A Comprehensive Review of AI-Based Reactive Power Compensation and Power Quality Enhancement in Grid-Connected Solar–Wind Hybrid Energy Systems

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Abstract: *The rapid penetration of renewable energy, particularly that from solar and wind power, has raised crucial concerns for power engineers regarding regulation of voltage, managing reactive power, and ensuring power quality in the modern power system. The grid-connected hybrid energy systems of solar and wind are intrinsically intermittent, often nonlinear, and do comprise voltage fluctuations, harmonic distortion, and poor system stability. In this regard, flexible AC transmission system (FACTS devices) like STATCOMs have found enormous relevance in providing dynamic reactive support and voltage control. In this review, as one important supplemental aspect, a detailed survey has been presented on the various control strategies in different configurations in hybrid power systems for STATCOM-based compensation, concentrating on AI-based optimization techniques. The first of the classical controllers (like voltage regulation and PQ-PI control schemes) pave the way for a strong discussion on the use of advanced operative knowledge tools-tools like Evolutionary Differential, genetic algorithm, and other SO techniques. A perspective then is set on the issue about optimal performance with AI-based controllers in harmonics mitigation, enhancement of the real power delivery, decrease in reactive power requirements, and adherence to the grid codes under variable load and generation condition. Amongst different recent studies, a comparison between performance outcomes is shown clearly that optimization-driven controllers surpass the traditional methods to a greater extent concerning their ability of simultaneously diminishing the THD and improving the power factor and system robustness. Also discussed in the final section are modeling approaches for one or combined solar PV sources, wind energy conversion systems, and cascaded multilevel inverter STATCOMs. Lastly, the paper has categorized a few research gaps and presented a direction of orientation for future research emphasizing an adaptable, scalable, and real-time intelligent control system geared towards the harmonious integration of large-scale renewable sources into smart grids.*

Keywords: *Solar–wind hybrid system, STATCOM, reactive power compensation, power quality, artificial intelligence, differential evolution, grid integration.*

