Article

Research on Voltage Deviation and Voltage Regulation Optimization Simulation of 10kV Distribution Network Connected with Distributed Photovoltaics

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Abstract: Driven by the carbon peaking and carbon neutrality goals, a large number of residential and industrial and commercial distributed photovoltaic systems have been connected to 10kV medium-voltage distribution networks. The output power of photovoltaics fluctuates in real time with light intensity, which easily causes a series of power quality problems such as over-limit voltage at the end of distribution networks, reverse power flow, and three-phase voltage unbalance. The traditional voltage control method relying on switched capacitor banks suffers from slow response speed and cannot adapt to the intermittent output characteristics of photovoltaic power generation. Taking a suburban 10kV radial distribution network as the research object, this paper establishes a mathematical model of photovoltaic arrays and builds a simulation model of the distribution network with distributed photovoltaics via MATLAB/Simulink. The influence rules of photovoltaic access capacity, access location, and light fluctuation on node voltage of lines are systematically analyzed. A coordinated reactive power control strategy based on photovoltaic inverters is proposed to address the problem of over-limit voltage, which relies on the residual reactive power capacity of inverters to adjust reactive power in real time and realizes combined voltage control together with fixed capacitors. Simulation test results demonstrate that the proposed combined voltage control scheme can stabilize the node voltage of the distribution network within the range specified by national standards, effectively suppress voltage deviation caused by photovoltaic power generation, and achieve a faster voltage control response speed than the traditional capacitor switching scheme, possessing practical engineering application value.

Keywords: distributed photovoltaics; distribution network; voltage deviation; reactive power control; simulink simulation; power quality

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1. Introduction

1.1. Research Background and Significance

China is actively advancing the strategic transition toward clean energy utilization. In recent years, a substantial number of rooftop distributed photovoltaic power generation systems have been integrated into the medium-voltage distribution infrastructure across county-level and township-level regions. The 10kV distribution network, originally engineered for conventional unidirectional power flow from substations to end-users, was not designed to accommodate significant reverse active power injection. During midday hours under clear-sky conditions, photovoltaic generation often reaches its peak output, resulting in substantial reverse power flow along distribution feeders. This reverse flow interacts with the inherent series impedance of overhead and underground lines, producing a pronounced voltage rise effect—particularly at downstream nodes near the feeder terminus—frequently causing terminal voltages to exceed permissible operational limits. Conversely, under low-irradiance conditions such as overcast weather, heavy rainfall, or during evening twilight, photovoltaic output declines rapidly and unpredictably, leading to sharp voltage drops that may approach or even breach the lower boundary of acceptable voltage tolerance [1]. Such bidirectional and time-varying voltage excursions compromise the reliability and service quality of residential electricity supply, accelerate aging of household appliances and protective devices, increase technical losses across the distribution system, and impose additional thermal and loading stress on distribution transformers and switchgear.

Conventional approaches for managing voltage profiles in distribution networks—such as mechanically switched capacitor banks and on-load tap-changing transformers—exhibit inherent limitations in dynamic response capability and resolution granularity. These devices typically operate with discrete adjustment steps and require tens to hundreds of milliseconds for mechanical actuation, rendering them poorly suited to counteract the rapid, second-scale fluctuations characteristic of photovoltaic generation under variable meteorological conditions. In contrast, modern grid-connected photovoltaic inverters possess inherent four-quadrant reactive power control functionality, enabling precise, continuous, and near-instantaneous absorption or injection of reactive power without altering active power delivery. This feature positions inverters as an agile, cost-effective, and widely distributed voltage support resource. To address the pronounced voltage distortion observed in rural 10kV distribution networks following high-penetration photovoltaic integration, this study establishes a detailed electromagnetic transient and power flow co-simulation model reflecting realistic line parameters, load diversity, and spatially distributed photovoltaic generation patterns. Through systematic parametric analysis, the model quantifies spatiotemporal voltage variation characteristics under multiple irradiance scenarios and load configurations [2]. Building upon these insights, a hierarchical and adaptive coordination strategy is proposed, integrating inverter-based reactive power modulation with staged capacitor switching to achieve smoother, more robust, and energy-efficient voltage profile management. The outcomes contribute methodologically to the advancement of distribution system planning and operation theory, while also offering practical implementation guidance for grassroots power supply units seeking to enhance grid resilience and service stability amid accelerating distributed energy resource deployment.

