

Article

An Intelligent Fuzzy Third-Order Sliding Mode Strategy for Energy Management of DFIG-Based Wind Energy Systems

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Abstract

The doubly fed induction generator (DFIG) has become one of the most widely adopted technologies in modern wind energy conversion systems due to its high efficiency, flexible operation, and capability to operate under variable wind-speed conditions. Nevertheless, maintaining high power quality, reducing harmonic distortion, and ensuring reliable operation under parameter uncertainties and grid disturbances remain major challenges. Conventional proportional–integral (PI)-based control approaches often suffer from limited robustness and sensitivity to system nonlinearities, which can adversely affect the dynamic performance and operational stability of wind energy systems. To address these limitations, this paper proposes an advanced hybrid control strategy based on the integration of fuzzy logic (FL) and a third-order sliding mode controller (TOSMC) for the control of DFIG-based wind turbines. The proposed FL–TOSMC combines the robustness and fast convergence properties of sliding mode control with the adaptive capability of fuzzy logic, thereby reducing dependence on accurate mathematical models and enhancing tolerance to parameter variations and external disturbances. The developed controller is applied to maximum power point tracking (MPPT) and direct field-oriented control of the DFIG to maximize energy extraction and ensure stable power regulation. The simulation results obtained in the MATLAB 2021/Simulink environment demonstrate that the proposed strategy improves the dynamic response of the system by reducing overshoot, accelerating error convergence, minimizing steady-state oscillations, and decreasing total harmonic distortion compared with the conventional TOSMC approach. Furthermore, the proposed controller provides enhanced tracking performance, improved robustness against parameter uncertainties, and better power-quality characteristics under various operating conditions. These results indicate that the FL–TOSMC approach is an effective control solution for improving the operational performance of DFIG-based wind energy conversion systems.

Keywords: fuzzy logic; third-order sliding mode controller; maximum power point tracking; direct field-oriented control; doubly fed induction generator

Academic Editor: Bo Yang

Received: 26 May 2026

Revised: 11 July 2026

Accepted: 13 July 2026

Published: 16 July 2026

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1. Introduction

Wind energy (WE) has become one of the fastest-growing renewable energy sources owing to its sustainability, environmental benefits, and ability to satisfy the increasing global demand for electrical power (EP). Wind turbines (WTs) convert the kinetic energy of the wind into mechanical power, which is subsequently transformed into electrical energy through electrical generators [1]. Compared with conventional fossil-fuel-based generation, WE contributes to reducing greenhouse gas emissions, lowering energy production costs, and improving energy independence, particularly in countries with limited fossil resources [2,3]. Among WT technologies, horizontal-axis wind turbines (HAWTs) are the most widely deployed because of their superior aerodynamic efficiency and higher power generation capability compared with vertical-axis wind turbines (VAWTs) [4–6].

To further increase energy capture, multi-rotor WT (MRWT) technology has recently attracted considerable attention. Instead of relying on a single large rotor, MRWT systems integrate multiple rotors within the same structure, leading to improved energy extraction, enhanced operational stability, and better performance under severe wind conditions [7–11].

Among the various electrical generators employed in WE conversion systems (WECSs), the doubly fed induction generator (DFIG) remains the preferred solution because of its variable-speed operation, independent active and reactive power (P_s and Q_s) control, reduced converter rating, low maintenance requirements, and relatively low implementation cost [12–19]. Nevertheless, DFIG-based WECSs still face important challenges, including power fluctuations, sensitivity to parameter variations, and deterioration of power quality (PQ), particularly under variable wind conditions.

Numerous control techniques have been proposed to improve the performance of DFIG-based systems, including direct torque control (DTC), synergetic control (SC), vector control (VC), backstepping control (BC), direct power control (DPC), field-oriented control (FOC), sliding mode control (SMC), and high-order SMC methods [20–27]. Among these approaches, FOC remains one of the most widely adopted owing to its simple implementation, fast dynamic response, and reliable decoupled control of P_s and Q_s [28–30]. Depending on the rotor flux orientation strategy, FOC can be implemented as direct FOC (DFOC) or indirect FOC (IFOC), where DFOC offers a simpler structure with fewer controllers while maintaining satisfactory dynamic performance [31–33].

Despite these advantages, conventional DFOC based on proportional–integral (PI) controllers suffers from power ripples, limited robustness, and relatively high current total harmonic distortion (THD), especially under parameter uncertainties [34]. Consequently, considerable research has focused on enhancing DFOC performance through advanced modulation and intelligent control techniques. Several studies have combined DFOC with modified space vector modulation (MSVM), fuzzy logic (FL), neural networks (NNs), super-twisting control, model predictive control, and higher-level multilevel converters to improve PQ, reduce THD, and enhance robustness [35–41]. Although these methods significantly improve certain performance indices, they often increase computational complexity, require accurate mathematical models, depend on heuristic tuning procedures, or still exhibit considerable power ripples under disturbed operating conditions.

The third-order SMC (TOSMC) method has recently emerged as an attractive nonlinear control strategy because of its strong robustness, fast dynamic response, low control gain, and reduced dependence on the mathematical model of the controlled system [42–45]. Its application to DFIG-based WT and MRWT systems has demonstrated noticeable improvements in tracking performance, MPPT efficiency, ripple reduction, and current quality compared with conventional PI-based DFOC [44,46]. Nevertheless, previous investigations indicate that TOSMC performance may still degrade under parameter uncertainties and external disturbances, motivating the development of more adaptive control strategies [46,47].

Among intelligent techniques, the FL method has proven particularly suitable for renewable energy applications because of its model-free nature, robustness against uncertainties, and successful implementation in numerous WE control systems [48–50]. Motivated by these advantages, this paper proposes a hybrid FL–TOSMC to improve both MPPT and DFOC performance in DFIG-based WECSs. Unlike previously reported approaches [51,52], the proposed controller combines the adaptive capability of FL with the robustness of TOSMC to achieve superior tracking accuracy, enhanced disturbance rejection, reduced power and current ripples, and lower current THD without requiring an accurate mathematical model.

The main contributions of this work are summarized as follows:

- Development of a novel FL–TOSMC controller for both MPPT and DFOC of DFIG-based WE systems.
- Significant enhancement in MPPT efficiency under variable wind conditions.
- Reduction in P_s/Q_s and current ripples.
- Improvement in system robustness against parameter variations and external disturbances.
- Reduction in current THD and overshoot compared with the conventional TOSMC strategy.

The remainder of this paper is organized as follows: Section 2 presents the mathematical model of the proposed WECS. Section 3 describes the FL–TOSMC controller. Section 4 introduces the proposed MPPT strategy. Section 5 presents the DFOC–FL–TOSMC power control scheme. The simulation results under different wind profiles are discussed in Section 6, while Section 7 concludes this paper.

2. WE Conversion System Model

This section presents the mathematical model of the proposed DFIG-based WECS. Figure 1 illustrates the overall architecture and the interactions among its principal components. The system consists of a WT, a gearbox (when required), a DFIG, a back-to-back power converter including the rotor-side converter (RSC) and the grid-side converter (GSC), a DC-link capacitor, an MPPT unit, the proposed DFOC–FL–TOSMC controller, and the electrical grid.

The WT converts the kinetic energy of the wind into mechanical power, which is transmitted to the DFIG shaft through the gearbox to achieve the required operating speed. The DFIG converts this mechanical power into EP while enabling variable-speed operation and independent regulation of the stator P_s and Q_s .

The RSC controls the rotor currents to regulate the electromagnetic torque and the exchanged P_s and Q_s . Simultaneously, the GSC maintains the DC-link voltage at its reference value while ensuring stable power exchange with the utility grid. The DC-link capacitor acts as an intermediate energy storage element that enhances system stability during transient operating conditions.

To maximize the harvested WE, the MPPT algorithm continuously adjusts the operating point according to wind speed (WS) variations. In addition, the proposed DFOC–FL–TOSMC strategy combines FL adaptation with the third-order SMC method to achieve accurate decoupled power regulation, improved disturbance rejection, fast dynamic response, and enhanced robustness against parameter uncertainties. Finally, the generated EP is injected into the grid while satisfying synchronization and PQ requirements.

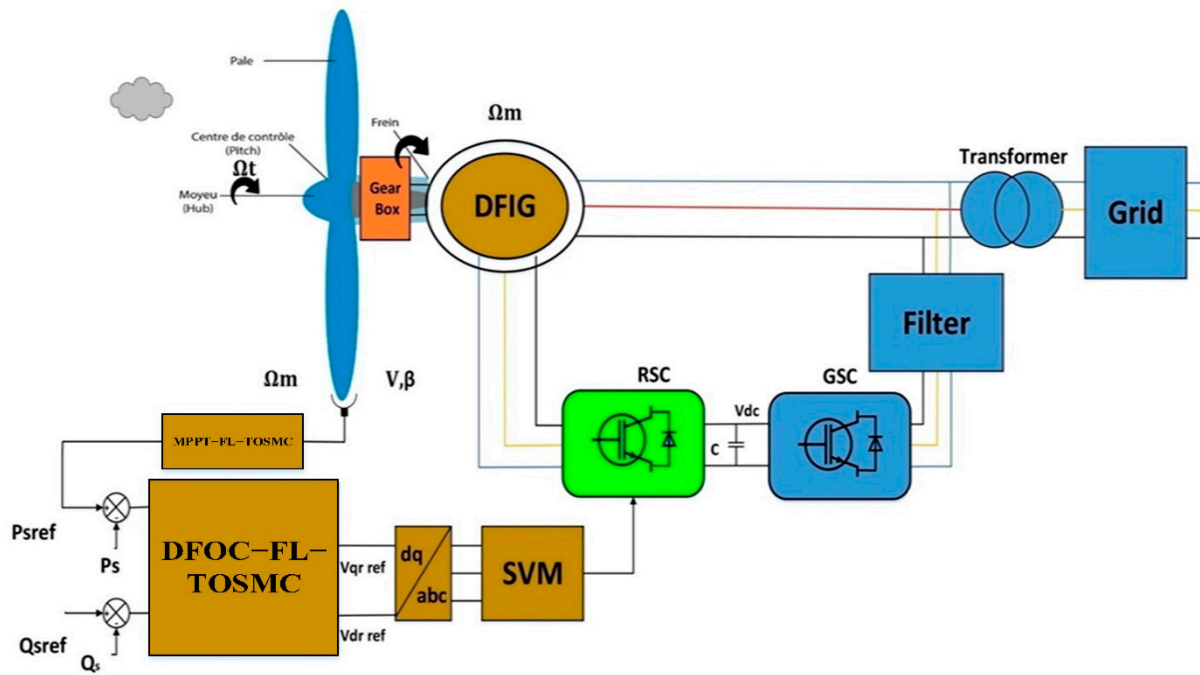


Figure 1. Proposed power system with DFOC-FL-TOSMC controller.

2.1. WT Model

In recent years, WTs have become one of the most effective technologies for converting WE into mechanical power for EP generation. Their widespread deployment has contributed to reducing greenhouse gas emissions and meeting the growing electricity demand. The power extracted from a WT mainly depends on WS and rotor dimensions, while the aerodynamic interaction between neighboring turbines in wind farms may reduce energy production if adequate spacing is not maintained. According to [53], the power available from the wind is expressed by Equation (1), which determines the mechanical power supplied to the generator for EP production.

$$p_t = \frac{1}{2} \rho \pi R_t^2 C_p(\lambda, \beta) V^3 \quad (1)$$

where ρ is the air density (kg/m^3), R_t is the blade radius of the wind turbine (m), V is the WS (m/s), and C_p is the power coefficient, which is a non-linear function of the tip-speed ratio (λ) and the blade pitch angle (β).

The power extracted from a WT is strongly influenced by the power coefficient $C_p(\lambda, \beta)$, which depends on the tip-speed ratio (TSR) and the blade pitch angle (β). According to [54], C_p is calculated using Equation (2).

$$C_p(\lambda, \beta) = 0.0068 \cdot \lambda + 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{-21}{\lambda_i}} \quad (2)$$

λ_i can be calculated using Equation (3).

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3)$$

As indicated by Equation (2), the maximum C_p is achieved when the blade pitch angle is $\beta = 0^\circ$. Moreover, C_p varies with the TSR, which depends on the WS and the turbine rotor dimensions. The TSR is calculated using Equation (4).

$$\lambda = \frac{\Omega_t \times R_t}{V} \quad (4)$$

From Equation (1), the aerodynamic torque driving the generator can be determined. In WECSs, the turbine operates at a lower rotational speed but produces a higher torque than the generator due to the gearbox ratio. According to [54], the aerodynamic torque is calculated using Equation (5).

$$T_{aer} = \frac{p_t}{\Omega_t} = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R_t^2 V^3 \frac{1}{\Omega_t} \quad (5)$$

Equation (6) represents the relationship between turbine torque and mechanical torque.

$$T_{mec} = \frac{T_t}{G} \quad (6)$$

The turbine speed differs from the generator speed, as a gearbox is used to regulate the speed. Equation (7) shows the relationship between the turbine speed (Ω_t) and the generator speed (Ω_g), and, using this equation, the turbine speed can be calculated. As is well known, the turbine speed is lower than the generator speed.

$$\Omega_t = \frac{\Omega_g}{G} \quad (7)$$

According to [55], the relationship between the DFIG torque and the WT torque can be expressed by Equation (8). This equation is of great importance in power generation and DFIG operation. Depending on the value of the difference between the two torques, the DFIG can be operated as a generator or as a motor.

$$T_t - T_{em} = \Omega_g \times f + J_{tot} \frac{d\Omega_g}{dt} \quad (8)$$

where T_{em} is the electromagnetic torque of the DFIG and T_t is the turbine torque. The total inertia torque and the friction coefficient are represented by J and f , respectively.

