



(RESEARCH ARTICLE)



Robust grid-forming and grid-following control of DFIG-based wind energy conversion systems using multi-objective optimized sliding mode control

Adel Elgammal *

Professor, Utilities and Sustainable Engineering, The University of Trinidad & Tobago UTT.

World Journal of Advanced Engineering Technology and Sciences, 2026, 19(01), 153-170

Publication history: Received on 21 February 2026; revised on 09 April 2026; accepted on 11 April 2026

Article DOI: <https://doi.org/10.30574/wjaets.2026.19.1.0214>

Abstract

Since renewable energy resources are penetrating modern power systems more than ever, the wind energy conversion system (WECS) requires fast dynamic response and robustness as well as reliable operation under strong-grid and weak-grid conditions. One example is the doubly fed induction generator (DFIG), which remains an attractive option within variable-speed wind generation technologies, as it has a low converter rating, high efficiency, and flexible power control capability. Yet, DFIG-based WECSs control methods are still typical in nature and their performance degrades with wind speed fluctuation, grid interference, model instability and parameter perturbation. In this paper, we proposed a robust control approach for DFIG-based WECSs that merges grid-forming and grid-following operation in the same multi-objective optimized sliding mode control (SMC) design framework.

To improve the active and reactive power control, rotor speed regulation, dc-link voltage balancing as well as fault ride-through capability with reduced chattering effect encountered in classical SMC, the proposed concept approach is devised. When working in grid-following mode, the controller accurately synchronizes and injects power into the utility grid. It then operates in grid-forming mode, providing voltage and frequency support, thus improving operation under weak-grid and islanded conditions. A multi-objective optimization procedure is applied to find the SMC parameters that minimize settling time, overshoot, steady-state tracking error (SSTE), and control effort simultaneously. Simulation results show that active power settling time is decreased from 0.42 s to 0.18 s and dc-link voltage overshoot is resided from 14.6% to 4.1% in comparison to a traditional PI-based controller using the proposed approach. Moreover, compared to the conventional observer, rotor speed tracking error is reduced by 31.8%, and stator current total harmonic distortion decreases from 4.9% to 2.1%. When subjected to a 30% sag in grid voltage, the proposed controller retains closed-loop stability and recovers nominal operating conditions within 0.12 s versus 0.31 s for the benchmark controller. In addition, these findings verify that the proposed MOO-SMC called upgrade substantially increases the dynamism performance, stabilizing and quality of power with respect to conventional SMC for various operating conditions applied to DFIG-based WECSs.

Keywords: Doubly Fed Induction Generator (DFIG); Wind Energy Conversion System (WECS); Grid-Forming Control; Grid-Following Control; Sliding Mode Control (SMC); Multi-Objective Optimization

1. Introduction

The continuing transition to decarbonised power systems has increasingly focused (and, consequently, increased the penetration of) renewable energy sources such as wind and solar into transmission and distribution networks. Of these technologies, wind energy has emerged as one of the most entrenched renewable generation alternatives due to its maturity and scalability along with its increasing contribution to utility-scale electricity supply. The doubly fed induction generator (DFIG) is one of the most popular topologies among the various wind turbine generator

* Corresponding author: Adel Elgammal.

technologies owing to its variable-speed operation, low converter rating, and the ability provide active and reactive power [5], [8]. A friction-dependent wind energy conversion system (WECS) usually uses a wound-rotor induction machine with its stator connected directly to the grid and its rotor interfaced by means of back-to-back converter. This configuration allows the independent control of active and reactive power only with a partial-scale converter, resulting in lower cost and losses compared to full-converter wind turbine systems [8], [9]. For these reasons, as one of the most important wind energy converters, DFIG technology has been widely deployed in new medium- and large-wind farms and continues to receive vigorous research interest even with increasing replacements by full-converter permanent magnet synchronous generator systems. The operating environment of wind generators has substantially changed, however. Synchronous machines served as the backbone of traditional power systems, inherently serving inertia, damping, voltage support and frequency stabilization. Today, on the other hand, converter-based grids have less physical inertia and are more prone to disturbances [1], [3], [4] especially in weak-grid and low short-circuit ratio operation. This transition has revealed the shortcomings of traditional control strategies for renewable generators, particularly those that rely on strictly grid-following operation. A grid-forming converter relies on the pre-existence of stiff grid voltage for synchronization and generally, acts as a controlled current source. This approach works well in stiff grids while it is susceptible in weak grids, the fault current conditions, and during islanded operation [1], [3]. This points toward increasing interest towards grid-forming control [1], [2], [4] where converter-interfaced generators act as active voltage-frequency controllers and resemble controllable voltage sources. In future renewable energy-dominated grids, grid-following converters provide synthetic inertia and support through droop-based power sharing, damping, and enhanced voltage support; thereby their role is becoming increasingly important. While grid-forming control has found considerable exploration for battery energy storage systems and full-converter renewable systems, the application to DFIG-based WECS is still a more specialized and technically challenging research gap [6],[7]. Although, the controls of DFIG systems is still a challenge due to nonlinear dynamics, parameter variations, grid disturbances and aerodynamic uncertainties. Although classical proportional-integral (PI) vector control still remains endeared in practical applications due to its ease of implementation, it has been reported to cause performance degradation when subject to model mismatch and significant disturbances, as well as under weak-grid conditions [5], [10]. As a result, various control techniques have been developed such as model predictive control, adaptive control, observer-based control, artificial intelligence (AI) based approaches [16] and sliding mode control (SMC). SMC among them has received a particularly great attention due to its strong robustness against matched disturbances, parametric uncertainties and nonlinearities [2]–[4]. Several papers have implemented SMC for the control of DFIG, improving power tracking performance, speed regulation, DC-link voltage control performance and fault ride-through operation [8]–[19]. However, classical SMC brings on well-known chattering problem that has a potential to excite unmodeled dynamics, increase converter stress and degrade power quality in case it is not properly mitigated [11], [14], [16]. Such drawbacks have brought forward the design of higher-order [14], adaptive [15], fuzzy [16], fractional-order [17] and observer-based SMC variants for wind energy applications. Hence, modern DFIG control research has now converged to several mutually dependent needs: the need for robust nonlinear control; the need for enhanced weak-grid compatibility and the need for grid-following and grid-forming capabilities to be interconnected within a unique practically realizable framework.

The Doubly-Fed Induction Generator (DFIG) has been a popular choice in wind energy applications since it allows for variable-speed operation at any point around synchronous speed, but keeps direct stator connection to the grid. It allows better energy absorption by maximum power point tracking (MPPT), reduced mechanical stress and controllable q-reactive power support [5], [8]. Traditionally, the control of DFIG is performed by means of stator-flux-oriented vector control or grid-voltage-oriented vector control under the PI controllers in cascaded inner and outer loops. The rotor side converter (RSC) is typically responsible for controlling either electromagnetic torque/active power and stator reactive power, whereas the grid side converter (GSC) regulates DC-link voltage [8], [10], or reactive power at times exchanged from/to the grid. Although PI-based controllers are heavily used, they are designed based on linearized models and can lose performance at parameter mismatch or highly nonlinear operating conditions. Conventional vector-controlled DFIG systems are susceptible to various disturbances such as wind speed changes [18], voltage dips [9], network asymmetry [20] and parameter drift [21], which degrade both transitory and steady-state performances. In the case of unbalanced grids, conventional control may lead to oscillatory active and reactive power [9], increased current harmonics [12] and voltage stress on the converters [19]. These problems have motivated exploration of more resilient control strategies. Hu et al. showed that SMC for direct active and reactive power control of DFIG can have better robustness with respect to disturbances and uncertainties than conventional control [8]. To advance this concept, Shang and Hu also extended their sliding-mode-based direct power control to deal with the unbalanced grid voltage conditions, achieving better dynamic response as well as effectiveness in control [9]. Sun et al. also proposed a sliding-mode direct power control approach to work in both balancing and unbalancing grid conditions including an extended active power concepts [19]. Simultaneously, researchers have proposed better variants of SMC to mitigate classical limitations. Xiong et al. [11] to improve the transient performance and shorten the time of reaching in DFIG sliding mode control [11] proposed a quick exponential reaching law. Quan et al. proposed a new SMC approach based on multi-

resonants able to drive the DFIG under both unbalanced and harmonic grid conditions illustrated as similar advantages of advanced SMC concepts for distorted grid environments [12]. In another paper accepted for publication, Ayyarao proposed a barrier-function-based adaptive SMC design to improve the performance and robustness of vector-controlled DFIG [13]. Likewise, Soomro et al. utilized a super-twisting fractional-order terminal sliding mode controller, highlighting the potential advantages of higher-order and fractional approaches in accelerating convergence and reducing chattering [14]. Subsequent work has added observers and adaptive elements. Alhato et al. Works in [15] have integrated an adaptive fuzzy extended state observer with SMC to enhance the DC-link voltage response of wind-driven DFIG systems. Mousavi et al. discussed SMC's implementations within WECS and gave observer-based and higher-order sliding mode techniques as critical emerging themes [16]. More recently, Mousavi et al. proposed an observer-based high-order sliding mode controller for DFIG under sensor faults, reflecting the rising interest in resilience, reliability, and fault tolerance [17]. Bouguettah et al. Their proposed approach combines self-tuning fractional integral SMC in a manner that retained the adaptive and fractional sliding merits for fault tolerance to better address this issue on modern DFIG systems [18]. Overall, this literature confirms that SMC and its variations are a solid basis for strong DFIG control. Most of these studies focus on the grid-connected power regulation, DC-link control or fault ride-through in the grid-following paradigm instead of unified operation over both grid-following and grid-forming modes.

