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Comparative analysis between classical and third-order sliding mode controllers for maximum power extraction in wind turbine system

Introduction. *Maximizing power extraction in wind energy conversion systems is crucial for efficiency but remains a challenge due to rapid wind speed variations and the high inertia of the generator. Conventional controllers, such as the PI controller, struggle to maintain optimal performance under such dynamic conditions, leading to suboptimal power capture and increased system oscillations. The* ***goal*** *of this study is to enhance the efficiency of wind turbine systems by applying linear and nonlinear controllers in a maximum power point tracking (MPPT) strategy. This approach focuses on improving generator speed regulation and power conversion performance.* ***Methods.*** *A comparative analysis is conducted using three different control strategies: third-order sliding mode control (TO-SMC), classical sliding mode control (SMC) and PI control. These controllers are implemented in the generator speed loop of a wind turbine system, and their performance is evaluated through MATLAB/Simulink simulations. The assessment focuses on key performance metrics such as tracking accuracy, total harmonic distortion (THD), response time, and system stability.* ***Results****. The simulation results confirm that all controllers achieve MPPT, but with varying levels of effectiveness. The TO-SMC outperforms both SMC and PI controllers, offering higher efficiency, reduced chattering, better disturbance rejection, and lower THD (reduced from 73 % in SMC to 68.09 %). Additionally, TO-SMC significantly improves dynamic response, reducing overshoot and enhancing system stability.* ***Originality.*** *This study introduces a TO-SMC for MPPT in wind turbine systems, demonstrating its superiority over conventional control techniques. The findings highlight its ability to maintain optimal power extraction even under rapid wind variations, making it a promising solution for advanced wind energy systems.* ***Practical value.*** *By improving power quality, reducing system oscillations, and enhancing overall wind turbine efficiency, the proposed TO-SMC contributes to the reliable integration of wind energy into power grids. These advancements can benefit renewable energy operators, power system engineers, and researchers seeking efficient and robust MPPT solutions for wind turbines.* References 13, figures 11.

Key words: **wind turbine, maximum power point tracking, third-order sliding mode control, variable speed wind turbines.**

Вступ*. Максимізація відбору потужності в системах перетворення енергії вітру має вагоме значення для ефективності, але залишається проблемою через швидкі зміни швидкості вітру та високу інерцію генератора. Звичайні контролери, такі як ПІ-контролер, важко підтримують оптимальну продуктивність в таких динамічних умовах, що призводить до неоптимального відбору потужності і збільшення коливань системи.* ***Метою*** *статті є підвищення ефективності систем вітряних турбін шляхом застосування лінійних та нелінійних контролерів у стратегії відстеження точки максимальної потужності (MPPT). Цей підхід фокусується на покращенні регулювання швидкості генератора та продуктивності перетворення енергії.* ***Методи****. Порівняльний аналіз проводиться з використанням трьох різних стратегій управління: керування ковзним режимом третього порядку (TO-SMC), класичне керування ковзним режимом (SMC) та ПІ-керування. Ці контролери реалізовані в контурі швидкості генератора системи вітряних турбін, а їх продуктивність оцінюється за допомогою моделювання MATLAB/Simulink. Оцінка фокусується на ключових показниках продуктивності, таких як точність відстеження, повне гармонічне спотворення (THD), час відгуку та стабільність системи.* ***Результати*** *моделювання підтверджують, що ці контролери досягають MPPT, але з різним рівнем ефективності. TO-SMC перевершує як SMC, так і ПІ-регулятори, пропонуючи більш високу ефективність, знижене коливань, краще зменшує перешкоди та має менше THD (знижений з 73 % у SMC до 68,09 %). Крім того, TO-SMC значно покращує динамічний відгук, зменшуючи перерегулювання та підвищуючи стабільність системи.* ***Оригінальність****. Це дослідження представляє TO-SMC MPPT в системах вітряних турбін, демонструючи його перевагу над традиційними методами управління. Результати підкреслюють його здатність підтримувати оптимальний відбір потужності навіть за швидких змін вітру, що робить його перспективним рішенням для сучасних вітроенергетичних систем.* ***Практична цінність****. За рахунок покращення якості електроенергії, зниження коливань системи та підвищення загальної ефективності вітрових турбін пропонований TO-SMC сприяє надійній інтеграції енергії вітру в електромережі. Ці досягнення можуть принести користь операторам відновлюваних джерел енергії, інженерам енергосистем та дослідникам, які шукають ефективні та надійні рішення MPPT для вітрових турбін.* Бібл. 13, рис. 11.

