

Power Quality Effects of Renewable Energy Generation on High-Voltage Transmission Lines

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Abstract- The integration of renewable energy sources into high-voltage (HV) transmission systems introduces complex power quality challenges due to the widespread use of power electronic converters in wind and solar generation. These converter-dominated units significantly affect harmonic characteristics, interharmonic propagation, voltage stability, and sub-synchronous oscillation behavior. The analysis presented in this study synthesizes the major power quality impacts observed in modern transmission grids with increasing renewable penetration. Results show that harmonic distortion and resonance risks intensify in networks where underground cables, MMC-HVDC links, and large inverter-based resources interact, shifting system impedance and lowering resonance frequencies. Voltage fluctuations and reactive power imbalance caused by large-scale wind integration further degrade stability, particularly in weak grids with low short-circuit strength. Sub-synchronous resonance mechanisms differ between turbine technologies, where DFIG units primarily trigger induction-generator-based SSR, while full-converter turbines exhibit control-interaction-driven SSCI. Mitigation strategies identified as most effective include MMC-HVDC systems, STATCOM and UPFC-based dynamic compensation, Battery Energy Storage Systems (BESS), and grid-forming inverter control. Overall, advanced converter control, coordinated reactive power support, and harmonic-aware transmission planning are essential to ensure secure and reliable operation in high-renewable HV networks.

Keywords: Harmonic Distortion, Power Quality, Renewable Energy, Sub-Synchronous Resonance, Transmission Lines

I. INTRODUCTION

The transition to renewable sources in energy systems is a strategic imperative, not only for environmental sustainability but also for energy supply security. However, the inherently variable and limitedly controllable nature of renewable generation introduces new impacts on power quality, especially at the transmission level [1].

Power quality is defined as the ability of voltage, frequency, and waveform to remain within ideal limits.

Disturbances such as harmonic distortion, flicker, voltage sags, phase shifts, and sub-synchronous oscillations adversely affect system performance and equipment lifespan [2].

In recent years, the proliferation of power electronics-based converters (inverters) in wind turbines, solar photovoltaic (PV) systems, and High Voltage Direct Current (HVDC) connected grids has increased the scale of these problems [3]. Power electronics is recognized as the "key technology" for the grid integration of modern renewable energy systems (RES), but it has also become the primary source of new harmonic and stability issues [3]. Notably, the increasing use of underground cables (UGC) can alter grid impedance, potentially leading to unexpected harmonic resonances [4].

In this context, a deep-dive investigation into the power quality effects of renewable energy generation on transmission lines is of critical importance for both academic research and system planning.

II. METHODOLOGY

2.1 Research Approach

This paper is based on a Systematic Literature Review (SLR) approach. The objective is to comprehensively reveal the impacts of renewable energy generation on power quality in transmission systems using data from peer-reviewed research published between 2010 and 2025. This paper aims to provide a holistic perspective on power quality issues by categorizing them dually based on problems (e.g., harmonics, SSR) and solutions (e.g., HVDC, FACTS), thereby contributing a synthesized overview to the literature.

2.2 Data Collection Process

Research data were obtained from the IEEE Xplore, ScienceDirect, Scopus, SpringerLink, MDPI, and Wiley Online Library databases.

The main keywords used are:

"Power quality", "harmonic distortion", "renewable integration", "transmission system", "HVDC", "STATCOM", "sub-synchronous resonance", "flicker", "dynamic line rating", "SSR".

As a result of the search, 189 studies were identified. Following the PRISMA 2020 protocol, studies focusing on distribution levels and microgrids (e.g., [5]) were excluded, and 24 high-quality papers were selected.

2.3 Inclusion and Exclusion Criteria

Table 1 summarizes the inclusion and exclusion criteria applied during the literature selection process.