2.2. DFIG Model

The second main component of the studied ES is the DFIG, which converts the mechanical power extracted from the wind into EP. Owing to its simple control, low cost, reduced maintenance requirements, and independent rotor-side control, the DFIG is widely adopted in variable-speed WECSs [11]. In addition, its stator is directly connected to the grid, eliminating the need for an intermediate interface and reducing system complexity and cost. The mathematical model (MM) of the DFIG has been extensively reported in the literature [9,17,21], where the Park transformation is commonly employed. According to [56], the DFIG model in the d-q reference frame is described by Equations (9)–(19). Equation (9) represents the stator and rotor voltage equations, relating the voltages to the corresponding currents and flux linkages.

$$\begin{cases} V_{ds} = R_s i_{ds} - \omega_s \varphi_{qs} + \frac{d\varphi_{ds}}{dt} \\ V_{qs} = \omega_s \varphi_{ds} + R_s i_{qs} + \frac{d\varphi_{qs}}{dt} \\ V_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - \omega_r \varphi_{qr} \\ V_{qr} = \frac{d\varphi_{qr}}{dt} + R_r i_{qr} + \omega_r \varphi_{dr} \end{cases} \quad (9)$$

Equation (10) shows the stator/rotor flux of DFIG [57].

$$\begin{cases} \varphi_{ds} = M i_{dr} + l_s i_{ds} \\ \varphi_{qs} = l_s i_{qs} + M l_r i_{qr} \\ \varphi_{dr} = M i_{ds} + l_r i_{dr} \\ \varphi_{qr} = l_r i_{qr} + M i_{qs} \end{cases} \quad (10)$$

The values of V_{ds} , V_{qs} , V_{dr} , and V_{qr} on the d-q axes represent the stator and rotor voltages, respectively. The currents i_{ds} , i_{qs} , i_{dr} , and i_{qr} represent the stator and rotor currents, while φ_{ds} , φ_{qs} , φ_{dr} , and φ_{qr} represent the stator and rotor flux components. The resistances of the rotor and stator windings on the $d - q$ axes are represented by R_r and R_s . Values L_s , L_r , and M denote the self-inductance of the stator, the self-inductance of the rotor and the mutual inductance between two coils, respectively, with $\omega_r = \omega_s - p \cdot \Omega_g$.

The value of Q_s and P_s for the stator of a generator can be calculated using currents and voltages according to Equation (11). This equation is used to estimate capabilities.

$$\begin{cases} P_s = \frac{3}{2} (V_{qs} i_{qs} + V_{ds} i_{ds}) \\ Q_s = \frac{3}{2} (-V_{ds} i_{qs} + V_{qs} i_{ds}) \end{cases} \quad (11)$$

The DFIG torque is largely related to the rotor. Rotor currents and flux can be used to calculate torque for DFIG. This torque can be calculated using Equation (12). To control and change the torque, it is sufficient to control the rotor currents.

$$T_{em} = \frac{3pM}{2l_s} (-\varphi_{ds} i_{qr} + \varphi_{qs} i_{dr}) \quad (12)$$

Using the stator flux orientation technique and choosing a Park reference frame linked to the stator flux while neglecting the stator resistance (R_s), we can obtain:

$$\varphi = \varphi_{ds} = \varphi_s \text{ et } \varphi_{qs} = 0 \quad (13)$$

Using Equation (13), the current and voltage can be written according to Equations (14) and (15).

$$\begin{cases} v_{ds} = 0 \\ v_{qs} = v_s = \omega_s \varphi_s \end{cases} \quad (14)$$

$$\begin{cases} i_{ds} = \frac{\varphi_s}{l_s} - \frac{M}{l_s} i_{dr} \\ i_{qs} = -\frac{M}{l_s} i_{qr} \end{cases} \quad (15)$$

Additionally, the P_s and Q_s equations can be expressed in terms of the rotor current components i_{dr} and i_{qr} by Equation (16).

$$\begin{cases} P_s = -V_s \frac{3M}{2l_s} i_{qr} \\ Q_s = -V_s \frac{3M}{2l_s} i_{dr} + \frac{3V_s^2}{2l_s \omega_s} \end{cases} \quad (16)$$

Equation (17) can be used to represent the torque.

$$T_{em} = -p \frac{3M}{2l_s} (\varphi_s i_{qr}) \quad (17)$$

The rotor voltage equations can be simplified by Equation (18).

$$\begin{cases} V_{dr} = \sigma l_r \frac{dI_{dr}}{dt} R_r i_{dr} + -\sigma l_r \omega_r i_{qr} \\ V_{qr} = \sigma l_r \frac{dI_{qr}}{dt} + \sigma l_r \omega_r i_{dr} + R_r i_{qr} + \omega_r \frac{M}{L_s} \varphi_s \end{cases} \quad (18)$$

Equation (19) represents the expression for σ used in Equation (18).

$$\sigma = 1 - \frac{M^2}{l_r \times L_s} \quad (19)$$

The power control of DFIG is commonly achieved using PI controllers due to their simple implementation and satisfactory dynamic response. However, their performance deteriorates under parameter variations, leading to poor PQ and increased current THD. To overcome these limitations, several advanced control techniques have been investigated, including nonlinear strategies such as SMC and BC, as well as intelligent methods based on PSO, FL, and NN approaches.

3. Description of the FL-TOSMC Approach

In this section, the proposed FL-TOSMC controller is introduced for DFIG power regulation. The proposed strategy combines the advantages of FL and TOSMC to enhance PQ and reduce current THD. Since the proposed approach is based on TOSMC, its main principles, advantages, and limitations are first presented.

3.1. TOSMC Technique

The TOSMC method is an advanced nonlinear control technique developed as an extension of second-order SMC, offering improved accuracy and robustness. In [58], TOSMC was applied to DFIG-based systems by replacing conventional controllers, demonstrating superior performance compared with PI controllers. However, sensitivity to parameter variations was still observed during robustness tests. According to [42], TOSMC is a modified version of the super-twisting controller, designed to improve tracking performance and robustness. The mathematical formulation of TOSMC has been presented in [42–44]. Unlike conventional model-based controllers, TOSMC does not require an accurate mathematical model of the system, which enhances its robustness against uncertainties. The sliding surface of the TOSMC approach is defined as given in Equation (20).

$$S_x = X^* - X \quad (20)$$

According to [42,44], the MM of the TOSMC technique can be expressed by Equation (21). From this equation, it is noted that the TOSMC technique is easy to apply to complex and simple systems, as it does not require complex calculations.

$$u(t) = k_1 \times \text{sign}(s) + k_2 \int \text{sign}(s) dt + k_3 \sqrt{|s|} \times \text{sign}(s) \quad (21)$$

To ensure optimal performance, the gains K_1 , K_2 , and K_3 are chosen based on a proportional hierarchy of magnitude:

- K_1 is sized to overcome the maximum boundaries of external disturbances.
- K_2 is set to a higher order of magnitude to accelerate integral error elimination and smooth the sliding phase.
- K_3 balances transient and steady-state tracking.

This proportional scaling allows the FL system to dynamically adapt the controller gains within smooth boundaries, significantly improving the DR and energy efficiency while reducing chattering.

Gain values for the TOSMC technique can be calculated using experimentation and simulation, or smart strategies such as genetic algorithms can be used.

To study the stability of the TOSMC approach, Lyapunov's theory can be used. This theory relies on using Equation (22) to give the stability condition. However, using this theory requires calculations and the use of mathematical equations. Compared to Lyapunov's theory, the Bode curve can be used to prove the stability of the TOSMC approach more easily. The Bode curve is a graphical method by which the stability of the TOSMC approach can be proven easily and without the need to perform complex calculations. The Bode curve method is based on the use of MATLAB, and results are obtained quickly.

$$S \times \dot{S} < 0 \quad (22)$$

Figure 2 presents the structure of the proposed TOSMC, which adopts a single-input single-output configuration. The controller receives the tracking error, defined as the difference between the reference and measured variables, and generates the required control signal to regulate the system states. The design is based on a third-order sliding surface that uses the error and its higher-order derivatives to improve convergence and robustness. Compared with conventional SMC methods, TOSMC reduces chattering while maintaining robustness against parameter uncertainties and external disturbances. Moreover, it ensures finite-time error convergence, leading to improved tracking accuracy, transient response, and steady-state performance.

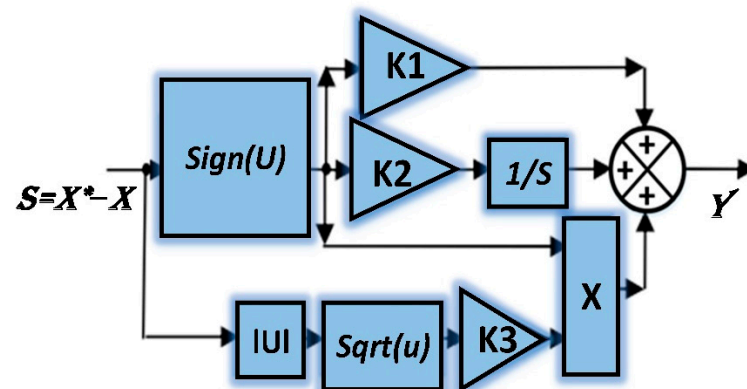


Figure 2. The TOSMC technique.

Although TOSMC provides high robustness and fast dynamic response, its application in ESs may still result in increased power ripples and current THD under parameter variations [42,43]. Therefore, several solutions have been investigated to enhance its performance. In [59], a hybrid TOSMC–BC strategy was proposed for induction motor speed regulation. Although this approach improved torque ripple reduction and current THD, it increased the controller complexity due to the large number of tuning gains.

In [60], an NN-based TOSMC was developed by replacing the sign function to improve control accuracy and robustness. The proposed strategy achieved better performance in terms of current THD reduction and power ripple mitigation compared with conventional TOSMC. However, its robustness was slightly affected by machine parameter variations, resulting in increased ripples and response time under disturbed conditions.

Furthermore, a fractional-order TOSMC (FO-TOSMC) was introduced in [61] to improve the performance of conventional TOSMC for DFIG power control. This method pro-

vided reduced power ripples and lower-current THD while maintaining simple implementation and model independence. Nevertheless, the requirement for parameter estimation limited its robustness against DFIG uncertainties. Therefore, despite these improvements, existing TOSMC-based approaches still present certain limitations, highlighting the need for an alternative solution capable of enhancing TOSMC performance while preserving simplicity, robustness, and independence from the system mathematical model. The proposed solution is presented in the following subsection.

3.2. FL-TOSMC Technique

This subsection presents the proposed FL-TOSMC controller, which is developed to enhance DFIG power control performance. The proposed strategy combines the robustness of TOSMC with the adaptive capability of FL control, resulting in a simple, efficient, and robust hybrid controller suitable for complex ESs. Unlike conventional model-based methods, FL-TOSMC does not require accurate knowledge of the system mathematical model, which improves its applicability under parameter uncertainties.

In conventional TOSMC, the $\text{sign}(u)$ function may introduce undesirable effects such as chattering. Replacing this function with an FLC mechanism enhances the controller performance, robustness, and tracking capability. Therefore, the proposed FL-TOSMC can be considered an improved version of TOSMC and is mathematically formulated in Equation (23), which is derived from Equation (21).

$$u(t) = K_1 \times \times (\text{Fuzzy}) + K_2 \int \text{Fuzzy} dt + K_3 \sqrt{|s|} \times (\text{Fuzzy}) \quad (23)$$

where K_1 , K_2 , and K_3 are the positive gains. With these gains, the DR and performance of the FL-TOSMC controller can be changed.

The FL-TOSMC controller gain values can be calculated using smart strategies such as PSO or grey wolf optimization. Also, the approach can be used for experimentation and simulation to calculate the values of these gains. In this work, the experiment and simulation method were relied upon to calculate the gain values for the FL-TOSMC controller due to its simplicity and ease of obtaining results without writing any complex programs or taking a large amount of time to obtain satisfactory results. The FL-TOSMC method differs from the neural TOSMC technique and the integral SMC technique in terms of performance and effectiveness. The FL-TOSMC approach reduces the chattering phenomenon and does not depend on the MM as in the integral SMC method.

Figure 3 illustrates the proposed FL-TOSMC, developed to enhance the performance of the MPPT strategy of the WT and the DFOC of the DFIG. The proposed controller combines the robustness and finite-time convergence characteristics of the third-order sliding mode controller with the adaptive decision-making capability of the FL method.

As shown in the figure, the sliding surface (S), defined as a function of the tracking error, is used as the input to the FL system. Based on the instantaneous value of the sliding variable, the fuzzy inference mechanism dynamically adjusts the controller gains K_1 and K_2 , enabling the control action to adapt to changes in operating conditions and system uncertainties. The output associated with K_1 provides a proportional correction term, while the branch containing K_2 and the integrator ($1/s$) generates an integral action that improves tracking accuracy and reduces steady-state error.

In addition, the nonlinear term ($|u|$) followed by $(\sqrt[3]{u})$ and gain K_3 contributes to the higher-order sliding mode action, enhancing convergence speed and disturbance rejection while mitigating the chattering phenomenon commonly encountered in conventional sliding mode controllers. The outputs of these three control channels are combined to generate the final control signal (Y), which is applied to the DFIG control loops.

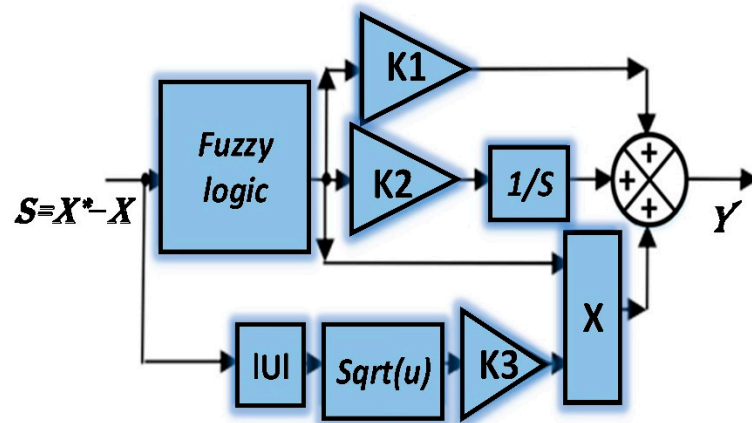


Figure 3. The FL-TOSMC approach.

