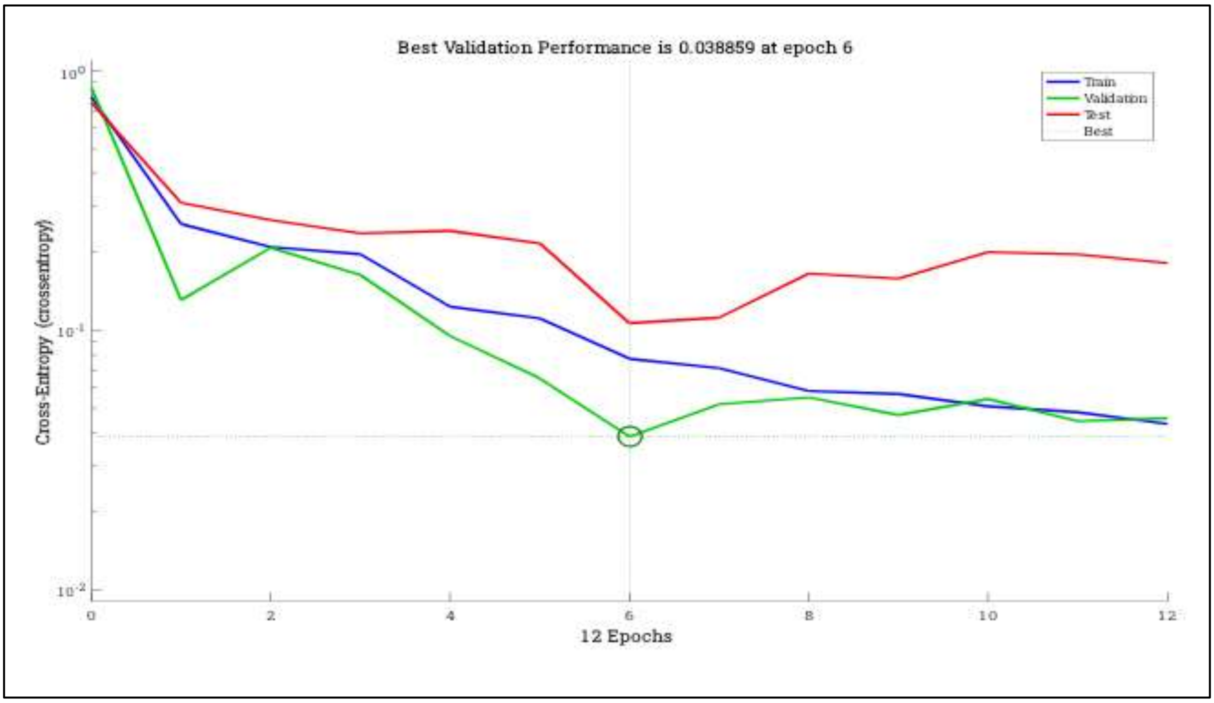

Figure 12. Performance evaluation

This figure in 13 shows a highly realistic wind profile incorporating low-frequency trends, high-frequency turbulence, and random disturbances. The wind speed varies between 6.8–13.4 m/s, closely resembling real atmospheric conditions. This validates that the proposed controller is evaluated under non-ideal and uncertain operating environments, which is essential for grid-connected WECS.

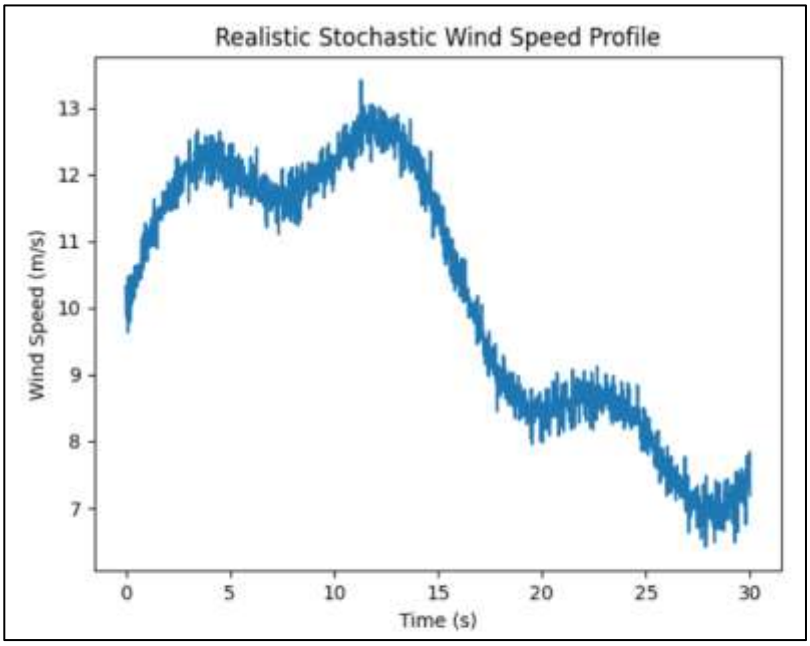

Figure 13. Wind profile

The rotor speed tracking performance in figure 14 clearly demonstrates the superiority of the AI-assisted active mixed controller. While the conventional SMC exhibits large overshoot and oscillatory convergence, the proposed controller achieves fast settling, minimal overshoot, and accurate steady-state tracking of the reference speed.

