



Integration Challenges of Wind Turbine Generators: A Review of Mitigation Techniques and Emerging Control Strategies

Dahiru Musbahu^{1,*}, Gbenga Abidemi Olarinoye², Adamu Abubakar Sa'idu², Abubakar Sani Musa², Zaharaddeen Haruna³, Bukhari Rabi Tanko²

¹Department of Electrical and Engineering, Federal University of Technology, Minna-Nigeria

²Department of Electrical Engineering, Ahmadu Bello University, Zaria-Nigeria

³Department of Computer Engineering, Ahmadu Bello University, Zaria-Nigeria

*Corresponding author: dahirumisbahu@gmail.com; +2347036271665

DOI: <https://doi.org/10.xxxx/xxxx>

Keywords:

*Energy storage system,
grid-forming control,
power quality,
wind energy integration,
wind turbine generator*

Article History:

Received: 22 August 2026

Revised: 6 October 2026

Accepted: 8 October 2026

Published: 20 October 2026

Article Info:

Homepage: <https://zjeet.com.ng>

Volume: 15, No. 1, 2026

Pages: 119-130

ABSTRACT

The increasing penetration of wind turbine generators (WTGs) has enhanced renewable energy utilization but has also introduced significant challenges to power system operation. This paper presents a comprehensive review of the major technical issues associated with WTG grid integration, including power quality disturbances, stability concerns, grid code compliance, and weak -grid operation. The review provides an integrated assessment of conventional mitigation technique and emerging control strategies for improving the reliability and resilience of wind-integrated power systems. The review identifies Flexible AC Transmission System (FACTS) devices, energy storage systems, harmonic compensation techniques, and grid reinforcement approaches as important solutions for mitigating integration challenges. Furthermore, advanced control methods such as model predictive control, artificial intelligence-based control, virtual synchronous machine control, and grid-forming control are highlighted as promising technologies for future converter-dominated power systems. The findings provide valuable insights for researchers, utilities, and policymakers seeking sustainable and reliable integration of wind energy resources.

1. INTRODUCTION

The global transition towards sustainable and low-carbon energy systems has accelerated the development of renewable energy technologies over the past two decades. Growing environmental concerns, increasing electricity demand, and international commitments to climate change mitigations have significantly reduced the dependence on conventional fossil-fuels [1]. Among the various renewable energy resources, wind energy has emerged as one of the most mature and economically viable technologies owing to its scalability, declining

installation costs, and environmental benefits .For instance, between 2015 and 2020, the global share of coal-based electricity generation declined from 37.9% to 33.0%, while the combined contribution of wind and solar increased from 4.6% to 9.8% [2]. The continuous advancement in wind-energy conversion technologies have enabled wind power to become a major contributor to global electricity generation, thereby supporting the realization of the Sustainable Development Goals (SDGs) and the objective of the Paris agreement on the climate change [3].

The GWEC report of 2024 indicated that more than 140,000 wind turbines were operating in approximately 70 countries, resulting in substantial reduction in carbon dioxide emission. The wind energy conversion system (WECS) technology has advanced considerably, and the global wind energy market has expanded significantly over the past decade, highlighting the growing importance of wind power in modern electricity systems [4].

The increasing penetration of WTGs into modern power systems has transformed the operational characteristics of electrical power networks worldwide. Recent report indicated that the cumulative installed capacity has surpassed one terawatt, with substantial growth projected for both onshore and offshore over the coming decades [3]. Modern wind farms predominantly employ variable-speed wind turbine technologies such as Doubly Fed Induction Generators (DFIGs) and Permanent Magnet Synchronous Generators (PMSGs), which offer improved energy conversion-efficiency and enhanced control capabilities [5]. The integration of these converter-based technologies has improved the operational flexibility of wind energy systems while simultaneously introducing new technical challenges associated grid stability and power system operation [6].

Despite the remarkable growth in wind-energy deployment, large-scale integration of WTGs presents numerous technical and operational challenges. The intermittent and stochastic nature of wind resources contribute to power quality and stability problems, as well as voltage and frequency variations [5]. Furthermore, the increasing replacement of conventional synchronous generator with converter-based wind generation has resulted in reduced system inertia, thereby exacerbating small-signal stability and transient stability concerns, particularly in weak and converter-dominated grids. Additional challenges including; compliance with grid code requirements such as low-voltage ride-through (LVRT), reactive power support, frequency regulations, and protection coordination under abnormal operating conditions [7]. Consequently, researchers and grid operators have

developed various mitigation techniques and advanced control strategies to enhance secure and reliable integration of wind power into modern electricity networks [8].

Existing reviews tend to examine wind turbine generators (WTGs) from specific technical perspective such as offshore infrastructure integration challenges, power quality, small-signal stability and grid-code requirements, rather than integrated and critically comparative assessment that connects different grid-integration challenges with their techniques, emerging control strategies, and their applicability to weak grid operating conditions.