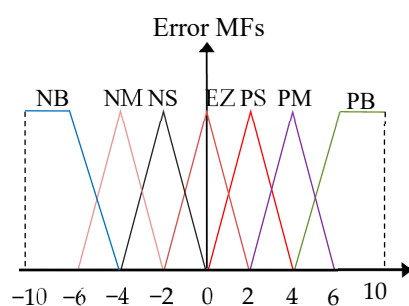
The stability of the FL-TOSMC approach can be proven using Lyapunov's theory, as Equation (22) can be used in this case. There is another simple method that can be relied upon to prove the stability of this designed approach. This strategy is represented by the Bode curve, which is a graphical method that is easy to use and obtains satisfactory results quickly without the need for complex calculations.

The FL-TOSMC approach relies on the FL approach to improve performance. Therefore, the efficiency of the FL-TOSMC approach depends on the characteristics of the FL approach used. Therefore, it is necessary to choose an appropriate number of rules to obtain distinctive and high performance for the FL-TOSMC approach.

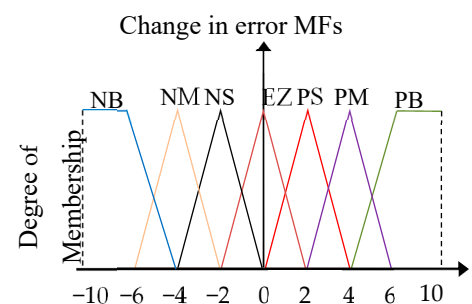
To embody the proposed controller, the FL technology of the Mamdani type was used. Also, an FL controller with 49 rules has been proposed. These rules are listed in Table 1. Figure 4 represents the membership functions used to embody the FL controller of the designer's approach.

Table 1. FL rules of the designed controller.

e Δe	NB	NM	NS	EZ	PS	PM	PB
PB	EZ	PS	PM	PB	PB	PB	PB
EZ	NB	NM	NS	EZ	PS	PM	PB
PS	NM	NS	EZ	PS	PM	PB	PB
NB	NB	NB	NB	NB	NM	NS	EZ
PM	NS	EZ	PS	PM	PB	PB	PB
NM	NB	NB	NB	NM	NS	EZ	PS
NS	NB	NB	NM	NS	EZ	PS	PM



(a) Error



(b) Change in error

Figure 4. Membership functions.

The FL–TOSMC approach can be experimentally implemented using real-time platforms such as dSPACE 1104 or hardware-in-the-loop (HIL) testing. Its implementation is relatively simple and does not require expensive technologies. In this work, FL–TOSMC is employed for two purposes: improving the MPPT performance of the WT, as presented in the following section, and enhancing the DFOC strategy of the DFIG.

4. Proposed MPPT–FL–TOSMC Approach

The MPPT technique is widely used in renewable energy systems to maximize energy extraction under variable operating conditions. It has been successfully applied in PV systems [62] and WT control applications [63]. In WECSs, MPPT determines the optimal reference P_s (P_s^*) according to WS variations. However, conventional MPPT methods based on PI controllers suffer from limited robustness under system parameter variations.

Several advanced approaches have been proposed to overcome these limitations. In [64], a BC-based MPPT strategy improved robustness and tracking performance, but its implementation complexity and large number of tuning parameters remain important drawbacks. The particle swarm optimization-based MPPT proposed in [65] enhanced controller parameter selection; however, its performance deteriorated under parameter uncertainties. A neural network–backstepping (NN–BC) MPPT strategy was introduced in [66], providing improved PQ and robustness, but with increased complexity, cost, and implementation difficulties. Similarly, FL-based MPPT [67] and feed-forward neural network (FF–NN)-based MPPT [68] achieved better performance than conventional methods, although they suffer from tuning difficulties and the absence of systematic design rules. In [69], a super-twisting controller-based MPPT strategy improved PQ; however, chatter effects remained a limitation.

Based on these observations, this section proposes a new MPPT strategy based on the FL–TOSMC approach to improve WT energy extraction while maintaining robustness, simplicity, and model independence. First, the conventional TSR-based MPPT strategy is presented.

4.1. TSR-Based MPPT Algorithm Structure

MPPT algorithms aim to maximize the power extracted from wind turbines by adjusting the operating speed according to WS variations. This adjustment affects the generated torque and consequently the quadrature rotor current (i_{qr}) of the DFIG [70]. Among different MPPT methods, the TSR technique is widely adopted due to its simple implementation and fast response [71]. The main objective of the TSR method is to maintain the TSR at its optimal value (λ_{opt}) to maximize $C_p(\lambda, \beta)$ [72]. Therefore, the reference generator speed Ω_g^* is calculated using Equation (24).

$$\Omega_g^* = \frac{\lambda_{opt}}{R} V \quad (24)$$

The value of the generator torque is related to the value of the aerodynamic torque by Equation (25).

$$T_g = \frac{1}{G} T_{aer} \quad (25)$$

where T_{aer} is the aerodynamic torque.

The MPPT method is used to determine the torque reference value. Using the torque reference value, the power reference value can be extracted.

The relationship between the speed of the generator and the difference between the torque of the generator and the turbine is shown in Equation (26).

$$\Omega_g = \frac{1}{J_s + f} (T_g - T_{em}) \quad (26)$$

where T_{em} is the electromagnetic torque.

The electromagnetic moment can be expressed by Equation (27).

$$T_{em} = K_p e_\Omega + \int K_i e_\Omega dt \quad (27)$$

where e_Ω is the speed generator error ($e_\Omega = \Omega_g^* - \Omega_g$).

According to [73], a speed controller is required to minimize the error between the reference speed given by Equation (24) and the measured generator speed. Conventional MPPT schemes generally employ PI controllers because of their simple implementation; however, their performance degrades under rapid reference variations and parameter uncertainties, resulting in a slower dynamic response [74]. To address these limitations, a TOSMC-based MPPT strategy was proposed in [75], providing faster convergence and higher robustness than the conventional PI-based approach.

4.2. MPPT-TOSMC Technique

The MPPT-TOSMC strategy replaces the conventional PI regulator with a third-order sliding mode controller to improve MPPT. Compared with the MPPT-PI approach, it provides faster and more accurate tracking, higher robustness against disturbances and parameter variations, reduced chattering, and improved energy extraction while remaining simple to implement. To ensure accurate tracking of the optimal generator speed, the sliding surface of the TOSMC-based MPPT controller is defined by Equation (28):

$$S_\Omega = \Omega_g^* - \Omega_g \quad (28)$$

According to the MPPT-TOSMC strategy, the torque expression is written by Equation (29).

$$T_{em} = K_1 \times \text{sign}(S_\Omega) + K_2 \int \text{sign}(S_\Omega) dt + K_3 \sqrt{|S_\Omega|} \times \text{sign}(S_\Omega) \quad (29)$$

The stability condition for this technique is given by Equation (30).

$$S_\Omega \times \dot{S}_\Omega < 0 \quad (30)$$

According to [43], the MPPT-TOSMC strategy still exhibits current and power ripples, limiting the achieved PQ. Therefore, a more effective control strategy is required to further enhance the MPPT performance.

4.3. MPPT-FL-TOSMC Technique

This subsection presents the proposed MPPT-FL-TOSMC strategy, which extends the conventional MPPT-TOSMC approach by integrating the FL technique described in [76]. The proposed hybrid controller combines the adaptive capability of FL with the robustness of TOSMC to achieve faster and more accurate MPPT while improving PQ and reducing power fluctuations. Moreover, the proposed method is simple to implement, does not require an accurate mathematical model, and differs from the approach reported in [77]. The reference torque is determined using Equation (31).

$$T_{em} = K_1 \times \text{Fuzzy}(S_\Omega) + K_2 \int \text{Fuzzy}(S_\Omega) dt + K_3 \sqrt{|S_\Omega|} \times \text{Fuzzy}(S_\Omega) \quad (31)$$

Using the FL-TOSMC strategy significantly improves the performance of wind-based power generation systems, offering a robust and efficient solution to maximize energy production. This proposed approach is represented in Figure 5. Figure 5 illustrates the detailed architecture of the proposed FL-TOSMC strategy. The controller is designed to maximize energy harvesting while protecting the DFIG from mechanical stress. The TOSMC core uses high-order sliding surfaces to ensure robust tracking of the P_s and Q_s references under variable wind profiles. To overcome the inherent chattering problem of conventional SMC method, the FL block dynamically adjusts the switching gains based on the sliding surface error (e) and its derivative (Δe). This intelligent adaptation smooths out the control signal, reduces THD, and ensures that the WT continuously operates at its MPPT with high efficiency and minimum energy loss.

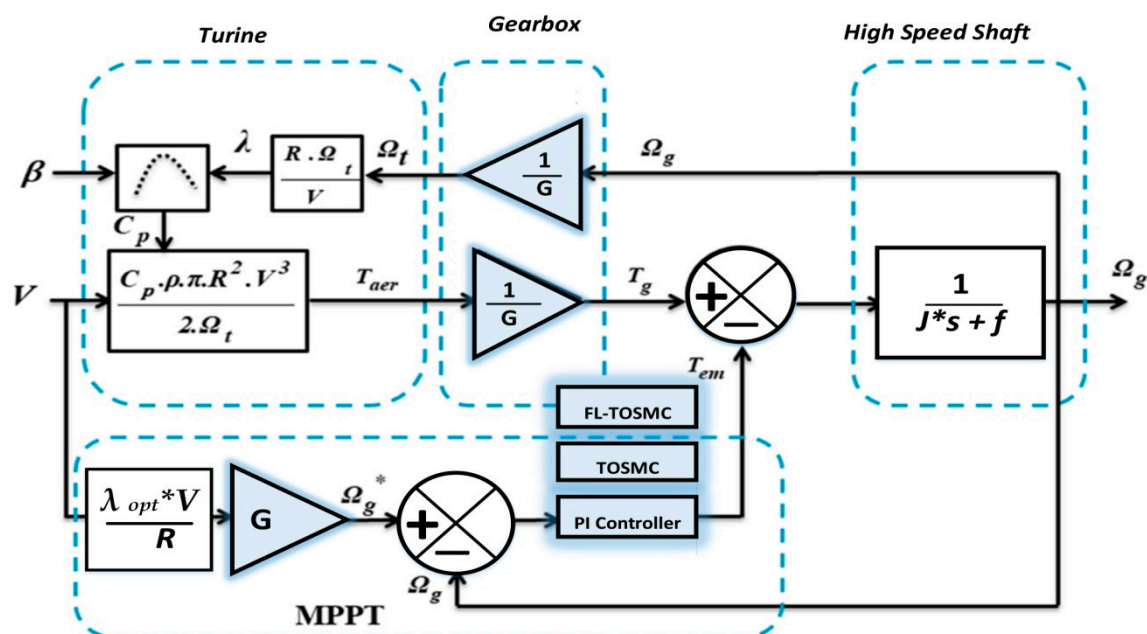


Figure 5. MPPT-FL-TOSMC technique.

5. Proposed DFIG Power Control Technique

This section presents the proposed DFIG power control strategy aimed at improving PQ, reducing current THD, and enhancing the dynamic response of P_s and Q_s . Since the proposed method is developed from the conventional DFOC, the DFOC–PI strategy is first briefly reviewed.

5.1. DFOC–PI Technique

The DFOC strategy is a widely adopted FOC scheme for DFIGs because of its simple implementation, low computational complexity, and fast dynamic response [78]. In the conventional DFOC approach, PI controllers regulate the AC stator P_s and Q_s based on the DFIG mathematical model [79]. The generated voltage references are typically converted into switching signals using space vector modulation, which improves power ripple performance at the expense of increased implementation complexity. According to

[46], the reference voltage components of the DFOC–PI strategy are calculated using Equations (32) and (33).

$$V_{rd}^* = K_1 e_{Ps} - g \times M \frac{V_s}{L_s} + \int K_2 e_{Ps} dt \quad (32)$$

$$V_{rq}^* = K_3 e_{Qs} - R_r \frac{V_s}{M \times w_s} + \int K_4 e_{Qs} dt \quad (33)$$

where e_{Ps} are e_{Qs} are the power errors, K_1 and K_2 are the PI controller gains for Ps , and K_3 and K_4 are the PI controller gains for Qs .

The values of the gains of K_1 , K_4 , K_3 , and K_2 can be calculated using a genetic algorithm, or the simulation and experimentation method can be used.

Figure 6 represents a schematic diagram of the DFOC–PI method used for power control of DFIG. The DFOC–PI method determines the voltage values of the rotor part in the dq axis.

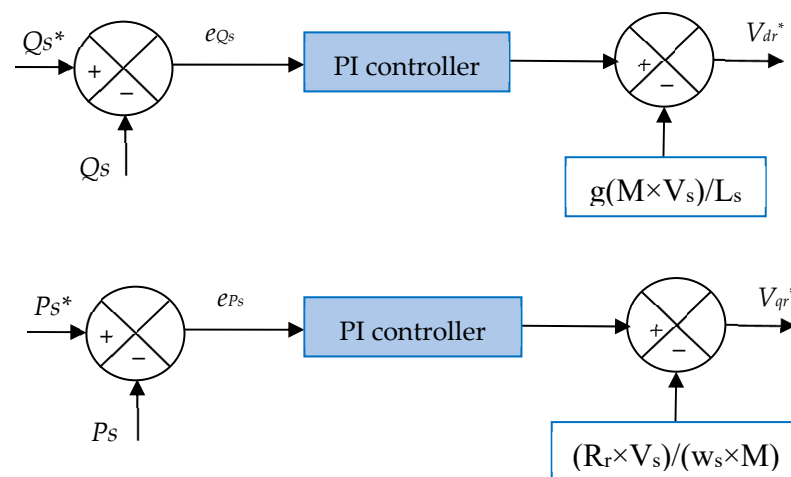


Figure 6. DFOC–PI technique.

