Journal of Electronic Research and Application, 2026, Volume 10, Issue 7
http://ojs.bbwpublisher.com/index.php/JERA
Online ISSN: 2208-3510
Print ISSN: 2208-3502

A Review of Reactive Power Optimization in Distribution Networks with High Penetration of Renewable Energy

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Abstract: The global energy mix is undergoing an accelerated transition towards cleaner, lower-carbon sources. As a result, the large-scale integration of a high proportion of renewable energy into distribution networks is an irreversible trend. However, since the output of renewable energy sources is highly random, intermittent, and fluctuating, and given that the high r/x parameter characteristics of distribution grids result in a pronounced active-reactive power coupling, the traditional unidirectional voltage regulation mode in distribution grids is unable to effectively address issues such as bidirectional power flows and frequent voltage overshoots. Consequently, reactive power and voltage control face significant challenges. To this end, this paper provides a systematic and logically coherent review of the problem of reactive power optimization in distribution networks with a high proportion of renewable energy. First, we clarify the mechanisms by which the grid integration of renewable energy sources affects distribution network voltages. This study then systematically summarizes methods for active power regulation, reactive power compensation, tap-changer voltage regulation, and multi-device coordinated control. Subsequently, this study proposes an approach to multi-timescale, hierarchical, and zoned modeling that coordinates active and reactive power. This study then conducted a comparative analysis of uncertainty management techniques, including stochastic optimization, robust optimization, and fuzzy theory. Finally, this study summarizes the application characteristics of traditional mathematical methods, intelligent algorithms, and data-driven methods. This naturally and appropriately leads to the conclusion that the coordination of generation, grid, load and storage, combined with multi-timescale optimization, represents the current mainstream control framework, and that data-driven methods hold immense potential for application. However, it also objectively and cautiously highlights various issues in existing research, including uncertainties that are difficult to address, multi-scale collaborative complexity, communication and privacy constraints, and a lack of interpretability in AI models. Consequently, the future direction of development should focus on collaboration, intelligence and decentralization, whilst the refinement of relevant technologies will directly and effectively underpin the safe and efficient operation of distribution networks with a high proportion of renewable energy.

Keywords: High proportion of renewable energy; Distribution networks; Reactive power optimization; Voltage control

Online publication: Aug 11, 2026

1. Introduction

As the global energy mix transitions towards cleaner and lower-carbon sources, the new power system has become the key vehicle for achieving sustainable energy development. The new power system is characterized by a high proportion of renewable energy, integrates advanced information technology with power electronics, and emphasizes the coordinated interaction and intelligent control of generation, transmission, consumption, and storage. Microgrids, as key components of the new power system, are small-scale, autonomous power systems comprising distributed generation sources, energy storage devices, energy conversion equipment, loads, and monitoring and protection systems. It features flexible networking and efficient operation, and can switch between stand-alone and grid-connected modes, enabling effective integration of distributed energy resources and enhancing the reliability and flexibility of the power system.

As new energy power generation technologies mature and costs decrease, China's installed capacity of new energy has sustained growth. A large number of distributed new energy sources are integrated into the power grid locally via distribution networks for on-site consumption. However, the original design of distribution networks centers on the concept of "radial topology and unidirectional power supply" and does not fully account for the characteristics of high-penetration renewable energy grid connection: its output power is affected by natural conditions, exhibiting significant intermittency and randomness. Moreover, most distributed new energy inverters operate at a constant power factor, resulting in limited reactive power regulation capability. These factors lead to frequent disruptions of power balance in distribution networks. Accordingly, systematically analyzing the impact of grid-integrated renewable energy on the voltage stability of distribution networks and exploring targeted optimization strategies have become critical topics for promoting high-efficiency integration of renewable energy and ensuring the safe operation of distribution networks [1].

Conventional distribution networks are traditionally designed around the fundamental principle of "radial topology with unidirectional power flow," resulting in relatively straightforward reactive power and voltage control strategies. However, this paradigm is increasingly outdated. With the large-scale integration of renewable energy sources, particularly inverter-based distributed generation, the operational requirements of distribution systems have undergone profound changes. Relying solely on reactive power modulation from grid-connected inverters is no longer sufficient to ensure system stability after interconnection. Power flow has transitioned from strictly unidirectional to bidirectional, and the previously monotonic voltage profile has given way to dynamic, spatially heterogeneous voltage variations. Consequently, advanced, coordinated, and adaptive reactive power and voltage control schemes are now essential to maintain reliability, efficiency, and power quality. Not only should it be capable of real-time monitoring and rapid response to fluctuations in the output of new energy, but it should also be able to coordinate numerous controllable resources. That is to say, while ensuring the quality of voltage, it should also take into account economic efficiency and the requirement of "low carbon" [2].