I. Introduction

The integration of renewable energy sources in contemporary power networks has shifted the whole paradigm of systems, with solar and wind grid-connected hybrids now coming into the picture as viable and sustainable technologies for satisfying the new electricity demand and cutting greenhouse gas emissions [1]. The combined nature of solar PV and wind energy enhances available and reliable energy; however, their intermittent and stochastic nature projects substantial challenges to reactive powers handling, voltage instability, harmonic distortion, and power quality degradation. While these factors are against conventional reactive compensation techniques for concrete realization of both reactive powers and voltage harmonics, real-time modes of dynamic operations may be ultimately realized without fear of distorting the signal in live circuits [2]. If mismatching is tolerated, the unfortunate consequences of insufficient gland-boxing of compensation can be overvoltage or under-voltage, poor power factor, total harmonic distortion (THD) increment, overheating of equipment, and a shortened life of network components. Fixed capacitor banks, synchronous condensers, and the likes of traditional PI-Controlled FACTS devices are lifely to be able to sufficiently cover up the nonlinear, time-varying, and uncertain nature of hybrid renewable energy systems as per their linearized models [3] they require frequent tuning and have very little adaptability under rapidly changing operating conditions. With this in mind, the field of artificial intelligence (AI)-based compensatory and enhancement endeavors have been receiving scholarly attention for their potential to learn from data, adapt to dynamic environments, and put into effect non-linear system behavior when the AI is deployed [4]. AI controllers employ real-time measurement of system features-such as voltage, currents, frequency, and so on, to name but a few-to determine optimal corrective actions to be taken in power electronic converters, active filters, and the FACTSs for fast response and accurate compensation in the face of severe grid disturbances and high levels of renewable integration [5]. In this light, ANNs enjoy extensive applications in areas of reactive power prediction and voltage regulation owning to their strong nonlinear mapping ability and fast response, which egress with keen estimates of reactive power and advance control signals operable to provide voltage source inverters or STATCOMs, without any system model being available [6]. FLCs, on the flip side, provide rule-based decision-making using linguistic variables, making them viable in the event of systems that have uncertainties and imprecise inputs, and it is this quality that builds their robustness under fluctuating solar irradiance and wind speeds by ensuring a maintained voltage profile and improving the power factor within hybrid systems [7]. ANFIS seeks to use the strengths derived from combining the learning capability of NNs and the interpretability of FLCs to provide enhanced responses while also reducing THD and ensuring tight control over the voltage regulation, compared to use in conventional controllers. Being a learning-based method, the metaheuristic optimization algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Differential Evolution (DE), and Ant Colony Optimization (ACO) have been utilized extensively in parameter tuning for the controllers, inverter switching angles, and set-points for reactive power to shorten the convergence speed, cut steady-state errors, and enhance the robustness of the system [8]. In recent times, Reinforcement Learning (RL) and Deep Reinforcement Learning (DRL) find increasing attention as potentially groundbreaking development, offering autonomous compensation of reactive power control, with powerful intelligent agents learning through interactions with the grid and maximizing the long-term objective, voltage stability, and power quality compliances [9]. AI systems control strategies are largely implemented through advanced power electronics interfaces and FACTS devices, e.g., STATCOM, Static VAR Compensator (SVC), and Unified Power Flow Controller (UPFC), by which they are able to create the quick and dynamic reactive power support key to the management of voltage fluctuations and harmonic distortion from grid-connected solar-wind hybrids. STATCOMs controlled by AI deliver exceptional performance under normal situations in keeping the voltage stiff, canceling the weighted current harmonics, and enhancing power networks under unbalanced and nonlinear load conditions, since AI-enabled UPFCs permit the concurrent control of the voltage magnitude, line impedance, and power flow to specifically avail themselves in networks heavily laden with renewable energy sources [10]. Through the introductory two words spoken, the QoS enhancement remains of utmost importance to hybrid systems, and AI approaches are vigorously employed side by side to aid the amelioration of these faults. As such, AI-based feed-forward systems save the trouble and enhance the flexibility of setting the current control-band switch in bands, but the mechanism must be pipelined so that the signals are properly decoded by the test control-oriented linear intelligent harmonic filters, suitably implanted to clear the inverter and nonlinear load-dominant harmonics presumably injected into the system, ensuring clean power is externalized to the grid [11]. Moreover, the benefits of AI-based reactive power compensation include adaptability and self-learning capability, fast dynamic response, robustness against parameter variations and uncertainties, less need for manual tuning, and improved overall grid reliability and efficiency. No doubt, the daunting task of computational complexity, data training necessitation, constraint of real-time operation, and general state of cybersecurity is still a challenge [12].

A. Evolution of Low-Voltage Distribution Networks

LV distribution networks were originally planned for unidirectional power flow from centralized power plants to the final end consumers. The design was based on predictable load patterns, balanced phases, and no possibility of putting in awkward positions distributed generation. But the increasing electrification coupled with the proliferation of sensitive electronic loads and distributed renewable resources have now made network behavior very distinct [3]. It must be stressed that, with some degree of derision, the idea of rooftop PV, electric vehicles, and smart appliances now involves mainly bidirectional and highly variable flows, thereby imposing very heavy stress on their entire asset base, such as the transformers and the cables [4]. The traditional regulation devices-tap-changers and capacitor banks- are too slow and rigid to manage such dynamics. As proactive networks gradually evolve into active distribution systems, more power electronic and control-based solutions become vital now to ensure the reliability, underway and applied then, along with robust system coordination gone along on old infrastructure [2]-[3]. Figure 1 represents Evolution of Low-Voltage Distribution Networks.