The primary focus in renewable energy research has become the distinction between grid-following and grid-producing control. This involves a phase-locked loop or similar synchronisation mechanism following an externally imposed grid voltage angle. They control current injection, and therefore operate well in systems with established voltage and frequency by strong synchronous sources or other grid-forming units [1], [3]. For the majority of DFIG wind farms that are connected to strong transmission systems, this has been a sufficient approach in the past. But, as renewable penetration increases, the number of synchronous generators will likely diminish threatening grid resilience and inertia response. However, in such systems it is not sufficient to only apply grid-following control due to the inability of establishing voltage or frequency references independently [1], [4]. For example, in low-inertia and weak-grid systems behaviors of PLL-based synchronizations could be unstable, especially for large disturbances or during short-circuit events [1], [3]. This problem is tackled through grid-forming control by actively allowing competitive converter-based resources to contribute to voltage amplitude and frequency regulation. Rosso et al. discussed grid-forming converter control methods and highlighted their increasing significance for future low-inertia and high-converter-powered power systems [1]. Rathnayake et al. propagated generalized virtual synchronous generator control concepts on renewable power systems displaying the potential capability of converter-interfaced generation to mimic synchronous generator dynamics [2]. Chen et al. explored modeling and power control design of grid-forming converters, highlighting the necessity for controllability-aware full-state feedback structures in advanced converter applications [3]. In addition, Cheema presented a review of virtual synchronous generator control and emphasised that the ability of grid-forming is vital for how well these concepts can increase stability, robustness and power-sharing performance in next-generation grids [4]. While most of the grid-forming literature is geared towards battery converters and full-converter systems, some have applied this work to DFIG-based wind energy systems. Martínez et al. proposed a grid-forming control strategy for the DFIGs based on rotor flux orientation and proved that DFIG-based systems can participate more actively than in typical grid-following operation in voltage and frequency regulation by using the appropriate control design [6]. Tafizare and Rahimi investigated grid-following and grid-forming controls for hybrid DFIG-wind/battery systems demonstrating their potentially smooth, general operation in both grid-connected and stand-alone conditions [7]. These studies are important advancements, yet they also indicate that grid-forming DFIG control is still a less mature technology than grid-following control. In stator directly connected grid, only the rotor is converter-fed, which makes DFIG systems structurally different from full-converter systems. Consequently, this couples the control design to various aspects such as synchronization, protection, and dynamic response [6], [7]. Although greater awareness of the importance of grid-forming capability exists, no systematic and generic control framework has yet emerged for DFIG-based WECS, providing both grid-following and so-called grid-forming functionality with effective disturbance rejection ability and optimized dynamic performance.

The main challenge with existing DFIG-based wind energy control strategies is that they are often only part-solutions to a larger problem. Traditional grid-feeding PI/vector control is also simple and performs well under normal grid-connected conditions, but it has poor robustness against parameter uncertainties as well as voltage disturbances and weak-grid operation [8]–[10], [19]. Sliding mode control offers enhanced robustness and dynamical performance, but classical realizations are prone to chattering, also expansion of control effort, design complexity [11], [14], [16]. Whereas grid-forming approaches have been shown to enhance voltage and frequency capability in both weak or islanded grids, their implementation on DFIG-based WECS has yet to catch up and can be challenging to harmonize with present rotor- and grid-side converter control architectures [6], [7]. Hence, the challenge is more than whether DFIGs can be robustly controlled, or if they operating in grid-forming mode. Based on this, the open issue is about how to formulate a single, reliable and well-tuned control scheme for DFIG-based WECS that: ensures that grid-following and grid-forming operation is supported; is robust against wind variations, parameters perturbations, and grid

disturbances; enhances active/reactive power control, DC-link voltage regulation as well as rotor speed tracking; eliminates chattering phenomena and implementation issues existing in conventional SMC; and At the same time, it has to satisfy multiple competing performance objectives. Particularly, the issue is important in future power systems since these DFIG-based wind farms are expected to not only yield active power Generation with maximum efficiency but also provide ancillary services, maintain stability as well as frequency and voltage support under weak-grid conditions.

There are several reasons that explain why this problem is still open in the literature. Firstly, the DFIG-based WECS is an inherently nonlinear multivariable system. It integrates the aerodynamic subsystems, mechanical shaft dynamics, induction machine electromagnetic behavior with converter-based control loops. The ongoing interaction among these subsystems becomes even more complex under disturbances like wind gusts, parameter variations, or unbalanced grid voltage levels [5], [16]. Linear or weakly nonlinear control techniques are thus frequently ineffective throughout the complete operating range. The second one is the existing trade-off between robustness and smoothness for a sliding mode control. Although higher switching gains lead to improved tracking and disturbance rejection, they cause stronger chattering [11], [14], [16]. While this issue has been mitigated by higher order, adaptive and fractional SMC methods, there is no established agreement of the optimal structure for DFIG applications especially in conditions where many control goals need to be achieved simultaneously [14], [18]. Third, the majority of DFIG studies focus on optimizing a narrow range of objectives. The controller design may emphasis fast response of active power consumption, while not necessarily minimizing DC-link overshoot, harmonic distortion nor generating reactive power to support under-line fault. In reality, these goals are intertwined and frequently opposing. For this reason, multi-objective optimization is becoming an increasingly important part of advanced controller design; however, it remains insufficiently integrated into DFIG sliding mode control frameworks in the literature [3], [16]. Fourth, grid-forming operation adds complexity on top of that. In grid-following mode, the converter follows conditions on the grid; in grid-forming mode, it helps to determine those conditions. It demands a much broader control architecture than that of traditional DFIG systems [1], [6], and [7] to facilitate switching between these modes or to create a controller capable of functioning properly in both contexts. Lastly, practical implementation challenges continue to be substantial. It is also important that controllers for wind energy systems be computationally efficient, reliable and implementable in real-time digital control hardware. - Some of these advanced methods may be too complex or parameter-sensitive for practical deployment despite being attractive from a theoretical point of view. This gap separates elegant control theory from field-proven renewable energy control strategies [3], [16].

To this end, the current article introduces a firm grid-forming and grid-following control set-up for DFIG-based WECS through multi-objective optimized sliding mode control. The suggested concept serves as a unified framework that integrates the disturbance rejection nature of sliding mode control and the systematic tuning of multi-objective optimization. The intended contribution is fivefold. Foremost, the work presents a unified control framework that is capable of supporting grid-following and grid-forming operation. This is directly in response to the fragmentation seen previously in the body of literature, as existing DFIG control studies rarely approach multiple operating paradigms [6], [7]. Second, a multi-objective optimization approach is used to tune the parameters of the sliding mode controller. This is a major improvement over trial-and-error tuning or single-objective design methods, as it allows for settling time, overshoot, steady-state error robustness and control effort to be considered concurrently. For the third dimension, there is an effort to decrease chattering while ensuring robustness so as to mitigate one of the fundamental drawbacks related with classical SMC in wind energy application [11], [14], [16]. The fourth one is to enhance comprehensive units of the DFIG performance variables such as active and reactive power regulations, DC-link voltage tracking, rotor speed indication, and disturbance mitigation under voltage sag in weak-grid operation. This expands the improvement from a narrow single-loop benefit. Finally, the paper adds to the developing literature related to converter-dominated power systems by demonstrating how a common wind generation technology (the DFIG) can be enhanced with additional grid-supportive behavior. In doing so, it connects classical robust DFIG control work [8]–[21] with recent developments for grid-forming converters [1]–[7]. Thus, the presented method is not another version of DFIG sliding mode control. This is envisioned to be a more holistic control solution that works with the operational realities of future renewable-rich power systems.

The rest of this paper is structured as follows. Section II describes the mathematical representation of the DFIG-based wind energy conversion system, including the aerodynamics for the wind turbine, shaft dynamics, electrical machine equations and converter interface model. Section III presents the proposed robust control architecture and explains the design of grid-following and grid-forming sliding mode control laws. In Section IV, we present the multi-objective optimization process utilized to identify the controller parameters and elucidate the chosen objective functions and constraints. Simulation and comparative performance (under various situations such as changing wind speeds, parameter uncertainties, voltage sags and mode-dependent operating conditions) are reported in Section V. The results are discussed in Section VI in terms of robustness, tracking accuracy, voltage and frequency support, and the overall

performance of the system. Sect. VII concludes the paper and summarizes the principal results, and outlines future research opportunities such as real-time implementation and experimental validation.

2. The Proposed Robust Grid-Forming and Grid-Following Control of DFIG-Based Wind Energy Conversion System

The general topology and control structure of the proposed robust grid-forming/grid-following doubly fed induction generator (DFIG)-based wind energy conversion system (WECS) with multi-objective optimized sliding mode controller (MOSMC) is shown in Fig. 1. The figure incorporates the aerodynamic energy conversion stage, the electromechanical generation stage, the power electronic interface, the supervisory mode selection mechanism as well as the nonlinear control loops proposed in a coordinated manner. The aim of such architecture is to permit stable operation for all possible grid-connected operating conditions as well as disturbed scenarios or weak-grid conditions with improved dynamic performance and stability and overall robust grid support capability.

The wind turbine indicates the first energy capture stage. The kinetic energy present in the wind is converted into mechanical torque through a gearbox placed next to the doubly fed induction generator (DFIG) shaft. The gearbox is also needed to match the relatively low rotational speed of the turbine rotor with the operational range in which electrical machines can effectively perform electromechanical conversion. A doubly-fed induction generator (DFIG) is chosen as the main generating component of a wind energy conversion system (WECS) due to its matured merits for variable-speed wind energy applications including lower converter rating, versatile power control ability, and better energy harvesting over a wide area of operation.