The reference voltage components obtained from Equations (32) and (33) are converted into switching signals for the RSC using the SVM technique. SVM is widely employed in renewable energy systems because it reduces switching losses and harmonic distortion, thereby improving energy efficiency and PQ [80]. In the DFOC–PI strategy, the estimation of Ps and Qs requires prior estimation of the stator flux, which is used to compute the power errors. The stator flux is calculated using Equation (34).

$$\begin{cases} \varphi_{r\beta} = \int_0^t (V_r - R_r \times i_{r\beta}) dt \\ \varphi_{r\alpha} = \int_0^t (V_r - R_r \times i_{r\alpha}) dt \end{cases} \quad (34)$$

Using Equation (34), the flux value of the rotor part can be calculated according to Equation (35).

$$|\varphi_r| = \sqrt{(\varphi_{r\beta}^2 + \varphi_{r\alpha}^2)} \quad (35)$$

The rotor part voltage can be used to calculate flux, as Equation (36) can be used to calculate flux directly from voltage.

$$|\bar{V}_r| = |\bar{\varphi}_r| \times w_r \quad (36)$$

Equation (37) represents the power estimate used in this work.

$$\begin{cases} Q_s = -\frac{3}{2} \left(\frac{V_s}{\sigma \times L_s} \times \varphi_{\beta r} - \frac{V_s \times L_m}{\sigma \times L_r \times L_s} \times \varphi_{\alpha r} \right) \\ P_s = -\frac{3}{2} V_s \times \varphi_{r\beta} \times \frac{L_m}{\sigma \times L_r \times L_s} \end{cases} \quad (37)$$

Despite its simplicity and fast dynamic response, the conventional DFOC–PI strategy suffers from significant power and current ripples, relatively high current THD, and limited robustness against machine parameter variations. These limitations motivate the development of more robust control strategies [43].

5.2. DFOC–TOSMC Technique

To overcome the shortcomings of DFOC–PI, the TOSMC-based DFOC strategy proposed in [46] replaces the conventional PI controllers with TOSMC regulators. This modification improves dynamic response, robustness, and energy conversion performance while preserving the simple structure of the conventional DFOC scheme. In the proposed DFOC–TOSMC strategy, the reference voltage components are determined using Equations (38) and (39).

$$\begin{aligned} V_{rq}^* &= K_1 \times \text{sign}(e_{ps}) + K_2 \int \text{sign}(e_{ps}) dt \\ &\quad + K_3 \sqrt{|e_{ps}|} \times \text{sign}(e_{ps}) - g \times M \frac{V_s}{L_s} \end{aligned} \quad (38)$$

$$\begin{aligned} V_{rd}^* &= K_4 \times \text{sign}(e_{qs}) + K_5 \int \text{sign}(e_{qs}) dt \\ &\quad + K_6 \sqrt{|e_{qs}|} \times \text{sign}(e_{qs}) - R_r \frac{V_s}{M \times w_s} \end{aligned} \quad (39)$$

where V_{rd}^* is the direct rotor voltage and V_{rq}^* is the quadrature rotor voltage.

The reference voltage components are converted into switching signals through the SVM technique. The combination of DFOC, TOSMC, and SVM improves the dynamic performance and efficiency of WECSs. However, despite its superior performance over the conventional DFOC–PI strategy, the DFOC–TOSMC approach remains sensitive to DFIG parameter variations, leading to increased power ripples and current THD under disturbed operating conditions [46]. These limitations motivate the development of a more robust control strategy.

5.3. Proposed DFOC–FL–TOSMC Technique

This subsection presents the proposed DFOC–FL–TOSMC strategy, which enhances the DFOC–TOSMC scheme by replacing the TOSMC regulator with the FL–TOSMC controller introduced in Section 3.2. By combining the robustness of TOSMC with the adaptive capability of FL, the proposed controller effectively handles system uncertainties and nonlinearities, resulting in improved stability, tracking accuracy, and PQ. The FL–TOSMC controller generates the reference voltage components from the power errors, as expressed by Equations (40) and (41).

$$\begin{aligned} V_{rq}^* &= K_7 \times \text{Fuzzy}(e_{ps}) + K_8 \int \text{Fuzzy}(e_{ps}) dt \\ &\quad + K_9 \sqrt{|e_{ps}|} \times \text{Fuzzy}(e_{ps}) - g \times M \frac{V_s}{L_s} \end{aligned} \quad (40)$$

$$V_{rd}^* = K_{10} \times \text{Fuzzy}(e_{Qs}) + K_{11} \int \text{Fuzzy}(e_{Qs}) dt + K_{12} \sqrt{|e_{Qs}|} \times \text{Fuzzy}(e_{Qs}) - R_r \frac{V_s}{M \times w_s} \quad (41)$$

where K_7 , K_9 , and K_8 are the FL-TOSMC controller gains for P_s , and K_{10} , K_{11} , and K_{12} are the PI controller gains for Q_s .

The gain values of the FL-TOSMC controller for the designed strategy can be calculated using the simulation and experimentation method due to its ease of use and the speed of obtaining results without the need to write complex programs. Smart strategies can also be used to calculate FL-TOSMC controller gain values. However, the method of simulation and experimentation was used in this work to calculate the gain values. Figure 7 represents the internal structure of the proposed DFOC-FL-TOSMC strategy for power control.

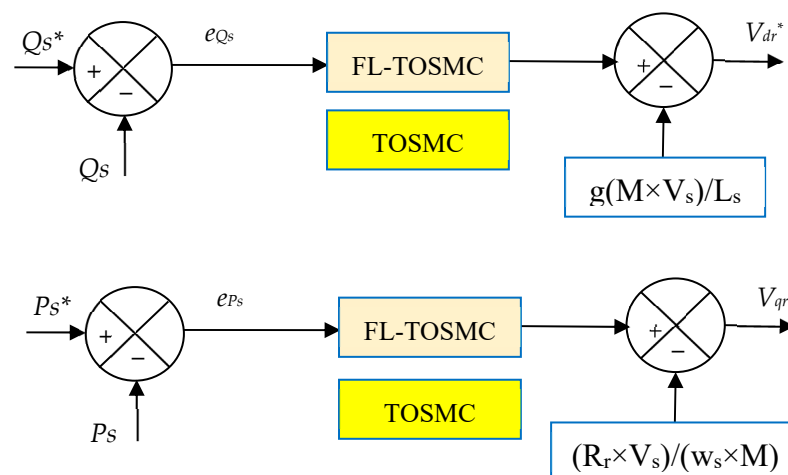


Figure 7. Proposed DFOC-FL-TOSMC approach.

The use of the FL-TOSMC controller in the DFOC strategy allows for improved tracking of references with high accuracy and allows for improved stability over time. The use of this strategy effectively reduces transient oscillations (chattering), thus reducing electrical losses associated with transients and frequent switching. In the next part, the DFOC-SVM approach based on the FL-TOSMC controller is implemented using MATLAB.

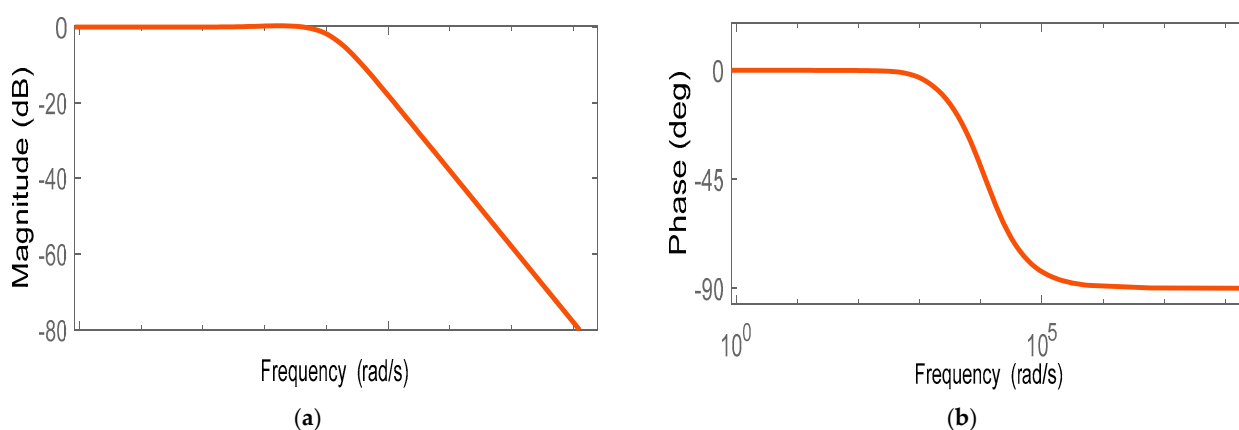
Table 2 compares the proposed FL-TOSMC strategy with conventional DPC and DTC methods based on the literature reviewed above, and the simulation results are presented in the next section. The comparison indicates that the proposed approach achieves superior PQ and current performance. However, DPC and DTC remain simpler to implement, require fewer tuning parameters, and generally involve lower implementation cost than the proposed method.

Table 2. A comparative study between the DFOC-FL-TOSMC and some approaches.

Approaches	Controller	Response Dynamic	Precision	Complexity	Robustness	THD Current
DTC	Hysteresis controller	Slow	Medium	Low	Low	High
DPC	Hysteresis controller	Slow	Medium	Low	Low	High
DVC	PI	Slow	Low	Low	Low	High
IVC	PI	Slow	Medium	Low	Low	High
DFOC-TOSMC	TOSMC	Quick	Good	High	High	Low
Proposed DFOC-FL-TOSMC	FL-TOSMC	Quick	Excellent	High	High	Low

The stability of nonlinear control strategies, such as FL-based controllers and FL-BC approaches, can be evaluated using frequency-domain analysis. Although these controllers do not always have a straightforward linear representation, their stability characteristics can be investigated through an equivalent linearized model or by analyzing the closed-loop system response. The Bode plot obtained using MATLAB provides an effective tool for assessing stability margins, including gain margin and phase margin. A positive gain margin and sufficient phase margin indicate that the designed nonlinear controller can maintain stable operation and robustness against disturbances. Consequently, MATLAB-based Bode analysis can be used to verify the stability performance of advanced nonlinear control strategies, such as FL controllers and FL-BC controllers.

The stability of the designed approach can be proven using Lyapunov's theorem. Lyapunov's theory is based on calculations, which makes it somewhat complicated, especially in the case of a complex system. Another reliable method to prove the stability of the proposed approach. This method uses the Bode curve. The Bode curve is a graphical method by which the stability of the proposed approach can be proven easily and does not require complex calculations. MATLAB extracts the Bode curve for the controllers used in this work. Figure 8 represents the Bode curve for two controls. This curve gives the variation in both magnitude (dB) and phase (deg) as a function of frequency for two controls. It is noted that the change in frequency is accompanied by a change in the value of both magnitude (dB) and phase (deg). From Figure 8, it is noted that for the traditional approach, the magnitude (dB) value changes from 0 dB to −80 dB (see Figure 8a), and in the case of the proposed controller, it changes from 0 dB to −120 dB (see Figure 8b). The magnitude (dB) value taking negative values highlights the stability of the proposed approach. Also, it is noted that the phase (deg) value in the case of two controls changes from 0 deg to −90 deg. Therefore, the two approaches are very stable.



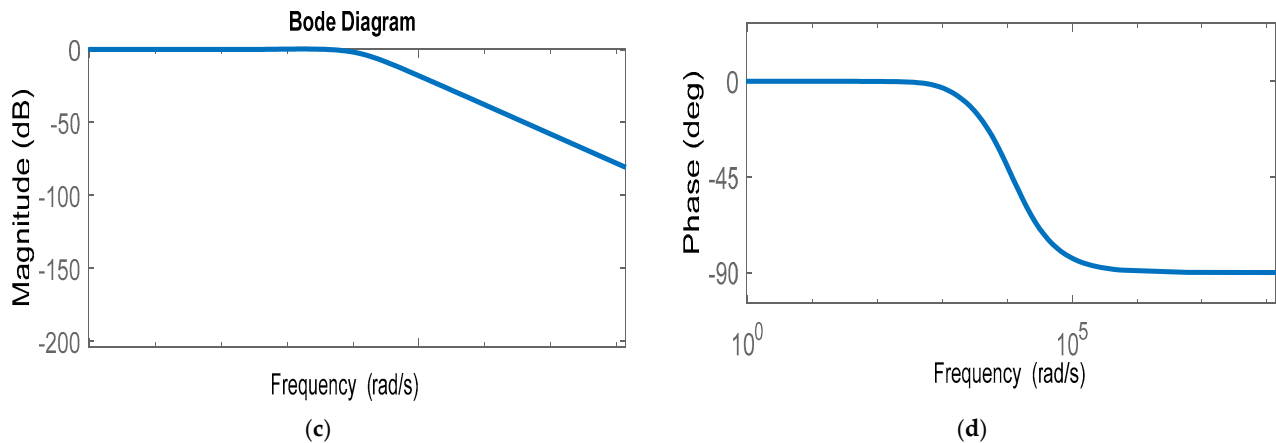


Figure 8. Bode diagram analysis for stability verification; TOSMC approach: (a) frequency response of magnitude (dB), (b) frequency response of phase (deg); FL-TOSMC approach: (c) frequency response of magnitude (dB), (d) frequency response of phase (deg).

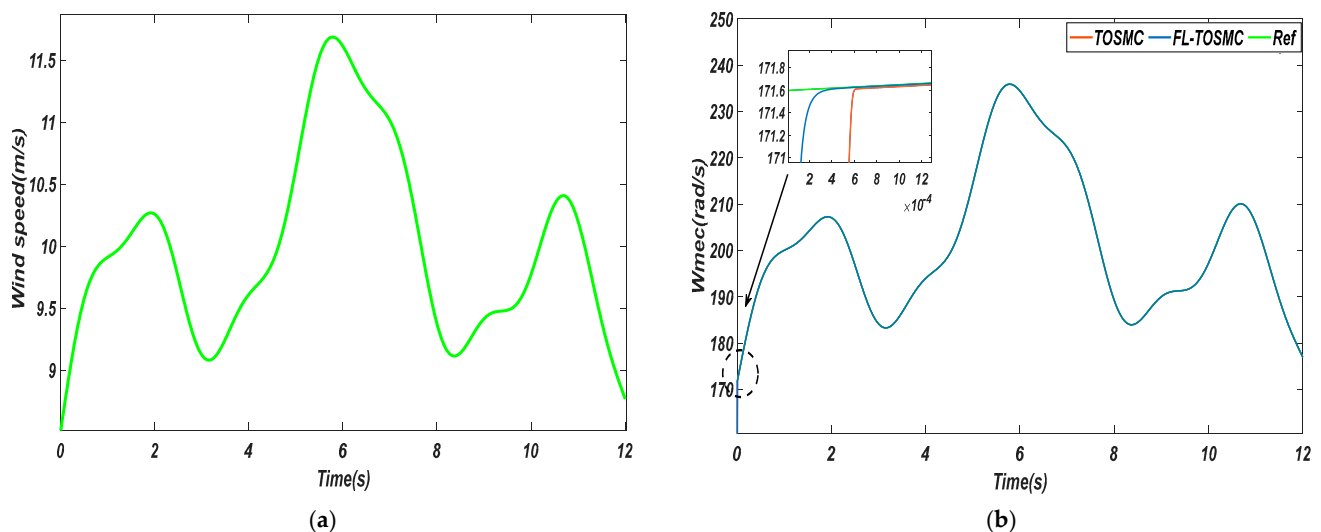
6. Results

This section evaluates the effectiveness of the proposed FL-TOSMC strategy through MATLAB simulations and compares its performance with the DFOC-TOSMC approach. The system parameters are provided in Appendix A, together with the FL-TOSMC controller gains used for the MPPT-TSR algorithm and the regulation of P_s and Q_s . The same controller parameters are adopted for both P_s and Q_s control.