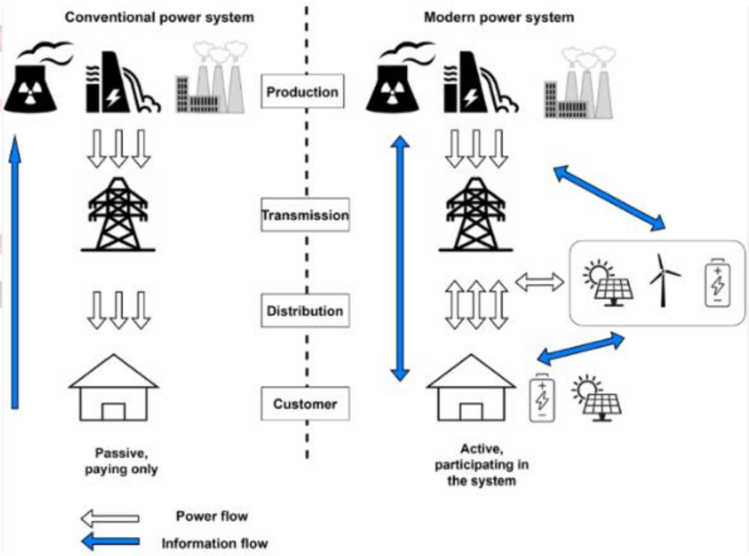

Figure 2 Evolution of Low-Voltage Distribution Networks [3]

B. Growth of Distributed Renewable Generation

Distributed renewable energy; especially rooftop PV, has witnessed rapid adoption fueled in equal parts by technology cost coming down, supportive policy and cleaner-energy enthusiastic consumers. A cluster of PV installations thus has the ability to produce more power than needed in the serving LV feeder, backward flow and localized overvoltage condition enactment [4]. The uneven power output comes from shadowing, variations in sunlight resulting from cloud movement and corresponding sudden alteration in voltage whereas variation in PV installation phase causes current imbalance and neutral overloading. Although integration of renewable energy produces sustainability and lowers the losses at the point of consumption, at the same time, it stands against the conventional controls imposed on the grid [5]. Thus, utilities create for the highest available renewable penetration into the system without destroying operative power quality, equipment health, or giving network reliability.

C. Need for Advanced Voltage and Power Flow Control

Traditional voltage control strategies in LV grids lack the speed and accuracy necessary to react to fast PV fluctuations. Mechanical systems wear out in time, while coordination is based upon rules rather than any artistic measures [5]. Efforts to rectify any problems are DESCH, that is, after the problem has already arisen. When PV penetration is high, real-time, joint control of voltage magnitude and current distribution is expected. They may provide fast control in multiple coordinated scenarios at once [6]. For instant access to power electronic controllers, they inject or suck voltage, manage reactive power, harmonize phase currents, and can keep the feeder at equilibrium under dynamic changes. Together, these two solutions can help prevent overvoltage severe current unbalances, increase the installed hosting capacity of PV systems, postpone expensive network extension projects, and enforce a more robust system [7]. Given these options, there is a great deal of impetus for investigations of innovative topologies, such as the UPFC-based solutions, for LV feeder voltage regulation and current balance.

II. Grid Integration Challenges and Power Quality Issues in Hybrid Renewable Systems

An essential strategy towards attaining the several energy objectives in the form of sustainability and low carbon demand ever since hybrid renewable energy systems came around has, for various industrial-environmental studies and hence over the past two decennia, influenced the lead time for time-based networks, as a strategy combining solar photovoltaics with wind energy source [8]. The introduction of drastic technical tasks is a result of such an integration and, thereby, the integration of renewable energy source systems with others will be a festival of grid charges, complex control, and wasteful degradations to power quality. The nature of their feeds being intermittent, fluctuating, and uncertain in the form of intermittent solar radiation and irregular winds makes these systems offer high levels of uncertainty that cause much rapid response to changes in active and reactive power, with such fluctuations being major grid integration challenges for network operators to preserve voltage power, frequency pacing and reliable power delivery, especially in sections of distribution networks with high levels of renewable power supply [9]. One of the chief impediments to grid integration is the management of reactive power, where no poor coordination at this side or not enough support could result in: adjusting (or voltage sag and swell), impaired power factor, increased power losses, and ultimately absurdly probable destruction with respect to voltage collapse in severe circumstances of operation. Pointing to the general obstructions to a balanced interaction with the grid is that of increased reliance on the power of electronic converters and inverters in the hybrid systems in question [10]. The introduction of these non-linear and harmonic-generating devices interferes with the quality of power to the absolute but adds to the level of distortion from phenomena such as: total harmonic distortion (THD), voltage flicker, waveform distortion, unbalanced currents, and subsequent disruption to the delicate loads and short-lived life of electrical devices. Furthermore, sudden changes in renewable generation or load demands in grid-tied hybrid systems can induce frequency instability, particularly in weaker grids with low inertia, where relatively small disturbances will most likely lead to significant frequency deviation [11].