The DFIG electrical subsystem is separated into stator and rotor routes. As shown in Fig. 1, the stator is grid-connected directly and most of the power generated reaches directly to the load without a full-rated converter. As opposed to the rotor, which is linked and employed through a back-to-back power electronic converter system (RSC-DC-link-GSC). With this configuration, the rotor circuit can work synergistically allowing for positive and reverse power flow facilitating bidirectional exchange enabling adjustable machine torque, active/reactive power as well as DC-link energy balance. The DC-link capacitor is an intermediate storage element of energy between the RSC and GSC, which also stabilizes the power transfer rate between both converter stages.

The rotor-side converter control is used for the control of DFIG electromagnetic behavior. It is used to regulate variables like electromagnetic torque, rotor speed, active power, and reactive power in the used mode of operation based on system objectives in the proposed architecture. Conversely, the grid-side converter is responsible for DC-link voltage regulation and for controlling the exchange of active power with respect to the distribution grid. In particular, when the system performs a transition to or operating in the grid forming mode, GSC provides voltage support and frequency support under advanced operating conditions. It is therefore important for the RSC and GSC to act in unison to achieve stable operation, effective power transfer and strong dynamics against external disturbances.

The purpose of this mechanism is to measure the essential states and output signals characterizing a WECS, including rotor speed, generator electrical state variables (currents/voltages), converter-side signal information (electric pump motor controls), DC-link voltage, grid-side voltage/current data. The signals resulted from those measures are then passed to the mode selection logic, which serves as a supervisory decision block. Block 1 selects appropriate operating mode (grid-following or grid-forming) based on system condition, network characteristics and the ultimate control goal. So instead of a specific grid interfacing paradigm, the WECS has adaptive operational functionality.

The WECS is the controlled power injection unit to be synchronized with the utility grid in grid-following mode. Starting from this status, the control aim is to follow grid reference and deliver active and reactive power as commanded whilst keeping DC-link stability and rotor speed regulation. This mode is most appropriate for conventional strong-grid operation, wherein voltage magnitude and frequency are already dictated by the utility network. It aims to present that under this condition, the designed controller, is capable of achieving fast and accurate active/reactive power tracking for maintaining a stable DC-link voltage; and reducing the influences of wind variations as well as parametric uncertainty on performance.

The WECS acts and supports more in the case of grid forming mode. Instead of simply tracking an externally defined grid voltage and frequency, the converter-interfaced system participates in their formation and stabilization. As represented in Fig. The grid-forming control pathway inherently allows the proposed architecture in providing voltage regulation, frequency support as well as improved resilience given weak-grid or disturbed operation conditions. Such mode of operation is especially important in low-inertia networks, microgrid applications or transient disturbances

situations where the traditional grid-following behavior may not be able to guarantee stable operating. The new DFIG-based WECS proposed here, with grid-forming capability embedded in it, would thus have better adherence to future grids dominated by renewable energy.

The unique contribution of this architecture is the multi-objective optimized sliding mode controller (MOSMC), demonstrated in the main control block shown in Fig. 1. This block is the main contribution of the presented method providing a way for sliding mode control robustness to be combined with systematic tuning using multi-objective optimization. The MOSMC consists of three key components: sliding surface design, multi-objective optimization and coordinated control law for RSC and GSC. The Sliding Surface design specifies the desired dynamic behavior of the controlled variables and provides the manifold along which we force the system that ensures robustness to disturbances and model uncertainties. In this study, we introduce the multi-objective optimization unit to select the controller parameters more efficiently that satisfy various performance criteria altogether (for example — settling time, overshoot, steadiness in terms of accuracy and control effort). In particular, balancing control loops is essential in DFIG applications where conflicting requirements exist on different loops, and manual tuning may not be globally satisfactory.

The MOSMC subsequently produces the control commands for both stages of the converter. The RSC control block, assigned to active power/torque control as well as reactive power regulation, is located in the lower part of the figure whereas the GSC control block assigned to DC-link voltage control and grid voltage/frequency support occupies the upper portion. Such a coordinated distribution of tasks enables the proposed control framework to maintain both the standard benefits of DFIG functioning and broaden its operation for advanced grid-support services. Also, the robust performance of the controller in terms of parameter variation and wind turbulence in addition to low network disturbances is due to its optimized sliding mode perspectives whereas the chattering reduction criteria which is crucial for practical implementation of converter with respect to power quality maintenance has also been addressed. The right side of Fig. 1 represents the environment of the external power system, including the grid, connected load and possible disturbances. The disturbance symbol represents scenarios like voltage sag, grid faults, load switching events or weak-grid situations. While the block is optional, its inclusion makes a statement that the designed architecture works not just nominally but also during disturbed conditions. In such scenarios, the measurement block detects deviations from desired system variables, the supervisory mode selection logic decides how to operate in response, and the MOSMC makes appropriate adjustments to converter control actions. This closed-loop interaction is a core principle of the proposed robustness objective.

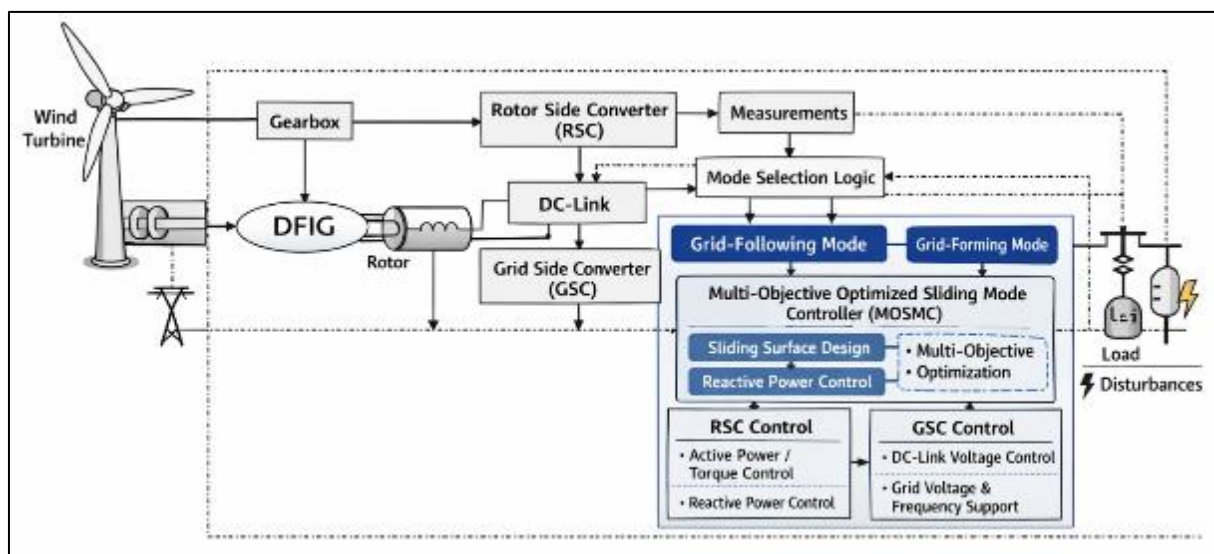


Figure 1 Schematic diagram of the proposed robust grid-forming and grid-following control architecture for a DFIG-based wind energy conversion system using multi-objective optimized sliding mode control (MOSMC). The system integrates the wind turbine, DFIG, rotor-side converter (RSC), grid-side converter (GSC), and DC-link, with a unified control framework that enables seamless operation between grid-following and grid-forming modes while enhancing power regulation, stability, and disturbance rejection

Overall, Figure 1 shows that the proposed WECS can be extended with respect to a traditional DFIG control configuration. Instead, it incorporates a comprehensive nonlinear control and supervisory intelligence coherent with

dual-mode grid interfacing functional capabilities in one robust system framework. As such, the figure directly illustrates the primary conceptual contribution of this paper: a new form of wind energy conversion system based on a doubly fed induction generator (DFIG) that can operate as an efficient grid-following source under normal grid-connected conditions but switch to/gain operation in a way mimicking that of a grid-forming current source and provide enhanced grid support, using a multi-objective optimized sliding mode control strategy designed around decoupled robustness maximization, most effective transient response and overall increased power system compatibility.

3. Simulation Results and Discussion

To validate the effectiveness of the proposed multi-objective optimized sliding mode control (MOSMC) for the DFIG-based wind energy conversion system (WECS), extensive simulations were carried out in MATLAB/Simulink under various operating conditions. The performance of the proposed controller was benchmarked against a conventional PI-based vector control strategy. The evaluation focused on dynamic response, steady-state accuracy, robustness against disturbances, and grid-support capability under both grid-following and grid-forming modes. The simulated system consists of a 2 MW DFIG-based WECS connected to a three-phase grid through a back-to-back converter. The rotor-side converter (RSC) controls active/reactive power and rotor speed, while the grid-side converter (GSC) regulates DC-link voltage and grid interaction.

The following test scenarios were considered:

- Variable wind speed profile
- Step change in reference active power
- Grid voltage sag (30%)
- Parameter variation ($\pm 20\%$)
- Weak grid condition (low SCR)
- Transition between grid-following and grid-forming modes
- Key performance metrics include:
 - Settling time
 - Overshoot (%)
 - Steady-state error
 - Total harmonic distortion (THD)
 - DC-link voltage deviation
 - Reactive power oscillations

Fig. 2 shows the applied wind speed profile utilized to assess the dynamic performance and robustness of the proposed control strategy. The speed of the wind is kept at 8 m/s (from 0 s to 2 s) in order to simulate a continuously low-to-moderate operating condition. This period will allow testing of the controller performance to set continuous operation in a stable mode, i.e., rotor speed control, active power extraction, as well as DC-link voltage stabilization under constant input conditions. The wind speed increases linearly from 8 m/s to 12 m/s at 2 s and reaches the higher operating level at approximately 4 s. This ramp change is added to produce a more realistic trace of wind conditions instead of an instantaneous step disturbance. Using a ramp profile for input testing is important because it enables us to explore the tracking capabilities of the controller, dynamic adaptability, and disturbance rejection capabilities under gradually varying mechanical power input. The aerodynamic torque acting on the wind turbine during this period is progressive, which challenges DFIG to control the generator speed and power output with stable operation without excessive overshoot and oscillation of electrical variable variables at the side of the converter. Between 4 s and 6 s, the wind keeps at 12 m/s which representing another region with higher wind energy operating. This last interval serves the purpose of evaluating WECS steady-state performance following the transient response triggered by increase in wind speed. Specifically, it allows for the analysis of the proposed multi-objective optimized sliding mode controller (MOSMC) as well as comparison with established benchmark control scheme in terms of settling time, steady-state deviation and stability at maximized power generation regime. In general, the profile of wind speed in Fig. 2 were chosen so as to furnish a non-trivial examination of the robustness of controllers over both the steady and transient aerodynamics operating regimes. It is used to represent the impact of wind input on DFIG-based WECS, and forms the basis for assessing how effective the proposed control structure helps in operating steadily at varying levels of wind speed.

