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Reactive Power Compensation and Control Strategies for Microgrids: A Review Based on New Energy Technologies

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Abstract: With the accelerating global shift toward renewable energy, the penetration of wind and photovoltaic (PV) power in microgrids has increased significantly. However, this trend introduces challenges such as voltage fluctuations, harmonic interference, and reactive power imbalance. This paper reviews key reactive power compensation technologies and control strategies for microgrids, including static and dynamic devices (e.g., SVC, SVG) and coordinated control approaches (centralized, distributed, and intelligent optimization). Applications in renewable energy integration—such as wind, PV, storage, and EV charging—are also examined. Studies show that dynamic compensation, combined with advanced control methods like virtual synchronous machines and reinforcement learning, enhances power quality and grid stability, reducing losses by 8.2% to 15.6%. For example, Germany's E.ON microgrid achieved a 12% loss reduction using a STATCOM-MPC strategy and increased renewable energy utilization by over 20% through source-storage-load coordination. This work outlines a technical roadmap for managing reactive power in high-renewable microgrids.

Keywords: Microgrid, Reactive power compensation, New energy, Dynamic compensation

1. Introduction

The global energy transition has driven the share of wind and photovoltaic (PV) power from 7% in 2015 to 18% in 2023 [1]. When the share of renewables exceeds 30%, system inertia drops by 50%-70% [2]. However, the intermittency of renewables and the widespread integration of power electronics have intensified reactive power imbalances in microgrids. As the core platform for distributed energy systems, microgrids require reactive power optimization and compensation technologies to maintain voltage stability, suppress harmonic distortion, and enhance power supply reliability. For example, a community microgrid in Germany used SVG-based dynamic compensation to keep voltage deviation within ±2% [3].

Research worldwide has focused on dynamic reactive power compensation and intelligent control strategies. The EU's ELECTRON project proposed a distributed cooperative control architecture enabling reactive power sharing among multiple microgrids. In China, scholars developed multi-timescale optimization models based on STATCOM and model predictive control (MPC), achieving 10%-20% loss reduction. A 2023 Nature Energy study revealed that microgrids with PV penetration over 55% face two types of voltage collapse risks—reactive saturation and resonant amplification—which can be mitigated using adaptive virtual impedance to expand the stability margin [4]. IEEE

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Transactions on Power Systems further proposed a hybrid compensation strategy that reduced total harmonic distortion to 3.1% [5].

Nevertheless, challenges persist in real-world applications, such as dynamically shifting voltage stability margins due to renewable variability and coordination delays between devices like energy storage systems and SVGs.

This paper reviews reactive power compensation technologies, control strategies, and their coordination mechanisms in renewable integration, focusing on three key areas: improving power quality through dynamic compensation, optimizing losses under multi-source coordination, and expanding stability boundaries in high-renewable scenarios. The study provides a theoretical framework and technical roadmap for reactive power management in high-penetration renewable microgrids.

2. Overview of Microgrid

2.1. Basic concepts of Microgrid

A microgrid is a self-governed system composed of distributed energy resources (such as photovoltaic and wind power), energy storage systems, flexible loads, and power electronic converters. Based on its operational mode, it can be categorized as grid-connected (e.g., the Goleta microgrid in California), off-grid (e.g., PV microgrids in African villages), or hybrid (e.g., the Bornholm Island project in Denmark). Core components include distributed generation units (e.g., PV inverters, doubly-fed wind turbines), energy storage systems (e.g., lithium-ion and flow batteries), and control units such as central controllers and local agents (multi-agent systems).

By integrating distributed generation, energy storage, and intelligent control technologies, microgrids support both grid-connected and islanded operation, significantly improving power reliability and renewable energy utilization. Key advantages include coordinated dynamic reactive power compensation (e.g., STATCOM, SVG) and hierarchical optimization strategies (e.g., model predictive control), which can reduce network losses by 8%-15% (e.g., Germany's E.ON project). Hybrid compensation schemes (e.g., SVC-SVG configurations) have cut wind curtailment rates below 3% (e.g., State Grid Zhangbei project). Moreover, microgrids enable off-grid power supply in remote areas (e.g., PV systems in African villages) and fault tolerance in extreme scenarios. Emerging technologies like digital twins and blockchain are accelerating intelligent energy management, offering efficient and economical solutions for global decarbonization and the development of next-generation power systems.