One of the other major challenges in integrating hybrid renewables has been related to the coordination between different energy sources and control schemes, since different dynamic operation and control strategies exist for solar and wind generators; quite recently, this has made power sharing and grid synchronization much too intricate for the entire system. The fluctuating nature of renewable energy further presents a known issue due to the variability of the output that demands unpredictability in forecasting, thereby complicating network planning, operation, reserve scheduling, and increasing the overall running costs and reliability [12]. As interesting words related to the power quality, we admit that the voltage rises sometimes occur in the above hybrid renewable systems when the generation is very high corresponding to low loads. In the same scenario, voltage drops occur, meaning there exists not much time for effective reactive power support. Voltage flickering due to continuous variations in wind speed and erratic shadow coverage on solar panels just worsens the nuisance. This could occur on the lighting or electronic equipment that pertains to the sensitive load here [13]. This leads to inconvenience for and lesser production of the end user. Among the very many harms, additionally, they can cause the transformers to overheat, protective devices to malfunction, increase neutral currents, and cause resonance inside the grid. On the other end, unbalanced loading and asymmetrical faults will tend to worsen current imbalance and neutral shift, specifically in distribution networks involving very low voltages, downgrading power quality and system reliability [14]. Lack of unified grid codes and disparate regulatory frameworks across different regions further complicates hybrid renewable integration, as voltage support, fault ride-through capability, and harmonic constraints associated with grid integration needs and service may vary significantly [15].

These make improper design and operation of the hybrid systems become a fold more challenging. Around the world, passive filters, capacitor banks, and traditional voltage regulators are being used to mitigate some of these issues, but such tools do not often afford the necessary quickness notwithstanding the unavoidably fast-shifting operational scenarios faced by hybrid renewable systems. The upshot: many advanced solutions that focus on intelligent control strategies, dynamic reactive power compensating devices, and also coherent inverter control are thus gaining ground to provide some relief with respect to grid integration challenges and power quality [16]. Even when hybrid renewables may usher in considerable environmental benefits and economic acumen, the issues linked to their large-scale integration into power grids of the world include voltage stability, reactive power management, harmonic regulation, frequency regulation, and overall power quality, which necessitate futuristic control, compensation, and grid-support schemes for making certain reliable, efficient, and good power consumption in modern and future-generation power systems.

III. Reactive Power Compensation Techniques in Distribution Networks

Reactive power compensation in modern grids becomes quite inevitable amid heavy load variability and high penetration of distributed energy solutions, holding captive the cardinal objective of voltage stability. Ideally, reactive power compensation or unbalance can showcase a high-pressure feature both within distribution networks as well as transmission networks [18]. The sensitivity of distribution systems to reactive power unbalance is much more pronounced as opposed to that in transmission systems, parallel to their high R/X ratio, radial configuration, and higher customer-consumer burden; these systems need effective compensation to avoid the following: drop-in voltage levels, maintenance of power levels, or high line-loss torture [19]. Normally, a fixed capacitor bank along with a shunt reactor acts as the sole line of defense to cope with reactive power unbalance in systems and is the best available equipment at the optimal cost and operation effectiveness when it comes to advancing power quality and voltage control; however, they have disadvantages like abrupt control, no dynamic control, resonance troubles, and insensitivity to transient voltage conditions. Developing and placing enhancing capacitor banks in distribution systems organization has created good response to the need for flexibility, the downside being the tolerance for timeliness of both responding and each switching cycle, which could eventually ruin one's equipment [20]. Though on-load tap-changing (OLTC) transformers and regulators are commonly used to control voltage in distribution networks, mechanical solutions are unsuitable due to their slow response and flailing to regulate fast voltage fluctuation from dynamic loads or driven by renewable energy penetration [21]. There is also an ever-pressing urgency to make continuous, dynamic reactive power compensation systems concerning dynamic and diversified loads and inverter-based distributed generation, owing to which two major groups of FACTS retaining their platform did make efforts to have some implementation under the name of 'Custom Power' for distribution system applications.