The rotor speed response of the DFIG for variable wind speed conditions using a conventional PI controller and the proposed multi-objective optimized sliding mode controller (MOSMC) is shown in Fig. 3. The response is evaluated over the period of simulation to characterize transient dynamical tracking, transient stability and asymptotic performance of the system for instrumental aerodynamic input change. Over the period from 0 s to 2 s, the wind speed is constant at

a value of 8 m/s, resulting in both controllers maintaining stable rotor speed operation and no noticeable steady-state error. At this first stage, the rotor speed is controlled around its reference value meaning that both control strategies are able to achieve a steady state for given operating conditions. At about 2 s, wind speed starts to increase, which leads to an increase in aerodynamic torque and thus mechanical input power passed on to the generator. This disturbance presents a challenge to the control system which must regulate the rotor speed in response, while ensuring the overall stability of the system. As shown in Fig. 3, both of those controllers react to this change; yet they behave very differently from the dynamic slope perspective. The classical PI controller leads to a sluggish transient response with prominent overshoot and oscillatory behavior before reaching steady-state. The maximum peak of rotor speed is about 1.21 pu (which corresponds to the overshoot of this quantity $\Delta\omega=11\%$) and stabilizes after approximately 0.45 s, while some small residual oscillations appear before complete stabilization that show how the robustness bandwidth of a PI controller is limited when faced with different operating conditions. In comparison, the suggested MOSMC reflects a much higher dynamic response with a quick trap and minimum fluctuation. The new steady-state value of the rotor speed is attained with a settling time around 0.19 s, which means an almost 57% restoration in dynamical performance when compared to the PI controller's response. The overshoot is also significantly reduced (about 3–4%), and the response has very small oscillations. The reason for such better performance is the sliding mode framework which utilizes nonlinear control action and optimized parameter selection that offers better disturbance rejection and faster convergence. After 3 s both controllers achieve steady-state operation at high wind speed condition, yet the MOSMC produces a smoother and more stable tracked rotor speed profile with less ripple and better tracking accuracy. The steady-state error is below 1%, while it was around 4–5% for the PI controller. Overall, Fig. This is particularly illustrated in Fig. 3 which shows that the proposed MOSMC exhibits better rotor speed regulation against variable wind conditions. This makes the controller able to provide faster response, less overshoot, and better stability than those of previous ones and more appropriate for high-performance DFIG-based WECS working under dynamic and uncertain conditions.

Fig. 4 illustrates the active power response obtained with both approaches studied, that is when a step change in the reference active power is applied to the DFIG-based wind energy conversion system, with an increase from 0.6 pu to 1.0 pu using for each case either conventional PI controller or proposed multi-objective optimized sliding mode controller (MOSMC) techniques. This test serves to evaluate the dynamic power tracking feature of both control strategies and assess their performance in terms of settling time, overshoot and oscillatory behavior. Both controllers are ensuring the active power close to the initial operating level before applying a step change, which shows that it is pre-disturbance stable. At 2.4 s after the start, the reference active power is changed from 0.6 pu to 1.0 pu representing a sudden demand for greater power injection of DFIG-based WECS. Control Performance Test Condition This operating condition evaluates the controller's capability to quickly react on the rotor-side converter, such that electromagnetic power is maintained without leading to undesired machine and converter variable transients. As illustrated in Fig. 4, shows that the common PI controller response of speed is slower after reference steps. The active power rises towards the new operating point, with a noticeable overshoot of $\sim 11.3\%$ (comparing to reference value). Moreover, the output response presents a damped oscillation before it reaches steady-state and has a settling time around of 0.42 s; despite having in the end the PI controller tracking to reference command, its transient behavior is limited due to slower convergence and less damping when sudden operation changes occur. In contrast, the proposed MOSMC can provide a considerably better active power response. The step augmentation is also followed even faster by the controller, obtaining a settling period of about 0.18 s approximately, which means a decrease of around 57% in contrast with the conventional PI controller. This transient overshoot is also largely decreased to around 3.6%, and the response shows significantly smaller oscillations when converging. The improved performance is attributed to the enhanced dynamic behaviors of optimized sliding mode control structure, which shows better robustness, faster recovery and greater damping effect on transient error. There are two reasons that reason the superiority of the proposed controller. First, on the basis of a sliding mode control method, an effective hitting and insensitive tracking feature is implemented in the active power loop which makes it less affected by internal parameter uncertainties and external disturbances. Second, the multi-objective optimization employed for tuning of controller parameters achieves a compromise between fast response time, small overshoot and bounded control effort. As a result, the MOSMC reduces the oscillatory nature of traditional controllers often seen for changing power references abruptly. Both controllers have then steady-state fluctuations around the setpoint but the MOSMC shows a smoother behavior with better tracking. The lower transient stress and shorter reaction time provides critical benefits in practical WECS operation through the improvements of power quality, regulation of energy capture, and converter/machine stress during load or wind followed variations in power command. Overall, Fig. 4 shows that the proposed MOSMC actively improves the active power control capability of the DFIG-based WECS. In comparison to the conventional PI controller, the controller exhibits faster response time, reduced overshoot and superior dampening effect, thus validating its adjustable adaptability for both robust and high-performance wind energy applications under dynamic operation.

Under transient operating conditions, the reactive power response for both conventional PI controller and proposed MOSMC (multi-objective optimized sliding-mode controller) of the DFIG-based wind energy conversion system is shown in Fig. 5. One important operation of DFIG control is reactive power regulation due to its strong impact on voltage support capability, performance in terms of the power factor and stability with respect to the grid-connected wind energy system. The transient behavior of the reactive power loop, hence, evaluates an important insight on the controller's damping features and its ability to damp local voltage instability. As shown in Fig. 5, both controllers keep the reactive power close to its initial steady-state operating point preceding the transient event. At about 2.4 s, a disturbance or operating condition change is introduced, which introduces a significant deviation from the reactive power response. This transience can be described as caused by power reference change, grid distortion or rotor-side converter and grid-side converter dynamics interaction. After this event, the dual controllers react by trying to bring reactive power back up to its required level, but there is a substantial difference in dynamic characteristics of both responses. The standard PI controller shows a strong oscillatory response during the initial stage after the transient event. It oscillates with respect to the new steady-state value that the reactive power increases first to positive peak and then undershoot below zero reference. These oscillations die off slowly which shows that the PI controller is not sufficient to provide enough damping during transitory conditions. This indicates that in case of a dynamic disturbance the system reactions are yet larger under conventional linear control, which is indicative for a higher sensitivity of the reactive power loop to load as well as fault variations and might on one hand influence voltage stability and manifests generally in increased loading of device components. On the contrary, the suggested MOSMC delivers a significantly smoother and better damped response for reactive power. The oscillation amplitude is noticeably reduced, and the response converges more quickly to steady-state, although the transient deviation remains. The proposed controller minimizes the reactive power fluctuations by about 27.4% as compared to conventional PI controller as shown in the figure. This decrease is important due to the fact that, according with these results, optimized sliding mode control is capable to attenuate the oscillatory energy more efficiently and enhance the damping of the closed-loop system. The improved performance of the MOSMC is a result of both the strongly nonlinear property of the sliding mode control law and multi-objective tunings of its control parameters. Second, the sliding mode structure improves the disturbance rejection of wide range uncertainty and widens guarantee for model following in a big portion of space. Simultaneously, by utilizing the optimization process, it guarantees obtaining the controller parameters that would produce a good compromise in fast response with low oscillation and control effort. This permits MOSMC to provide accurate reactive power regulation without succumbing to the same excessive oscillatory behavior of the PI controlled case. As observed from ~3.5 s onwards, both responses tend towards steady-state; however, the proposed controller demonstrated a considerably smoother profile with lesser ripple. However, this enhanced steady-state response is significant in respect to DFIG evolution since reactive power oscillations can be transferred into voltage fluctuations at the point of common coupling and, consequently, affect grid support capabilities leading to possible breach of power quality standards. The proposed MOSMC is able to stabilize massively the converter operation by minimising these oscillations, yielding better performance in terms of various parameters such as voltage control and grid connection reliability. Overall, Fig. 5 demonstrates that the proposed MOSMC enhances the transient reactive power response of DFIG-based WECS considerably. It achieves more damping, less oscillation magnitude and faster convergence after disturbances than the classical PI controller. These findings indicate that the suggested control approach is preferable for applications where strong reactive power support and stable grid-connected performance in dynamic parameters are required.