Table 1. Inclusion and Exclusion Criteria

| Criterion | Included | Excluded |
|------------------|---|--|
| Subject | Renewable energy – transmission system – power quality relationship | Distribution level, microgrids |
| Method | Analytical, simulation, or experimental studies | Purely conceptual discussions |
| Publication Type | Peer-reviewed journal/conference papers | Theses, technical notes, book chapters |

2.4 Analysis Process

The studies were classified using thematic content analysis. For each paper, the following parameters were extracted:

Method used (modeling, experiment, measurement)

System type (HVAC / HVDC)

Power quality parameters addressed (THD, flicker, voltage sag, SSR)

Control or solution technique used (STATCOM, filter, HVDC, BESS, Grid-Forming, etc.)

These data were organized into a comparative literature matrix.

2.5 Methodological Reliability

All DOI numbers were verified via CrossRef, confirming the validity of the sources. Data selection was cross-checked by two independent researchers, and discrepancies were resolved through consensus.

III. KEY POWER QUALITY CHALLENGES

The literature review demonstrates that the primary challenges of RES integration in transmission systems can be grouped into four main categories.

3.1 Harmonic Distortion, Interharmonics, and Resonance

The most common form of power quality degradation is harmonic distortion, originating from the nonlinear switching characteristics of inverters and other power electronic devices (e.g., rectifiers, VFDs) [1]. Measuring this with the traditional Total Harmonic Distortion (THD) is insufficient for modern systems.

Power electronic devices generate supra-harmonics in the frequency range above 2 kHz and interharmonics that are not integer multiples of the fundamental frequency. [6] highlighted that conventional THD factors are inadequate for measuring these new forms of pollution and emphasized the necessity of new metrics based on "frequency groupings" (e.g., THDG, THDS) as defined in the IEC 61000-4-7 standard.

More critically, physical changes in the transmission grid structure can amplify the effects of these harmonics. Ref. [4] demonstrated that in grids where overhead lines (OHL) are replaced with underground cables (UGC), the high capacitance of the cables lowers the grid's parallel resonance frequency. This shift can cause it to coincide with the low-order harmonics generated by inverters (e.g., 11th and 13th), leading to a dangerous amplification of voltage distortion to hazardous levels.

3.2 Voltage Fluctuations (Flicker) and Reactive Power Imbalance

The variable power output of wind turbines (WT) in particular causes continuous power flow variations in transmission lines, leading to voltage fluctuations (flicker) [7]. This effect is especially pronounced in

"weak grids" (those with a low short-circuit ratio). Ref. [8] noted that in large-scale wind farms connected to weak transmission grids, the increased demand for reactive power (Q) severely destabilizes voltage.

The root of this problem lies in reactive power management. Unlike conventional plants, RES inverters must provide reactive power support through active control strategies. Insufficient or slow reactive power compensation leads to inefficient use of transmission line capacity and voltage instability.

3.3 Sub-Synchronous Resonance (SSR / SSO)

One of the most critical stability issues in RES integration is Sub-Synchronous Resonance (SSR) or Sub-Synchronous Oscillation (SSO). This phenomenon is particularly observed in wind farms connected to series-compensated transmission lines. The literature reveals that different wind turbine types trigger different SSR mechanisms:

Type 3 (DFIG) Turbines: A comparative analysis by [9] showed that Type 3 Doubly-Fed Induction Generators (DFIGs) are prone to SSR via the Induction Generator Effect (IGE) mechanism. This effect can cause instability even at low RES penetration levels (e.g., 19%) and creates severe mechanical stress on turbine shafts.

Type 4 (PMSG/DDWG) Turbines: Full-converter Permanent Magnet Synchronous Generators (PMSG) or Direct-Driven Wind Generators (DDWG) do not exhibit the IGE. However, interactions between their control systems (especially PLLs) and the weak grid impedance can lead to a different type of instability known as Sub-Synchronous Control Interaction (SSCI) [9], [10].

Ref. [10] conducted a probabilistic analysis of SSOs caused by DDWG-based wind farms, demonstrating that these oscillations could occur with high probability under specific control parameters and grid scenarios.

3.4 HVDC and Power Electronics Interactions

For connecting remote (especially offshore) wind farms, HVDC systems offer a more efficient solution than HVAC. However, these systems also introduce

their own power quality challenges. Ref. [11] comprehensively analyzed the integration of PV and wind plants into Modular Multi-level Converter (MMC) HVDC lines. While MMCs reduce harmonic distortion, the control interactions between converter stations and fault conditions create complex dynamics.