This paper presents a comprehensive review of the major challenges associated with wind turbine generator grid integration and critically examines the mitigation techniques and emerging control strategies reported in the literature. The paper reviews global trends in wind energy deployment and wind turbine generator technologies, discusses the technical challenges affecting grid-connected wind power systems, and evaluates mitigation approaches, including Flexible AC Transmission System (FACTS) devices, energy storage technologies, harmonic mitigation techniques, and reactive power compensation schemes. Emerging control strategies such as virtual synchronous machine control (VSM). Model predictive control (MPC), and intelligent control techniques are also examined. Finally future research directions are discussed to provide useful insights for researchers, engineers, and policymakers involved in the planning, operation, and modernization of wind-integrated power systems.

2. REVIEW METHODOLOGY

This paper adopts structured narrative review approach to examine the major challenges associated with the integration of wind turbine generators (WTGs) into modern power systems, together with the mitigation techniques and emerging control strategies reported in the literature. The review covers four major aspects of WTG grid integration: power quality, stability, grid-code compliance, and weak grid operation. Particular attention was given to the effects of increasing penetration of wind power generation

and associated need for enhance grid support capabilities.

Relevant literatures were selected based on their relevance to wind turbine generator integration, including studies addressing wind turbine technologies, power quality disturbances, voltage and frequency stability, fault ride-through capability (FRT), weak grid operation, FACT devices, energy storage system, harmonic compensation, grid reinforcement, conventional control, advance control, grid-forming control, and coordinated control strategies. The foundational studies were considered where they provide important theoretical or technological background, while greater emphasis placed on recent literatures addressing emerging grid integration requirements and converter dominated power system. The selected literature was organized thematically to the major integration challenges and corresponding mitigation schemes.

The review therefore, focuses on synthesizing the relationships between the integration challenges, mitigation scheme, control strategy, applicability and limitation, with particular emphasis on evolving requirement of weak and low-inertia power system

3. GLOBAL WIND ENERGY GENERATION AND WIND TURBINE TECHNOLOGIES

3.1 Global wind energy generation trend

Wind energy has experienced remarkable growth over the last two decades and has become one of the fastest-growing renewable energy resources worldwide. Increasing concerns regarding climate change, energy security, and sustainable development have significantly accelerated investment in both onshore and offshore wind-power generations. According to the Global Wind Energy Council (GWEC), cumulative installed wind-energy capacity has exceeded 1 TW in 2023, representing a major milestone in the global renewable-energy transition [3, 9]. Furthermore, global wind-power installations are projected to increase substantially by 2030 to meet growing demand for clean and sustainable electricity.

The rapid development of wind-energy technologies has been driven by advances in turbine design,

declining installation cost, improved converter technologies, and supportive government policies across developed and developing countries. Onshore wind farms currently account for more than 90% of the global installed wind power capacity owing to their relatively lower capital cost and technological maturity as illustrated in Table 1. However, offshore wind farms have recently attracted significant attention because of its higher energy yield, reduced land constraint, and improved wind resource availability. Recent projections indicate substantial growth in offshore wind installations, particularly across Europe, Asia, and North America, making offshore wind a strategic component of future power systems [10-12].

Table 1: Cumulative wind power capacity: Historical and projected values [10-12]

Period	Year	Onshore Capacity (GW)	Offshore Capacity (GW)	Status
Historical	2014	340.195	8.362	Installed
Historical	2015	404.600	12.352	Installed
Historical	2016	452.599	14.385	Installed
Historical	2017	496.208	17.629	Installed
Historical	2018	540.250	22.432	Installed
Historical	2019	594.481	27.362	Installed
Historical	2020	699.350	33.266	Installed
Historical	2021	770.336	53.536	Installed
Historical	2022	839.263	60.676	Installed
Historical	2023	944.536	66.276	Installed
Projected	2030	1,787	228	Projected
Projected	2050	5,044	1,000	Projected

The cumulative global growth of wind power capacity from 2014 to 2023 and projected expansion toward 2030 and 2050 was illustrated in Table 1. Historical installed capacity increased substantially over the period with onshore remaining the dominant component of global wind power deployment. Offshore wind capacity also increased progressively, although its contribution remained considerably small than that of onshore.

3.2 Wind turbine generator technologies

Wind turbine generators (WTGs) can generally be classified into fixed-speed and variable speed technologies based on their operating principles and

control capabilities [13]. Fixed-speed wind turbine generators are primarily based on Squirrel Cage Induction Generators (SCIGs), which are characterized by simple construction, robustness, and low maintenance requirements. However, their limited speed control capability and substantial reactive power consumption restrict their application in modern large-scale wind power plants [14].