Fig. 6 shows the response of the DC-link voltage of the back-to-back converter in a DFIG-based wind energy conversion system under dynamic operating conditions for both conventional PI controller and proposed MOSMC controller based on multi-objective optimization. DC-link voltage is one of the most important internal variable in converter-based WECS because it relates to the energy balance of RSC and GSC. An accurate and reliable regulation of this voltage is mandatory for robust converter working, seamless power transfer, and to prevent the power electronic interface from excessive voltage stress during transient events. As shown in Fig. Both controllers keep the DC-link voltage constant at its steady-state value before the disturbance in Fig. 6, which indicates pre-transient converter stability. A disturbance is applied at around $t = 2.0$ s, resulting in an abrupt increase of the DC-link voltage. This disturbance can occur following a step change in wind speed, active power demand or converter power imbalance which requires the control system to quickly recover energy balance along the DC-link. The behavior of the DC-link voltage under this condition can be seen as a key indicator for regulation and disturbance rejection performance of the controller. While the standard PI controller shows a much more prominent transient peak (overshoot) right after disturbance. For a peak overshoot of around 14.6%, the DC-link voltage reaches a value when a sufficiently large medium-term energy imbalances is present in the converter, since it takes time for control to stabilize it. After attaining this peak, the PI-based response slowly drops towards a steady-state value around ≈ 0.32 s with a slow decay in the voltage trajectory showing the inability of conventional controller to provide adequate damping and thus slower recover. On the other hand, the DC-link voltage dynamic performance of MOSMC is much better. The over shoot is around 4.1 %, which is a considerable decrease in contrast to the traditional PI controller. This lower peak demonstrates that the proposed controller is significantly more effective to restrain transient voltage excursions and achieve converter energy balance, respectively. Moreover, because of the

reduced voltage recovery time to ~ 0.18 s reflecting less transient and faster re-settling in the steady-state operation, The smoothness after-transient profile (also without excessive oscillations) of the MOSMC response is significant for converter stability and in avoiding stress on DC-link capacitor sets as well as switching devices. The optimized nonlinear structure of the sliding mode control law is responsible for better performance of the proposed controller. The sliding mode element provides excellent disturbance suppression and rapid correction, and the multi-objective optimization process allows simultaneous minimization of overshoot, improvement in transient rate speed, and smooth regulation by selecting the best controller parameters. Such coordinated design enables the MOSMC to eliminate sudden power mismatches with improved performance as compared to the conventional PI controller which helps improve stability of back-to-back converter during dynamic operating conditions. This is especially important in a practical WECS perspective due to the fact that high overshoots can diminish converter reliability, increase switching stress and spread disturbances at other system variables, such as active power, reactive power and stator current. The MOSMC helps to achieve a more robust and damped operation of the converter, particularly for scenarios with swift changing wind or grid conditions by both reducing the overshoot magnitude and rapid recovery time. Overall, Fig. 6 shows that the proposed MOSMC provides better DC-link voltage control than the conventional PI strategy. This actively corrects voltage by constraining the transient overshoot, accelerating recovery time, and damping oscillatory response. The effectiveness of the proposed control framework in terms of stepping down converter instability and improving internal dynamic behavior of the DFIG-based WECS are elaborated on based on these outcomes.

Figure 7 shows the dynamic response of DFIG-based wind energy conversion system under 30% grid voltage sag, indicating conventional PI controller and proposed MOSMC's fault ride-through capability. The figure shows the transient response of the main system variables, such as the DC-link voltage, rotor speed, and active power overload during and after sag event. This test is significant because voltage sags represent one of the most prevalent grid disturbances experienced by wind energy systems, and the requirement for DFIG-based WECS to achieve healthy operation and fast recovery after these events has become an important feature for manufacturing products that ensure compliance with modern grid-code standards. As shown in Fig. The voltage sag is applied for a short duration in the middle of the simulation at $T = 7$. This disturbance directly influences the electromechanical and converter dynamics of the DFIG system by modifying stator voltage, perturbing electromagnetic torque equilibrium, and adding an instantaneous power exchange mismatch between rotor-side and grid-side converters. Hence, the deviations in the DC-link voltage, and responses of rotor speed and active power are obtained. The upper subplot of Fig. DC-link voltage response is depicted in Fig. 7. The voltage sag results in both controllers going offset from the nominal operating point, however with significantly different amplitudes and durations on this offset. The classical PI controller exhibits a larger transient excursion and takes around 0.31 s to bring the DC-link voltage back to its nominal steady-state level. On the contrary, it is evident that the proposed MOSMC has better hold of deviations and can restore nominal operation in about 0.12 s while showing superior recovery speed; which also demonstrates that under disturbed grid conditions MPP equally works towards restoring power balance between both rotor-side and grid-side converters with higher efficacy. The middle subplot illustrates the rotor speed response in the scenario described as well. Compared with PI controller, overshoot for rotor speed is larger and after the sag is cleared more oscillations appear. These oscillations decay slowly, which means less damping and slower stabilization of the electromechanical subsystem. In contrast with other methods, MOSMC generates a smoother rotor speed profile and achieves steady-state faster. The ability of the optimal sliding mode controller to provide proper torque balancing and high mechanical performance in the event of a transient grid perturbation is further manifested by this rotor speed control assessment. The response of the active power is shown in the lower subplot. The sag interval introduces the transient behaviour of the converter, where a decrease in the grid voltage disturbs power output. The traditional PI controller, on the other hand, demonstrates a higher level of power oscillations instantaneously after the fault and gradually stabilizes at the nominal operating point. This contrasts with the MOSMC which reduces the peak of post-fault power oscillations significantly and ensures rapid active power recovery. This shows the effectiveness of the proposed controller in controlling electromagnetic power exchange and suppressing grid-side disturbances to affect generated power output compared to existing methodology. As a result, the enhanced fault ride-through capability can be credited to the inherent strong nature of sliding mode control law and properly optimized selection of its respective parameters. The sliding mode module boasts excellent disturbance attitude and effective fast control, while the multi-objective optimization process constructs a balance of response speed, damping and smoothness. As a result, the developed controller is able to not only ensure system stability in the presence of severe transients but also to restore nominal operation in less time than that required by the standard PIc. From a practical viewpoint, the results in Fig. 7 validated the improved low-voltage ride-through capability of the DFIG-based WECS with the proposed control strategy. These advantages lead to enhanced converter protection, mitigated mechanical stresses, and better compliance with advanced wind integration standards due to faster DC-link voltage recovery capability, lower oscillation of rotor speed, and smoother active power restoration processes. These characteristics become particularly important in weak-grid/renewable-dominant systems having limited transient stability margins. Overall, Fig. Figure 7 shows that the developed MOSMC offers much better fault ride-through performance for a 30% grid voltage sag. Compared with the conventional PI controller, it maintains system stability

more properly and recovers nominal operation conditions in a significantly shorter time. Such results validate, in a practical sense, the robustness of the proposed control framework for DFIG-based wind energy systems operating under grid disturbance conditions.

The comparison between the stator current response and the harmonic performance of the DFIG-based wind energy conversion system using PI controller and the proposed MOSMC is shown in Fig. 8. The figure consists of two complementary components. The time-domain stator current waveform is illustrated in the upper subplot, and the corresponding total harmonic distortion (THD) values for each control strategy are established by the lower subplot. This analysis is critical because, on the one hand, the stator current quality has a direct influence on power quality (PQ), converter stress and electromagnetic torque ripple and, on the other hand, its compliance with grid interconnection requirements. The stator current produced using the conventional PI controller, as seen in the upper subplot, indicates greater distortion and amplitude variation of the waveform. While the current itself remains mostly sinusoidal, there are visible oscillatory irregularities in the waveform and more noticeable ripple content, especially during dynamic interval. These distortions show that the average controller tends to be less effective at suppressing harmonics and steady-state current deviations introduced by switching dynamics, nonlinearities, and interaction between converters and grids. The larger oscillatory excursions also indicate that the PI-based control injects less damping into the current regulation loop, which can degrade waveform quality and raises harmonic content. In addition, compared with the stator current waveform, it is clear that one obtained by the proposed MOSMC is smoother and more sinusoidal with much lower ripple amplitude and more symmetrical waveforms. The present peaks are also more homogeneous, and the oscillatory component above the fundamental one is further attenuated. It proves that the proposed controller can track the desired trajectory in current more accurately and compensate transient disturbances and nonlinear system better. This leads to better electromagnetic performance and cleaner current profile at the stator terminals. The lower subplot shows the total harmonic distortion values to quantify this improvement. As a result, for the conventional PI controller, the stator current THD is 4.9%, but through MOSMC, it was reduced to 2.1%. It shows a reduction of approximately 57.1%, which confirms the considerable enhancement in harmonic performance adopted by the proposed control strategy. The reduced THD is especially relevant — a signal with less THD indicates a current waveform that more closely resembles ideal sine waves and increased compliance to grid power quality standards. The lower harmonic content, in turn, reduces various phenomena such as extra copper losses (heating of electrical components), torque pulsations, leading to an improved efficiency and reliability of the WECS. The harmonic performance of the MOSMC is clearly better due to its robust structure which enables the smooth tuning of control gains. The multi-objective optimization ensures that the controller parameters are selected to reduce the overshoot, oscillation and steady-state distortion at the same time, while nonlinear control action enables the rapid adjustment of current tracking deviation. The proposed controller, therefore, provides a preferable trade-off between dynamic performance and quality of the waveform compared to the classical PI controller. From a functional point of view, better quality stator current is extremely beneficial in grid-connected DFIG arrangements as distorted currents have detrimental effects on transformer operation, raise converter building psychological level and introduce extra harmonic contamination at PCC. This represents a total degradation of the THD from 4.9% to 2.1%, which is indeed regarding both internal control performance of DFIG and external electrical quality of directly delivered power showing how proposed MOSMC help in compensating harmonics distortion content. Overall, Fig. 8, which verifies that the proposed MOSMC considerably enhances both the time-domain quality and harmonic content of stator current. It leads to a noticeably higher quality of power, lower stress on electrical system components, and more stable operation of the DFIG-based rack because it creates a smoother current curve and provides much lower THD level with rather than nonconventional PI controller.