Two different WS profiles are considered to assess the proposed strategy under various operating conditions. The comparison focuses on reference tracking, PQ, current THD, overshoot, and SSE.

(a) First test

The first test is conducted to evaluate the dynamic performance of the proposed control strategies (TOSMC and FL-TOSMC) under variable WS conditions. The WS profile applied in this test is shown in Figure 9a. The corresponding simulation results are presented in Figures 9 and 10, while the quantitative performance indices are summarized in Table 3.



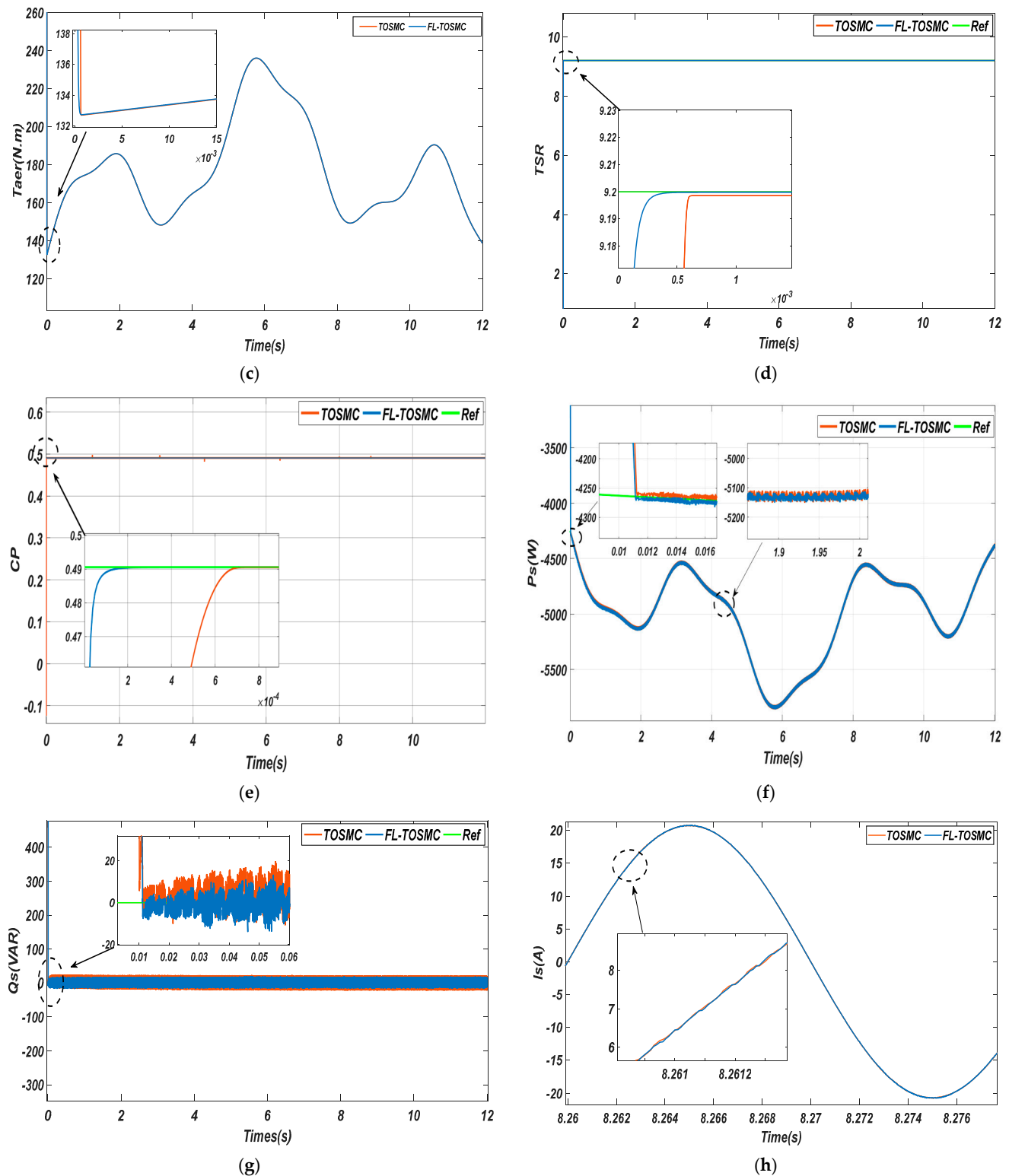


Figure 9. Performance and dynamic response under the proposed FL-TOSMC strategy: (a) variable WS profile (m/s), (b) rational speed, (c) aerodynamic torque, (d) TSR, (e) C_p , (f) P_s , (g) Q_s , and (h) stator current.

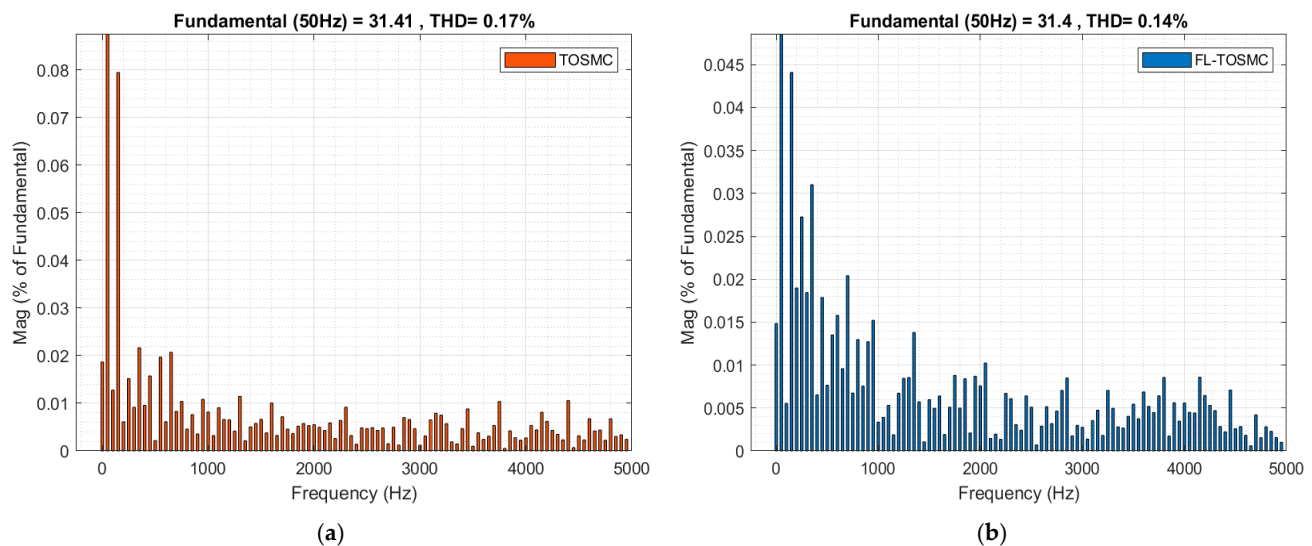


Figure 10. Current THD of two controllers (Test 1): (a) DFOC-TOSMC and (b) DFOC-FL-TOSMC.

Table 3. Value and ratios of RT, overshoot, SSE, and power ripples of TOSMC and FL-TOSMC (Test 1).

		P_s (W)	Q_s (VAR)
TOSMC	Ripples	31	20
	Overshoot	4260	29.91
	RT (ms)	0.21	0.12
	SSE	0.1	0.5
FL-TOSMC	Ripples	16	13.2
	Overshoot	4269	0.49
	RT (ms)	0.11	0.08
	SSE	0.05	0.15
Ratios (%)	Ripples	48.38	34
	Overshoot	−0.211	98.36
	RT (ms)	47.61	33.33
	SSE	50	70

Figure 9b illustrates the rotor rotational speed of the DFIG. It is observed that the rotor speed closely follows the variations in WS, reflecting the effectiveness of the MPPT control strategy. In both cases, the speed profile exhibits the same general trend as the wind profile; however, the proposed FL-TOSMC demonstrates a faster response time, improved tracking accuracy, and reduced transient deviations compared with the conventional TOSMC. This indicates enhanced dynamic performance and better damping characteristics under changing operating conditions.

Figure 9c presents the aerodynamic torque response for both controllers. The torque varies consistently with WS changes, confirming proper energy conversion behavior. Nevertheless, FL-TOSMC achieves smoother torque dynamics with reduced oscillations and faster settling time, which reflects improved stability in the mechanical-to-electrical energy conversion process.

Figure 9d shows the TSR. It is observed that the TSR is effectively regulated around its optimal value, ensuring maximum power extraction. The proposed FL-TOSMC maintains the TSR more efficiently under transient wind variations, with faster convergence compared to TOSMC, indicating improved MPPT performance.

Figure 9e represents the power coefficient, which remains close to its optimal value (approximately 0.5) during operation. Although the power coefficient is theoretically constrained by turbine characteristics, the proposed controller ensures faster convergence to the optimal operating point after wind-speed changes. FL-TOSMC achieves a quicker stabilization of power coefficient, demonstrating improved energy capture efficiency.

Figure 9f shows the P_s response for both controllers. The P_s closely follows its reference and varies according to WS fluctuations, including negative values during certain operating conditions. The FL-TOSMC controller provides superior performance in terms of faster response, reduced overshoot, and lower ripple content compared to TOSMC, indicating improved power regulation capability.

Figure 9g illustrates the Q_s . It is observed that Q_s remains well regulated and approximately constant despite variations in WS, confirming effective decoupling between P_s and Q_s control. However, FL-TOSMC achieves faster dynamic response and significantly reduced ripple levels compared to the conventional controller, reflecting improved voltage regulation performance.

Figure 9h presents the stator current waveforms. The results show that the current remains sinusoidal for both control strategies, confirming stable grid-connected operation. However, the FL-TOSMC controller produces a cleaner waveform with lower distortion and reduced transient oscillations. The variation in current magnitude is consistent with changes in WS due to the MPPT mechanism, which adjusts the P_s reference accordingly. Overall, the proposed controller ensures higher current quality and improved dynamic behavior compared with TOSMC.

These results collectively demonstrate the effectiveness of the FL-TOSMC approach in enhancing both the mechanical and electrical performance of the DFIG system. The proposed controller provides improved tracking accuracy, faster transient response, reduced ripples, and better PQ compared with the conventional TOSMC strategy, confirming its suitability for high-performance WECSs.

Figure 10 compares the stator current THD obtained with the conventional TOSMC and the proposed FL-TOSMC strategies under the first test. As shown, the proposed controller reduces the THD from 0.17% (Figure 10a) to 0.14% (Figure 10b), corresponding to an improvement of approximately 17.65%. This reduction demonstrates the superior ability of FL-TOSMC to suppress harmonic components and improve current quality.

The lower THD indicates that the proposed controller effectively attenuates high-frequency oscillations associated with converter switching and transient dynamics, resulting in smoother stator currents and improved electromagnetic torque behavior. Moreover, both strategies preserve the same fundamental current component at 50 Hz, confirming that the THD reduction is achieved through harmonic suppression rather than changes in the fundamental power level.

These results demonstrate that the proposed FL-TOSMC strategy provides better current quality than the conventional TOSMC, making it well suited for grid-connected DFIG-based WE systems.

Table 3 compares the dynamic and steady-state performances of the conventional TOSMC and the proposed FL-TOSMC controllers under Test 1. The proposed controller consistently outperforms TOSMC in terms of power ripples, response time, overshoot, and SSE.

For P_s , the ripple is reduced from 31 W to 16 W (48.38%), while the Q_s ripple decreases from 20 VAR to 13.2 VAR (34%). These improvements result from the adaptive capability of the FL component, which mitigates oscillations and stabilizes the power exchange between the stator and rotor.

The overshoot of P_s remains almost unchanged (4260 W versus 4269 W, -0.211%), whereas the overshoot of Q_s is dramatically reduced from 29.91 VAR to 0.49 VAR (98.36%), indicating a significant improvement in transient damping.

The dynamic response is also enhanced, with RT decreasing from 0.21 ms to 0.11 ms (47.61%) for P_s and from 0.12 ms to 0.08 ms (33.33%) for Q_s . Moreover, the SSE is reduced from 0.10 to 0.05 (50%) for P_s and from 0.50 to 0.15 (70%) for Q_s , demonstrating improved tracking accuracy and robustness against parameter uncertainties.

Overall, the results confirm that integrating FL with TOSMC significantly improves both transient and steady-state performance, leading to smoother power regulation and more stable operation of the DFIG-based WECS.

(b) Second test

The objective of this test is to evaluate the robustness of the TOSMC and FL-TOSMC controllers under DFIG parameter variations. For this purpose, the stator and rotor resistances (R_s , R_r) are doubled, while the mutual and leakage inductances (L_m , L_s , L_r) are reduced by 50%. The same WS profile as in Test 1 is applied to ensure a fair comparison, and the obtained results are presented in Figures 11 and 12.