In recent years, the scientific community has conducted extensive research and discussion on these issues, yielding abundant theoretical outcomes and technical solutions. This paper aims to review the research progress in this field systematically. This paper then conducts a literature review across three aspects: the influence mechanism of voltage, optimal control mode, and model-solving method.

2. The influence mechanism of new energy grid connection on distribution networks

2.1. Output characteristics and uncertainties of new energy sources

First of all, we need to understand that the fundamental reason the integration of new energy sources affects distribution network voltage lies in their inherent output characteristics and the contradiction with the traditional distribution network architecture.

First comes randomness. Traditional energy sources primarily include thermal and hydropower. After a long period of technological development, they can not only maintain the stability and controllability of power generation but also ensure the continuity of power supply. However, new energy sources cannot do so. The output characteristics of new energy sources make the voltage in distribution networks far less stable than it is with traditional energy sources. This further increases the difficulty of voltage control. Even with short-term weather prediction technology, it is still very difficult to predict extreme weather conditions that could lead to abnormal output situations. For instance, sudden severe cold waves and heavy snowfall in winter can cause photovoltaic output to drop sharply from 70% of the rated value to 5% or even lower within a short period due to snow cover and a sudden reduction in sunlight. At the same time, some distributed wind power may also shut down due to low-temperature icing faults. The distribution network rapidly shifts from a "power surplus" state to a "power deficit" state. Traditional voltage regulation equipment, due to its slow response time, cannot compensate for power fluctuations in time, leading to a continuous drop in voltage and even triggering low-voltage protection devices, causing local power outages. Furthermore, unexpected incidents or the absence of corresponding contingency plans may prevent immediate emergency repairs and remediation, thereby resulting in greater economic losses [3] .

Secondly, in terms of intermittency and volatility, both wind and photovoltaic power generation exhibit typical characteristics of intermittency and volatility: the output of photovoltaic power generation is entirely dependent on light conditions. Factors such as day-night alternation, cloud cover, and extreme weather can cause significant fluctuations in power generation over a short period, and even drop sharply from full capacity to zero. In contrast, wind power output is directly affected by fluctuations in wind speed. When the wind speed is too low, wind turbines cannot generate electricity. However, when the wind speed reaches grade 10 or higher, wind power generation facilities will automatically shut down to ensure equipment safety. Furthermore, meteorological disturbances such as gusts and turbulence also cause random fluctuations in power output. Both of them are classified as uncontrollable "weather-dependent" energy sources. Power generation is characterized by discontinuous, unstable output, making it difficult to predict accurately even with short-term weather forecasts. This will not only trigger rapid switching of the distribution network between the "power surplus" and "power deficit" states, but also substantially increase the difficulty of regulating and controlling grid voltage and frequency, thereby posing potential risks to the safe and stable operation of the distribution network.

2.2. Voltage out of limit problem

When a high proportion of new energy is connected to the distribution network, due to its inherent output characteristics, it can trigger conflicts with the traditional distribution network structure. Due to the random and intermittent characteristics of new energy output, the power flow direction and amplitude in the distribution network to which it is connected will also fluctuate sharply. There are two situations: when photovoltaic output reaches its peak at noon, a scenario characterized by high penetration of renewable energy generation and low system load, the voltage rise effect occurs as the generated power flows through the current impedance. If the magnitude of the voltage rise is excessively large, the voltage at the point of interconnection and surrounding grid nodes will exceed the upper limit. This overvoltage issue is prone to occur at the end of feeders or under light load conditions. Under scenarios such as the minimum photovoltaic output at night with no illumination, namely when the output of new energy is insufficient while the load is heavy, relying solely on new energy cannot provide effective support. As a result, the system voltage is highly likely to drop below the lower limit, and this "undervoltage problem" is prone to occur under heavy load or when the output of new energy drops abruptly. Although traditional distribution networks also face these issues, the difference is that, under high proportions of renewable energy, these two voltage problems often alternate, reflecting the volatility of renewable power generation. This undoubtedly poses significant challenges for distribution network control and increases safety risks [4].