1.2. Domestic and Overseas Research Status

International research on voltage management for distributed photovoltaic systems connected to low-voltage distribution networks began at an earlier stage. In European and North American contexts, technical approaches typically integrate local reactive power adjustment capabilities of grid-connected inverters with centralized or distributed energy storage systems, enabling coordinated voltage support across multiple generation units. These methods rely heavily on robust communication infrastructure embedded within the distribution network to facilitate real-time data exchange and synchronized control actions. Nevertheless, the associated hardware investment—including advanced inverters with extended reactive power ranges, bidirectional energy storage units, and dedicated communication modules—results in significantly elevated capital and operational expenditures. Such cost-intensive configurations are not economically viable or technically scalable for the widespread deployment of small-capacity, spatially dispersed residential photovoltaic installations commonly found in township-level power grids across China, where infrastructure standardization and maintenance capacity remain comparatively limited [3].

Within China, academic attention has predominantly centered on voltage management techniques applicable to large-scale, centralized photovoltaic power plants integrated at transmission or sub-transmission levels [4]. In contrast, systematic investigation into coordinated voltage support strategies tailored specifically for clusters of small-scale, geographically scattered residential photovoltaic units—particularly those interconnected at the medium-voltage (e.g., 10 kV) rural distribution level—remains underdeveloped. A prevailing limitation in current domestic proposals is the exclusive reliance on inverter-based reactive power modulation, without leveraging the existing passive compensation infrastructure already deployed in many rural distribution networks, such as fixed or mechanically switched shunt capacitor banks. This omission places undue stress on inverter reactive power reserves, potentially compromising active power output capability and diminishing overall photovoltaic energy yield. Furthermore, several proposed methodologies emphasize abstract mathematical formulation without incorporating realistic grid parameters, load profiles, or topology characteristics representative of typical county-level 10 kV feeders, thereby limiting their practical implementation feasibility. To address these gaps, this study proposes a hybrid voltage support framework that synergistically combines the fine-grained, continuous reactive power adjustment of modern inverters with the economical, stepwise reactive compensation provided by legacy capacitor banks, and validates its performance through comprehensive comparative simulation under representative rural distribution network conditions.

1.3. Main Research Contents

This study systematically organizes the foundational theoretical frameworks governing distributed photovoltaic integration into medium-voltage distribution systems, with particular emphasis on energy conversion principles, power electronics interfaces, and network interaction dynamics. Rigorous mathematical representations are developed for key components: the photovoltaic cell—including single-diode and double-diode models incorporating temperature and irradiance dependencies; the grid-connected inverter—modeling both voltage-source and current-source operational modes with pulse-width modulation dynamics; and the 10 kV distribution network lines—employing π-equivalent circuit formulations that account for resistance, inductance, capacitance, and line length effects under steady-state and quasi-transient conditions.

A high-fidelity Simulink-based simulation platform is constructed to replicate a typical suburban 10 kV radial distribution network topology, featuring realistic load profiles, line parameters, and substation configurations. Multiple comparative scenarios are rigorously defined—including varying photovoltaic penetration levels (from 10% to 120% of peak feeder load), diverse connection locations (near substation, mid-feeder, and at feeder extremities), and dynamic irradiance sequences simulating clear-sky, cloudy, and ramping conditions. Comprehensive node voltage sensitivity analysis is performed across all scenarios to quantify spatial and temporal voltage deviations, identify critical vulnerability points, and establish empirical relationships between photovoltaic injection characteristics and distribution-level voltage stability margins.

A critical evaluation reveals inherent constraints in conventional fixed or switched capacitor-based reactive power compensation methods, including stepwise control granularity, slow response time, limited controllability under fluctuating generation, and potential overcompensation during low-load periods. To address these limitations, a hierarchical, adaptive reactive power coordination framework is proposed—integrating real-time inverter reactive power capability with staged capacitor bank switching logic. The control strategy employs local voltage measurements and distributed communication protocols to enable seamless, continuous, and bidirectional reactive power support while respecting equipment thermal limits and harmonic distortion constraints.

Extensive simulation experiments are conducted to comparatively assess the performance of three distinct reactive power management approaches: standalone capacitor-based adjustment, inverter-only reactive power modulation, and the integrated coordinated method. Evaluation metrics include voltage deviation magnitude, standard deviation across nodes, regulation speed, energy efficiency, and robustness under stochastic irradiance variations. Results demonstrate that the coordinated approach achieves superior voltage profile flattening, reduces maximum node voltage deviation by over 40% compared to single-method strategies, minimizes reactive power exchange with the upstream grid, and enhances overall system resilience without requiring additional infrastructure investment.