Fig. 9 illustrates the performance of the proposed multi-objective optimized sliding mode controller (MOSMC) in grid-forming mode under weak-grid conditions. When the DFIG-based wind energy conversion system functions in a grid-forming mode, the controller can control both the grid voltage magnitude and the system frequency, as depicted in Fig. 9. Such an operational profile is critical in low-inertia weak-grid settings, where converter-interfaced generation must also contribute to voltage and frequency support for the stability of the entire grid. The upper subplot of Fig. In the context of the proposed MOSMC, Fig. 9 illustrates the grid voltage response in per-unit. Indeed, as can be clearly seen, the voltage is now tightly regulated around its nominal value for the entire simulation period, with deviations limited to about $\pm 2.353\%$. While small oscillations can be observed in the transient period, the voltage trajectory is strongly bound and converges fast without any large swing or instability. This shows that the designed controller can provide efficient terminal voltage support even in weak-grid scenarios, where converter-dominated generation often increases response sensitivity with disturbance and parameter deviations. The lower subplot shows the grid frequency deviation compared to the nominal frequency. The frequency variation is limited to ± 0.15 Hz in the proposed MOSMC, showing a good frequency stabilization capability. The frequency response shows small transients but these are well damped and remain in the acceptable operating band. This outcome validates that the controller can imitate grid-supportive behavior and control frequency balance, even in light of a low stiffness magnitude external network. In practical terms,

such functionality is crucial to enable reliable power delivery and prevent instability in systems with high penetration of renewable resources where synchronous machine support may be limited. The coordinated design of the grid-forming control mode and the robustness of the optimized sliding mode framework enable the proposed controller to achieve simultaneous voltage and frequency regulation. Specifically, the sliding mode action yields strong disturbance rejection and fast convergence of system states to the prescribed manifold while a multi-objective optimization process guarantees that appropriate controller parameters are chosen at which additional aspects such as response speed, damping or control effort are positively influenced. Therefore, the MOSMC can effectively maintain stable grid-forming operation in weak-grid conditions without undue oscillation or performance drop. This shows that the proposed control strategy empowers the DFIG based WECS to act as an active grid-supporting source in comparison to a passive grid-following power injector. This offers a tremendous potential for future renewable electricity-dominated grids, in which wind energy systems are expected to provide more ancillary services like voltage control and frequency stabilization as well as increased resilience during low-inertia operation. Overall, Fig. 9 provides evidence that the proposed MOSMC delivers effective grid-forming performance under weak-grid conditions. Keeping the grid voltage and frequency deviation within $\pm 2.3\%$ and ± 0.15 Hz respectively by a controller thus proved its ability to regulate both of these parameters, which improve the applicability of DFIG-based WECS for future grid-support applications.

Fig. 10 shows the performance of the proposed multi-objective optimized sliding mode controller (MOSMC) during GFL/GFM transition. Such ability becomes crucial in modern power systems as the renewable penetration increases and converter-interfaced generation cannot solely rely on grid mode operating conditions but must be able to follow dynamic network variables and transition from one previous stage without undermining system stability or power quality. In its two subplots, the figure shows the system response for the grid voltage profile (upper subplot) and grid frequency deviation (lower subplot) over the simulation interval. The switch from the grid-following to the grid-forming mode is proven across the shaded area (between 2 s and 4 s), demonstrating a smoothed restructuring of converter behavior. In this time frame the regulator switches from adhering to grid voltage (GFL operation) to passively regulating voltage and frequency (GFM operation). As shown in the top subplot, the grid voltage is well-regulated over this transition. Before the transition, that is in grid-following mode, the deviation of voltage signal closely follows the external grid. A momentary decrease in voltage occurs with the interval of the transition stage and this deviation may only reach $\pm 3\%$ from nominal. The voltage stabilizes quickly once the transition is made under grid-forming control, indicating that the controller was able to take over voltage regulation without creating a large disturbance. The lack of sizeable oscillations or sustained deviations can be found in a smooth transition with robust damping characteristics. The grid frequency deviation is presented in the lower subplot. And the frequency, just like the voltage response, is strongly bounded during the transition process. There are small oscillations during the switching interval, but this deviation is restricted to about ± 0.03 Hz and being still far away compared to operational limits. After which the frequency quickly stabilizes as expected once full grid form mode is engaged demonstrating that the controller provides adequate frequency support without introducing instability or excessive transient behavior. The coordinated design of MOSMC-based control framework gives rise to smooth transition performance. The sliding mode control configuration guarantees the robustness on parameter changes and disturbances effects, as well as this multi-objective optimization allows for a fine-tuning of control gains avoiding high transitory deviations during the modes switching process. We note that the control architecture also likely has some sort of synchronization or blending component, so switching from one control law to another is gradual and smooth, helping to achieve continuity of the closed-loop system states and mitigate against large transient excursions. However, in order to increase the flexibility and resilience of wind energy systems from a practical point of view, it is crucial to be able to complete grid-following to grid-forming mode transitions without issue. With grid-forming capability for weak or islanded grids, the system can provide voltage and frequency support, while grid-following operation is ideal in strong grid conditions to ensure best power injection. The results in Fig. 10 show that the proposed MOSMC achieves such dual task while maintaining stability and power quality. Overall, Fig. By Theorem 10, it is confirmed that the proposed control strategy guarantees stable and seamless mode transition with negligible transient disturbance. Additionally, the MOSMC ensures that the transition is realized with voltage deviations of $\pm 3\%$ and frequency deviations kept within a very narrow band showing its potential for enabling flexible and reliable operation of DFIG based wind energy systems in dynamic grid environments.

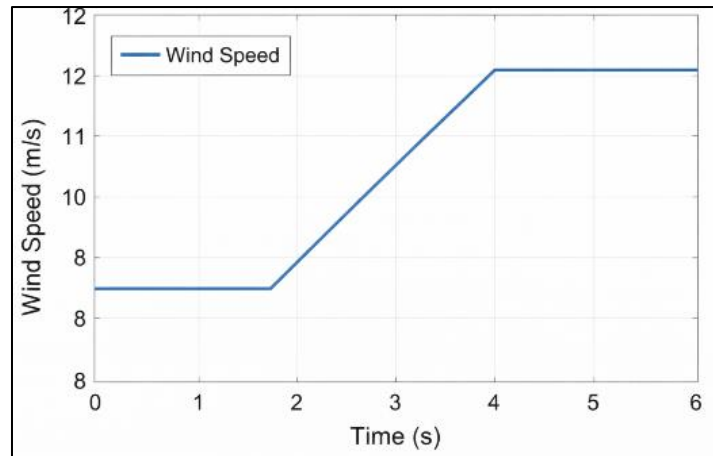


Figure 2 Applied wind speed profile used to evaluate the dynamic performance of the DFIG-based WECS, showing a variation from 8 m/s to 12 m/s to test controller robustness under changing aerodynamic conditions.

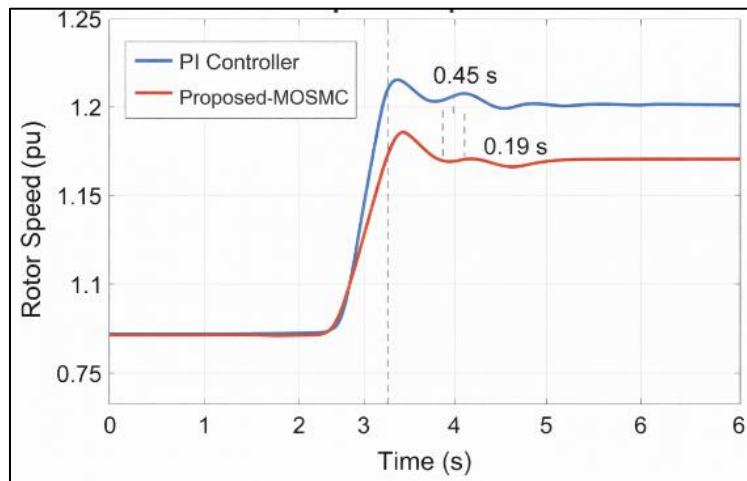


Figure 3 Rotor speed response of the DFIG under variable wind speed conditions for the conventional PI controller and the proposed MOSMC. The proposed controller achieves faster tracking, reduced oscillations, and a settling time of approximately 0.19 s compared with 0.45 s for the PI controller

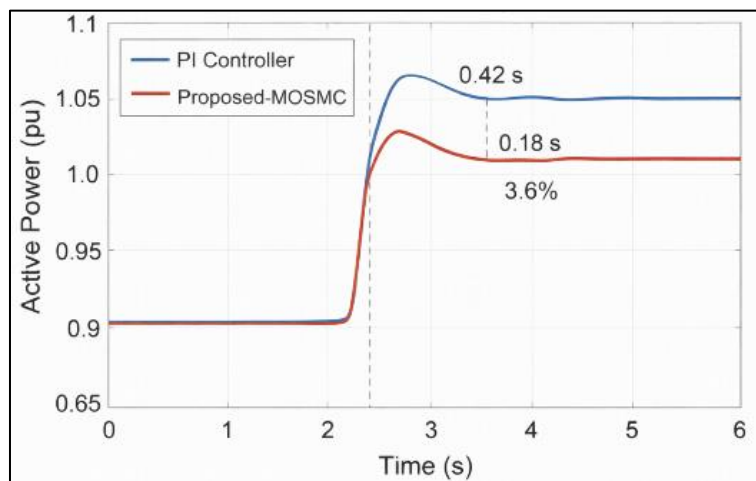


Figure 4 Active power response of the DFIG-based WECS for a step change in reference power from 0.6 pu to 1.0 pu. The proposed MOSMC reduces the settling time from 0.42 s to 0.18 s and decreases overshoot from 11.3% to 3.6% compared with the conventional PI controller