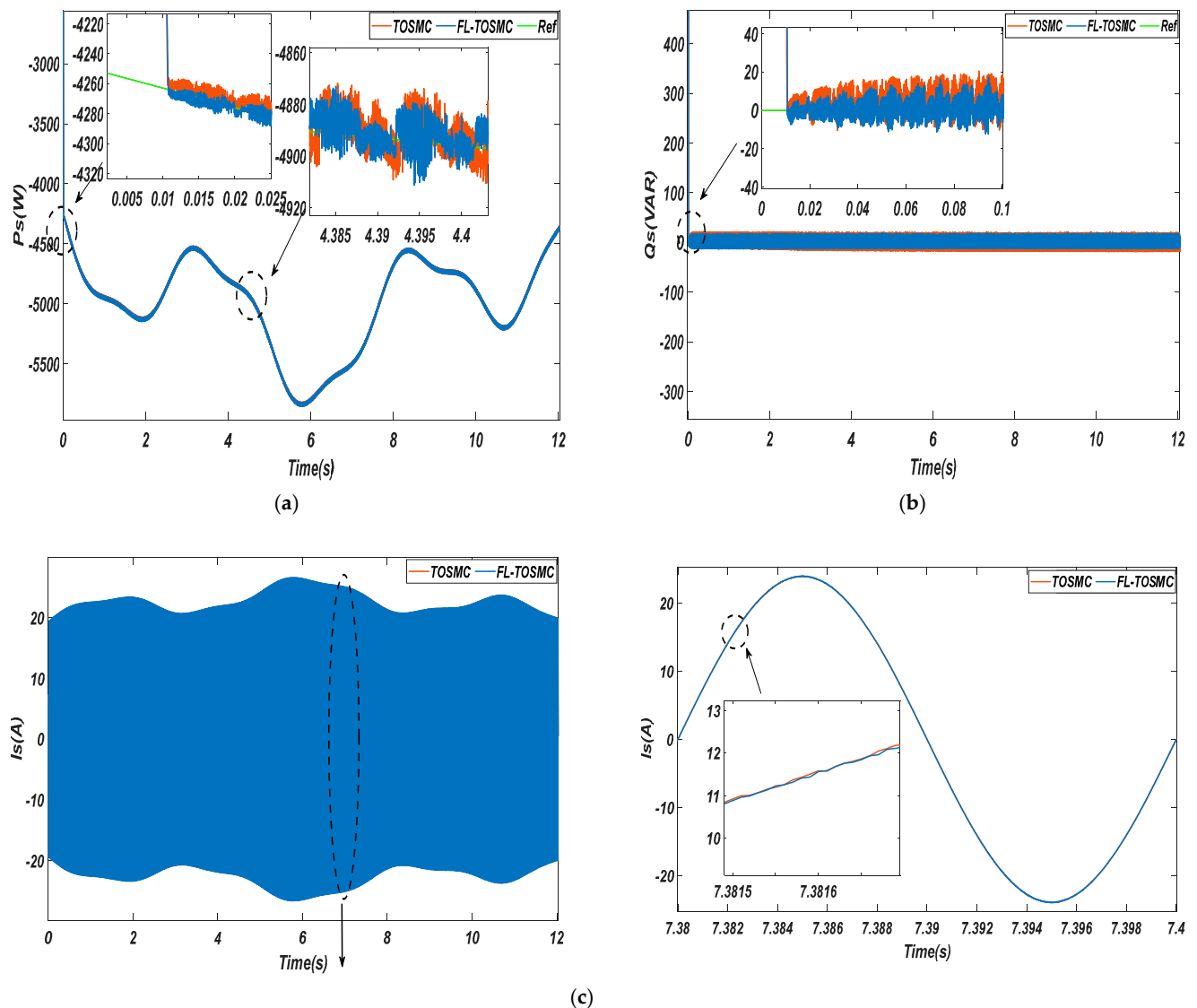


Figure 11. Second test results: (a) P_s , (b) Q_s , and (c) stator current.

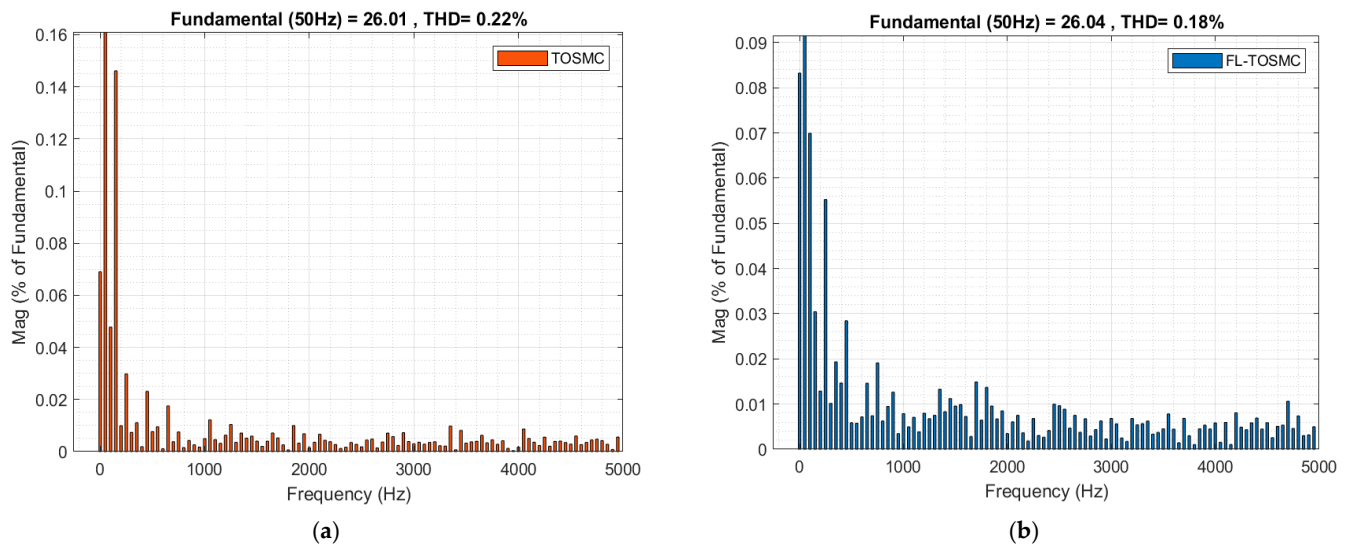


Figure 12. THD values (Test 2): (a) TOSMC and (b) FL-TOSMC.

Figure 11a shows the P_s response under parameter uncertainties. Both controllers maintain reference tracking; however, FL-TOSMC provides faster convergence, lower settling time, and reduced power ripples compared with TOSMC, demonstrating improved robustness and power regulation capability.

Figure 11b presents the Q_s response. Although both controllers maintain acceptable regulation despite parameter variations, FL-TOSMC achieves faster dynamics, better disturbance rejection, and lower Q_s oscillations, confirming its enhanced robustness.

The stator current waveform shown in Figure 11c remains sinusoidal for both approaches under severe parameter changes. Nevertheless, FL-TOSMC produces a smoother current with reduced harmonic distortion, indicating improved current quality and harmonic suppression capability.

Overall, Figures 11 and 12 confirm the superiority of the proposed FL-TOSMC strategy under uncertain operating conditions. By maintaining accurate power tracking, reducing oscillations, and improving PQ, the proposed controller provides a more reliable solution for DFIG-based WECSs.

Figure 12 presents the comparison of stator current THD for the DFIG system under the TOSMC and FL-TOSMC control strategies in Test 2. As shown in Figure 12a, the conventional TOSMC yields a THD value of 0.22%, whereas the proposed FL-TOSMC approach reduces this value to 0.18%, as illustrated in Figure 12b. This corresponds to a reduction of approximately 18.18% in current harmonic distortion, confirming the superior capability of the proposed controller in improving PQ.

From a physical perspective, the reduction in THD is directly related to the improved smoothness of the stator current waveform. Lower harmonic content reduces unwanted oscillations in the electromagnetic torque and decreases additional copper and iron losses associated with high-frequency current components. Since harmonic currents contribute to extra heating in the stator windings, their reduction leads to improved electrical performance and more stable generator operation under variable wind conditions.

In addition, it is observed that both control strategies maintain the fundamental component of the stator current at approximately 50 Hz. However, the FL-TOSMC approach exhibits a higher amplitude of the fundamental component compared to the conventional TOSMC, indicating improved utilization of the generated power and more effective energy conversion. This improvement is consistent with the enhanced tracking capability and reduced oscillations achieved by the proposed controller.

Overall, the results demonstrate that the FL-TOSMC strategy significantly enhances current quality by reducing harmonic distortion while preserving the fundamental frequency component, making it a promising control approach for high-performance DFIG-based WECSs and other industrial applications requiring strict PQ standards.

Table 4 summarizes the dynamic and steady-state performance of the conventional TOSMC and the proposed FL-TOSMC controllers under Test 2 operating conditions. The obtained results clearly demonstrate the effectiveness of the proposed controller in improving PQ, tracking accuracy, and transient response.

Table 4. Ratios/value of overshoot, response time, SSE, and power ripples of TOSMC and FL-TOSMC (Test 2).

		P_s (W)	Q_s (VAR)
TOSMC	Ripples	48	31.7
	Overshoot	4259	9.669
	RT (ms)	0.20	0.11
	SSE	0.11	1.3
FL-TOSMC	Ripples	22	20.31
	Overshoot	4265	1.32
	RT (ms)	0.10	0.07
	SSE	0.0748	0.234
Ratios (%)	Ripples	54.16%	35.9%
	Overshoot	−0.14%	86.34%
	RT (ms)	50%	36.36%
	SSE	32%	82%

For P_s , the ripple magnitude is reduced from 48 W with TOSMC to 22 W with FL-TOSMC, corresponding to a reduction of 54.16%. Likewise, the Q_s ripple decreases from 31.7 VAR to 20.31 VAR, representing a reduction of 35.9%. This improvement indicates that the proposed controller is more effective in attenuating oscillations caused by wind-speed variations and system nonlinearities. From a physical perspective, the FL mechanism continuously adapts the controller gains according to the operating conditions, while the third-order sliding mode action suppresses high-frequency oscillations, resulting in smoother P_s and reactive power profiles and enhanced PQ.

Regarding overshoot, the P_s response exhibits only a negligible variation, changing from 4259 W to 4265 W, which corresponds to a difference of approximately −0.14%. This result indicates that both controllers provide a similar transient peak for P_s regulation. However, a substantial improvement is achieved in Q_s control, where the overshoot decreases from 9.669 VAR to only 1.32 VAR, corresponding to an 86.34% reduction. Such a reduction demonstrates the superior damping capability of the FL-TOSMC controller, which effectively limits excessive transient excursions and reduces oscillatory behavior during reference changes and disturbances.

The RT is also significantly improved. For P_s regulation, the RT decreases from 0.20 ms to 0.10 ms, corresponding to a 50% reduction. Similarly, for Q_s control, the RT decreases from 0.11 ms to 0.07 ms, yielding a 36.36% reduction. These improvements confirm the ability of the proposed controller to accelerate the convergence of tracking errors and achieve faster stabilization following operating condition changes. The enhanced dynamic response is mainly due to the finite-time convergence property of the TOSMC method combined with the adaptive adjustment provided by the FL system.

Concerning the SSE, the proposed FL-TOSMC controller reduces the P_s error from 0.11 to 0.0748, corresponding to a 32% reduction. For Q_s regulation, the SSE decreases dramatically from 1.3 to 0.234, representing an 82% reduction. These results indicate that

the proposed controller achieves more accurate reference tracking and better steady-state performance. Physically, the reduction in SSE reflects the controller's improved capability to compensate for modeling uncertainties and external disturbances while maintaining the operating point close to its desired reference value.

Overall, the results of Table 4 confirm that the FL-TOSMC controller outperforms the conventional TOSMC approach under Test 2 conditions. The proposed controller provides lower power ripples, significantly reduced Q_s overshoot, faster RTs, and improved steady-state accuracy, thereby ensuring enhanced robustness, superior PQ, and more stable operation of the DFIG-based WE conversion system.

Table 5 presents a comparison between the results of Test 1 (Table 3) and the results of Test 2 (Table 4). The percentage change is calculated using the following relationship:

$$\text{Change}(\%) = \frac{\text{Value}_{\text{Test2}} - \text{Value}_{\text{Test1}}}{\text{Value}_{\text{Test1}}} \times 100\% \quad (42)$$

Table 5. Rates of change for both fluctuations, SSE, overshoot, and response time between Test 1 and Test 2.

Parameter	Active Power		Reactive Power	
	TOSMC	FL-TOSMC	TOSMC	FL-TOSMC
Ripples	+54.84%	+37.50%	+58.50%	+53.86%
Overshoot	−0.023%	−0.094%	−67.67%	+169.39%
RT	−4.76%	−9.09%	−8.33%	−12.50%
SSE	+10.00%	+49.60%	+160.00%	+56.00%

A comparative analysis was performed to evaluate the variation in overshoot, RT, SSE, and power ripples between Test 1 and Test 2 for both TOSMC and FL-TOSMC controllers.

For P_s , the ripple magnitude of TOSMC increased from 31 W in Test 1 to 48 W in Test 2, corresponding to an increase of 54.84%. Similarly, the ripple magnitude of FL-TOSMC increased from 16 W to 22 W, representing an increase of 37.50%. Although both controllers experienced higher oscillations under Test 2 conditions, FL-TOSMC maintained significantly lower ripple levels.

Regarding Q_s , the ripple value increased from 20 VAR to 31.7 VAR for TOSMC (+58.50%) and from 13.2 VAR to 20.31 VAR for FL-TOSMC (+53.86%). Despite the increase, the proposed FL-TOSMC controller continued to provide superior ripple attenuation.

The overshoot of P_s remained almost unchanged for both controllers. TOSMC decreased slightly from 4260 W to 4259 W (−0.023%), while FL-TOSMC increased marginally from 4269 W to 4265 W (−0.094%). For Q_s , the overshoot decreased considerably from 29.91 VAR to 9.669 VAR for TOSMC (−67.67%) and increased from 0.49 VAR to 1.32 VAR for FL-TOSMC (+169.39%). Nevertheless, the absolute overshoot of FL-TOSMC remained substantially lower than that of TOSMC.