Table 1 Comparison of Reactive Power Compensation Techniques [18]-[19]-[20]

Technique	Type	Response Speed	Compensation Nature	Harmonic Mitigation	Cost	Suitability / Remarks
Fixed Capacitor Bank	Passive	Very Slow	Discrete	No	Low	Simple and economical; ineffective for varying loads
Switched Capacitor Bank	Passive / Semi-active	Slow	Discrete	No	Low–Medium	Better adaptability; switching causes wear and transients
Shunt Reactor	Passive	Very Slow	Continuous (Absorption)	No	Low	Used to absorb excess reactive power under light load
OLTC Transformer	Electromechanical	Slow	Indirect Voltage Control	No	Medium	Effective for steady-state voltage regulation only
Static VAR Compensator (SVC)	FACTS	Fast	Continuous	Limited	Medium	Thyristor-based; performance degrades at low voltage
STATCOM	FACTS	Very Fast	Continuous	Limited	High	Superior performance; effective in weak grids
D-STATCOM	FACTS (Distribution)	Very Fast	Continuous	Moderate	High	Ideal for distribution networks and renewable integration
UPFC	FACTS	Very Fast	Continuous (Series + Shunt)	Limited	Very High	Comprehensive control but complex and expensive
Active Power Filter (APF)	Power Electronic	Very Fast	Continuous	Yes	High	Compensates harmonics and reactive power simultaneously
Hybrid Filter	Passive + Active	Fast	Continuous	Yes	Medium	Cost-effective compromise for harmonic mitigation
Inverter-Based Compensation	Renewable Inverter	Very Fast	Continuous	Moderate	Low	Utilizes existing PV/wind inverters for reactive support
AI-Based Compensation	Intelligent Control	Very Fast	Adaptive	Yes	Medium–High	Best performance under dynamic and uncertain conditions

IV. Voltage Regulation Challenges in LV Feeders with High PV Penetration

A few studies have examined voltage regulation, reactive power management, and power quality difficulties that are brought about by high photovoltaic (PV) penetration in distribution networks. A UPFC-linked configuration was suggested for low-voltage feeders having significant PV infeed, where the coordinated series and shunt converters were employed to provide required and flexible upsertion of volts and compensation of phase current imbalance [1]. The simulation showed that it made significant improvements in voltage profiles and current balancing for different levels of PV generation, mutually alleviating overvoltage conditions in an attempt not to decrease PV power; nevertheless, the only limitation here is that the study only did simulation analysis and does not consider hardware validation, economic feasibility, and scalability. All aspects to assess the techno-economic impact for increasing penetration of solar PV for a given distribution feeder associated with voltage violations, reverse power flow, and feeder losses at different penetration levels were considered. The results revealed continuous violation of voltage limits and elevated costs, mostly associated to investing in voltage control infrastructure with increasing levels of PV Integration, whereas several mitigation measures were not proposed while accounting for real-time operational constraints. A scheme was formulated under dual control within inverters as well as storage units to absorb greater variations in voltage in low-voltage circuits accommodating PV generation and battery energy storage units [3]. Simulation results showed strengthened voltage stability and reduced unwanted trigger of over-voltages at peak times when power output is highest visual aspects may present high consideration factors to be pursued; complexity, an increased cost of initial investment, and were of concern. With detailed networked simulations and load/generation data chiefly derived from real-world systems, congestion management, and voltage consistency in medium-and low-voltage networks with massive PV integration were estimated [4]. The nonregulation of PV integration further increased the potential of asset overloads and voltage rise phenomena, and calfalstd for essential continuity in mindful voltage and congestion management strategies; yet, a glaring lack was witnessed for an extensive active power compensation by the power electronic VAR control equipment. Employing feeder simulations, a separate study focused on how high PV penetration interacts with traditional voltage regulation apparatus like tap changers and voltage regulators [5].