Fault detection on HVDC lines is a particularly critical issue. Ref. [12] in their fault analysis method for wind farm-integrated HVDC lines, demonstrated that it is possible to accurately detect the fault location and type (e.g., pole-to-ground) using only the voltage signals from the rectifier end and a Fuzzy Inference System (FIS).

IV. SOLUTION STRATEGIES AND MITIGATION TECHNIQUES

The analyzed literature presents multi-layered solution strategies for the identified power quality challenges. These solutions can be categorized into three main axes: hardware (transmission infrastructure), control (power electronics software), and planning (system design).

4.1 Transmission Infrastructure Solutions: HVDC and FACTS

The most effective hardware solutions for overcoming these challenges are HVDC and FACTS technologies.

HVDC Systems: Specifically, MMC-HVDC (Modular Multi-level Converter HVDC) stands out as the most advanced technology for the integration of remote, large-scale RES (especially offshore wind) [11]. MMC-HVDC prevents fault propagation by asynchronously connecting systems, can control active and reactive power independently of the AC grid, and produces very low harmonic distortion [13], [14]. [15] in a techno-economic analysis of VSC-HVDC systems, confirmed that these systems offer flexibility and reliability for offshore wind integration.

FACTS Devices: In AC transmission lines, Flexible AC Transmission Systems (FACTS) devices are used to dynamically improve power quality.

- **STATCOM (Static Synchronous Compensator):** This is the most frequently cited solution in the

literature. A STATCOM dampens voltage fluctuations (flicker) and voltage sags by instantaneously injecting or absorbing reactive power from the grid [2], [7].

- UPFC (Unified Power Flow Controller): In a techno-economic analysis by [8] various FACTS devices (Capacitor Banks, SVC, STATCOM, SSSC, UPFC) were compared for weak grids connected to wind farms. The findings showed that the UPFC, with its ability to independently control both active and reactive power flow, offers the technically superior performance and most rapidly improves system stability.

4.2 Power Electronics and Control Paradigms

Inverters, the source of the problem, are also the key to the solution. Modern control paradigms enable inverters to "support" the grid rather than be a "burden" [3].

Grid-Forming Control: Traditional "Grid-Following" inverters act as current sources, require a strong grid voltage to operate, and offer no inertia. The new generation of "Grid-Forming" inverters acts as voltage sources, mimicking a Virtual Synchronous Generator (VSG) to actively "form" the grid voltage and frequency [3], [16]. This method is a direct solution to the problem of diminishing system inertia as RES penetration increases.

Active Power Control: Recent literature consistently indicates that active power curtailment and converter-based control strategies are essential for ensuring grid stability and improving power quality in high-renewable transmission systems.

4.3 System-Level Planning, Storage, and Management

Power quality issues must be addressed not only during operation but also at the system planning stage.

Holistic Planning (REZ and Techno-economics): Ref. [17] propose a systematic planning process, the Renewable Energy Zones (REZ) process, which identifies high-potential RES areas and then optimizes the necessary transmission investments using comprehensive engineering studies (production cost, load flow, stability analysis). Ref. [18] argue that

harmonic constraints must also be included in these planning models as a cost component (harmonic power loss), ensuring that techno-economic optimization also accounts for power quality.

Energy Storage Systems (BESS): Battery Energy Storage Systems (BESS) are critical for "smoothing" the variability of RES. Ref. [16] proved through simulations that BESS integrated with PV plants can maintain a constant power output to the grid during sudden production drops (e.g., cloud cover), thereby contributing directly to transient stability and frequency regulation.

Operational Strategies: Ref. [8] introduced the concept of "mid-career repowering". In this approach, efficiency losses in wind farms due to the "wake effect" (turbines blocking wind from each other) are compensated by increasing the turbine hub height and adding reactive power compensation, presenting this as a techno-economically feasible solution. Ref. [19] studied the impact of transmission line congestion on grid losses, finding that at low transmission power, RES reduces losses (local consumption), but at high transmission power (transporting to distant loads), it increases losses.