The research concludes with a consolidated synthesis of findings, emphasizing the technical feasibility and operational advantages of coordinated inverter-capacitor reactive power management for photovoltaic-rich distribution networks. Key limitations are explicitly acknowledged—including assumptions of ideal communication latency, simplified load models, and absence of harmonic resonance analysis under high inverter penetration. Future work directions are outlined to extend the methodology toward multi-objective optimization incorporating active power curtailment, integration with distribution management systems, validation using hardware-in-the-loop platforms, and adaptation to meshed or hybrid AC/DC distribution architectures.

1.4. Overall Structure of the Paper

This paper is structured into six logically sequenced chapters to ensure methodological coherence and progressive knowledge development. Chapter 1 presents the motivation driving this investigation, reviews the evolution of photovoltaic integration technologies globally and within domestic practice, and delineates the core research objectives and scope. Chapter 2 establishes the essential theoretical foundations, deriving and validating mathematical models for photovoltaic generation units, power electronic inverters, and distribution network components. Chapter 3 details the construction of the simulation environment, conducts parametric sensitivity studies, and elucidates the physical mechanisms linking photovoltaic injection patterns to voltage profile distortion [5]. Chapter 4 introduces the design rationale, architecture, and implementation logic of the coordinated reactive power management strategy. Chapter 5 executes comprehensive comparative simulations, interprets quantitative outcomes, and validates performance claims against established benchmarks. Chapter 6 offers a reflective synthesis of contributions, identifies boundary conditions and unresolved challenges, and proposes concrete pathways for further academic inquiry and engineering application.

2. Basic Theories and Mathematical Models of Distributed Photovoltaics and Distribution Networks

2.1. Output Characteristic Model of Photovoltaic Cells

The core principle of photovoltaic cells is the photovoltaic effect, a physical phenomenon wherein semiconductor materials convert incident solar radiation directly into electrical energy. Their output power exhibits strong dependence on environmental variables, particularly irradiance and ambient temperature. Under standard test conditions—defined as an irradiance of 1000 W/m², cell temperature of 25°C, and air mass 1.5 spectrum—the current-voltage relationship follows a well-established single-diode model. This model captures the essential electrical behavior through parameters reflecting material properties and device construction [6]. Accurate characterization of this relationship is foundational for system-level performance prediction, grid integration analysis, and optimal sizing of power electronics interfaces.

$$I = I_{ph} - I_0\left[e^{\frac{U + IR_S}{n V_T}} - 1 \right] - \frac{(U + IR_S)}{R_{sh}}$$

In the single-diode model, I_ph denotes the photocurrent generated proportionally to incident irradiance; I_0 represents the reverse saturation current, which depends exponentially on temperature and material bandgap; R_s signifies the series resistance associated with bulk semiconductor and contact losses; R_sh indicates the shunt resistance arising from leakage paths across the p-n junction; A is the diode ideality factor, typically ranging between 1 and 2; and V_T denotes the thermal voltage, equal to kT/q, where k is Boltzmann's constant, T is absolute temperature in kelvins, and q is the elementary charge. These parameters collectively determine the shape of the I-V curve and influence maximum power point tracking efficiency [1].

As irradiance increases, the photocurrent rises nearly linearly, leading to higher maximum output power; conversely, elevated ambient or cell temperature reduces open-circuit voltage due to increased carrier recombination and decreased bandgap, thereby diminishing overall conversion efficiency. Consequently, peak power output typically occurs around local solar noon under clear-sky conditions, coinciding with maximal irradiance and moderate temperature rise. This temporal alignment results in significant active power injection during midday hours, which—when distributed across low-voltage feeders—can induce pronounced voltage elevation, reactive power imbalance, and potential violation of statutory voltage regulation limits in distribution networks.

2.2. Reactive Power Regulation Principle of Grid-Connected Inverters

Grid-connected photovoltaic inverters commonly employ a double-loop control architecture to ensure stable and responsive power conversion [1]. The outer voltage loop maintains the DC-side voltage at an optimal level by tracking the maximum power point of the photovoltaic array, while the inner current loop precisely governs the injection of active and reactive current components into the grid. When the photovoltaic generation is operating below its rated active power capacity, the inverter retains unused current-carrying capability, which can be strategically allocated to deliver either capacitive or inductive reactive current. This allocation enables dynamic support for local voltage conditions without compromising active power delivery.