Variable-speed wind turbine generators comprising a Doubly Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Generator (PMSG) have emerged as the dominant technologies in contemporary wind energy conversion systems due to their superior energy capability and enhanced grid support functionalities [5]. DFIG-based wind turbine remains one of the most widely adopted technologies because it requires a partially rated back-to-back converter, thereby reducing converter cost while providing independent active and reactive power control [15]. DFIG-based wind turbines are capable of contributing to voltage regulation and improving system dynamic performance if appropriate control strategies were adopted.

Permanent Magnet Synchronous Generator (PMSG)-based wind has gained increasing popularity, particularly in offshore wind applications, onto their high efficiency, improved Fault Ride-Through (FRT) capability, and gearbox free requirements in direct-drive configurations. Unlike DFIG-based wind turbine, PMSG-based wind turbines employ fully

rated power electronic converters that provide greater flexibility in grid support and power control. The enhanced controllability of PMSG technologies make them attractive candidates for future grid-forming and low-inertia power systems [16].

The selection of an appropriate wind turbine generator technology significantly influences the overall performance of grid-connected wind farms, particularly with respect to power quality, voltage stability, frequency regulation, and FRT capabilities. Therefore, understanding the operational characteristics and control capabilities of different WTGs technologies is essential when assessing the challenges associated with their integration into modern power systems dynamics. Table 2 illustrates the comparative assessment of wind turbine generator technologies.

Table 2: Comparative Assessment of WTGs

Parameter	SCIG	DFIG	PMSG
Speed control	Fixed	Variable	Variable
Converter rating	Nil	Partial	Full
Reactive power support	Poor	Good	Excellent
Grid support capability	Limited	Good	Excellent
Cost	Low	Moderate	High
FRT capability	Poor	Good	Excellent
Typical application	Small-scale wind farm	Onshore wind	Offshore

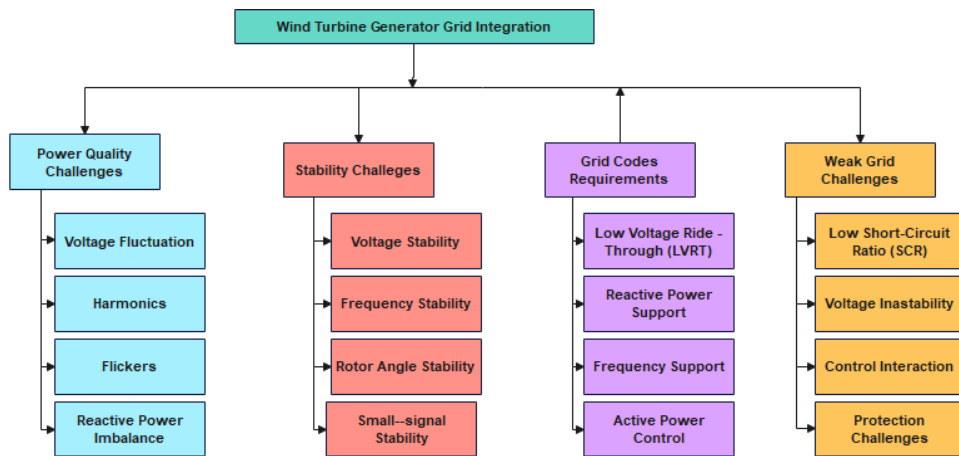


Fig. 1: Major wind turbine generator integration challenges

4. WIND TURBINE GENERATOR INTEGRATION CHALLENGES

The rapid growth of wind-power generation has significantly transformed the operational characteristics of modern power systems. Although wind turbine generators offer numerous environmental and economic benefits, their integration into conventional electricity networks introduces several technical challenges that may adversely affect grid reliability, stability, and operational performance. These challenges primarily arise from the intermittent nature of wind resources, the extensive use of power electronic converters, and the increasing displacement of conventional synchronous generators [5, 8]. Consequently, power-system operators are required to adopt appropriate mitigation techniques and advanced control strategies to ensure the secure and reliable integration of wind power into electricity networks. Figure 1 illustrate the major WTG integration challenges. It classified integration challenges according to their principal impacts on grid operation which provide the basis for the subsequent discussion of individual integration challenges.

4.1 Power quality challenges

Power quality remains one of the major concerns associated with wind turbine generator integration. Variations in wind speed result in fluctuations in active- power output, which may subsequently lead to voltage fluctuations and flicker phenomena at the point of common coupling (PCC). Furthermore, the widespread utilization of power electronic converters in modern wind energy conversion systems introduces harmonic distortions that can adversely affect sensitive electrical equipment and degrade system performance [17, 18].

Power-quality issues commonly observed in grid-connected wind power systems include voltage sag and swell, harmonic distortion, flicker emissions, reactive imbalance, and poor power factor characteristics. These disturbances become increasingly significant under high-wind penetration scenarios and weak grid conditions. international standard such as IEC 61400-21 and IEEE establishes requirements for power quality assessment and grid

interconnection of renewable energy systems. Effective mitigation of these power-quality problems is essential for maintaining acceptable voltage profiles and ensuring compliance with applicable grid codes.