Advanced Monitoring and Management: Advanced monitoring systems are essential for detecting power quality issues. Ref. [20] designed and installed a GPS-synchronized multi-point measurement system to analyze the impacts of RES on the grid. Ref. [21] proposed innovative management mechanisms such as "Energy Routers" and a "Blockchain" architecture for secure data exchange in grid operations.

V. DISCUSSION

The reviewed literature clearly indicates that the power quality challenges arising from renewable energy integration on transmission lines are not isolated, singular problems, but rather a deeply interconnected and complex set of interactions. This discussion synthesizes the findings from the 24 analyzed papers to thoroughly examine the fundamental dilemmas facing modern transmission systems and the technological trends emerging from these dilemmas. The primary takeaway is that RES integration is forcing a "paradigm shift" in

transmission grids, with "power electronics" technologies at the epicentre of this shift.

The Dual Role of Power Electronics: Source of the Problem and the Solution

The most prominent theme in the literature is the dual role played by power electronic inverters [1], [3]. In conventional energy systems, large, rotating-mass synchronous generators provided the grid with a natural "inertia" and short-circuit power, keeping the system stable. Frequency and voltage were "naturally" regulated by the physical behavior of these massive machines. However, PV and Type 4 (full-converter) wind turbines lack this physical connection; their only link to the grid is through power electronic inverters that react in milliseconds [3].

The first consequence of this, as detailed by [1] is harmonic pollution. The high-frequency switching (PWM) operations of inverters distort the ideal sine wave, producing numerous harmonic components. Ref. [6] demonstrate that this problem extends beyond classic THD (Total Harmonic Distortion) measurements; inverters also generate "interharmonics" (non-integer multiples of the fundamental frequency) and "supra-harmonics" (above 2 kHz). These high-frequency components can cause traditional filters to be ineffective and lead to erroneous trips in protection relays.

An even more critical issue is the risk of resonance, highlighted by [4]. This study, using real data from the Danish transmission grid, reveals how replacing overhead lines (OHL) with underground cables (UGC) for environmental reasons dramatically alters the system impedance. The high capacitance of the cables lowers the grid's parallel resonance frequency, pulling it dangerously close to the natural switching harmonics of the inverters (e.g., 11th and 13th harmonics). The result was an unexpected and dangerous voltage "amplification" at these frequencies. This finding proves that RES integration interacts complexly not just with the RES units themselves, but also with other "green" changes in the grid topology.

However, the literature shows that the source of the problem, power electronics, is also the key to the solution. Ref. [3] and [16] highlight a new control

paradigm: "Grid-Forming" inverters. Traditional "Grid-Following" inverters passively track the grid and require a strong grid voltage to operate. In a weak grid, these inverters are prone to instability. In contrast, "Grid-Forming" inverters mimic a synchronous generator (also known as a Virtual Synchronous Machine - VSG), actively "forming" the grid voltage and frequency. In this way, RES plants can provide "inertia" [16] and contribute directly to grid stability and fault ride-through [11]. This signifies a transformation from a passive producer to an active grid-support element.

Stability Dilemmas: SSR, Weak Grids, and Turbine Types

One of the most dangerous issues at the transmission level is Sub-Synchronous Resonance (SSR/SSO). The groundbreaking comparative analysis by [9] demonstrates that this problem is not uniform for all wind turbines. The stability impacts of Type 3 (DFIG) and Type 4 (PMSG) turbines are fundamentally different.

According to [9] findings, Type 3 (DFIG) turbines, when interacting with series-compensated lines, trigger a phenomenon called the Induction Generator Effect (IGE). This is essentially an electrical resonance problem and can lead to instability in the grid and destructive mechanical vibrations on the turbine shafts, even at very low RES penetration levels (e.g., 19%).

In contrast, Type 4 (PMSG) turbines, being full-converter, do not exhibit this IGE. However, this does not mean the problem is solved; it merely means the problem changes form. The integration of Type 4 turbines causes conventional synchronous generators to reduce their power output (de-rating). This, in turn, reduces the damping coefficients of the synchronous generators, causing the system's own natural oscillation modes (e.g., 25.4 Hz) to become unstable. More importantly, a Sub-Synchronous Control Interaction (SSCI) can occur between the Type 4 turbine's own control loops (especially the PLL) and the grid impedance [10]. [10] studied the probabilistic nature of these SSCI events and revealed that the combination of specific control parameters and weak grid conditions dramatically increases the risk of SSO.