Ключові слова: **вітряна турбіна, відстеження точки максимальної потужності, керування ковзним режимом третього порядку, вітряні турбіни зі змінною швидкістю.**

Introduction. The use of renewable energies is increasing day by day, all over the world to reduce pollution and carbon dioxide emissions, and to reduce climate change. Due to the significant rise in oil and gas prices many countries have put within their strategies to develop the electricity sector the exploitation of wind energy as a priority because it is one of the cleanest and most preferred sources of electricity generation [1]. Among the most widely used wind energy conversion systems that depend on the doubly fed induction generator (DFIG) [2, 3], its main advantage is that the rotor side converter, which exceeds 30 % of the rated power and therefore the lowest cost of the power converter, and their capacity to power at constant voltage and frequency, whatever the speed of the rotor rotation [4, 5]. There are modern methods developed to control wind turbines in order to maximum power point tracking (MPPT) [6, 7]. The principle of the method is modeling turbine and the DFIG, and then a synthesis of the different control strategies [8, 9]. We can cite some strategies which are used. The vector control is the most popular method used in the DFIG [10].

The **goal** of this paper is the enhancement of wind turbine system performance through the application of a third-order sliding mode control (TO-SMC) controller. This controller improves performance by minimizing overshoot, ensuring a more stable and controlled response, reducing response time to enhance efficiency, and eliminating the error between reference and measured values. Additionally, addressing the chattering problem is crucial, as it mitigates high-frequency disturbances around the sliding mode surface, leading to smoother operation and greater overall stability. This controller can also reduce the mechanical stresses by isolating the vibration between the rotor blades and generator shaft. The TO-SMC controller is used to perform the non-linear system compared to PID controller which can only be used for linear system.

Modeling of wind turbine. The main purpose of wind turbines is to convert kinetic energy into aerodynamic power through the blades. In order to model a wind turbine, the following elements must be modeled: Modeling of the wind speed, modeling of the aerodynamic part and modeling of the mechanical system.

Modeling of wind speed. It is usually modeled by complex and random variations with deterministic effects and stochastic fluctuations due to turbulence:

$$V(t) = A_0 + \sum_{i=1}^{n} A_i \sin\cdot\left(\frac{2\pi t}{T_i}\right), \quad (1)$$

where A_0 is the average wind value; A_i is the amplitude of each turbulence; $2\pi/T_i$ is the pulsation of every turbulence.

Modeling of the aerodynamic part. This model represents the aerodynamic power at the slow part level of a turbine. In addition, it evaluates the aerodynamic torque T_{ar} as a function of wind turbine angular speed ω_t. In general, the aerodynamic power available form a wind turbine changes with wind speed and can be expressed as:

$$P_{ar} = \frac{1}{2}\rho C_p(\lambda,\beta)SV^3, \quad (2)$$

where P_{ar} is the aerodynamic power; ρ is the air density; C_p is the power coefficient; λ is the tip-speed ratio; β is the pitch angle; S is the blade surface; V is the wind speed.

Knowing the speed of the wind turbine, the aerodynamic torque can be expressed as [5–8]:

$$T_{ar} = \frac{1}{2\Omega_t}\rho C_p(\lambda,\beta)SV^3, \quad (3)$$

where Ω_t is the turbine speed.

Modeling of the mechanical system. In fact, the mechanical system of wind turbines consists of many elements, and therefore its entire representation is complex. In this system, there are many models: 6 masses, 3 masses, 2 masses and 1 mass. It is hence essential to choose the dynamics to represent and the typical values of their characteristic parameters. In this work, the mechanical system is represented by one mass model. In this model, the inertia of the wind turbine on the slow shaft is transferred to the fast shaft. The turbine speed Ω_t and driving torque T_g in the fast shaft are given by:

$$\begin{cases} \Omega_t = \Omega_g / N; \\ T_g = T_{ar} / N, \end{cases} \quad (4)$$

where N is the gearbox ratio.

The generator speed Ω_g is given by:

$$J_t \frac{d\Omega_g}{dt} = T_g - T_{em} - f_t\Omega_g, \quad (5)$$

where

$$J_t = J_r / N^2 + J_g \quad \text{and} \quad f_t = f_r / N^2 + f_g,$$

J_g is the inertia of the generator; J_r is the inertia of the wind turbine; J_t is the total moment of inertia; f_g is the viscous friction coefficient of the generator rotor; f_r is the viscous friction coefficient of the turbine rotor; f_t is the total viscous friction coefficient.