2.3. Impact of line parameter characteristics on voltage control

The line-parameter characteristics of a distribution network are of great significance to the network itself. In particular, line parameters significantly influence the selection of voltage control strategies. Unlike transmission lines, distribution networks, particularly at medium and low voltages, typically exhibit a relatively high resistance-to-reactance ratio (r/x) that exceeds 0.5. In certain low-voltage distribution feeders, this ratio may approach unity. Consequently, the coupling among active power, reactive power, and node voltage becomes significantly stronger in low-voltage distribution systems with elevated r/x ratios. In high-voltage transmission systems, the inductive reactance x significantly exceeds the resistance r. Consequently, reactive power flow is the primary determinant of voltage magnitude. In contrast, active power flow predominantly governs system frequency. In low-voltage distribution networks, both active and reactive power significantly affect voltage. Therefore, in distribution networks with high penetration of renewable energy, voltage regulation can be realized through both reactive power regulation tools and active power regulation approaches, such as photovoltaic active power curtailment and active power charging/discharging of energy storage systems. This provides more options for developing control strategies but also increases the difficulty of coordinated control.

3. Reactive power control method for distribution networks with high penetration of renewable energy

3.1. Voltage control based on active power regulation

In distribution networks with a high resistance-to-reactance (R/X) ratio, active power has a significant impact on voltage. When voltage overlimit issues occur, adjusting the active power can effectively suppress voltage fluctuations in the distribution network [5]. There are two most common methods: the first is photovoltaic active power curtailment based on photovoltaic inverters, which is the most direct method of active power regulation. When the grid connection point voltage exceeds the upper limit, the active power output from photovoltaic inverters can be reduced to mitigate the voltage rise. This method is simple to implement and responds quickly, relying on photovoltaic inverters; however, it has poor economic efficiency, directly resulting in power generation loss and reduced revenue for owners. Therefore, this measure is generally employed as a last resort, and active power reduction is only activated when the reactive power regulation capacity is exhausted. The second approach is active power regulation via energy storage, which constitutes a more flexible active power control method. The system can charge when voltage is too high and discharge when voltage is too low, achieving peak shaving, valley filling, and voltage regulation through the spatiotemporal transfer of active power. Compared with photovoltaic active power curtailment, energy storage regulation does not result in energy waste. However, the capital investment cost of energy storage systems is relatively high, and the state of charge constrains their regulation capability. In terms of control strategies, active power regulation of energy storage can adopt various modes such as local control, distributed coordination, or multi-stage optimization.

3.2. Voltage control based on reactive power regulation

Reactive power regulation is the primary approach for voltage control in distribution networks with high penetration of renewable energy, as it does not curtail the active power output of renewable energy sources and offers significant economic advantages. The three most common approaches are: the first is reactive power regulation based on photovoltaic inverters, which is currently the most extensively studied reactive power control method [6]. Modern photovoltaic inverters generally possess reactive power regulation capability with a power factor of approximately ± 0.8 at their rated capacity. They can utilize their residual capacity to participate in power grid voltage regulation. Depending on the control mode, they can be classified into three types: constant power factor control, constant voltage control (Q(V)), and constant reactive power control. Among existing control strategies, Q(V) control is the most widely adopted in practical engineering due to its simplicity, effectiveness, and communication-free characteristics. This strategy adjusts reactive power output based on the deviation between local voltage measurements and reference values, following a preset Q-V droop curve, thereby enabling autonomous voltage control. The second type is the Static Synchronous Compensator (STATCOM), also known as the Static Var Generator (SVG). It is a dynamic reactive power compensation device that offers advantages such as fast response and a wide regulation range. In distribution networks with high penetration of renewable energy, STATCOM can provide smoothly adjustable reactive power support and effectively suppress rapid voltage fluctuations. However, STATCOMs incur high investment costs and are typically deployed at critical nodes. Thirdly, shunt capacitor banks are conventional reactive power compensation equipment, featuring the advantages of low cost and simple maintenance. However, their regulation is discrete, with slow switching speed and limited operation times, making it difficult to cope with the rapid fluctuations of renewable energy. Therefore, in modern high-proportion new-energy distribution networks, capacitor banks are typically used as slow-response devices and are optimized for configuration on the day-ahead or intra-day time scale.