At this juncture, the concept of the "weak grid" (low short-circuit ratio), emphasized by [8] becomes centrally important. Weak grids are more susceptible to interactions with the control systems of RES inverters. In these grids, even a small change in wind speed (studied as "flicker" by [7]) can cause large voltage fluctuations. Ref. [8] examining a weak grid in Pakistan, showed that the "wake effect" between wind farms not only reduced energy production (active power) but also increased reactive power draw from the grid, further deteriorating voltage stability.

Holistic Solution Strategies: Hardware, Storage, and Planning

The literature demonstrates that these complex problems cannot be solved with a single "magic bullet"; they require a holistic approach that combines hardware, control, and system planning.

Hardware Solutions (HVDC and FACTS):

For connecting remote RES (especially offshore wind), HVDC technology offers clear advantages over AC. [Ref. 13] note that HVDC provides an asynchronous connection, preventing the propagation of stability problems between two systems and reducing losses. Specifically, MMC-HVDC (Modular Multi-level Converter) produces a near-perfect sine wave, largely solving harmonic issues [11], [14]. However, HVDC systems are also vulnerable to faults. Ref. [12] proposed innovative protection methods using Artificial Intelligence (Fuzzy Logic) for DC fault detection.

In AC systems, FACTS devices offer "dynamic" solutions to power quality. Ref. [2] and [7] showed that STATCOM successfully dampens voltage fluctuations (flicker) and sags with instantaneous reactive power support. In a more comprehensive analysis, [8] techno-economically compared various FACTS devices (capacitor bank, SVC, STATCOM, UPFC). This study concluded that the UPFC (Unified Power Flow Controller), thanks to its unique ability to independently control both active and reactive power flow, is the technically superior and most flexible solution for voltage stability and power quality, especially in weak grids.

Storage and Operational Strategies:

Hardware solutions are expensive. Sometimes, smarter operational strategies can be more efficient. Ref. [16] simulated the role of Battery Energy Storage Systems (BESS) in managing RES variability. BESS, by rapidly discharging during sudden production drops (e.g., cloud cover on a PV plant), "smoothes" the total power injected into the grid. This not only prevents voltage fluctuations but also helps regulate system frequency (inertia support), thus enhancing overall electromechanical stability.

[8], propose an operational strategy called "mid-career repowering". Efficiency losses in wind turbines due to the wake effect are compensated by increasing the turbine hub height and adding reactive power support, presented as a techno-economically feasible solution (based on NPV and payback period).

Holistic Planning and Management:

The reviewed papers show that trying to "fix" power quality and stability issues after plants are built is highly costly. The solution is to predict these issues during the "planning" stage. Ref. [17] detail the "Renewable Energy Zones" (REZ) process used in the US. This approach aims to identify high-RES potential areas and then optimize the required transmission investments to connect these zones to load centers through a comprehensive engineering study involving production cost, load flow, and stability analyses.

Ref. [18] take this planning philosophy a step further, arguing that "harmonic constraints" must be added to traditional grid expansion planning (GEP/TEP) models. In this model, the extra losses created by harmonics (harmonic power loss) become a direct part of the economic optimization. Thus, the system is planned not only for the lowest investment cost but also to ensure it meets harmonic limits (e.g., THD < 5%) and operates with the lowest losses.

Finally, managing such a complex system also requires new approaches. Ref. [20] showed that a GPS-synchronized multi-point measurement infrastructure is essential to understand power quality in a grid with widespread RES. Ref. [21] offer a more futuristic perspective, proposing the automation of this distributed energy resource management (RES, BESS, etc.) using "Energy Routers" and a secure, decentralized data management architecture via

Blockchain, suggesting that even power quality management (QoS - Quality of Service) can become autonomous and distributed.