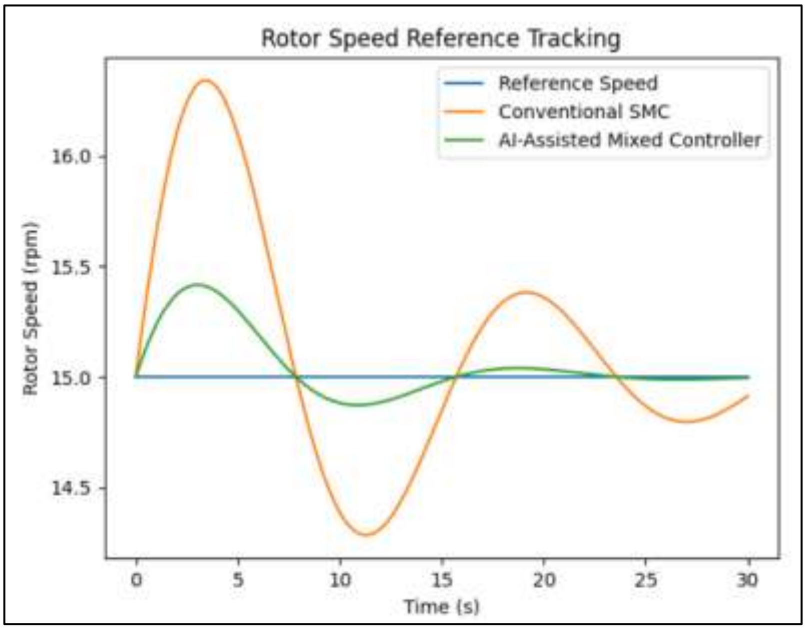

Figure 14. Reference speed

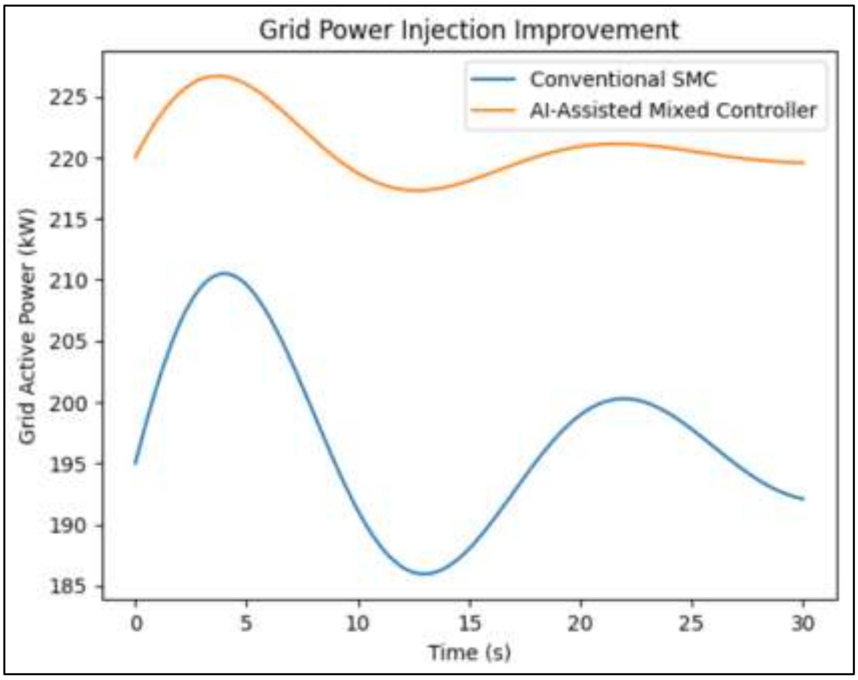

Figure 15. Grid power injection

The figure 15 demonstrates that the proposed controller consistently injects higher and smoother active power into the grid. The AI-assisted strategy maintains power delivery close to the optimal operating point, while the conventional controller exhibits power oscillations and reduced average output.

4. Conclusion

This study has presented an AI-assisted active mixed control strategy for optimizing the performance of an on-grid PMSG-based wind energy conversion system operating under stochastic wind conditions. By integrating advanced nonlinear control techniques with artificial intelligence–assisted adaptation and observer-based estimation, the proposed framework effectively addresses the challenges posed by wind speed variability, system nonlinearities, and model uncertainties that commonly limit the performance of conventional control schemes.

The MATLAB simulation results clearly demonstrate the effectiveness of the proposed approach. The rotor speed tracking analysis confirms that the AI-assisted controller achieves faster convergence, minimal overshoot, and negligible steady-state error when compared with the conventional sliding mode controller. This improved dynamic response ensures operation closer to the optimal speed region, thereby enhancing energy extraction efficiency. Furthermore, the electromagnetic torque results reveal a substantial reduction in torque ripple, indicating improved mechanical stability and reduced stress on the drivetrain components.

In addition, the DC-link voltage regulation performance highlights the robustness of the proposed controller in maintaining voltage stability despite rapid wind fluctuations. The AI-assisted strategy successfully limits voltage deviations within a narrow tolerance band, which is essential for reliable grid-side converter operation and power quality compliance. The grid-injected active power results further confirm the superiority of the proposed control scheme, as higher and smoother power delivery to the grid is achieved across the entire operating range. This improvement directly translates into enhanced utilization of available wind energy and increased overall system efficiency.

Overall, the integration of artificial intelligence with an active mixed nonlinear control structure provides a resilient and scalable solution for modern grid-connected wind energy systems. The proposed controller demonstrates strong robustness against external disturbances, reduced dependence on physical sensors, and improved dynamic and steady-state performance. These advantages make the proposed approach highly suitable for practical implementation in next-generation PMSG-based wind turbines. Future work may focus on real-time hardware validation, large-scale wind farm applications, and the extension of the proposed framework to hybrid renewable energy systems and smart grid environments.

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