In scenarios where the distribution network experiences elevated voltage levels at the point of interconnection, the inverter adjusts its output to absorb inductive reactive current, thereby mitigating overvoltage stress on downstream equipment and improving overall system voltage profile stability.

Conversely, when the distribution network voltage falls below nominal range, the inverter injects capacitive reactive current to provide localized voltage support, enhancing voltage magnitude recovery and contributing to improved power quality and grid resilience under variable generation conditions.

Reactive current control in modern grid-connected inverters operates with millisecond-level response time, enabling continuous, stepless, and highly precise adjustments [4]. Unlike conventional mechanical devices such as tap-changing transformers or switched capacitor banks, this electronic method incurs no wear, delay, or transient disturbance, offering superior controllability and reliability. Its fast, lossless, and bidirectional nature makes it especially well-suited for integration with intermittent renewable sources like photovoltaics, where rapid voltage fluctuations require equally agile compensation mechanisms.

2.3. Voltage Drop Model of 10kV Distribution Networks

In 10 kV overhead distribution lines, voltage drop arises due to the combined effects of line impedance—comprising both resistive and reactive components—under active and reactive power transmission. In conventional radial distribution networks, power flows unidirectionally from substations toward downstream loads; consequently, voltage magnitude decreases progressively along the line, resulting in lower terminal voltages compared to the substation bus voltage. However, with the widespread integration of distributed photovoltaic generation units, especially at medium-voltage distribution nodes, bidirectional power flow becomes increasingly common. When local generation exceeds local load demand, reverse active power flow occurs, inducing a reversal in the direction of voltage drop across affected line segments. This phenomenon elevates node voltages at points downstream of the generation injection point, potentially causing voltage magnitudes to exceed statutory operational limits (e.g., ±7% of nominal voltage per GB/T 12325–2008). Such overvoltage conditions pose risks to equipment insulation integrity, protective relay coordination, and overall grid stability.

A widely adopted simplified analytical expression for estimating voltage drop in radial 10 kV distribution lines is employed to quantify this effect under both forward and reverse power flow scenarios [7].

$$\Delta U = \frac{PR + QX}{U_N}$$

Where P and Q represent active power and reactive power transmitted by lines; R and X represent unit length resistance and reactance of lines; U_N is the rated voltage of 10kV lines. The increase of reverse active power raises the value of P, reverses ΔU and continuously lifts the terminal voltage. This mathematical relationship underscores how distributed generation alters classical voltage profile assumptions, necessitating revised planning criteria, adaptive voltage regulation strategies—including on-load tap changers, dynamic reactive power compensation, and intelligent feeder reconfiguration—and updated technical standards for interconnection compliance.

2.4. Allowable Voltage Range Specified by National Standards

Per the national standard GB/T 12325-2022 on power quality and supply voltage deviation, the permissible voltage deviation for three-phase systems in 10 kV distribution networks is ±7% of the nominal rated voltage, corresponding to an operational voltage range of 9.3 kV to 10.7 kV under normal conditions [7]. This tolerance band ensures stable equipment operation, minimizes energy losses, and maintains compatibility with connected loads. Exceeding this specified deviation threshold indicates noncompliant voltage regulation, potentially leading to malfunction of sensitive electronic devices, reduced efficiency of motors and transformers, and accelerated insulation aging. Continuous monitoring and timely corrective actions—such as tap changer adjustment or reactive power compensation—are therefore essential to sustain grid reliability and service quality within statutory limits.

3. Simulation Modeling and Voltage Deviation Analysis of 10kV Distribution Networks with Distributed Photovoltaics

3.1. Construction of Simulation Model

The MATLAB/Simulink simulation platform is employed to construct a representative suburban 10kV single-radial distribution network model, carefully calibrated to reflect typical operational parameters observed in rural distribution systems across the country. This includes realistic line impedances, load profiles, and equipment ratings, ensuring fidelity to field conditions while maintaining computational tractability for comprehensive voltage performance evaluation [8, 9].

Power supply side: A 110kV/10kV step-down substation serves as the primary source, with the 10kV busbar operating at its nominal rated voltage to provide stable upstream supply conditions for the downstream feeder.

Distribution lines: Overhead aluminum stranded conductors are modeled over a total length of 5 kilometers, arranged in a radial configuration; three distinct load nodes are strategically positioned along the feeder to capture spatially distributed demand and enable localized voltage assessment under varying generation and consumption scenarios.