4.2 Stability challenges

The integration of large-scale wind turbine generators presents significant stability challenges in modern power systems. Unlike conventional synchronous generators that inherently provide rotational inertia and electromechanical damping, most modern wind turbines are connected through power electronic converters, thereby contributing limited inertia to the interconnected grid [19].

Voltage stability issues are particularly prominent in weak transmission grids where inadequate reactive power support and transmission limitations can lead to voltage collapse during disturbances. Similarly, frequency stability has become increasingly critical due to the reduction in synchronous inertia resulting from the displacement of conventional generating units by converter-interfaced renewable energy sources. Small-signal stability problems may also arise from poorly damped electromechanical oscillations and interactions. Furthermore, transient stability concerns are often observed during severe disturbances such as short circuit faults and sudden wind power fluctuations [5]. These stability challenges become more pronounced in converter-dominated power systems and necessitate the implementation of advanced control techniques capable of providing virtual inertia, dynamic reactive power support, and enhanced damping characteristics.

4.3 Grid-code and fault-ride-through requirements

Modern electricity grids impose stringent technical requirements on WTGs to ensure reliable and secure system operation. Grid codes have evolved considerably over the past decade and now require wind farms to actively participate in voltage regulations, frequency support, and fault management operations [8].

One of the most critical grid code requirements is Low Voltage Ride-Through (LVRT) capability, which mandate wind turbines remains connected to the grid

during temporary voltage disturbances rather than disconnecting immediately. Contemporary grid codes also specify reactive power support requirements, frequency response capabilities, and active power support control functionalities during abnormal operating conditions [20].

Failure to comply with these technical requirements may compromise overall system reliability, particularly in networks experiencing high renewable penetration. Therefore, modern WTGs are increasingly being equipped with advanced control schemes that enhance their ability to satisfy grid code specifications while contributing positively to the system reliability.

4.4 Weak grid integration challenges

The integration of wind power into weak grids has emerged as one of the most significant challenges facing modern renewable-energy development, particularly in developing countries. Weak grids are typically characterized by low short-circuit ratios, inadequate transmission infrastructure, poor voltage profiles, and limited reactive power support capabilities [21]. Under such conditions, large-scale wind turbine integration may exacerbate voltage instability, increase converter control-interactions, and reduce overall system stability margins.

Converter-interfaced WTGs are particularly sensitive to weak-grid conditions because their control performance is highly dependent on grid strength and

impedance characteristics. High wind penetration in weak networks may lead to voltage oscillations, synchronization problems, and reduced fault ride-through capabilities. Consequently, weak grid operation has become an active area of research, with recent studies focusing on grid-forming control strategies, virtual synchronous machine concepts, and advanced reactive-power compensation techniques to improve the dynamic performance of wind-integrated power systems [22].

Addressing weak grid integration challenges is especially important for emerging power systems in developing economies, where renewable energy resources are often located far from the major load centers and existing transmission infrastructure remains relatively limited.

5. MITIGATION TECHNIQUES FOR WIND TURBINE INTEGRATION CHALLENGES

Several mitigation techniques have been proposed in literature to address the technical challenges associated with wind turbine generators (WTGs) integration into modern power systems. These techniques aim to improve power quality, enhance system stability, satisfy grid code requirements, and facilitate reliable operation under weak grid operating condition. The selection of an appropriate mitigation strategy largely depends on the grid characteristics, wind penetration level, and operational requirements of the interconnected power system.

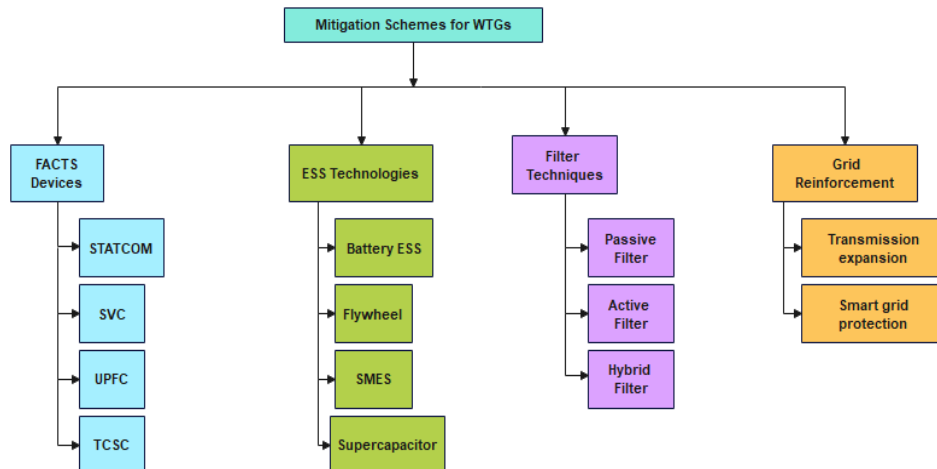


Fig. 2: Mitigation Schemes for Wind Turbines Generators Integration Challenges

Figure 2, illustrate the mitigation schemes applied to WTG integration challenges. The mitigation approaches are classified according to their primary function in addressing challenges associated with integration of WTG as discussed in subsequent subsection.