The result was a transient spike in due to rapid PV output excursions, adding plausible insight for PV inverters to operate coordinate with or adjustment in opposite to older technology for the course of conventional regulator functioning. A modified UPFC with DC-link voltage ripples was used to counter the adverse impacts of PV intermittency on converter performance in low-voltage feeders [6]. Simulations showed noticeable effects improved voltage regulation and reduced stress on the converter for the most part; however, there was no regard for experimental validation or overall robustness analysis in varying operating environments. To counteract overvoltage and minimize the need for active power curtailment, a two-stage voltage control strategy that combined both decentralized and supervisory control was implemented in distribution systems having very high PV panels [7]. Even though the approach showed smoother voltage regulation, it overly relied on communication infrastructure, presenting latency, security, and scalability concerns. Power quality degradation by HV integration within low- and medium-voltage distribution systems was analyzed in terms of harmonics, voltage unbalance, and flicker assessment through simulations [8]. The outcome demonstrated a deterioration in power quality through unrestricted PV integration but mitigation of such effects can be provided by inverter-based control; however, real-time validation, as well as economic analysis, were excluded. A virtual layout of the high-impact smart inverter features like Volt/Var, and Volt/Watt control strategies toward distribution feeders with a big chunk of PV destiny to be evaluated through feeder-based simulations [9]. The research outcome emerged in the improved regulation of voltage and an increased hosting capacity, while reactive power injection of high level results in an increased inverter loss, thus compromising the economic viability. Ultimately, the use of reactive power control and network reconfiguration techniques to mitigate the problem of voltage rise under high penetration of PV were also illustrated in a detailed study for the regional distribution system [10]. The results showed a significant improvement in voltage profiles with less PV curtail, although the applicability of this project to other grid topologies and working conditions is still an open question.

V. Conventional Control Strategies for STATCOM-Based Compensation

Several studies have focused on voltage regulation, hosting capacity enrichment, and power quality management in distributed systems where high and intermittent penetration of photovoltaics (PV) is observed. Integrated strategies to cope with voltage regulation, combining OLTC, capacitor banks, and PV reactive support, have provided tangible improvements in terms of voltage stability by minimizing excessive tap operations and preventing significant risk of PV coring [11]. Though efficient in tackling voltage violations, this process heavily depends on centralized control implementation, setting concerns about communication dip, scalability, and infrastructure reliance. Hybrid deep reinforcement learning strategies for battery energy storage management have been suggested for ameliorating voltage flicker and current unbalance in asymmetric unbalanced low-voltage networks with increasing penetration of PV [12]. Data-driven solutions work quite well under dynamic operating conditions; however, such approaches encapsulate a strong deterrent for practical deployment due to the extensive computational burden, requisite transactions of ample datasets for training, and sheer complexity for implementation. The analyses for hosting capacity at the MV level involved thermal limits, overvoltage issues, and protection of overhead and cable feeders that highlight substantially lower PV capacity in cable feeders, vis-à-vis the increased effect of capacitor [13]. Nevertheless, such assessments remain predominantly static methods without considering voltage control options on their own. Smart metering-data-based insights improved voltage visibility and imbalance detection to some extent in three-phase LV feeders with high PV penetration [14], increasing somewhat in the accuracy of planning and monitoring without proposing correlative control measures and adding the requirements of swift metering technologies. However, other joint energy storage support schemes, together with voltage regulation, allow for extra hosting capacity of PV systems in distribution feeder microgrids, thereby preserving voltage stability [15]. But, however, the emergence of huge battery investment costs and long-term degradation issues cloud the fast-tracking capacity of battery inverters. Distributed voltage regulation with BSS has found impressive resilience against communication delays in low-voltage networks highly penetrated by PV. But the overall system takes a hit when communication links go down, while adaptability to changing system sizes is a challenge [16]. Local controller reactive power and power factor control methods with inverter control have played a crucial role in maintaining proper power quality at feeder ends. Only local measurements have been used to control the reactive power with the controller-in essence, a step in the right direction towards improved reliability while also encouraging lots of reactive power mismanagement in collaboration due to multiple PV installations.