Load configuration: Composite loads comprising residential domestic consumption and small-scale industrial processing facilities are integrated, each exhibiting characteristic diurnal variation patterns—residential loads peak in the evening, while small processing plants show higher daytime utilization, collectively forming a temporally diverse and realistic aggregate demand profile.

Distributed photovoltaics: Photovoltaic generation units are interfaced via inverters at the second and third load nodes, with each inverter configured to a rated capacity of 500 kVA, enabling bidirectional power flow and introducing time-varying injection points that significantly influence local voltage magnitudes and phase angles.

Reactive power compensation devices: Four banks of 100 kvar shunt capacitor units are installed at Node 2, configured for discrete, stepwise switching to support voltage magnitude maintenance through reactive power injection during periods of low system loading or high photovoltaic output.

3.2. Setting of Simulation Working Conditions and Analysis of Voltage Variation Rules

To systematically investigate the dynamic behavior of node voltages under varying operational scenarios, three distinct comparative simulation configurations are established, each representing different load profiles and distributed generation penetration levels; voltage measurements are continuously collected at key network nodes from 06:00 to 18:00, covering peak morning, midday, and evening demand periods, thereby enabling comprehensive temporal analysis of voltage stability, fluctuation amplitude, and deviation trends across the entire diurnal cycle.

3.2.1. Working Condition 1: No Photovoltaic Access

Under Working Condition 1—characterized by the absence of photovoltaic generation integration—the distribution network operates with a conventional unidirectional power flow pattern, where active power is delivered exclusively from the substation toward downstream loads. As a result, voltage magnitudes exhibit a monotonic decline along feeder segments, remaining within the permissible operational envelope stipulated by national technical standards for 10 kV distribution systems. The lowest recorded node voltage is 9.42 kV, which satisfies the minimum allowable threshold and confirms the absence of under-voltage violations or over-limit conditions across the entire network [10].

3.2.2. Working Condition 2: Photovoltaics Connected to the Middle Section of the Line (Node 2) with Installed Capacity of 500kVA

At solar noon, when incident irradiance attains its maximum value under clear-sky conditions, photovoltaic generation reaches rated capacity, resulting in reverse active power flow toward the distribution substation. This injection causes localized voltage elevation along the feeder, with Node 2—where the 500 kVA photovoltaic system is connected—exhibiting a measured voltage of 10.78 kV, which surpasses the statutory upper limit of 10.7 kV specified in GB/T 12325–2008 for 10 kV distribution networks. Concurrently, the downstream terminal Node 3 registers 10.72 kV, also exceeding the permissible threshold, indicating voltage rise propagation along the line due to distributed generation. As solar irradiance declines after 17:00, photovoltaic output diminishes progressively, allowing system voltage to gradually recover and stabilize within the acceptable operational range of 10.1–10.7 kV, thereby confirming the strong correlation between real-time generation profile and nodal voltage regulation performance.

3.2.3. Working Condition 3: Photovoltaics Connected to the Terminal of the Line (Node 3) with Installed Capacity of 500kVA

The terminal node exhibits the highest equivalent impedance within the distribution line configuration, resulting in pronounced voltage rise due to reverse power flow from photovoltaic generation. Under peak solar irradiance conditions at noon, the measured voltage at Node 3 reaches 10.91 kV, exceeding the permissible upper limit of the nominal 10 kV system by 9.1%, thereby indicating a critical overvoltage condition. This magnitude of deviation is substantially greater than that observed when photovoltaic units are connected at intermediate locations along the same feeder, reflecting the strong spatial dependence of voltage regulation performance on interconnection point selection. The elevated voltage stress not only compromises equipment insulation integrity and service life but also triggers protective relay misoperations and reduces allowable hosting capacity for additional distributed energy resources.

A systematic comparative analysis across all three operational scenarios reveals consistent and quantifiable trends: first, increasing photovoltaic installed capacity directly correlates with higher amplitude voltage rise at downstream nodes; second, proximity of the photovoltaic interconnection point to the line terminal intensifies local voltage elevation due to cumulative impedance effects and reduced upstream voltage support; third, dynamic solar irradiance variation—driven by cloud transients and diurnal cycles—induces continuous, low-amplitude voltage oscillations at affected nodes, challenging conventional static voltage control strategies and necessitating adaptive reactive power compensation or advanced inverter-based grid-support functions to maintain compliance with national technical standards for voltage quality.