VI. CONCLUSION AND RECOMMENDATIONS

This systematic literature review has comprehensively evaluated the power quality impacts of large-scale renewable energy generation on high-voltage transmission systems by analyzing 24 peer-reviewed studies. It is clear that the integration of RES is causing a paradigm shift, moving the grid's foundation from synchronous generators to power electronic inverters. This transition, while essential for decarbonization, introduces new and complex challenges to grid stability and power quality.

6.1. Key Findings

The Dilemma Of Power Electronics (Double-Edged Technology): The clearest conclusion emerging from the entire reviewed literature is that power electronic technologies (inverters, HVDC converters) are both the "key enabling technology" [3] for RES integration and the "primary source" [1] of power quality problems. These devices lead to a lack of inertia (not found in conventional systems), harmonic pollution [6] and complex control interactions [10].

The Evolution Of Harmonic Problems: The harmonic issue has moved beyond simple THD limits. Inverters produce supra-harmonics (above 2 kHz) and interharmonics [6]. More importantly, changes in grid topology (especially the increased use of underground cables - UGC) alter the grid impedance, causing these harmonics to enter resonance and leading to dangerous amplification at specific frequencies [4]. This shows that harmonic management is no longer just about filtering the source but requires an analysis of the entire system's impedance profile.

The Diversification Of Stability Problems (Ssr/Sso/Ssci): RES integration has created new challenges in the field of sub-synchronous oscillations. The literature clearly demonstrates that different turbine technologies trigger different instability mechanisms. Type 3 (DFIG) turbines cause electromechanical instability (SSR) via the Induction Generator Effect (IGE) on series-compensated lines

[9] whereas Type 4 (PMSG/DDWG) turbines cause electrical instability (SSCI) through the interaction of their control systems (e.g., PLLs) with the grid [10]. Both pose serious risks to transmission systems.

The Necessity Of A Holistic Solution Portfolio: The studies show that these complex problems cannot be solved by a single technology. An effective integration requires a multi-layered solution portfolio:

- **Hardware (Transmission):** MMC-HVDC technology is superior for integrating remote RES (especially offshore wind) due to its asynchronous connection and high power quality [11], [13].
- **Hardware (Compensation):** FACTS devices (especially STATCOM and UPFC) are critical for dynamically managing voltage fluctuations (flicker) and reactive power imbalances in AC grids [7], [8].
- **Software (Control):** To solve the fundamental problem of low inertia, the inverter control philosophy must evolve from "Grid-Following" to "Grid-Forming" (GFM), allowing inverters to mimic synchronous generators and actively create the grid frequency and voltage [3], [16].
- **System (Support):** Battery Energy Storage Systems (BESS) have become an indispensable complement, providing "power smoothing" services to manage RES variability and contribute to frequency regulation and transient stability [16].

The Growing Importance Of Planning: Power quality and stability are no longer just operational issues, but fundamental planning problems. Future grid expansion planning models must incorporate harmonic constraints and losses directly into their economic optimization [18]. Systematic approaches, such as the Renewable Energy Zone (REZ) process, which integrate stability and load flow analysis from the outset, are essential for future investments [17].

6.2 Recommendations for Future Work

This literature review also highlights significant research gaps. Future work should focus on the

following areas to ensure a secure transition to a 100% RES-based transmission system:

Technological Development and Modeling Recommendations

- **Standardization and Large-Scale Application of Grid-Forming Inverters:** GFM control is identified as the most promising solution to the low-inertia problem [3]. However, existing research (e.g., [16]) is mostly focused on singular inverters or small systems. Future work must model how hundreds of GFM inverters will operate in a coordinated and stable manner on a transmission grid that also includes HVDC and FACTS devices. The standardization of their fault ride-through (FRT) response and fault current contributions is an urgent research topic.
- **Integrated Modeling of Complex Interactions (Hybrid Systems):** The literature often addresses problems in isolation (e.g., only harmonics [4] or only SSR [9]). However, in a real system, these problems coexist. Future work must focus on comprehensive simulation platforms capable of modeling the integrated electromechanical and harmonic interactions (e.g., the combined effect of SSCI and harmonic resonance) between MMC-HVDC lines, BESS, FACTS devices, and inverters in different control modes (GFM/GFL).
- **New Measurement Metrics and Monitoring Infrastructure:** The rise of supra-harmonics and interharmonics [6] proves that traditional monitoring infrastructure is inadequate. The GPS-synchronized multi-point measurement systems proposed by [20] must be widely deployed and integrated with operational data like DLR (Dynamic Line Rating). Furthermore, broadband, real-time grid impedance measurement techniques are needed for resonance detection.
- **AI and Digital Twin-Based Management:** The stochastic nature of RES and the complex interactions of power electronics make deterministic analysis difficult. Building on the probabilistic scenario-based approaches used for SSO analysis [10] Artificial Intelligence (AI)-based predictive control models are needed. These models should anticipate potential power quality violations or instabilities (SSO/SSCI) before they occur. Furthermore, leveraging the "Energy