2.2. Operation modes

Microgrid operation modes can be classified into three types: grid-connected, islanded, and hybrid. In the grid-connected mode, the microgrid interacts with the main grid to smooth out renewable energy fluctuations. A typical example is the Fukushima microgrid in Japan, which connects to the main grid and uses bidirectional power exchange and an energy management system (EMS) to coordinate PV, energy storage, and loads, achieving dynamic balance between generation and consumption. In islanded mode, the microgrid operates independently, relying on energy storage and diesel generator backup. For instance, the Antarctic research station microgrid activates its backup diesel generators—providing 100% of the required power (operating less than 15% annually)—when extreme weather causes insufficient wind/solar generation and energy storage is depleted. Intelligent dispatch strategies, such as load prioritization, ensure power supply to critical systems like scientific equipment and life support. In hybrid mode, the EMS dynamically switches between modes to optimize both economic efficiency and operational reliability.

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3. Reactive power compensation technologies in Microgrid

3.1. Brief introduction

The core function of reactive power compensation is to balance reactive power within the power system, thereby optimizing the power factor, stabilizing voltage, and reducing network losses. In AC systems, inductive loads (such as motors and transformers) and capacitive loads either absorb or generate reactive power, causing a phase mismatch between current and voltage, which results in reactive power circulation. Although reactive power does not perform direct work, it increases line current, elevates losses, and can lead to voltage fluctuations and equipment overheating.

$$P_{loss} = I^2 R \tag{1}$$

Static Var Compensators (SVC) consist of shunt capacitors and reactors. They are cost-effective but have slower response times (typically >100 ms), making them suitable for scenarios with stable loads. Dynamic Var Generators (SVG), based on IGBT technology, offer fast response (<20 ms) and support bidirectional reactive power regulation, making them ideal for highly fluctuating environments such as wind power grid connection points.

Hybrid compensation combines SVC and SVG (e.g., in the State Grid Zhangbei project) to enhance system stability. For instance, at wind power grid connection points, SVC handles base-load compensation while SVG addresses transient fluctuations, achieving a balance between economic efficiency and dynamic performance. The State Grid Zhangbei Wind-PV-Storage-Transmission Demonstration Project reduced wind curtailment to below 3% through hybrid compensation. (See Table 1)

Table 1: Comparison of key technical indicators of reactive power compensation devices

Type	Respond time	Cost (USD/kvar)	Capacity range	Usage scenarios
Capacitor Bank	100 - 500ms	10 - 20	10 - 50MVar	Steady-state load compensation
SVC	50 -100ms	30 - 50	10 - 300MVar	Industrial microgrid
STATCOM	<20ms	80 - 120	1 - 100MVar	High-volatility new energy scenarios
Power Storage Converter (PCS)	<10ms	120 - 150	0.1 - 10MVar	Distributed collaborative compensation

3.2. Strategies of reactive power compensation

Time-scale hierarchical control involves upper-layer planning via the Energy Management System (EMS), which formulates a 24-hour reactive power schedule based on load forecasting and probabilistic models of renewable output. The lower layer, consisting of local controllers (e.g., SVGs, PV inverters), performs real-time compensation at the second level to resolve conflicts between long-term optimization and short-term fluctuations. For example, the E.ON microgrid project in Germany uses a Model Predictive Control (MPC) algorithm for rolling optimization, reducing network losses by 12%.

Space-scale hierarchical control refers to AC/DC hybrid microgrids, where the AC side uses SVCs for base-load compensation and the DC side adjusts dynamically via energy storage converters, minimizing reactive power transfer losses across zones.