To optimize the power generated, it is therefore appropriate for the generator to have a power or characteristic torque follows the maximum line $C_{p,\max}$ with the angle of $\beta = 0°$. Figure 1 shows an example of power coefficient curves of a wind turbine, showing the evolution of the power coefficient C_p as a function of the tip-speed ratio λ for different values of the pitch angle β.

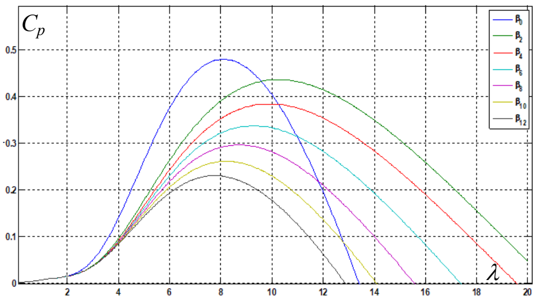


Fig. 1. Power coefficient C_p as a function of λ and β

Figure 2 shows the block diagram of the aerodynamic and mechanical modeling for the wind turbine.

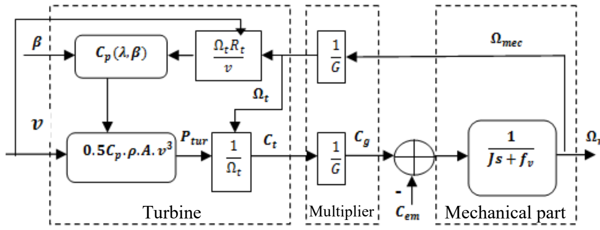


Fig. 2. Modeling of the mechanical part of the wind turbine

Control of variable speed wind turbine below rated power. The objective of variable speed wind turbine control, when the wind speed is below the rated speed, is to maximize the aerodynamic power by using the different power maximization strategies. This power is maximized through the electromagnetic torque control. At a wind speed above the rated speed, the objective of the control is to limit the aerodynamic power transmitted to the generator and to keep the turbine within its operating limits by using the different control strategies. Indeed, effective control of variable speed wind turbines can improve the dynamic characteristics, increase the turbine lifetime and reduce the transient load on the drive shaft. Many techniques have been proposed for the maximum extraction or limitation of aerodynamic power from variable speed wind turbine in the last decade. Generally, the control of wind turbine goes through 3 different operating zones which depend on the wind speed, the maximum allowable generator speed and the desired power (Fig. 3) [8].

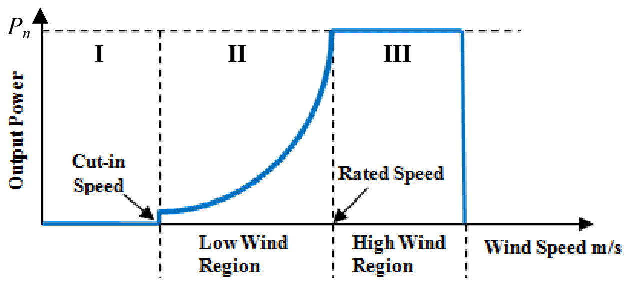


Fig. 3. Wind region classification

Zone I. In this zone, the generator is stopped, because the wind speed is not high enough to operate the wind system, and therefore it does not produce any electrical power P_{el}

$$\begin{cases} V \le V_{\min}; \\ P_{el} = 0. \end{cases} \tag{6}$$

Zone II. This area is characterized by operation at wind speeds less than or equal to the nominal speed. For this reason, we seek to maximize the aerodynamic power in order to extract the maximum aerodynamic power. With this strategy, we seek the maximum power point for each wind speed, it is the MPPT. This area is called is characterized by operation at partial load. In this case, it should be noted that the orientation angle of the blades must be constant and always equal to zero ($\beta = 0°$), and the relative speed of the turbine is at its optimum value (λ_{opt}). In this area:

$$\begin{cases} V_{\min} < V \le V_n; \\ P_{aer,\max} = 0.5 \cdot C_{p,\max} \rho S V^3. \end{cases} \tag{7}$$

Zone III. This zone is characterized by operation at wind speeds higher than the nominal speed. It is called the nominal load operating zone. In this zone, a control action is used on the turbine blades to maintain the aerodynamic power P_{aer} within its nominal power value P_n, to ensure the safety of the generator and to limit the mechanical loads transmitted to the nacelle and the tower. If the wind speed exceeds the maximum speed, the control system adjusts the blade pitch angle to the value ($\beta = 90°$) to stop the generator. In this zone:

$$\begin{cases} V_n < V \le V_{\max}; \\ P_{aer} = P_n. \end{cases} \tag{8}$$

The synthesis of this controller can be carried out in 3 successive steps [11, 12]:

- definition of the surface;
- choice of the Lyapunov's function to ensure the stability of the system;
- determination of the equivalent control law.