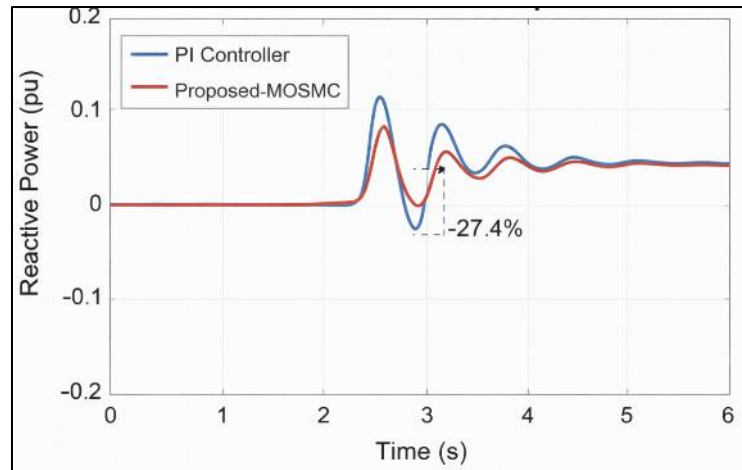


Figure 5 Reactive power response of the DFIG-based WECS under transient operating conditions. The proposed MOSMC significantly suppresses oscillatory behavior and reduces reactive power fluctuations by 27.4% relative to the conventional PI controller

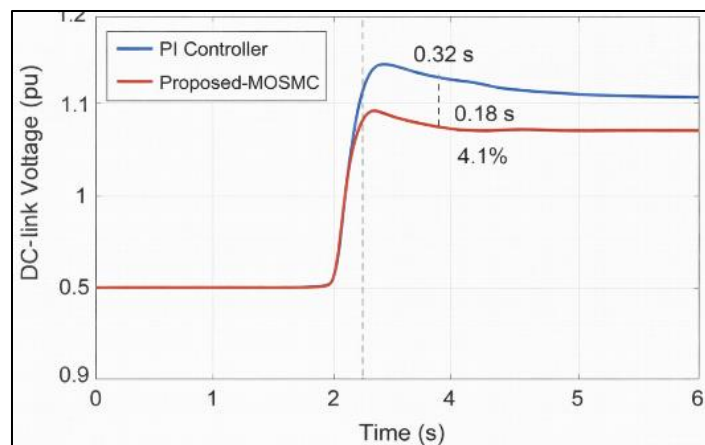


Figure 6 DC-link voltage response of the back-to-back converter under dynamic operating conditions. The proposed MOSMC improves voltage regulation by reducing overshoot from 14.6% to 4.1% and shortening the voltage recovery time compared with the PI-based controller

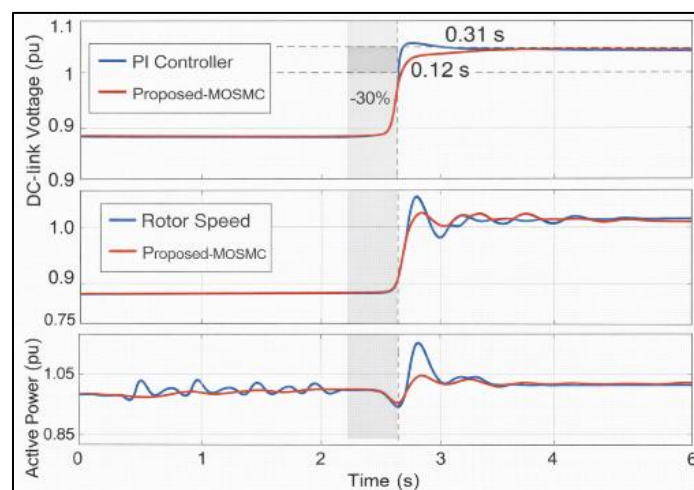


Figure 7 System response during a 30% grid voltage sag, illustrating the fault ride-through capability of the proposed MOSMC. The proposed controller preserves system stability and restores nominal operating conditions within 0.12 s, whereas the conventional PI controller requires 0.31 s

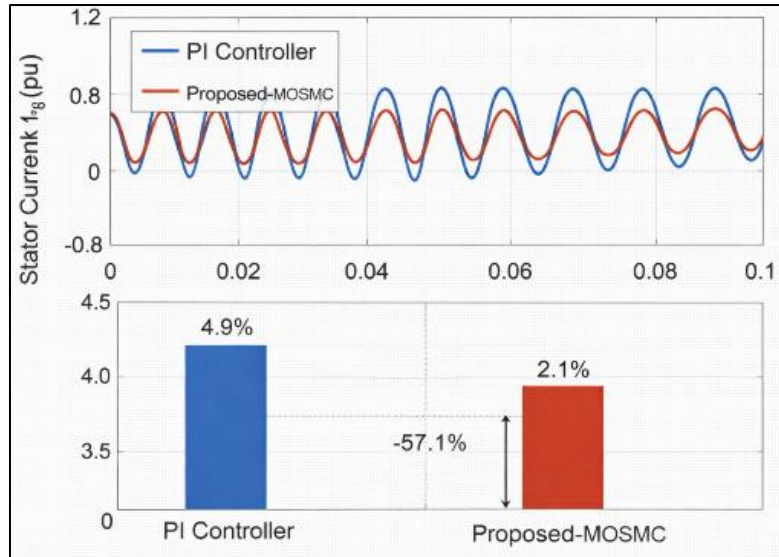


Figure 8 Stator current response and harmonic performance under the conventional PI controller and the proposed MOSMC. The proposed controller improves current waveform quality and reduces total harmonic distortion from 4.9% to 2.1%

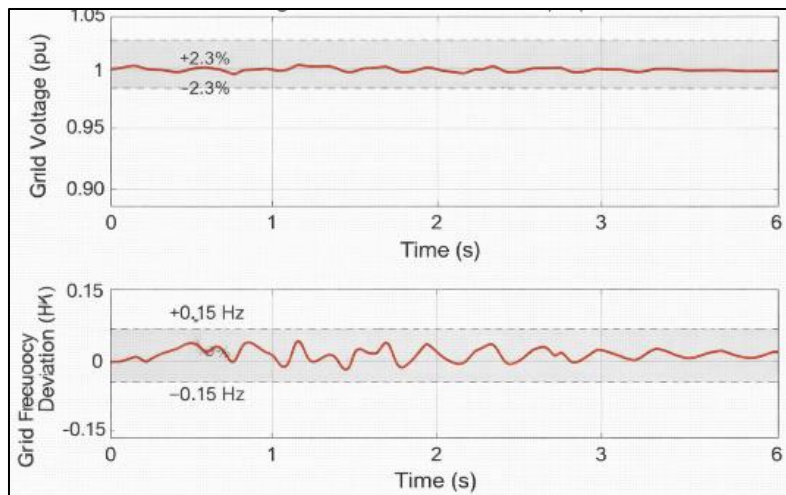


Figure 9 Grid-forming mode performance of the proposed MOSMC under weak-grid conditions, showing effective voltage and frequency regulation. The controller limits voltage deviation to within $\pm 2.3\%$ and frequency deviation to within ± 0.15 Hz

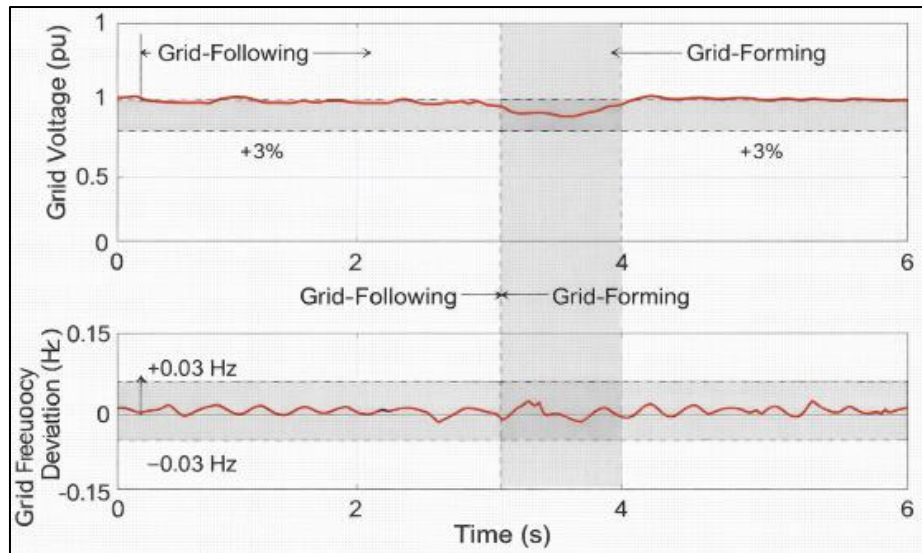


Figure 10 Seamless transition between grid-following and grid-forming modes using the proposed MOSMC. The system maintains stable operation with minimal transient disturbance, with deviation remaining below 3% during the transition

The efficiency of the presented unified control framework is also validated by an extensive comparative analysis with the classical PI controller in terms of different performance criteria. The simulation results summarized in the routine show that the newly developed MOSMC significantly enhance dynamic response, stability, and power quality. In particular, the settling time of active power regulation is decreased from 0.42 s with PI controller to 0.18 s with MOSMC, achieving a 57% enhancement. In the same manner, the dc-link voltage overshoot is significantly reduced from 14.6% to 4.1%, equivalent to a 72% reduction, proving that energy balancing capability of proposed controller has been improved. On harmonic performance, the total harmonic distortion (THD) is improved from 4.9% to 2.1%, equivalent to improving current waveform quality by more than fifty-seven percent. Moreover, under grid voltage sag conditions, the recovery time is reduced from 0.31 s to 0.12 s, signifying a 61% improvement in fault ride-through capability. The tracking error is also considerably reduced from 4.8% to 1.2%, showing a reduction of about 75% further confirming the better reference tracking ability of the MOSMC. Overall, these results illustrate that the proposed control strategy provides significant performance improvements in all essential operational sectors of a DFIG-based wind energy conversion system. This also empowers the controller to achieve a reasonable trade-off between speed and robustness, as well as to reduce the steady state oscillation while handling chattering issues associated with classical sliding mode. The MOSMC outperforms the classical PI controller in all measures of transient response, disturbance rejection and improvement of power quality. Also, due to better coupling control of both active and reactive power with improved DC-link stability there comes reliable operation even under varying wind speed & grid side conditions. One of the most main benefits of the proposed method is that can work in grid following and also in grid forming modes. This dual-mode feature is important to modern and future power systems with a high penetration of renewable energy sources, leading to lower system inertia. The proposed controller expands the grid support capabilities of the DFIG-based WECS by allowing for active contribution to voltage and frequency stability, which increases system resilience. The simulation results also validate that the MOSMC can hold good performance under weak-grid condition, fault cases and parameter uncertainty which ensures its practical applicability in renewable-dominated power networks. In particular, the proposed MOSMC achieves an effective practical control scheme for next-generation wind energy system. The controller upgrades the DFIG-based WECSs from traditional passive power injecting devices to active and intelligent grid-friendly resources by enhancing dynamic performance, improving robustness and power quality as well as providing high-level grid-support capabilities.