5.1 FACTS-based mitigation techniques

Flexible AC Transmission System (FACTS) devices have been extensively employed to improve the dynamic performance of grid-connected wind farms. Their capability to provide fast reactive power compensation and voltage regulation makes them particularly suitable for mitigating voltage instability and enhancing fault ride-through performance [23].

Commonly adopted FACTS devices include static synchronous compensator (STATCOM), Static VAR Compensator (SVC), Unified Power Flow Controller (UPFC), and Thyristor Controlled Series Compensator (TCSC). STATCOM has received significant attention owing to its superior dynamic reactive power support capability during voltage disturbance [24]. Several studies have demonstrated that STATCOM can significantly improve the low-voltage ride-through (LVRT) capability of DFIG-based wind farms, and enhance voltage stability under transient conditions. Similarly, UPFC simultaneously regulates voltage magnitude, line impedance, and power flow, thereby improving both transient and steady-state stability [7].

5.2 Energy storage system-based mitigation techniques

Energy storage systems (ESSs) play a crucial role in compensating for the intermittent nature of wind power-generation. the stochastic characteristics of wind speed often result in undesirable power fluctuations that adversely affect grid stability and frequency regulations. ESS technologies provide fast power-balancing capabilities that contribute can contribute significantly to maintaining system reliability [25].

Various energy storage technologies have been investigated for wind power applications, including battery energy storage systems, flywheel energy storage systems, superconducting magnetic energy

storage (SMES), and supercapacitors [7]. These technologies can smooth wind-power output, improve voltage and frequency regulation, and provide reserved power during transient disturbances.

Battery energy storage systems are widely preferred because of their technological maturity and declining costs. Flywheel and SMES technologies, on the other hand, offer rapid response characteristics suitable for transient stability enhancement and frequency support applications. Recent studies have also highlighted the growing importance of hybrid energy storage systems for improving the operational flexibility of renewable-energy systems.

5.3 Harmonic and reactive power compensation technique

The extensive use of power electronic converters in modern WTGs necessitates the implementation of harmonic-mitigation and reactive-power compensation techniques. Harmonic distortions and reactive power imbalances adversely affect power quality and may lead to non-compliance with grid interconnection standards

Passive, active, and hybrid power-filters configurations are commonly employed for harmonic compensation in grid-connected renewable energy systems. Passive filters are relatively simple and cost-effective but may suffer from resonance and fixed-compensation limitations. Active power filters offer superior harmonic-compensation capabilities and dynamic reactive-power support, although generally involve higher implementation costs. Hybrid filter topologies combine the advantages of passive and active filtering techniques and are increasingly being adopted in high-power applications [18].

Reactive-power compensation techniques are equally important for maintaining acceptable voltage profiles in wind-integrated power systems. Dynamic reactive power support provided by converter-based WTGs, FACTS devices, and advanced control schemes can significantly contribute to voltage regulation and improved power-system stability [26]

5.4 Grid reinforcement and hybrid mitigation approaches

Grid reinforcement has become an essential strategy for facilitating the large-scale integration of wind power into existing electricity networks. Reinforcement measures include transmission-network expansion, improved protection coordination, enhanced communication infrastructure, and the adaptation of grid monitoring technologies [27].

Hybrid mitigation approaches that combine multiple technologies can provide superior performance compared to standalone solutions. For instance, the coordinated operation of WTGs with STATCOM devices and battery energy storage systems has been shown to improve voltage stability, fault ride-through capability, and power quality simultaneously [28]. Similarly, coordinated-reactive control strategies and advanced converter-control techniques can enhance the operational resilience of wind-integrated power systems under weak-grid conditions.

The increasing complexity of modern power systems suggest that future wind-farms integration will increasingly rely on coordinated mitigation strategies that combine energy-storage technologies, FACTS devices, intelligent controllers, and grid modernization initiatives to achieve reliable and sustainable operation.

Table 3 presents the recently reported mitigation schemes addressing WTG integration challenges in the modern power systems.

The reviewed mitigation techniques differ considerably in their effectiveness, implementation requirements, cost and suitability for different grid operating conditions. therefore, no single mitigation technology can be regarded as optimal for all WTG integration challenges. The appropriate solution depends on the nature and severity of the disturbance,

wind penetration, wind turbine technology classification, grid strength, and time of response.