3.3. Simulation Test on Defects of Traditional Capacitor Voltage Regulation Scheme

The conventional reactive power compensation strategy employs only four capacitor banks for voltage adjustment, with a fixed switching interval of three minutes—consistent with standard operational delay settings in distribution networks. Under peak photovoltaic generation conditions at midday, even full engagement of all capacitor banks fails to suppress the terminal voltage below 10.7 kV, indicating insufficient reactive power capacity and inadequate dynamic response capability [11, 12]. Furthermore, rapid fluctuations in solar irradiance—such as those caused by passing cloud cover—induce abrupt changes in active power injection, which capacitors alone cannot track in real time due to their discrete, stepwise, and inherently slow switching mechanism. This results in persistent voltage excursions beyond permissible limits and measurable time lags between voltage deviation onset and corrective action. Consequently, standalone capacitor-based reactive power support proves fundamentally inadequate for mitigating the bidirectional voltage deviations introduced by distributed photovoltaic generation, especially in weakly regulated or long-feeder distribution systems where impedance effects amplify sensitivity to reactive–active power coupling.

4. Design of Coordinated Reactive Power Voltage Regulation Control Strategy for Inverters and Capacitors

4.1. Overall Control Idea

The complementary characteristics of inverter-based reactive power support and fixed capacitor bank compensation are leveraged to establish a hierarchical voltage management architecture, wherein control responsibilities are distributed across distinct functional layers based on response speed, resolution, and capacity constraints [7].

Fast fine-tuning layer: Distributed photovoltaic inverters operate as continuously controllable reactive power sources, performing real-time monitoring of local node voltage magnitudes; they dynamically allocate available reactive power reserves—within their operational limits—to suppress minor deviations from the nominal voltage band, thereby ensuring rapid stabilization of transient fluctuations without introducing stepwise changes.

Coarse adjustment layer: Parallel-connected capacitor banks function as discrete, stepped reactive power compensation units; they are engaged only when sustained voltage excursions exceed predefined thresholds and the inverter's reactive power headroom has been fully utilized, enabling bulk reactive power injection or absorption to restore voltage within acceptable operational bounds.

This layered coordination strategy synergistically integrates the high-speed, high-resolution capability of power electronic inverters with the high-capacity, cost-effective nature of passive capacitor compensation, effectively mitigating the limitations inherent in either method used in isolation; by minimizing unnecessary switching events in capacitor banks, the approach significantly reduces mechanical wear, lowers maintenance frequency, enhances overall system reliability, and contributes to extended equipment service life while maintaining stringent voltage compliance across distribution networks under variable generation and load conditions [13].

4.2. Reactive Power Regulation Control Logic of Inverters

Real-time monitoring of the node voltage U is performed continuously, and the measured value is classified into three distinct operational zones to guide inverter reactive power response. This classification enables precise coordination between voltage level and reactive power injection or absorption, ensuring stable grid operation while respecting equipment capability limits.

When the node voltage falls within the nominal band of $9.3\ kV < U < 10.7\ kV$, the system operates under standard conditions; the inverter maintains unity power factor operation and refrains from injecting or absorbing reactive power, thereby minimizing unnecessary losses and preserving system efficiency without compromising voltage stability.

If the measured node voltage exceeds the upper threshold of 10.7 kV, indicating overvoltage conditions, the inverter initiates controlled absorption of inductive reactive power. This action counteracts excessive voltage rise by drawing reactive current, continuing until either the voltage returns to the acceptable range or the inverter's reactive power absorption capacity reaches its design limit.

Conversely, when the node voltage drops below the lower threshold of 9.3 kV, signifying undervoltage conditions, the inverter supplies capacitive reactive power to support voltage recovery. This reactive power injection increases local voltage magnitude through leading current flow, enhancing voltage profile compliance while remaining within thermal and converter rating constraints.

4.3. Graded Switching Logic of Capacitors

To ensure stable and reliable operation of the reactive power compensation system, a voltage dead zone is deliberately implemented to suppress unnecessary or excessive capacitor switching actions that could lead to mechanical wear and electrical stress on switching devices [2]. Specifically, when the inverter has fully utilized its reactive power regulation capability and the node voltage remains above the upper threshold of 10.75 kV, one group of shunt capacitors is automatically energized to inject reactive power and support voltage levels. Conversely, if the node voltage falls below the lower threshold of 9.25 kV under similar conditions, one group of capacitors is systematically de-energized to prevent overvoltage at downstream loads. Furthermore, a mandatory time delay of 3 minutes is enforced between successive switching operations to mitigate rapid cycling, thereby enhancing equipment longevity, reducing maintenance frequency, and improving overall grid resilience against transient disturbances.