Router" concept [21] the creation of Digital Twins of the entire transmission system is critical for risk analysis of complex interactions and fault scenarios [12].

Grid Planning and Policy Recommendations

- **Power Quality-Centric Grid Planning:** The planning approaches outlined by [17] and [18] contain a fundamental lesson for policymakers: power quality and stability are not problems to be "fixed" after grid expansion; they are constraints that must be part of the design. All future transmission investments must include harmonic and stability analyses as mandatory components.
- **Urgent Update of Grid Codes:** Current grid codes are largely designed for a system based on synchronous generators [22]. These codes must be urgently updated to mandate the new and advanced capabilities of inverter-based resources, such as providing inertia and frequency formation ("Grid-Forming") [3].
- **Development of Techno-Economic Models:** The techno-economic analyses by [8] and [15] highlight the importance of cost in RES integration. Future planning must utilize comprehensive Life Cycle Cost Analyses (LCOE, NPV) that include not only the initial investment costs (CAPEX) of different mitigation technologies (e.g., STATCOM vs. UPFC vs. BESS) but also their impact on system losses (OPEX), the ancillary services they provide, and their effect on overall system reliability.

REFERENCES

- [1] J. Kaur and S. K. Bath, "Harmonic distortion in power systems due to electronic control and renewable energy integration: a comprehensive review," *Discover Electron.*, vol. 2, no. 1, p. 67, 2025, doi:10.1007/s44291-025-00111-9.
- [2] K. P. Kumar, S. Venkateshwarlu, and G. Divya, "A review on power quality in grid-connected renewable energy system," *CVR J. Sci. Technol.*, vol. 5, no. 1, pp. 57–61, 2013, doi:10.32377/cvrjst0510.
- [3] F. Blaabjerg, Y. Yang, K. A. Kim, and J. Rodriguez, "Power electronics technology for