6. EMERGING CONTROL STRATEGIES FOR WIND TURBINE GENERATORS

The increasing penetration of converter-interfaced wind turbine generators has necessitated the development of advanced control strategies capable of enhancing power-system stability, improving grid support functionalities, and ensuring compliance with modern grid codes. Unlike conventional synchronous generators WTGs rely heavily on power electronic converters and sophisticated control algorithms to regulate active power, reactive power, voltage, and frequency. However, significant research efforts have been directed towards developing intelligent and adaptive control strategies that improve the dynamic performance of wind-integrated power systems.

6.1 Conventional control

The conventional control methods remain widely employed in commercial wind turbine generators due to their simplicity, robustness, and ease of implementation. The most common approaches include Proportional-Integral (PI) and Proportional-integral-Derivative (PID) controllers, which are extensively used for rotor-side converter and grid-side converter control in DFIG-based and PMSG-based wind energy conversion systems [29].

PI-based controllers are effective under normal operating conditions and provides satisfactory regulations of active and reactive power outputs [30]. However, their performance may deteriorate under parameter uncertainties, nonlinear operating conditions, and severe grid disturbances. The growing complexity of modern power systems has motivated the development of more advanced control techniques capable of addressing these limitations.

Table 3: Comparative assessment of mitigation techniques for WTG grid integration

Grid Integration Challenges	Mitigation Technique	Primary Benefit	Effectiveness	Complexity	Limitation	Research Gap
Voltage Instability	STATCOM, SVC	Voltage support	High	High	High investment and rating requirements	Optimal coordination with WTG converters
Frequency deviations	Battery ESS, flywheel ESS	Fast active power balancing	High	high	Limited energy duration	Hybrid storage and coordinated control strategies
Harmonic distortions	Active and Hybrid filters	Harmonic compensation	High	Moderate-high	Converter rating and switching losses	Improved compensation under changing grid impedance
LVRT and voltage support	STATCOM, UPFC	Reactive Power support during grid faults	High	High-Very-High	increased equipment and control requirement	Coordinated fault-response control with WTG converters
Wind intermittency	ESS technologies	Power smoothing and frequency support	High	High	Energy capacity and cost constraint	Optimal sizing, placement and coordinated control of WTG-ESS
Weak grid operation	Hybrid control approaches	Reduction of grid impedance and voltage support	High	Very High	Geographical and infrastructure constraints	Cost-effective alternative for remote wind resources
Reduced system inertia	Virtual inertia techniques	Frequency and synthetic inertia support	High potential	Moderate-high	Depend on available power reserve	coordination with grid-forming control and energy storage
Multiple simultaneous challenges	Coordinated WTG-ESS-FACTS control	Muti-objective grid support	High potential	High	communication coordination, and control complexity	Real-time coordinated and adaptive control

6.2 Advanced and intelligent control

Under varying operating conditions, the advanced control methods have been proposed to improve the dynamic response and robustness of WTGs. Model predictive control (MPC), adaptive control, robust control, and sliding-mode control are among the advanced control schemes investigated for wind-integrated power systems.

Model predictive control has emerged as a promising solution owing to its capability to handle multivariable systems, operational constraints, and nonlinear dynamics. MPC utilizes a predictive model of the system to optimize future control actions over a

specified prediction horizon, thereby improving system performance and stability [31].

In recent years, artificial intelligence-based approaches such as fuzzy-logic control, artificial neural networks (ANNs), and machine learning technique have also been investigated for wind power applications. Fuzzy logic controllers can offer improve performance under uncertain operating conditions, while neural-network-based controllers possess learning capabilities that enable adaption to changing system dynamics. These intelligent techniques have demonstrated considerable potential in enhancing maximum power extraction, voltage regulation, and oscillation damping in wind-integrated power systems.

6.3 Grid-forming and virtual inertia control

The transition towards converter-dominated power systems has accelerated interest in grid-forming control strategies. Traditional wind turbine generators typically operate using grid-following control schemes that rely on existing grid-voltage signals for synchronization. However, high renewable energy penetration can reduce system inertia and may compromise frequency stability during disturbances [19].

Grid-forming control strategies address these challenges by enabling converter-based wind turbine generators to establish and regulate grid voltage and frequency [32]. Through autonomous voltage and frequency regulation capabilities, grid-forming converters can contribute to system stability in a manner analogous to conventional synchronous generators.

Closely related to this concept is Virtual Synchronous Machine (VSM) control, which emulates the inertial and damping characteristic of synchronous generator using power electronic converters and advanced control algorithms. VSM-based WTGs can provide synthetic inertia, improve frequency response, and enhance small-signal stability [7]. The grid-forming and virtual inertia control strategies are increasingly viewed as key enabling technologies for future low-inertia power systems.