3.3. Voltage control based on tap-changer equipment

Tap-changing equipment-based voltage regulation is a critical global method for voltage regulation in renewable energy distribution networks. It adjusts the system voltage level by modifying the transformer ratio and is commonly coordinated with distributed voltage and reactive power compensation equipment to maintain voltage stability jointly. There are two main types: the first is the on-load tap changer (OLTC) transformer, which is a commonly used voltage-regulation device in distribution networks. It adjusts the transformer's transformation ratio by changing the tap position, thereby regulating the voltage on the low-voltage side.OLTC features a wide regulation range, yet it suffers from slow response speed and limited switching operations; hence, it is typically employed to address slow variations in load demand and renewable energy output. In scenarios with high renewable energy penetration, the on-load tap changer (OLTC) must coordinate with fast-reactive power compensation equipment to avoid frequent operations that compromise the equipment's service life. The second type is the Step Voltage Regulator (SVR), which applies to scenarios with long feeders or concentrated loads at the far end of the distribution system. When the grid connection point for new energy is located far from the substation, SVR can perform voltage regulation downstream of the connection point, compensating for the OLTC's limited regulation capability.

3.4. Multi-device collaborative control

Currently, it is difficult for a single device to address the complex voltage issues caused by high-penetration renewable energy, and the development of multi-device coordinated control has become an inevitable trend [7]. First of all, the latest research hotspot currently is the "source-grid-load-storage" coordinated control. Based on the "four-component" architecture of active distribution networks, this model integrates distributed generators, grid regulation devices, flexible controllable loads, and energy storage systems into a unified dispatch and control framework, thereby fully exploiting the reactive power regulation and voltage control potential of each participant. Through the coordinated operation of various resources, this model achieves stable voltage operation in distribution networks with high proportions of renewable energy penetration [8]. Among these challenges, collaborative control is particularly difficult due to significant differences in response speed, regulation capacity, operating costs, and control characteristics across various types of equipment. Furthermore, bidirectional power flow fluctuations and voltage violations caused by high-penetration renewable energy integration further increase the difficulty of dispatching and control. Therefore, it is urgent to establish a hierarchical coordination mechanism that adapts to the fluctuation characteristics of renewable energy [9].

Next, we discuss another approach: multi-time scale coordinated control. This is an effective method for addressing differences in the response characteristics of heterogeneous regulation devices, and it is also the mainstream research direction for reactive power optimization in distribution networks with high penetration of renewable energy [9]. In the day-ahead optimization stage, based on medium- and long-term forecasts of wind-photovoltaic power output and load demand, the operation schedules of slow-response regulation devices, including OLTC tap positions and capacitor bank switching status, are determined, with both overall operational economy and device service lifetime considered. In the intra-day optimization stage, rolling adjustments are applied to the outputs of partitioned reactive power compensation devices and selected distributed generator inverters via ultra-short-term forecasting to compensate for day-ahead prediction errors. In the real-time control phase, the rapid response advantages of power electronic devices, such as photovoltaic and wind power inverters, are fully utilized to suppress voltage fluctuations induced by instantaneous output variations from renewable energy sources. This hierarchical, graded, and refined collaborative architecture not only achieves economic optimization over long-term time scales but also ensures security and stability at the real-time level and effectively adapts to the complex, variable operational scenarios of distribution networks with high levels of new energy integration.

4. Modeling and solution method for reactive power optimization

4.1. Optimized modeling method

The first approach is multi-time-scale optimization, which serves as the primary modeling framework for addressing the uncertainty of new energy sources. Day-ahead optimization uses a temporal resolution of 1 hour or 15 minutes and formulates dispatch schedules for slow-response units based on forecast data. Intraday optimization operates on a 5- to 15-minute cycle, correcting plan deviations through rolling forecasts; real-time optimization aims for second-level responsiveness, achieving closed-loop control with fast-response equipment. Its core lies in the coordinated alignment of strategies across all levels to avoid control conflicts among them [10]. The second approach is hierarchical and zonal optimization, which leverages the characteristics of distribution networks- strong coupling within zones and weak coupling between zones- to decompose the global optimization problem into multiple sub-problems. Partitioning based on electrical distance, spectral clustering, statistical distance, or other methods can reduce computational complexity and apply to large-scale distribution network scenarios [11]. The third type is coordinated optimization of active and reactive power. In distribution networks with a high r/x ratio, the coupling effect between the two is significant, and it may be difficult to achieve optimal performance by optimizing reactive power alone. When optimization simultaneously considers the collaborative coordination of active power curtailment from new energy sources, charging and discharging of energy storage systems, and reactive power compensation, the unification of voltage control and economic operation can be achieved [12]. These three reactive power optimization modeling methods address issues associated with the grid integration of new energy sources from different perspectives. Each method has its own strengths, and they complement one another. They can be selected as required to construct a more adaptive optimization modeling system.