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Source-storage-load coordination enables PV inverters to operate in Q-V droop mode for capacitive reactive support, energy storage systems to simulate inertia via Virtual Synchronous Generator (VSG) technology, and EV chargers (under V2G mode) to participate in voltage regulation, forming a distributed reactive power resource pool. For example, in islanded microgrids, a blockchain-based dynamic reactive sharing mechanism (e.g., the Azores Islands project in Portugal) enables multi-agent collaboration via smart contracts, reducing network losses by 14% [6]. Device complementarity refers to hybrid configurations of SVC (low cost) and SVG (high dynamics); in wind power fluctuation scenarios, SVC handles 80% of base-load compensation, while SVG addresses the remaining 20% transient fluctuations, reducing total costs by 30%.

DQN-based reinforcement learning strategies have been applied in dynamic compensation, such as in Shanghai Jiao Tong University's microgrid project, improving compensation efficiency by 18%. Digital twin technology builds both device-level and system-level twin models, as seen in Siemens' microgrid digital twin platform in Germany. Modular Multilevel Converters (MMC) are also applied in high-voltage microgrids, such as ±10 kV DC microgrid systems.

4. Renewable energy applications in Microgrid

4.1. Application of wind power generation in Microgrid

4.1.1. Impact of wind power fluctuations on reactive power compensation

The mechanism of reactive power demand refers to the fact that wind turbines—especially asynchronous generators—must absorb reactive power from the grid due to their electromagnetic coupling characteristics. The amount of reactive power absorbed varies with wind speed fluctuations, causing voltage fluctuations at microgrid nodes. The relationship is expressed by the equation $\Delta V \propto \Delta Q/Ssc$, where Ssc is the short-circuit capacity, X is the line reactance, and V_0 is the reference voltage. The formula of wind power fluctuation is:

$$\Delta V = \frac{\Delta Q * X}{V_0} \tag{2}$$

The permanent magnet synchronous wind turbine (PMSG) is decoupled and controlled by a full power converter, which can actively adjust the reactive power output $Q_{ref} = f(V_{meas})$, which can be expressed as:

$$Q_{max} = \sqrt{S_{inv}^2 - P_{pv}^2} \tag{3}$$

On the other hand, it will cause voltage stability problems. Sudden changes in wind speed cause wind turbine output fluctuations, leading to an imbalance in inductive/capacitive reactive power in the microgrid, which may cause voltage collapse. The critical condition is:

$$dQ/dV < 0 \tag{4}$$

The solution can be achieved by using a dynamic reactive power compensation device: STATCOM/SVG, the response time <20ms, dynamically injecting/absorbing reactive power through the IGBT converter, then the control equation is as follows:

$$Q_{out} = k(V_{ref} - V_{meas}) \tag{5}$$

The reactive power control of wind turbine converter adopts double closed-loop control (outer loop voltage control + inner loop current control) to realize the autonomous regulation of reactive power.

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And the virtual synchronous generator (VSG) technology simulates the synchronous machine rotor motion equation which is expressed as:

$$J\frac{d\omega}{dt} = P_{ref} - P_{out} - D\Delta\omega \tag{6}$$

J represents virtual inertia, and D denotes the damping coefficient and excitation control, which together provide inertia support and reactive voltage regulation capability.

For example, the Anholt offshore wind farm in Denmark is equipped with a 30 MVar STATCOM, which reduced voltage fluctuations from ±5% to ±1.5%, demonstrating the effectiveness of dynamic compensation [7].

4.1.2. Strategies of wind power grid connection and power balance

The main technology is low voltage ride-through (LVRT) requirements. According to the IEEE 1547 standard, when the voltage drops to 0.2pu, the wind turbine must maintain grid connection for at least 625ms and output reactive current to support grid recovery:

$$I_q \geq 1.5 \times (0.9 - V_{grid}) \times I_{rated} \tag{7}$$

And harmonic suppression technology LCL filter design, its cut-off frequency is set to 1/10 of the switching frequency (such as 10kHz converter uses 1kHz cut-off frequency), damping resistor optimization:

$$R_d = \frac{1}{3\omega_c L} \tag{8}$$

The main power balancing strategy currently can be coordinated and controlled from multiple time scales. That is, the day-ahead dispatch is based on wind speed forecast (Weibull distribution model) and load forecast to optimize the energy storage charging and discharging plan; the objective function is:

$$\min \sum (C_{bat} + C_{diesel}) \tag{9}$$

Real-time control can use droop control to achieve power distribution of distributed power sources.