The purpose of the TO-SMC controller is to ensure that the measured value follows the trajectory of the reference value. The generator speed tracking error can be defined as follows. To apply the SMC strategy a surface must be defined. Equation (9) represents a sliding surface for controlling the speed generator:

$$S_{\Omega g} = \lambda \Omega_g^* - \lambda \Omega_g + \frac{\mathrm{d}(\Omega_g^* - \Omega_g)}{\mathrm{d}t}. \tag{9}$$

From (9) the derivative of the error is given by:

$$\dot{S}_{\Omega g} = \lambda \dot{\Omega}_g^* - \lambda \dot{\Omega}_g + \ddot{\Omega}_g^* - \ddot{\Omega}_g. \tag{10}$$

Substituting (5) and the derivative of (5) into (10) we obtain:

$$\begin{aligned} \dot{S}_{\Omega g} = {} & \lambda \dot{\Omega}_g^{ref} - \frac{\lambda}{J_g}\left[T_g - T_{em} - f_g \Omega_g\right] + \\ & + \ddot{\Omega}_g^* - \frac{1}{J_g}\left[\dot{T}_g - \dot{T}_{em} - f_g \dot{\Omega}_g\right] \end{aligned} \tag{11}$$

For the stability study of the closed-loop system, we will use the Lyapunov's stability theorem. The Lyapunov's candidate stability function is defined by:

$$V_{\Omega g} = \frac{1}{2} S(\Omega_g)^2. \tag{12}$$

The derivative of the Lyapunov's function is defined in the next expression:

$$\dot{V}_{\Omega g} = \dot{S}(\Omega_g) \cdot S(\Omega_g) < 0. \tag{13}$$

The control law has to ensure the stability condition and the convergence of the trajectories of the system on the sliding surface $S(\Omega_g) = 0$ from:

- if $S(\Omega_g) < 0$ and $\dot{S}(\Omega_g) < 0$, therefore $S(\Omega_g)$ will increase to 0;
- if $S(\Omega_g) > 0$ and $\dot{S}(\Omega_g) < 0$, therefore $S(\Omega_g)$ will increase to 0.

In steady state, the equivalent control is calculated by considering that the developed electromagnetic torque and its reference are equal, so the control law becomes:

$$T_{em}^* = \alpha_{\Omega g} \sqrt{\left|S(\Omega_g)\right|}\,\mathrm{sign}\big(S(\Omega_g)\big) + \beta_{\Omega g} \int \mathrm{sign}\big(S(\Omega_g)\big)\mathrm{d}t, \tag{14}$$

where $\alpha_{\Omega g}$ and $\beta_{\Omega g}$ are the controller gains and must be positive.

Simulation results and discussion. In order to highlight the performance of the MPPT control algorithms applied to the one-mass wind turbine and the objective a comparison of the control techniques that we have presented, we will carry out a series of simulations in MATLAB/Simulink environment (Fig. 4). All these simulations will be carried out under the same conditions:

- the wind speed profile by (1);
- the blade orientation angle is maintained at its zero value ($\beta = 0°$). The wind turbine parameters are reported in [12, 13].