The RT of P_s improved in Test 2. TOSMC decreased from 0.21 ms to 0.20 ms (−4.76%), while FL-TOSMC decreased from 0.11 ms to 0.10 ms (−9.09%). For Q_s , RT decreased from 0.12 ms to 0.11 ms (−8.33%) for TOSMC and from 0.08 ms to 0.07 ms (−12.50%) for FL-TOSMC, indicating faster transient dynamics in Test 2.

Concerning SSE, the SSE of P_s increased from 0.10 to 0.11 for TOSMC (+10.00%) and from 0.05 to 0.0748 for FL-TOSMC (+49.60%). For Q_s , SSE increased significantly from 0.50 to 1.30 for TOSMC (+160.00%), whereas FL-TOSMC increased from 0.15 to 0.234 (+56.00%). Although the error increased in both cases, FL-TOSMC consistently maintained lower SSE values.

Overall, the results indicate that Test 2 represents a more demanding operating condition, leading to larger power ripples and SSEs. Nevertheless, the proposed FL-TOSMC controller preserves its superiority over the conventional TOSMC by maintaining lower overshoot, faster RTs, reduced SSEs, and lower power ripples under both test scenarios.

(c) Third test

In the third test, the proposed strategy is evaluated under a different stepped WS profile, as shown in Figure 13a. The obtained results are presented in Figures 13 and 14, while the numerical comparisons are summarized in Table 6.

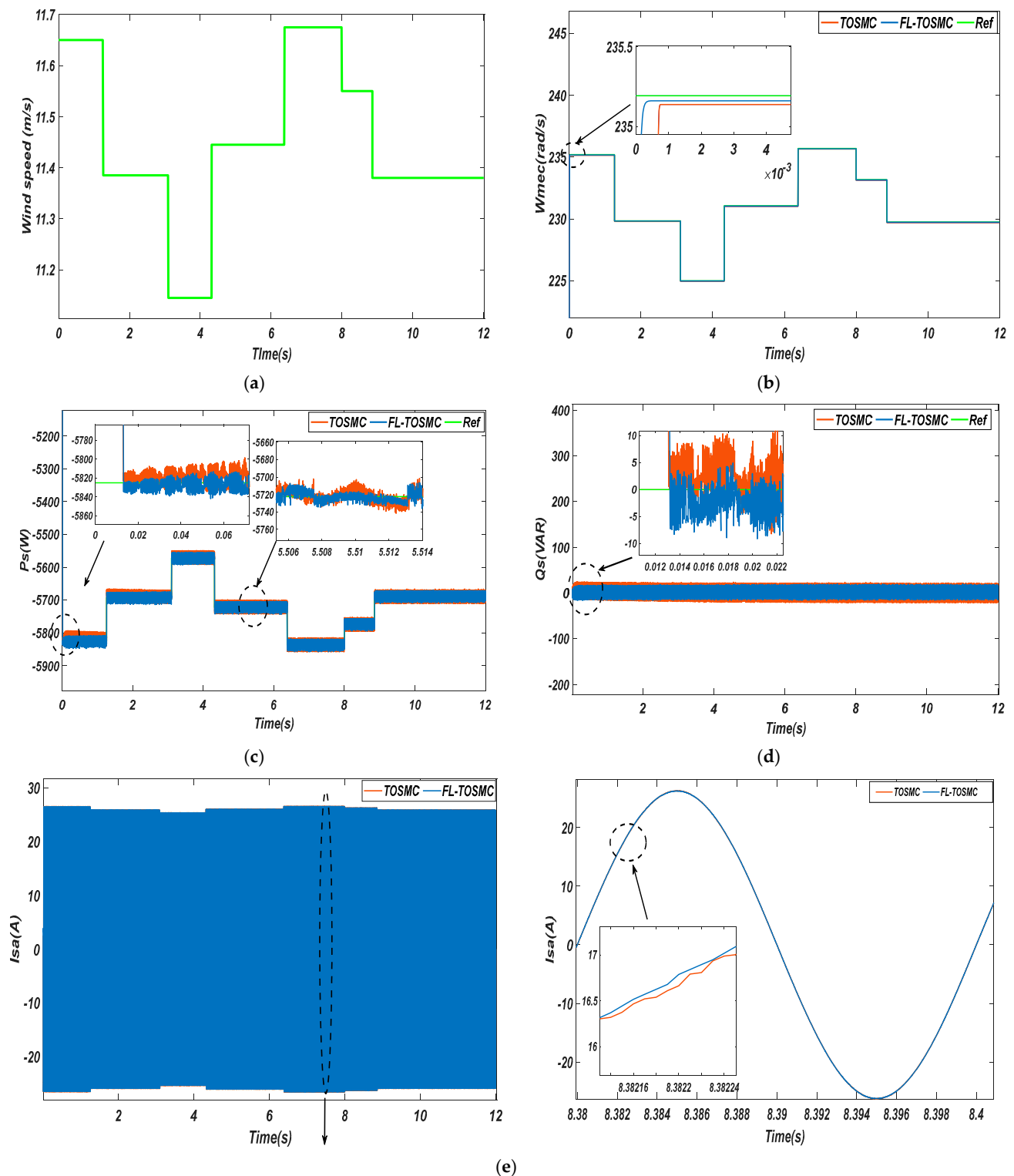


Figure 13. Third test results: (a) steps WS profile, (b) generator speed, (c) P_s , (d) Q_s , (e) current.

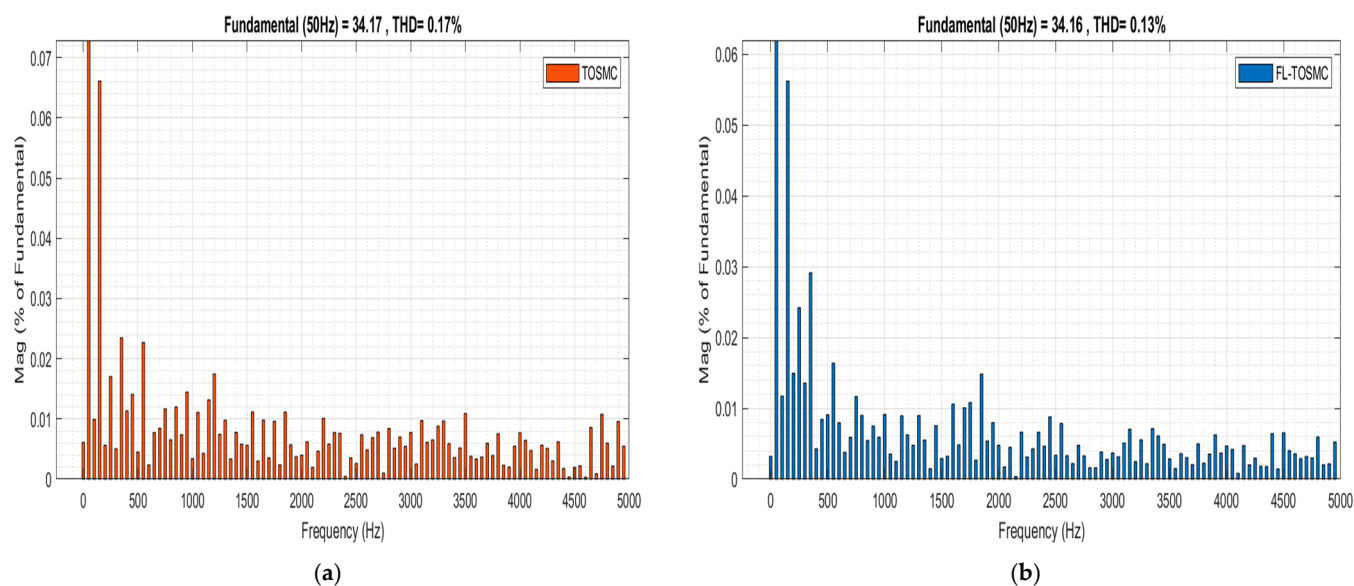


Figure 14. THD value of stator current (Test 3): (a) TOSMC; (b) FL-TOSMC.

Table 6. Value and ratios of overshoot, RT, SSE, and power ripples of TOSMC and FL-TOSMC (Test 3).

		P_s (W)	Q_s (VAR)
TOSMC	Ripples	65	16.7
	Overshoot	5824	19.58
	RT (ms)	0.23	0.18
	SSE	8	2.13
FL-TOSMC	Ripples	13	11.52
	Overshoot	5834	1.74
	RT (ms)	0.17	0.10
	SSE	6	0.58
Ratios (%)	Ripples	80	31
	Overshoot	0.17	91.11
	RT (ms)	26.03	44
	SSE	25	72.76

Figure 13 illustrates the dynamic behavior of the DFIG-based WE conversion system using TOSMC and FL-TOSMC controllers. Figure 13b shows that both controllers successfully track the optimal rotor speed required by the MPPT strategy. However, FL-TOSMC provides faster convergence, lower transient deviations, and improved speed tracking due to the adaptive capability of the FL component.

Figure 13c,d presents the P_s and Q_s responses, respectively. The active power follows the WS variations accurately for both controllers, but FL-TOSMC achieves smoother tracking with reduced oscillations, lower ripples, and shorter settling time, especially during abrupt WS changes. Q_s remains well regulated, confirming the effectiveness of the DFOC decoupling strategy; nevertheless, FL-TOSMC provides faster disturbance rejection and improved stability compared with TOSMC.

The stator current waveform shown in Figure 13e remains sinusoidal for both approaches. However, FL-TOSMC produces a smoother current with reduced distortion and fewer transient oscillations, confirming its ability to improve PQ under variable wind conditions.

Overall, the results of Figure 13 demonstrate that the proposed FL-TOSMC controller outperforms the conventional TOSMC strategy in terms of dynamic response, power-

tracking accuracy, ripple reduction, disturbance rejection, and current quality. These improvements confirm its suitability for DFIG-based WECSs operating under rapidly varying wind conditions.

Figure 14 presents the current THD comparison between the conventional TOSMC and the proposed FL-TOSMC controllers. The TOSMC approach results in a THD value of 0.17% (Figure 14a), while FL-TOSMC reduces this value to 0.13% (Figure 14b), corresponding to an improvement of approximately 23.53%.

This enhancement is attributed to the combination of the adaptive capability of FL and the robustness of TOSMC, which enables better disturbance rejection and effective suppression of current oscillations. Consequently, the proposed controller produces a smoother current waveform with reduced harmonic components.

Moreover, the fundamental component at 50 Hz remains almost unchanged for both controllers, confirming that the THD reduction is achieved through harmonic attenuation rather than modification of the fundamental current magnitude. These results demonstrate the effectiveness of FL-TOSMC in improving current quality and satisfying the PQ requirements of grid-connected DFIG-based WECSs.

Table 6 presents the performance comparison between the conventional TOSMC and the proposed FL-TOSMC controllers under Test 3 operating conditions. The results clearly demonstrate the superiority of the proposed controller in terms of power ripple suppression, transient response, and steady-state accuracy.

For P_s , the power ripple amplitude is reduced from 65 W with TOSMC to 13 W with FL-TOSMC, corresponding to an 80% reduction. Similarly, for Q_s , the ripple magnitude decreases from 16.7 VAR to 11.52 VAR, representing a 31% reduction. This significant attenuation of oscillations is mainly attributed to the adaptive nature of the FL component, which continuously adjusts the control gains according to the operating conditions. As a result, the controller is able to suppress fluctuations caused by wind-speed variations and parameter uncertainties more effectively than the conventional TOSMC. Lower ripple levels indicate smoother power injection into the grid and improved PQ.

Regarding overshoot, the P_s overshoot remains nearly unchanged, increasing slightly from 5824 W to 5834 W, which corresponds to a negligible variation of only 0.17%. However, a remarkable improvement is observed for the Q_s response, where the overshoot is reduced from 19.58 VAR to only 1.74 VAR, corresponding to a reduction of 91.11%. Physically, this behavior indicates that the proposed controller significantly improves damping during transient conditions and prevents excessive energy accumulation in the electromagnetic dynamics of the DFIG, thereby reducing oscillatory behavior after reference changes.

The RT is also improved by the proposed controller. For P_s regulation, the RT decreases from 0.23 ms to 0.17 ms, yielding a reduction of 26.03%. For Q_s control, the RT decreases from 0.18 ms to 0.10 ms, corresponding to a reduction of 44%. These improvements confirm that the FL-TOSMC controller accelerates error convergence and allows the DFIG to reach its steady-state operating point more rapidly following disturbances or wind-speed variations. The faster response is a direct consequence of the higher-order sliding mode action combined with the adaptive tuning capability of the FL system.

Concerning the SSE, the proposed controller reduces the P_s error from 8 to 6, corresponding to a 25% reduction. For Q_s regulation, the SSE decreases from 2.13 to 0.58, yielding a substantial reduction of 72.76%. The lower SSE values demonstrate the improved tracking precision of the FL-TOSMC approach and its ability to maintain the generated power close to the desired reference values despite the presence of disturbances and system nonlinearities.

Overall, the results of Table 6 confirm that the proposed FL-TOSMC controller provides superior dynamic and steady-state performance compared with the conventional

TOSMC. The combination of FL adaptive tuning and TOSMC effectively enhances robustness, accelerates system dynamics, reduces power oscillations, and improves tracking accuracy, making the proposed approach particularly suitable for DFIG-based WECSs operating under variable and challenging conditions.

Table 7 presents a study of the changes in the results obtained for overshoot, RT, SSE, and power ripples between Test 1 and Test 3. A comparative analysis between Test 1 and Test 3 reveals the impact of the changed operating conditions on the dynamic performance of both controllers. For P_s , the ripple magnitude of the conventional TOSMC increased significantly from 31 W in Test 1 to 65 W in Test 3, corresponding to an increase of 109.68%. In contrast, the FL-TOSMC ripple level decreased from 16 W to 13 W, representing a reduction of 18.75%, which demonstrates the superior capability of the proposed controller in suppressing power oscillations under more demanding operating conditions. For Q_s , the ripple value decreased from 20 VAR to 16.7 VAR for TOSMC (−16.50%) and from 13.2 VAR to 11.52 VAR for FL-TOSMC (−12.73%).

Table 7. Percentage change in performance indices between Test 1 and Test 3.