4.4. Overall Control Flow of Coordinated Voltage Regulation

The coordinated voltage management strategy operates through a hierarchical, real-time decision-making process. First, node voltages across the distribution network are continuously monitored using synchronized measurement devices. Subsequently, a comparative assessment determines whether each measured voltage falls within the permissible operational range defined by technical standards. For minor deviations—typically within ±3% of nominal voltage—inverter-based distributed energy resources autonomously adjust reactive power output to restore voltage levels [12]. Should inverter reactive power capacity reach its physical limits without achieving acceptable voltage conditions, the system initiates a staged switching sequence for shunt capacitor banks, prioritizing minimal switching actions to preserve equipment longevity and grid stability. Once voltage parameters return to and remain stably within the normal band for a predefined duration, all control devices retain their most recent operational configuration to avoid unnecessary actuation and ensure system inertia.

5. Simulation Comparison and Result Analysis of Voltage Regulation Schemes

Under identical operational conditions characterized by maximum photovoltaic generation output and associated voltage over-limit scenarios, three distinct technical approaches for managing terminal voltage levels are systematically evaluated. The comparative analysis focuses on the dynamic behavior of Node 3—the designated terminal point—over a continuous sixty-minute interval spanning from 12:00 to 13:00. Voltage time-series data are acquired at uniform sampling intervals to ensure temporal resolution and measurement consistency. This experimental setup enables rigorous assessment of transient response characteristics, steady-state deviation magnitude, convergence speed, and overall stability performance across all three methods under realistic grid-integrated renewable generation conditions.

5.1. Scheme 1: Voltage Regulation Only by Capacitor Switching

Following the sequential energization of all four capacitor banks, the node voltage settles at 10.73 kV, which remains above the upper permissible threshold stipulated in GB/T 12325–2008 for supply voltage deviation in 10 kV distribution systems. Under conditions of minor irradiance variation—simulating typical daytime cloud cover transitions—the voltage exhibits dynamic fluctuations within a band of 10.70 kV to 10.82 kV. This oscillatory behavior violates the standard's requirement for steady-state voltage tolerance (±7% of nominal), thereby indicating inadequate control responsiveness and insufficient damping capability inherent to capacitor-only reactive power compensation [14, 15]. Consequently, power quality metrics such as voltage total harmonic distortion and flicker severity also deteriorate, further compromising system reliability and end-user equipment compatibility.

5.2. Scheme 2: Voltage Regulation Only by Photovoltaic Inverters

The inverter continuously absorbs inductive reactive power to support voltage control at the point of common coupling, successfully maintaining the node voltage at a stable level of 10.62 kV, which remains well within the permissible limits specified by national grid interconnection standards. However, sustained operation at maximum reactive power absorption capacity places significant constraints on the inverter's active power delivery capability. This operational trade-off reduces the overall utilization efficiency of the photovoltaic generation system, leading to a measurable decline of 3.2% in annual energy yield. Consequently, the economic viability of the installation is compromised due to underutilized generation potential and suboptimal return on investment over the system lifetime.

5.3. Scheme 3: Coordinated Voltage Regulation of Inverters and Capacitors

In this coordinated control strategy, the inverter is prioritized for reactive power absorption to achieve precise and responsive voltage adjustment at the point of common coupling. When the node voltage remains elevated despite inverter-based reactive power consumption, two preconfigured capacitor banks are sequentially energized to provide additional reactive support. This hierarchical approach ensures that the inverter operates well within its reactive power capability margin—typically utilizing less than 15% of its rated reactive capacity—thereby preserving thermal headroom and extending service life. As a result, the steady-state voltage is consistently maintained between 10.45 kV and 10.65 kV, fully complying with national grid interconnection technical specifications for distribution-level photovoltaic integration. Crucially, active power generation from the photovoltaic units remains virtually unaffected throughout the entire control sequence, demonstrating minimal curtailment impact. Furthermore, capacitor switching occurs only once per voltage excursion event, significantly lowering mechanical wear, contactor degradation, and associated energy losses compared to frequent cycling schemes.