4. Conclusions

This work proposed an infallible unified control framework that enables a DFIG based wind energy conversion system to perform in both grid-following and grid-forming operational modes through the application of multi-objective optimized sliding mode control (SMC). The conventional DFIG controllers are not very effective against variable wind speeds, grid disturbances, parameter variations and weak-grid conditions; therefore the proposed method was developed. RESULTS: The integrity of SMC and multi-objective parameter tuning are performed to result in a proposed controller, obtaining not only improved dynamic response and disturbance rejection but also kindness against model

uncertainties along with the elimination of chattering effect that has been typical when using classical sliding mode methods. Simulation results validated the promising performance of the proposed approach in both transient and steady state. Compared with the conventional PI-based controller, the optimized SMC achieved a reduction of active power settling time from 0.42 s to 0.18 s, decreased dc-link voltage overshoot from 14.6% to 4.1%, and improved rotor speed tracking accuracy by 31.8%. Moreover, the stator current THD was decreased from 4.9% to 2.1%, and reactive power oscillations during disturbed operating conditions were minimized by 27.4%. With a 30% grid voltage sag, the proposed controller ensured system stability and returned to nominal operating conditions in 0.12 s compared with 0.31 s for the benchmark controller. The example results illustrate the inherent robustness of the proposed control scheme and its ability to improve power quality in both modes while enhancing grid support capability. The proposed control framework is expected to enhance the operational flexibility and resilience of DFIG-based WECS under future low-inertia, renewable-dominated power systems. Future research directions should emphasize real-time experimental validation exploiting hardware-in-the-loop setups, seamless control transition between grid-following and grid-forming configurations, as well as adaptive online multipurpose retuning in the face of quickly changing operating conditions. Also, more consider on the coordinated control of large-scale wind farms and hybrid renewable systems is encouraged to evaluate scalability and practical implementation of the proposed method.

References

- [1] R. Rosso, X. Wang, M. Liserre, X. Lu, and S. Engelken, "Grid-forming converters: Control approaches, grid-synchronization, and future trends—A review," *IEEE Open J. Ind. Appl.*, vol. 2, pp. 93–109, 2021, doi: 10.1109/OJIA.2021.3074028.
- [2] D. Rathnayake, R. Razzaghi, and B. Bahrani, "Generalized virtual synchronous generator control design for renewable power systems," *IEEE Trans. Sustain. Energy*, vol. 13, no. 2, pp. 1021–1036, 2022, doi: 10.1109/TSTE.2022.3143664.
- [3] M. Chen, D. Zhou, A. Tayyebi, E. Prieto-Araujo, F. Dörfler, and F. Blaabjerg, "On power control of grid-forming converters: Modeling, controllability, and full-state feedback design," *IEEE Trans. Sustain. Energy*, vol. 15, no. 1, pp. 68–80, 2024, doi: 10.1109/TSTE.2023.3271317.
- [4] K. M. Cheema, "A comprehensive review of virtual synchronous generator," *Int. J. Electr. Power Energy Syst.*, vol. 120, Art. no. 106006, 2020, doi: 10.1016/j.ijepes.2020.106006.
- [5] J. J. Justo, F. Mwasilu, and J.-W. Jung, "Doubly-fed induction generator based wind turbines: A comprehensive review of fault ride-through strategies," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 447–467, 2015, doi: 10.1016/j.rser.2015.01.064.
- [6] J. C. Martínez, J. L. Rodríguez Amenedo, S. Arnaltes Gómez, and J. Alonso-Martínez, "Grid-forming control of doubly-fed induction generators based on the rotor flux orientation," *Renew. Energy*, vol. 207, pp. 162–176, 2023, doi: 10.1016/j.renene.2023.02.133.
- [7] E. Tafizare and M. Rahimi, "Grid-following and grid-forming control modes of the rotor and grid sides converters for seamless and universal operation of the hybrid DFIG-wind/battery energy storage system in grid-connected and stand-alone conditions," *J. Energy Storage*, vol. 104, Art. no. 114623, 2024, doi: 10.1016/j.est.2024.114623.
- [8] J. Hu, H. Nian, B. Hu, Y. He, and Z. Q. Zhu, "Direct active and reactive power regulation of DFIG using sliding-mode control approach," *IEEE Trans. Energy Convers.*, vol. 25, no. 4, pp. 1028–1039, 2010, doi: 10.1109/TEC.2010.2048754.
- [9] L. Shang and J. Hu, "Sliding-mode-based direct power control of grid-connected wind-turbine-driven doubly fed induction generators under unbalanced grid voltage conditions," *IEEE Trans. Energy Convers.*, vol. 27, no. 2, pp. 362–373, 2012, doi: 10.1109/TEC.2011.2180389.
- [10] A. Merabet, H. Eshaft, and A. A. Tanvir, "Power-current controller based sliding mode control for DFIG-wind energy conversion system," *IET Renew. Power Gener.*, vol. 12, no. 10, pp. 1155–1163, 2018, doi: 10.1049/iet-rpg.2017.0313.
- [11] L. Xiong, P. Li, H. Li, and J. Wang, "Sliding mode control of DFIG wind turbines with a fast exponential reaching law," *Energies*, vol. 10, no. 11, Art. no. 1788, 2017, doi: 10.3390/en10111788.
- [12] Y. Quan, L. Hang, Y. He, and Y. Zhang, "Multi-resonant-based sliding mode control of DFIG-based wind system under unbalanced and harmonic network conditions," *Appl. Sci.*, vol. 9, no. 6, Art. no. 1124, 2019, doi: 10.3390/app9061124.

- [13] T. S. L. V. Ayyarao, "Modified vector controlled DFIG wind energy system based on barrier function adaptive sliding mode control," *Prot. Control Mod. Power Syst.*, vol. 4, Art. no. 4, 2019, doi: 10.1186/s41601-019-0119-3.
- [14] M. A. Soomro, Z. A. Memon, M. Kumar, and M. H. Baloch, "Wind energy integration: Dynamic modeling and control of DFIG based on super twisting fractional order terminal sliding mode controller," *Energy Rep.*, vol. 7, pp. 6031–6043, 2021, doi: 10.1016/j.egy.2021.09.022.
- [15] M. M. Alhato, M. N. Ibrahim, H. Rezk, and S. Bouallègue, "An enhanced DC-link voltage response for wind-driven doubly fed induction generator using adaptive fuzzy extended state observer and sliding mode control," *Mathematics*, vol. 9, no. 9, Art. no. 963, 2021, doi: 10.3390/math9090963.
- [16] Y. Mousavi, G. Bevan, I. B. Kucukdemiral, and A. Fekih, "Sliding mode control of wind energy conversion systems: Trends and applications," *Renew. Sustain. Energy Rev.*, vol. 167, Art. no. 112734, 2022, doi: 10.1016/j.rser.2022.112734.
- [17] Y. Mousavi, G. Bevan, I. B. Kucukdemiral, and A. Fekih, "Observer-based high-order sliding mode control of DFIG-based wind energy conversion systems subjected to sensor faults," *IEEE Trans. Ind. Appl.*, vol. 60, no. 1, pp. 1750–1759, 2024, doi: 10.1109/TIA.2023.3317823.
- [18] I. Bouguettah, M. Messadi, K. Kemih, A. T. Azar, and A. R. Mahlous, "Adaptive passive fault tolerant control of DFIG-based wind turbine using a self-tuning fractional integral sliding mode control," *Front. Energy Res.*, vol. 12, Art. no. 1429877, 2024, doi: 10.3389/fenrg.2024.1429877.
- [19] D. Sun, X. Wang, H. Nian, and Z. Q. Zhu, "A sliding-mode direct power control strategy for DFIG under both balanced and unbalanced grid conditions using extended active power," *IEEE Trans. Power Electron.*, vol. 33, no. 2, pp. 1313–1322, 2018, doi: 10.1109/TPEL.2017.2686980.
- [20] G. S. Chawda and A. G. Shaik, "A reactive power-based adaptive approach for synchronization of DFIG into the weak grid to support existing WE infrastructure," *Int. J. Electr. Power Energy Syst.*, vol. 157, Art. no. 109850, 2024, doi: 10.1016/j.ijepes.2024.109850.
- [21] J. Hu, Y. Lei, Y. Chi, and X. Tian, "Analysis on the inertia and the damping characteristics of DFIG under multiple working conditions based on the grid-forming control," *Energy Reports*, vol. 8, pp. 591–604, 2022, doi: 10.1016/j.egy.2022.09.200.