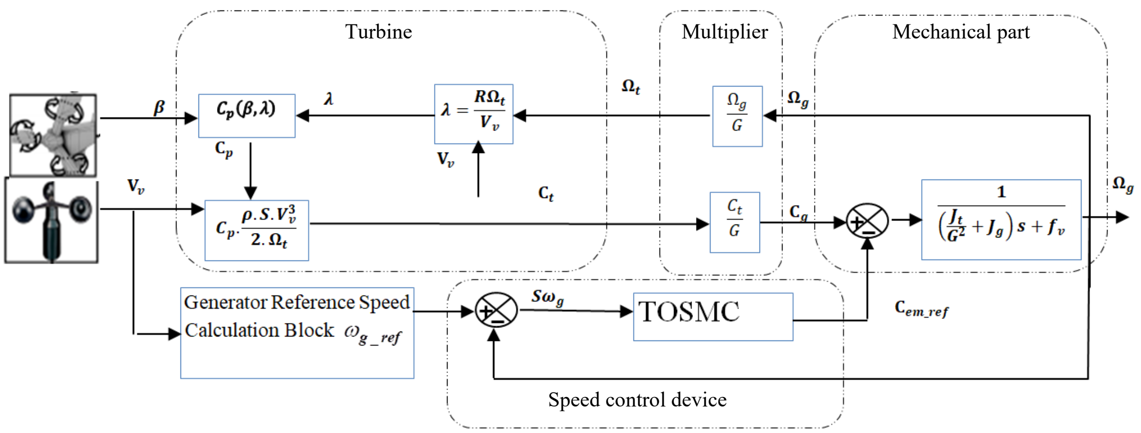


Fig. 4. Block diagram of the TO-SMC

Figures 5–10 illustrate wind turbine MPPT performance as a function of wind speed using (1). From the simulation results it is observed that for TO-SMC the power extracted by the turbine follows the desired trajectory with good efficiency. For the SMC and PI controllers the variations of the wind speed cause significant oscillations of the aerodynamic torque, which increases the mechanical stress of the turbine and electromagnetic vibrations at the generator level, which affects the quality of the electrical energy supplied to the electrical grid. From Fig. 5–10 it can be seen that this proposed TO-SMC strategy has better response characteristics in settling time and overshoot compared with both SMC and PI.

Figures 11,*a*,*b* show harmonic spectral analysis, which show the total harmonic distortion with the SMC controller (THD = 73.2 %) are significantly attenuated with the TO-SMC controller (THD = 68.09 %).