As a natural next step after that, extensions incorporating Volts/VARs and Volts/Watts within the inverter control design could improve voltage profiles further and reduce the extent of PV curtailment [18], with careful consideration regarding coordination due to the existence of inverter capacity limits and interactions with the historical voltage regulation devices. Placement and sizing approaches under traditional paradigms for commercial capacitor banks have been pushing the boundaries of feeder-related efficiency, establishing improvements in voltage profiles under different circumstances [19]. Nevertheless, these techniques lack the flexibility to respond immediately to sudden power fluxes from PV installations. Leakage studies on the influence of sudden PV output variations induce several power-quality issues, including voltage flicker and harmonic distortions: this effect could be ameliorated by storage systems or electric vehicles [20], given that all parties are willing to comply and an EV infrastructure is duly expanded.

VI. Artificial Intelligence–Based Optimization Techniques for Power Quality Enhancement

Voltage regulators of advanced classes which employ real-time voltage acquisition and the adaptive strategy have emerged as promising, in protecting against voltage rise and in managing system stability in certain PV-borne feeder studies [21], with considerations of long-term economic feasibility and cost benefits having been virtually ignored. Data-driven hierarchical control structures that are an aggregation of local inverter control and superior-level coordination have been demonstrated to facilitate voltage regulation and reduce control device stress to a significant extent [22] which, for the most part, is dependent upon robust communication infrastructure, while cybersecurity and cost concerns need to be addressed. Analyses of voltage regulation challenges in high-PV-penetration cases have outlined how primitive voltage regulation techniques [23] are just inappropriate and that any ad-vanced coordination solution stays conjectural without explicit implementation solutions. Advanced voltage control schemes using digitally controlled transformers and intelligent grid devices have shown better voltage management over combined PV and electric vehicle loading cases [24], while, in similar cases, decentralized control has come with additional complexity at the system level -- and no solution is seen available for the induced latency, yet. Load flow-based studies are a convincing demonstration of the conflict with voltage regulation on medium-voltage networks over PV penetration with the rise on the curve [25]; unfortunately, not enough attention is given to dynamic operation conditions and control. Congestion management through active power curtailment and network reconfiguration has allowed high penetration of PVs and greatly improved voltage stability [26]; only without exaggerated trade-offs with respect to equity, consumer participation, and renewable energy uptake. Decentralized coordination between OLTCs and PV inverters that relies on local measurements has indeed been achieving effective voltage regulation with minimal amount of tap operations [27]. Being scalable and stable, this approach comes at the cost of global optimality. High-level reviews have classified voltage control devices and control strategies and enumerated the strengths and limitations of smart inverters, energy storage, OLTCs, and power electronics [28]. Again, real-world validation and data-driven comparison are notably absent from the discussion. Local reactive power support, alongside smart inverter Volt/Var control, offers opportunities for better voltage management and enhanced PV hosting capacities [29], and although future work will need to assess increased inverter losses and possible long-term consequences, field-data-based research on rooftop PV integration projects in low-voltage networks that have represented voltage violations and PQ issues resulting from uncoordinated deployment of PV will reintroduce the need for a regulatory framework and coordinated strategies for Randomized Controlled Trials (RCTs) and long-term resilience planning design while pointing out gaps.