5.4. Simulation Conclusion

The coordinated voltage control strategy demonstrates superior overall performance relative to individual control approaches, achieving a balanced improvement across multiple critical operational metrics—including reduction of voltage deviation, enhancement of photovoltaic energy utilization efficiency, and mitigation of stress on distribution equipment, thereby extending its operational service life. This integrated methodology effectively addresses the voltage fluctuation and overvoltage issues commonly observed in 10 kV medium-voltage distribution networks when integrating substantial amounts of grid-connected distributed photovoltaic generation, particularly under high-irradiance or low-load conditions [8, 10]. Its adaptability to dynamic load and generation profiles further supports stable and reliable network operation.

6. Conclusion and Prospect

6.1. Main Conclusions

This study addresses voltage deviation challenges arising in 10 kV distribution networks integrated with distributed photovoltaic generation units. A comprehensive mathematical framework was developed to characterize the electrical behavior of photovoltaic modules, grid-connected inverters, and the underlying radial distribution network topology. Through systematic Simulink-based simulations, the sensitivity of nodal voltage profiles to both the installed capacity and physical location of photovoltaic units was rigorously examined. Results consistently indicate that voltage excursions beyond permissible limits occur most frequently—and with greatest magnitude—when photovoltaic generation is connected near the line terminus, due to cumulative reactive power flow and reduced short-circuit strength at remote nodes. To overcome limitations inherent in conventional fixed capacitor banks—including delayed response and inability to modulate continuously—and to mitigate energy curtailment associated with inverter-only reactive power control, a synergistic reactive power coordination mechanism was formulated. This approach dynamically allocates reactive power support between inverters and switched capacitors based on real-time voltage deviation, rate of change, and equipment operational constraints. Validation via comparative simulation confirms that the proposed strategy maintains all node voltages within the ±7% tolerance band specified in relevant technical standards for medium-voltage distribution systems. Furthermore, it demonstrates superior transient response characteristics, improved utilization efficiency of photovoltaic generation capacity, and enhanced longevity of switching devices—making it particularly suitable for deployment in rural distribution infrastructure where cost-effective, low-maintenance solutions are prioritized.

6.2. Deficiencies of the Research

The simulation model presented in this study is intentionally simplified to isolate core dynamics, focusing exclusively on a single 10 kV radial distribution line; it does not represent the structural complexity, topological diversity, or operational interdependencies characteristic of real-world interconnected distribution networks comprising multiple feeders, looped configurations, or meshed architectures. The control logic implemented operates solely on locally measured voltage magnitudes at photovoltaic inverters, without incorporating any centralized or distributed communication infrastructure—such as IEC 61850-based messaging or time-synchronized data exchange—that would enable coordinated voltage support across geographically dispersed photovoltaic clusters. Furthermore, the modeling framework deliberately excludes interactions with other distributed energy resources, including wind generation units whose stochastic output profiles introduce distinct temporal and spatial variability, as well as electrochemical energy storage systems whose bidirectional power flow and state-of-charge dynamics significantly influence voltage stability and reactive power dispatch. These omissions reflect methodological constraints rather than conceptual limitations, and future work will extend the model to incorporate multi-source coupling, hierarchical control layers, and realistic network topologies.

6.3. Prospect of Follow-Up Research

Integrating energy storage batteries into the existing framework would enable the development of a coordinated wind–solar–storage system capable of delivering continuous, adaptive voltage support across diurnal cycles; this enhancement would significantly improve the temporal consistency of voltage profiles by absorbing surplus generation during peak production periods and injecting power during lulls, thereby mitigating both upward and downward deviations with greater responsiveness and reduced reliance on reactive power compensation alone.

Incorporating Internet of Things communication infrastructure—such as low-latency wireless mesh networks and standardized data exchange protocols—would facilitate real-time coordination among distributed photovoltaic inverters along an entire distribution feeder, allowing for spatially aware, decentralized decision-making that collectively optimizes terminal voltage magnitude while preserving local autonomy and fault resilience.

Embedding machine learning models trained on high-resolution historical irradiance, temperature, and load data would permit short-term forecasting of photovoltaic generation with improved accuracy; such forecasts could be integrated into predictive control loops to proactively adjust inverter setpoints and auxiliary devices prior to voltage excursions, thereby minimizing oscillation amplitude, reducing actuation frequency, and extending equipment service life.

Constructing a scaled-down physical experimental platform—including representative feeder topology, programmable inverters, controllable loads, and synchronized measurement instrumentation—would provide empirical validation of the proposed control strategies under realistic hardware-in-the-loop conditions, enabling rigorous assessment of dynamic response, timing synchronization fidelity, and robustness against communication delays or sensor noise not fully captured in simulation environments.

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