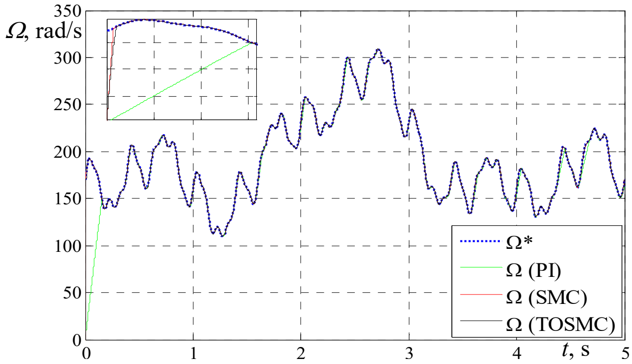


Fig. 5. Generator rotation speed

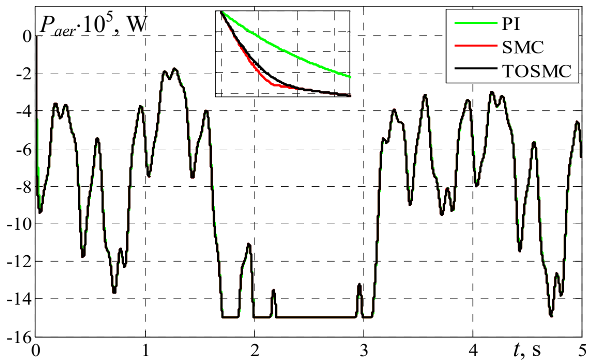


Fig. 6. Aerodynamic power

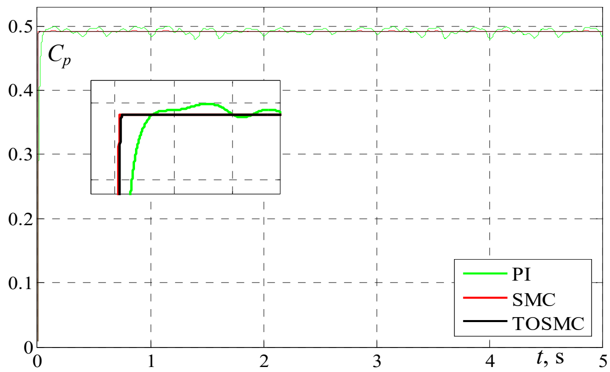


Fig. 7. Power coefficient

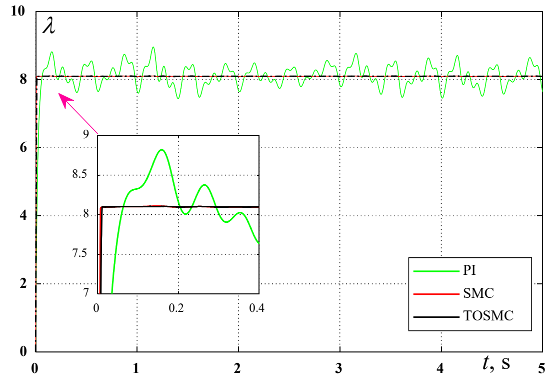


Fig. 8. Tip speed ratio

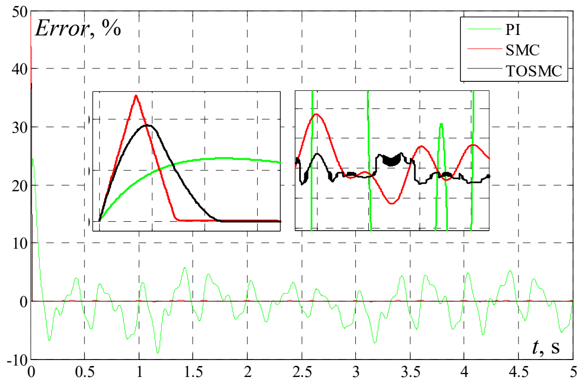


Fig.9. Generator rotation speed error

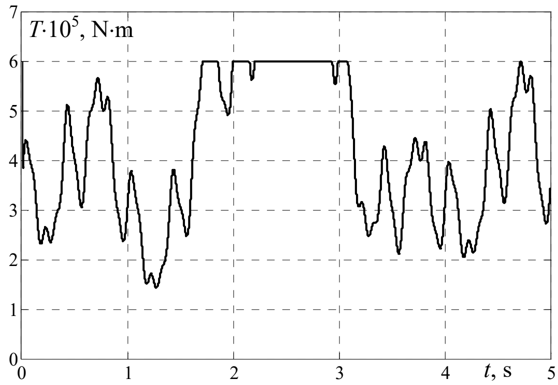
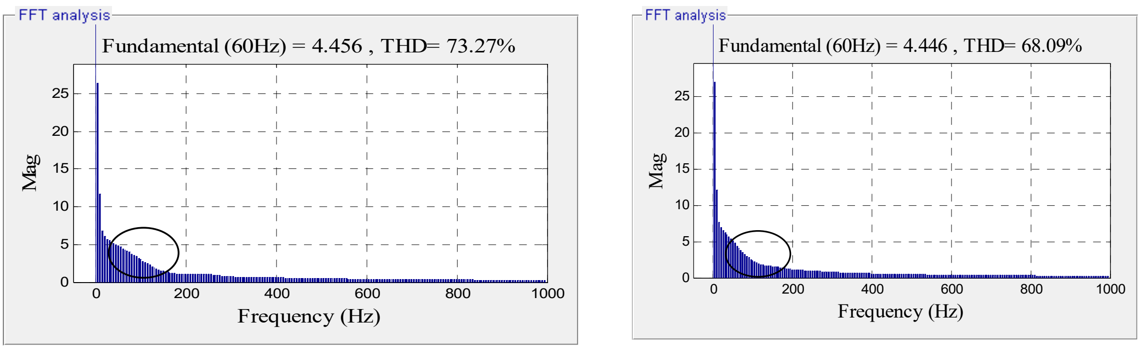


Fig. 10. Generator torque



a) SMC *b*) TO-SMC

Fig. 11. Total harmonic distortion

Conclusions. In this study, the TO-SMC is used to perform the tip speed ratio strategy in order to extract maximum power from the wind energy. The results obtained illustrate that non-linear controller TO-SMC can improve the performance of wind turbine system by accurately tracking the generator speed reference and achieving the maximum power coefficient. A comparative analysis of PI, SMC and TO-SMC controllers highlights the superior effectiveness of TO-SMC controller. Compared to the other controllers, TO-SMC generates less chattering, provides better disturbance rejection, and reduces mechanical stress on the transmission shaft. In contrast, conventional PI-based direct speed control and classic SMC exhibit lower efficiency, increased oscillations, and diminished overall performance.

The practical significance of this work is evident in the improved wind turbine efficiency, reflected by a reduction in THD from 73 % to 68.09 %, along with enhanced dynamic response, minimized overshoot, and faster settling time. These improvements contribute to more stable and higher-quality power generation, supporting the seamless integration of wind energy into electrical grids.

Conflict of interest. The authors declare that they have no conflicts of interest.

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