Parameter	Active Power		Reactive Power	
	TOSMC	FL-TOSMC	TOSMC	FL-TOSMC
Power Ripples	+109.68%	−18.75%	−16.50%	−12.73%
Overshoot	+36.71%	+36.66%	−34.54%	+255.10%
Response Time	+9.52%	+54.55%	+50.00%	+25.00%
SSE	+7900.00%	+11,900.00%	+326.00%	+286.67%

Regarding overshoot, the P_s overshoot increased from 4260 W to 5824 W for TOSMC (+36.71%) and from 4269 W to 5834 W for FL-TOSMC (+36.66%), indicating a comparable increase for both controllers due to the altered test conditions. For Q_s , the overshoot decreased from 29.91 VAR to 19.58 VAR for TOSMC (−34.54%), while it increased from 0.49 VAR to 1.74 VAR for FL-TOSMC (+255.10%). Nevertheless, the absolute overshoot value of FL-TOSMC remained substantially lower than that of TOSMC.

RT also exhibited noticeable variations. For P_s , RT increased from 0.21 ms to 0.23 ms for TOSMC (+9.52%) and from 0.11 ms to 0.17 ms for FL-TOSMC (+54.55%). Similarly, for Q_s , RT increased from 0.12 ms to 0.18 ms for TOSMC (+50.00%) and from 0.08 ms to 0.10 ms for FL-TOSMC (+25.00%). Although RTs increased in Test 3, the proposed FL-TOSMC still maintained faster dynamics than the conventional TOSMC.

Concerning SSE, a significant increase was observed under Test 3 conditions. For P_s , SSE increased from 0.1 to 8 for TOSMC (+7900%) and from 0.05 to 6 for FL-TOSMC (+11,900%). For Q_s , SSE increased from 0.5 to 2.13 for TOSMC (+326.00%) and from 0.15 to 0.58 for FL-TOSMC (+286.67%). Despite this increase, the proposed FL-TOSMC consistently achieved lower SSE values than TOSMC.

Overall, the comparison between Test 1 and Test 3 demonstrates that Test 3 represents a significantly more challenging operating scenario. Nevertheless, the FL-TOSMC controller preserves its superior performance by maintaining lower power ripples, reduced overshoot in Q_s regulation, faster RTs, and smaller SSEs compared with the conventional TOSMC controller.

The results show that Test 3 imposes considerably more demanding operating conditions, particularly in terms of overshoot and SSE. However, the FL-TOSMC controller maintains lower absolute values of ripples, overshoot, RT, and SSE than the conventional TOSMC controller in most performance metrics.

Table 8 represents a study in the change in the THD value for two controls during the three tests performed. Equations (43) and (44) are used to complete this study. This study is based on studying the effect of the THD value on changing the system parameter

values and the shape of the WS change. From Table 8, it is noted that the THD value changed in the tests for the two controls. The THD value increased during the second test compared to the first test due to the change in DFIG parameters.

$$[A] = \frac{THD_{test2} - THD_{test1}}{THD_{test2}} \quad (43)$$

$$[B] = \frac{THD_{test3} - THD_{test1}}{THD_{test3}} \quad (44)$$

Table 8. Study of the change in THD value in the three tests.

	TOSMC	Proposed FL-TOSMC	Ratios (%)			
			TOSMC	FL-TOSMC	[A]	[B]
			[A]	[B]		
First Test	0.17	0.14				
Second test	0.22	0.18	22.73	0	22.22	−7.14
Third test	0.17	0.13				

The DFOC-FL-TOSMC approach presented a percentage change in the THD value between the first and second tests compared to the DFOC-TOSMC approach. This percentage change was 22.73% and 22.22% for both the designed approach and the DFOC-TOSMC approach, respectively. The THD value in the third test did not change compared to the first test if the DFOC-TOSMC approach was used. Therefore, the effect rate is estimated at 0%. However, if the designed approach was used, the THD value decreased in the third test compared to the first test. This decrease was estimated at 7.14%.

This study highlights that the THD value is affected by both a change in DFIG parameters and a change in the shape of the WS. Therefore, it is necessary to propose a control that has high performance and a great ability to improve the THD value, regardless of the shape of the WS or the change in the DFIG parameters. Table 8 gives a clear picture that the designed approach improves the THD value significantly compared to the DFOC-TOSMC approach, which makes it a promising solution in other industrial fields.

Table 9 presents a comparative evaluation of the proposed FL-TOSMC strategy against several advanced control techniques reported in the literature using the THD index as a performance criterion. As can be observed, the proposed controller achieves THD values of 0.14%, 0.18%, and 0.13% under the considered test scenarios, which are among the lowest values reported. Compared with conventional approaches such as TOSMC (0.83%), ISMC (1.33%), DRAPC (1.08%), DPC-STSMC (0.85%), DPC-NSTSMC-SVM (0.99%), ANN-DPC (2.22%), and SMC-SVM control (5.76%), the proposed method provides a substantial reduction in harmonic distortion, indicating superior power-quality performance.

Table 9. Comparison table of the proposed approach and other control techniques.

Techniques	THD (%)	References
DPC-STSMC	0.85	[81]
DPC-ANFIS-STSMC	0.46	[82]
TOSMC-DRAPC	0.23	[83]
ISMC	1.33	[84]
TOSMC	0.83	[76]
DRAPC	1.08	[85]
DPC-NSTSMC-SVM	0.99	[86]

DFTC-SOCSM	0.23	[87]
SMC-SVM control	5.76	[88]
ANN-DPC	2.22	[89]
0.14	Proposed technique	
0.18		
0.13		

Furthermore, even when compared with high-performance controllers such as DPC-ANFIS-STSMC (0.46%), TOSMC-DRAPC (0.23%), and DFTC-SOCSM (0.23%), the proposed approach consistently achieves lower THD levels. This improvement can be attributed to the effective integration of the FL method and the TOSMC method, where the FL component enhances adaptability to operating condition variations, while the TOSMC component ensures fast error convergence and strong robustness against disturbances and parameter uncertainties. As a result, current and power oscillations are significantly attenuated, leading to improved waveform quality and reduced harmonic content.

Overall, the results presented in Table 9 demonstrate that the proposed FL-TOSMC controller outperforms several recently published control strategies in terms of THD reduction, confirming its effectiveness for enhancing PQ and dynamic performance in DFIG-based WECSs.

Table 10 compares the RTs achieved by the proposed FL-TOSMC controller with those reported in several recent studies. The proposed approach attains response times ranging from 0.10 ms to 0.17 ms for P_s and from 0.07 ms to 0.10 ms for Q_s , demonstrating a significantly faster dynamic response than all referenced methods.

Table 10. Comparison with other works in terms of RT power.

References	RT (ms)	
	P_s	Q_s
[90]	0.9	2.10
	2.50	3
	2.65	3.25
	4.80	5.40
[91]	2.2	0.90
[92]	1.70	1.85
	1.34	1.183
[93]	17	18
	9	5
[94]	15	80
[95]	3.87	2.58
	1.29	0.46
[96]	33.8	34.5
[97]	5	4
[98]	12.15	10.08
	11.25	9.85
	11.85	10.05
[99]	-	28
[100]	0.310	0.550
	0.475	0.650
	0.120	0.200
[101]	1.78	8.50
[102]	1.50	0.80
Proposed approach	0.170	0.100

	0.100	0.070
	0.110	0.080

For P_s regulation, the best response times reported in the literature are 0.12 ms in [100], 0.31 ms in [100], and 0.90 ms in [90]. Compared with the best literature value of 0.12 ms, the proposed controller achieves a response time of 0.10 ms, corresponding to an improvement of approximately 16.7%. Relative to the 0.31 ms and 0.90 ms values, the improvement reaches 67.7% and 88.9%, respectively. Furthermore, when compared with controllers exhibiting RTs greater than 1 ms, such as [91] (2.2 ms), [94] (15 ms), and [96] (33.8 ms), the proposed method reduces the RT by approximately 95.5%, 99.3%, and 99.7%, respectively.

Similarly, for Q_s control, the proposed approach achieves response times between 0.07 ms and 0.10 ms, while the best reported values in the literature are 0.20 ms in [100], 0.46 ms in [95], and 0.80 ms in [102]. Consequently, the proposed controller provides improvements of approximately 65%, 78.3%, and 87.5%, respectively. Even larger gains are observed when compared with slower techniques, such as [90] (2.10–5.40 ms), [94] (80 ms), and [99] (28 ms), where the reduction in response time exceeds 95% and reaches more than 99% in several cases.

The superior dynamic performance of the proposed FL–TOSMC controller can be attributed to the combination of FL method adaptation and the TOSMC method. The FL component continuously adjusts the control action according to the operating conditions, while the third-order sliding mode structure ensures rapid error convergence and strong robustness against parameter uncertainties and external disturbances. This synergy enables the controller to minimize transient duration, accelerate power tracking, and maintain stable operation under varying conditions.

Overall, the results of Table 10 demonstrate that the proposed FL–TOSMC strategy provides one of the fastest power response characteristics reported in the literature, confirming its effectiveness for high-performance DFIG-based WECSs requiring rapid P_s and Q_s regulation.

7. Conclusions

This paper proposed a hybrid FL–TOSMC strategy to enhance the performance of a DFIG-based WECS under the DFOC framework. The proposed controller combines the robustness and finite-time convergence of TOSMC with the adaptive capability of FL to improve system performance under variable operating conditions.

The effectiveness of the proposed approach was verified through several simulation tests and compared with the conventional TOSMC strategy. The results demonstrated significant improvements in both transient and steady-state performances. The proposed FL–TOSMC reduced the stator current THD by approximately 17.65%, 18.18%, and 23.53% for the considered tests. Moreover, it achieved substantial reductions in P_s and Q_s ripples, reaching up to 80% and 35.9%, respectively. Improvements in RT, SSE, and Q_s overshoot further confirmed the enhanced tracking accuracy and PQ performance of the proposed controller.

The robustness evaluation under DFIG parameter variations showed that FL–TOSMC maintains stable operation despite significant changes in machine parameters. The proposed strategy successfully reduced oscillations and preserved accurate tracking, demonstrating its capability to handle uncertainties commonly encountered in practical WECSs.

However, this study has some limitations. The validation was performed only through MATLAB/Simulink simulations without experimental implementation. Further-

more, the robustness analysis was limited to DFIG parameter variations, while other practical disturbances, including grid faults, measurement noise, converter nonlinearities, DC-link voltage fluctuations, and severe wind turbulence, were not considered. In addition, the comparison was mainly performed against TOSMC, while other advanced controllers were evaluated only through literature-based comparisons.

Future research will focus on experimental validation using real-time platforms and HIL testing. Further studies will investigate the performance of the proposed controller under a wider range of disturbances, including grid-voltage disturbances, sensor noise, converter constraints, and DC-link perturbations. Comprehensive comparisons with advanced control techniques, including PI, super-twisting SMC, fuzzy SMC, and optimization-based controllers, will also be conducted. Moreover, automatic parameter tuning using optimization algorithms and the extension of the proposed strategy to hybrid wind–photovoltaic energy systems will be explored.

Author Contributions: A.B.: Conceptualization; Methodology; Software; Validation; Formal analysis; Investigation; Resources; Data curation; Writing—original draft preparation; Writing—review and editing; Visualization; Supervision; Project administration. M.L.: Conceptualization; Methodology; Formal analysis; Investigation; Resources; Data curation; Writing—original draft preparation; Writing—review and editing; Visualization; Supervision. H.B.: Conceptualization; Methodology; Formal analysis; Investigation; Resources; Data curation; Writing—original draft preparation; Writing—review and editing; Visualization; Supervision; Project administration; Funding acquisition. S.G.: Formal analysis; Investigation; Resources; Data curation; Writing—review and editing; Visualization; Supervision. A.M.: Conceptualization; Methodology; Software; Validation; Formal analysis; Investigation; Resources; Data curation; Writing—original draft preparation; Writing—review and editing; Visualization; Supervision. G.B.: Conceptualization; Methodology; Formal analysis; Investigation; Resources; Data curation; Writing—review and editing; Visualization; Supervision. N.B.: Methodology; Formal analysis; Investigation; Resources; Writing—review and editing; Visualization; Supervision; Project administration; Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was fully supported by the PubArt program of the National University of Science and Technology POLITEHNICA Bucharest, and partially supported by the Experimental—Demonstration project PN-IV-P7-7.1-PED-2024-0567 (Improving the Fuel Cell Hybrid Electric Vehicle Drivetrain by Implementing a Novel Optimal Real-Time Power Management Strategy), contract No. 58PED, 2024–2025.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

FL	Fuzzy logic	TOSMC	Third-order sliding mode control
DFIG	Doubly-fed induction generator	THD	Total harmonic distortion
WE	Wind energy	WS	Wind speed
SVM	Space vector modulation	PQ	Power quality
PI	Proportional–integral controller	MPPT	Maximum power point tracking
SMC	Sliding mode control	EP	Electrical power
WT	Wind turbine	DTC	Direct torque control
FOC	Field-oriented control	DFOC	Direct field-oriented control
BC	Backstepping control	DPC	Direct power control
RSC	Rotor-side converter	GSC	Grid-side converter

Appendix A

(a) System parameters

Tables A1 and A2 represent the parameter values of the ES studied in this work.

Table A1. Parameters of the WT.

Parameter	Value
f	0.0024
G	2
J	7.68 kg·m ²
R_t	3.19 m
ρ	1.22 kg/m ³

Table A2. Parameters of the DFIG.

Parameter	Value
V_s	220 V
R_s	0.95 Ω
R_r	1.8 Ω
L_s	0.094 H
L_r	0.088 H
M	0.082 H
f_s	50 Hz
p	3

(b) Parameters of the TOSMC controller gains

In Table A3, the gain values of the TOSMC controller used in this simulation are listed.

Table A3. Parameters of the TOSMC controller gains.

MPPT-TSR	$K_1 = 20$	$K_2 = 5$	$K_3 = 1000$
DFIG	$K_1 = 2$	$K_2 = 90$	$K_3 = 90$

Table A4 presents the gain coefficients of the FL controller.

Table A4. Parameters of the FL controller gains.

Error Scaling Factor	K_e	1.0
Change-of-Error Scaling Factor	K_{e1}	0.05
Output Adjusting Scaling Factor	K_u	120
Fuzzy Universe of Discourse	U	$[-1, \dots, 1]$

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