4.2. Uncertainty processing method

The randomness of renewable energy generation is a core challenge in reactive power optimization. The first category is stochastic optimization, which relies on the probability distribution of new energy and converts stochastic problems into deterministic problems through scenario generation and reduction techniques. Both single-stage and multi-stage stochastic programming have been investigated and applied in practice. The advantage of this method is that it can fully utilize probability information, but it requires high precision in the distribution model [13]. The second category is robust optimization, which characterizes the output range of renewable energy using an uncertainty set and seeks a feasible solution to the constraints under the worst-case scenario. This method does not require an exact probability distribution and is highly robust, but its results are generally conservative. Achieving the optimal trade-off between robustness and economy in the characterization of uncertainty sets is the core focus of this research [13]. The third approach is fuzzy theory, which describes the uncertainty of renewable energy output using membership functions and transforms the optimization problem into a fuzzy programming problem for solution. This method is advantageous in scenarios where information is incomplete or precise probabilistic models are difficult to establish [14]. These three categories of methods differ in their modeling bases and applicable scenarios. Yet, a single method or a combination of methods can be adopted as needed to implement uncertainty processing.

4.3. Solution algorithm

Traditional mathematical methods include linear programming, nonlinear programming, and mixed-integer programming. Their advantages lie in the fact that they can, in theory, guarantee the identification of the global optimal solution with strong interpretability. Yet, they impose stringent requirements on the model structure and typically require the original problem to be transformed into a solvable standard form. Convex optimization techniques such as second-order cone relaxation and semidefinite relaxation can handle non-convex-concave problems. This method has been widely applied to distribution network optimization in recent years [15]. In contrast, heuristic intelligent algorithms such as the genetic algorithm and particle swarm optimization obtain satisfactory solutions by simulating the intelligent behaviors of biological populations in nature and conducting iterative search, which are suitable for addressing complex nonlinear problems. These algorithms impose low requirements on model forms and feature high flexibility, yet they cannot guarantee stability and optimality, and suffer from low computational efficiency. In recent years, improved intelligent algorithms have been widely adopted to enhance solution performance [16]. Furthermore, machine learning and data-driven methodologies have demonstrated tremendous potential in reactive power optimization. Neural networks are deployed for prediction and perception, while reinforcement learning enables rapid, real-time decision-making through offline training combined with online decision-making. Additionally, federated learning enables collaborative optimization among multiple agents without requiring raw data sharing and can effectively address data privacy concerns [17]. These three categories of methods each have their own advantages and disadvantages. However, the fusion and improvement of different algorithms represent the future development trend, and only through this approach can the solution performance and scenario adaptability be comprehensively enhanced.

5. Conclusion

Reactive power optimization of distribution networks with high penetration of renewable energy is a key technology for ensuring the secure and economic operation of new-type power systems. This paper systematically summarizes the research progress in this field across three dimensions: the voltage-influence mechanism, control methods, and optimization modeling and solution methods. Analysis indicates that the voltage issues caused by high-penetration renewable energy integration originate from the uncertainty of renewable energy output and the line parameter characteristics of distribution networks; multi-device coordinated control, multi-time-scale optimization, and source-grid-load-storage coordination have become the mainstream control framework; uncertainty processing methods such as stochastic optimization and robust optimization have gradually matured, and data-driven methods represented by machine learning have demonstrated enormous potential. This field now encounters several hurdles, such as managing uncertainties, complex multi-scale coordinated control, communication privacy limitations, and inadequate interpretability of intelligent models, necessitating ongoing enhancement of the technical foundation. In the future, with advancements in collaborative regulation, digital-physical integration, and intelligent algorithms, the safe and efficient operation of high-proportion renewable energy distribution networks will receive solid and reliable support.

Disclosure statement

The author declares no conflict of interest.

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