- large-scale renewable energy generation,” *Proc. IEEE*, vol. 111, no. 4, pp. 335–355, 2023, doi:10.1109/JPROC.2023.3253165.
- [4] V. Akhmatov, B. S. Bukh, C. L. Skovgaard, and B. C. Gellert, “Novel harmonic distortion prediction methods for meshed transmission grids with large amounts of underground cables,” *Energies*, vol. 16, no. 9, 3965, 2023, doi:10.3390/en16093965.
- [5] J. Wang and X. Lu, “Sustainable and resilient distribution systems with networked microgrids: point of view,” *Proc. IEEE*, vol. 108, no. 2, pp. 238–241, 2020, doi:10.1109/JPROC.2019.2963605.
- [6] A. Arranz-Gimon, A. Zorita-Lamadrid, D. Morinigo-Sotelo, and O. Duque-Perez, “A review of total harmonic distortion factors for the measurement of harmonic and interharmonic pollution in modern power systems,” *Energies*, vol. 14, no. 20, 6467, 2021, doi:10.3390/en14206467.
- [7] P. Kumar, S. Chand, R. K. Gupta, and A. B. Singh, “Impact of renewable energy integration on power quality: challenges and solutions,” *Int. J. Innov. Res. Eng. Manag.*, vol. 11, no. 4, pp. 95–99, 2024, doi:10.55524/ijirem.2024.11.4.12.
- [8] R. Z. Butt et al., “Techno-economic and environmental impact analysis of large-scale wind farms integration in weak transmission grid from mid-career repowering perspective,” *Sustain.*, vol. 14, no. 5, 2507, 2022, doi:10.3390/su14052507.
- [9] C.-H. Lin, “Comparison of impact on turbine shaft torsional behavior for integration of two types of wind farm into a series-compensated transmission system,” *Energies*, vol. 15, no. 18, 6796, 2022, doi:10.3390/en15186796.
- [10] Z. An et al., “Scenario-based analysis and probability assessment of sub-synchronous oscillation caused by wind farms with direct-driven wind generators,” *J. Mod. Power Syst. Clean Energy*, vol. 7, no. 2, pp. 243–253, 2019, doi:10.1007/s40565-018-0416-2.
- [11] M. I. Hossain, M. Shafiullah, F. A. Al-Sulaiman, and M. A. Abido, “Comprehensive analysis of PV and wind energy integration into MMC-HVDC transmission network,” *Sustain.*, vol. 15, no. 1, 253, 2022, doi:10.3390/su15010253.
- [12] S. Agarwal, A. Swetapadma, C. Panigrahi, and A. Dasgupta, “Fault analysis method of integrated high-voltage direct current transmission lines for onshore wind farm,” *J. Mod. Power Syst. Clean Energy*, vol. 7, no. 3, pp. 621–632, 2019, doi:10.1007/s40565-018-0483-4.
- [13] N. Imdadullah, B. Alamri, M. A. Hossain, and M. S. J. Asghar, “Electric power network interconnection: current status, future prospects and research directions,” *Electronics*, vol. 10, no. 17, 2179, 2021, doi:10.3390/electronics10172179.
- [14] T. Karunakar, F. T. Josh, J. J. Joseph, P. S. Mayurappriyan, and M. S. P. Subathra, “Hybrid wind-energized back-to-back HVDC modular converter for AC grid networks,” *Neuroquantology*, vol. 20, no. 22, pp. 2719–2725, 2022, doi:10.48047/NQ.2022.20.22.NQ10263.
- [15] H. Li, W. Xu, H. Xu, D. Ni, and Y. Yang, “Study on influencing factors of technical-economy effect of VSC-HVDC system based on improved ISM method,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 366, 012062, 2018, doi:10.1088/1757-899X/366/1/012062.
- [16] J. C. Lopes and T. Sousa, “Transmission system electromechanical stability analysis with high penetration of renewable generation and battery energy storage system application,” *Energies*, vol. 15, no. 6, 2060, 2022, doi:10.3390/en15062060.
- [17] N. Lee and C. Barrows, “Transmission planning studies for the renewable energy zone (REZ) process,” *Natl. Renew. Energy Lab. (NREL), Rep. No. NREL/TP-7A40-71005*, 2018, doi:10.2172/1465321.
- [18] S. L. Gbadamosi, N. I. Nwulu, and P. Siano, “Harmonics constrained approach to composite power system expansion planning with large-scale renewable energy sources,” *Energies*, vol. 15, no. 11, 4070, 2022, doi:10.3390/en15114070.
- [19] P. Xia, W. Y. Liu, F. C. Liu, and X. W. Fu, “Mechanism research about impact of transmission channel power constraint on grid loss with large-scale wind power integration,”

Adv. Mater. Res., vols. 1070–1072, pp. 919–922,
2014,
doi:10.4028/www.scientific.net/AMR.1070-
1072.919.

- [20] J. Bruna et al., “Design and installation of a novel multi-point measurement system for a renewable energy grid,” *Renew. Energy Power Qual. J.*, vol. 11, 2013, doi:10.24084/repqj11.591.
- [21] G. Gong et al., “Electric power system operation mechanism with energy routers based on QoS index under blockchain architecture,” *Energies*, vol. 13, no. 2, 418, 2020, doi:10.3390/en13020418.
- [22] F. O. Resende and J. A. P. Lopes, “Management and control systems for large-scale integration of renewable energy sources into electrical networks,” in *Proc. IEEE EUROCON—Int. Conf. Computer as a Tool*, 2011, pp. 1–6, doi:10.1109/EUROCON.2011.5929423.