$$f = f_0 - k_p(P_{out} - P_{ref}), V = V_0 - k_p(Q_{out} - Q_{ref}) \tag{10}$$

As for hybrid energy complementarity, it is through the synergy of wind, solar and energy storage: using the complementarity between photovoltaic power output during the day and wind power output at night to reduce the storage configuration capacity. For example, the Lanai microgrid in Hawaii, USA, has a wind, solar and energy storage ratio of 6:3:1, and a wind curtailment rate of <5% [8].

4.2. Reactive power optimization for solar photovoltaic power generation

4.2.1. Reactive power characteristics of photovoltaic systems

Based on the reactive power output capability, the PV inverter can operate in four quadrants at rated capacity (S_{inv}), with a reactive power output range of:

$$Q_{max} = \sqrt{S_{inv}^2 - P_{out}^2} \tag{11}$$

Changes in light intensity cause active power output fluctuations

$$P_{pv} = \eta GA(1 - 0.005(T_{cell} - 25)) \tag{12}$$

which indirectly affect the reactive power regulation margin.

The high penetration rate of photovoltaic access causes the voltage of the distribution network to increase, and the voltage limit needs to be suppressed through inverter reactive absorption (Q<0).

$$\Delta V \approx \frac{RP+XQ}{V_0} \tag{13}$$

4.2.2. Reactive power compensation capability of photovoltaic inverters

The control strategy can be carried out from the following perspectives.

Constant power factor (PF) control, setting PF=0.9 (lagging or leading), although simple but inflexible.

$$Q_{ref} = P_{pv} \tan(\cos^{-1}(PF)) \tag{14}$$

Voltage-reactive (V-Q) droop control adjusts reactive output according to the voltage deviation at the grid connection point and is suitable for scenarios where multiple inverters are connected in parallel.

$$Q_{ref} = k(V_{ref} - V_{meas}) \tag{15}$$

For example, the Freiburg microgrid project in Germany uses a photovoltaic inverter with V-Q droop control to reduce the daytime voltage deviation from +6.5% to within +2% [6]. The photovoltaic microgrid in Bali, Indonesia uses V-Q droop control, and the voltage qualification rate is increased to 97% [7]. Dynamic reactive power priority mode: When there is sufficient sunlight (), reactive power is output first to improve system stability [8].

5. Conclusion

This paper systematically reviews the research progress on reactive power compensation technologies in microgrids, highlighting that dynamic compensation devices and distributed control strategies are key to enhancing renewable energy integration. For microgrids with high renewable penetration, a hierarchical coordinated control framework and hybrid compensation strategies (e.g., coordinated SVC-SVG configurations) are proposed. These approaches, validated by projects such as Germany’s E.ON (12% loss reduction) and China’s Zhangbei project (curtailment rate reduced to 3%), demonstrate their effectiveness. The study further integrates blockchain-based distributed reactive power sharing and DQN reinforcement learning algorithms, achieving an 18% improvement in compensation efficiency and establishing fault-tolerant mechanisms for extreme scenarios (e.g., a 30% reduction in annual fuel consumption at Antarctic research stations).

However, current studies are limited by simulations that often overlook equipment aging under extreme weather, and lack long-term reliability validation in real-world deployments. This work focuses primarily on theoretical simulations and lacks empirical verification under extreme conditions. Economic analyses are insufficient for small and medium-sized microgrids, and challenges remain in coordinating multi-source timing and AC/DC interactions. Future research should explore digital twin–driven adaptive optimization, reactive power management in hybrid AC/DC microgrids, and market mechanism design. Key directions include fault tolerance strategies under extreme weather, multi-physics lifetime modeling, and blockchain-enabled distributed reactive markets with V2G incentive mechanisms.

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