6.4 Coordinated control

Recent research has focused on coordinated control approaches that mitigate multiple control devices and resources to achieve enhanced system performance. These strategies typically involve the coordinated operation of WTGs, energy storage systems (ESS), FACTS devices, and conventional generators.

For instance, coordinated control between DFIG-based wind farms and STATCOM devices has been shown to improve voltage stability and fault ride-through capability [33]. Similarly, the integration of battery energy storage systems with wind farms can improve frequency regulations and mitigate of wind-power fluctuations. Wide-area measurement systems and communication-assisted control schemes can

further enhance the effectiveness of coordinated control approaches by enabling real-time monitoring and system-wide optimization.

As modern power system continues to evolve towards renewable-dominated architecture, coordinated control strategies are expected to play an increasingly important role in ensuring reliable, resilient, and sustainable grid operation.

7. CONCLUSION AND RECOMMENDATION

The increasing penetration of wind turbine generators (WTGs) supports the transition toward sustainable electricity generation but introduces challenges related to power quality, voltage and frequency stability, reduced system inertia, fault ride-through, and weak-grid operation. These challenges become more significant as converter-interfaced wind generation replaces or complements conventional synchronous generator.

This review examined the major WTG integration challenges and critically assessed established mitigation techniques and emerging control strategies. The finding indicates that no single technique can adequately address all integration challenges. FACTS devices provide rapid voltage and reactive-power support, while energy storage improves power smoothing and frequency response. Harmonic compensation enhances power quality, whereas grid reinforcement provides broader network support but generally requires greater investment. Advanced approaches, including model predictive control, artificial intelligence-based control, virtual inertia, and grid-forming control, offer additional capabilities for improving the stability and resilience of converter-dominated systems.

The review therefore indicates that future wind-grid integration should increasingly adopt coordinated and application-specific mitigation strategies. Stronger grids may be adequately supported by conventional compensation and converter controls, whereas weak and low-inertia grids require greater integration of FACTS, energy storage, and advance or grid-forming controls. Future research should focus on coordinated control, cost-effective weak-grid solutions,

cybersecurity, interoperability, and validation under realistic large-scale operating conditions.

REFERENCES

- [1] L. H. Melnyk, L. V. Shaulska, O. I. Matsenko, V. S. Piven, V. V. Konoplov, and Y. O. Mazin, "Modern Trends in the Production of Renewable Energy: the Cost Benefit Approach," *Mechanism of Economic Regulation*, vol. No. 1, 2021.
- [2] J. Dave, "Global electricity analysis: H1-2020," *EMBER*, vol. <https://ember-climate.org/insights/research/global-electricity-h12020/>, 2020.
- [3] L. Joyce *et al.*, "GLOBAL WIND REPORT 2024," *GWEC*, 2024.
- [4] B. Desalegn, D. Gebeyehu, B. Tamrat, T. Tadiwose, A. J. C. E. Lata, and Technology, "Onshore versus offshore wind power trends and recent study practices in modeling of wind turbines' life-cycle impact assessments," vol. 17, p. 100691, 2023.
- [5] S. W. Ali *et al.*, "Offshore wind farm-grid integration: A review on infrastructure, challenges, and grid solutions," vol. 9, pp. 102811-102827, 2021.
- [6] T. R. Ayodele, A. Jimoh, J. L. Munda, and J. T. Agee, "Challenges of grid integration of wind power on power system grid integrity," *World 2020*, 3, 6, 2020.
- [7] M. Bajaj and A. K. J. I. J. o. E. R. Singh, "Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques," vol. 44, no. 1, pp. 26-69, 2020.
- [8] N. Nkosi, R. C. Bansal, T. Adefarati, R. Naidoo, S. K. J. I. J. o. M. Bansal, and Simulation, "A review of small-signal stability analysis of DFIG-based wind power system," vol. 43, no. 3, pp. 153-170, 2023.
- [9] A. Dhabhi, "Renewable capacity statistics 2026, ..," *International Renewable Energy Agency*, 2026.
- [10] GWEC, "Global Wind Energy Report 2023," 2024.
- [11] L. Granwal, "Total onshore wind energy generation capacity in Australia 2014-2023 " 2024.
- [12] W. Power, "offshore production Capacity," 2024.
- [13] D. Musbahu, G. Olarinoye, A. Saidu Abuabkar, U. Abubakar, and I. Basheer Balarabe, "ANALYSIS AND SIMULATION OF DOUBLE FEED INDUCTION GENERATOR," 2021.
- [14] N. K. Saxena, A. Kumar, D. J. E. P. C. Wenzhong Gao, and Systems, "Review of excitation techniques for squirrel cage induction generator based micro grid using dynamic compensation," vol. 50, no. 3, pp. 149-165, 2022.
- [15] G. O. Igbinsosa, N. Owomano, A. O. Bolarinwa, and Y. J. I. T. Maaji, "Modeling and Dynamic Analysis of a 9 MW DFIG-Based Grid-Connected Wind Energy Conversion System," vol. 14, no. 1, pp. 58-72, 2026.
- [16] X. Lyu, I. Subotić, and D. J. a. p. a. Groß, "Unified Grid-Forming Control of PMSG Wind Turbines for Fast Frequency Response and MPPT. arXiv 2022."
- [17] S. A. Almohaimeed and M. J. A. S. Abdel-Akher, "Power quality issues and mitigation for electric grids with wind power penetration," vol. 10, no. 24, p. 8852, 2020.
- [18] N. Alwaz, S. Raza, S. Ali, M. K. L. Bhatti, and S. Zahra, "Harmonic power sharing and power quality improvement of droop controller based low voltage islanded microgrid," *In 2019 International Symposium on Recent Advances in Electrical Engineering (RAEE)* vol. (Vol. 4, pp. 1-6). IEEE., 2019.