Table 2 Comparative Analysis of Voltage Regulation Techniques under High PV Penetration

Ref.	Focus Area	Methodology	Key Results	Limitations
[11]	Coordinated voltage regulation	OLTC–capacitor–PV inverter coordination	Reduced voltage violations and tap operations	Centralized control, scalability issues
[12]	DRL-based voltage control	Deep reinforcement learning for BESS scheduling	Adaptive and effective voltage regulation	High training and computational complexity
[13]	PV hosting capacity	Comparative MV feeder analysis	Hosting capacity limits identified	No active voltage control strategies
[14]	DER voltage impact	Smart meter–based feeder modeling	Accurate voltage and unbalance assessment	No corrective voltage control
[15]	Hosting capacity enhancement	Coordinated energy storage and voltage control	Increased PV hosting capability	Battery cost and degradation not considered
[16]	Distributed voltage control	BESS with delay-aware control	Robust voltage regulation under delays	Sensitive to large communication failures
[17]	Local PV control	Decentralized inverter-based reactive power control	Effective overvoltage mitigation	Limited coordination among PV units
[18]	Hosting capacity increase	Combined Volt/Var and Volt/Watt control	Improved voltage compliance and reduced curtailment	Inverter operational constraints
[19]	Capacitor-based regulation	Optimal capacitor placement using load flow	Improved voltage profile and efficiency	Ineffective for rapid PV fluctuations
[20]	PV fluctuation impact	Measurement-based power quality analysis	Identified flicker and PQ degradation	Dependence on EV availability
[21]	Series voltage regulation	Power-electronic series voltage regulator	Fast and accurate voltage correction	Converter losses and cost concerns
[22]	Hierarchical control	Data-driven local and supervisory coordination	Reduced control conflicts and stress	Communication overhead and cybersecurity
[23]	PV voltage challenges	Analytical and simulation-based evaluation	Identified limitations of conventional control	No mitigation techniques proposed
[24]	PV and EV voltage issues	Active voltage coordination strategies	Improved voltage stability	Centralized control complexity

[25]	MV voltage impact	Load-flow-based PV penetration analysis	Voltage rise effects identified	No mitigation strategy included
[26]	Congestion control	Curtailment and network reconfiguration	Reduced congestion and improved stability	Renewable energy curtailment
[27]	OLTC–PV coordination	Decentralized local measurement-based control	Reduced tap operations	Loss of global optimality
[28]	Voltage regulation review	Comparative literature survey	Identified research gaps	No quantitative comparison
[29]	Smart inverter VAR support	Local Volt/Var control	Increased hosting capacity	Higher inverter losses
[30]	Rooftop PV impact	Field data analysis and simulation	Voltage violations and imbalance observed	Observational study only

VII. CONCLUSION

Grid integration and power quality decay in grid-connected solar-wind hybrid power systems, with special emphasis on reactive power compensation and voltage regulation in distribution networks, were comprehensively explored in this review. The study revealed the penetration of inverter-based renewables brings numerous problems ranging from voltage rise and drop, harmonic distortions, poor power factor, and reduced system stability, created by the inherent intermittency, nonlinearity, and high penetration of the inverter-based renewable sources. Various anti-oxidative power compensation enhancement options, such as capacitor banks, OLTC, and conventional control based FACTS devices, and these can hardly fully adapt or are unduly slow in response time to the rapid variation of renewable generation. As such, STATCOM-based compensation strategies come into view as a more attractive solution giving the benefit of faster reaction, providing steady earth power and performance improvements in weak and low-voltage systems. We also delved into the current approaches to realizing harmonic attenuation, voltage regulation, improved power factor, and increased robustness for system performance under varying operating conditions than these Artificial Intelligence-based control and optimization methods, which include neural networks, fuzzy logic, evolutionary algorithms, and reinforcement learning algorithms. Nonetheless, prospects for massive deployment face issues like real-time operation, communication lag, high computational responsibilities, economic viability, and cyber security. Future research should focus on developing hybrid and explainable AI-based control frameworks that combine learning capability with transparency and reliability for grid operators.

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