- [19] B. Sahu, B. P. J. J. o. M. P. S. Padhy, and C. Energy, "Design of Power System Stabilizer for DFIG-Based Wind Energy Integrated Power Systems under Combined Influence of PLL and Virtual Inertia Controller," 2023.
- [20] A. Chakraborty and T. J. E. P. S. R. Maity, "A novel application of adaptive filtering algorithm for LVRT capability enhancement of grid-connected DFIG-based wind energy conversion systems (WECS)," vol. 217, p. 109179, 2023.
- [21] B. B. Adetokun and C. M. J. E. R. Muriithi, "Impact of integrating large-scale DFIG-based wind energy conversion system on the voltage stability of weak national grids: A case study of the Nigerian power grid," vol. 7, pp. 654-666, 2021.
- [22] T. Lund, B. Yin, G. Andersen, and M. Gupta, "Challenges and solutions for integration of wind power in weak grid areas with high inverter penetration," in *19th Wind Integration Workshop*, 2020, vol. 11.
- [23] N. J. E. Mbuli, "Improvement of Low Voltage Ride-Through (LVRT) of Doubly Fed Induction Generator (DFIG)-Based Wind Energy Conversion Systems (WECSs) by STATCOMs: A Systematic Literature Review," vol. 19, no. 2, p. 443, 2026.
- [24] N. S. Ugwuanyi, O. A. Nwogu, I. O. Ozioko, and A. O. J. S. A. Ekwue, "An easy method for simultaneously enhancing power system voltage and angle stability using STATCOM," vol. 25, p. e02248, 2024.
- [25] M. M. Aly, M. Abdel-Akher, S. M. Said, and T. Senjyu, "A developed control strategy for mitigating wind power generation transients using superconducting magnetic energy storage with reactive power support," *International Journal of Electrical Power & Energy Systems*, vol. 83, 485-494, 2016.
- [26] J. Su *et al.*, "An Optimal Allocation Method for Dynamic Reactive Power Compensation Device in Receiving Power grid with High Proportion of New Energy access," in *2023 IEEE 6th International Electrical and Energy Conference (CIEEC)*, 2023, pp. 280-287: IEEE.
- [27] A. M. Alshamrani, M. A. El-Meligy, M. A. F. Sharaf, W. A. M. Saif, and E. M. J. I. A. Awwad, "Transmission expansion planning considering a high share of wind power to maximize available transfer capability," vol. 11, pp. 23136-23145, 2023.
- [28] F. Zhao *et al.*, "Energy-storage enhanced STATCOMs for wind power plants," vol. 10, no. 2, pp. 34-39, 2023.
- [29] A. Shalbfian and F. J. S. R. Amiri, "Enhanced power capture for the wind turbine system via a novel second-order nonsingular fast terminal sliding mode control strategy," vol. 16, no. 1, p. 4801, 2026.
- [30] M. Bahgat, M. Ezzat, M. A. Attia, S. Mekhamer, and N. M. J. S. R. Elbehairy, "Comparative analysis of PI and fuzzy logic controller for grid connected wind turbine under normal and fault conditions," vol. 15, no. 1, p. 1954, 2025.
- [31] P. Lu, N. Zhang, L. Ye, E. Du, and C. J. A. i. A. E. Kang, "Advances in model predictive control for large-scale wind power integration in power systems," vol. 14, p. 100177, 2024.
- [32] K. Mahmoud, P. Astero, P. Peltoniemi, and M. J. I. A. Lehtonen, "Promising grid-forming VSC control schemes toward sustainable power systems: Comprehensive review and perspectives," vol. 10, pp. 130024-130039, 2022.
- [33] A. Muthanna Nori, A. Kadhim Abdulabbas, O. Alrumayh, and T. M. J. M. Aljohani, "Robust Voltage Stability Enhancement of DFIG Systems Using Deadbeat-Controlled STATCOM and ADRC-Based Supercapacitor Support," vol. 14, no. 8, p. 1254, 2026.