

Research on Reactive Power Regulation and Control Measures in Power Systems

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Abstract: Aiming at problems such as voltage fluctuations and increased power losses caused by reactive power imbalance in power systems, this study focuses on the core technical strategies of reactive power regulation and control. It systematically elaborates on optimization approaches for traditional reactive power regulation equipment, application technologies of new power electronic compensation devices, and multi-source coordinated regulation strategies. By constructing core mathematical models and parameter optimization methods, the accuracy of reactive power regulation is improved. Technical formulas are employed to support the analysis, and small comparative tables of equipment performance are used to clarify applicable scenarios. Through the coordinated application of various regulation technologies, voltage stability can be effectively maintained and network power losses can be reduced. The results provide technical references for the optimized design of reactive power regulation and control systems and have clear engineering application significance.

Keywords: Power system; reactive power regulation; control measures

Introduction

The safe and stable operation of power systems relies on the coordinated balance of active and reactive power. Reasonable allocation and precise regulation of reactive power directly determine voltage quality and operational efficiency. With the large-scale integration of renewable energy into power grids and the increasing presence of flexible loads, system operating characteristics have become increasingly complex, and traditional reactive power regulation methods can no longer meet dynamic operating requirements. Reactive power imbalance can cause deviations in node voltage, leading to

equipment damage and a rapid increase in line losses, posing serious threats to system security. This paper focuses on the core technologies of reactive power regulation and control, directly addressing the technical implementation stage. Through formula derivation and data comparison, key technical points are clarified, providing practical operational support for engineering applications and optimization upgrades.

1. Control Technologies of Traditional Reactive Power Regulation Equipment

1.1 Reactive Power Regulation and Control of Synchronous Generators

As the core power source, synchronous generators



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possess inherent reactive power regulation capability. Precise control of reactive power output is achieved by adjusting the excitation current, and the performance of the excitation system directly determines the response speed and stability of regulation. The mainstream control approach is regulation through an automatic voltage regulator (AVR). During operation, the excitation winding current is adjusted in real time according to system voltage variations, thereby changing the generator's no-load electromotive force to realize dynamic reactive power regulation. The reactive power output of a synchronous generator can be calculated using the following formula:

$$Q = \frac{E_0 U}{X_d} \cos \delta - \frac{U^2}{X_d}$$

where Q is the reactive power output of the synchronous generator, E_0 is the no-load electromotive force, U is the terminal voltage, X_d is the direct-axis synchronous reactance, and δ is the power angle. This formula clearly defines the quantitative relationship between system parameters and reactive power output, providing a basis for setting excitation regulation parameters. In practical control implementation, the AVR collects terminal voltage signals and compares them with rated values to generate an error signal, which is processed by a PID module to output control commands. These commands drive the excitation regulator to adjust the excitation current, thereby maintaining voltage stability and achieving reasonable reactive power allocation ^[1]. For large-capacity generating units, the dynamic response characteristics of the excitation system must be optimized. Measures such as increasing regulator gain and optimizing filter parameters are adopted to prevent regulation delays from exacerbating voltage fluctuations.

1.2 Group Switching Control of Shunt Capacitor Banks

Shunt capacitor banks are widely used reactive power compensation devices. By injecting capacitive reactive power to offset inductive load consumption, they improve the power factor and reduce line losses. The core of regulation control lies in optimizing group switching strategies. Through reasonable grading of capacity levels, stepwise and accurate compensation can be achieved. Control should follow the principle of voltage priority while taking into account switching

frequency and equipment lifespan, avoiding losses and system impacts caused by frequent switching operations. In the control logic, upper and lower voltage threshold values are set. When the voltage falls below the lower limit, capacitor groups are sequentially switched in; when the voltage exceeds the upper limit, capacitor groups are sequentially switched out. To suppress inrush currents and overvoltage during switching, vacuum circuit breakers are typically selected as switching devices, combined with inrush current suppression equipment. Group capacities usually adopt a configuration of "main capacity plus fine-tuning capacity," enabling more flexible and precise reactive power compensation.

1.3 Reactive Power Absorption Control of Shunt Reactors

Shunt reactors are used to absorb excess capacitive reactive power in power systems, primarily addressing the problem of reactive power surplus during no-load or light-load operation of long-distance transmission lines. They suppress power-frequency overvoltage and help maintain voltage stability. Regulation and control methods can be divided into fixed switching and adjustable types, with adjustable shunt reactors being more suitable for dynamic system changes and thus having broader application prospects. Adjustable shunt reactors regulate the amount of reactive power absorption by changing inductance values. Common approaches include magnetically controlled reactors and thyristor-controlled reactors. Magnetically controlled reactors achieve continuous reactive power regulation by adjusting excitation current to alter the saturation state of the core, while thyristor-controlled reactors realize stepwise regulation through control of the thyristor conduction angle. Control strategies must evaluate the degree of capacitive reactive power surplus in real time based on parameters such as line voltage, current, and power factor, and calculate the required regulation magnitude ^[2]. For long-distance ultra-high-voltage transmission lines, a combination of online monitoring and closed-loop control is typically adopted to match regulation response speed with system requirements. At the same time, appropriate regulation ranges and limit parameters must be correctly set to prevent over-regulation.

2. Application Technologies of New Power Electronic Reactive Power Compensation Devices

2.1 Precision Control Technology of Static Var Generators

Static Var Generators (SVGs), featuring fast response, continuous adjustability, and a wide compensation range, have become key reactive power regulation devices in modern power systems. An SVG converts DC-side voltage into AC voltage with the same frequency and phase as the grid through a three-phase bridge converter. By regulating the magnitude difference between the output voltage and the system voltage, flexible absorption and injection of reactive power are achieved. Core control technologies include pulse width modulation (PWM) control and closed-loop current control in the dq coordinate system. In the dq coordinate system, three-phase currents are decomposed into active and reactive components through Park transformation. Precise tracking and control of the reactive component enable rapid regulation. A combined control scheme of PI regulators and hysteresis comparators is commonly adopted, where the PI regulator eliminates steady-state error and the hysteresis comparator improves dynamic response. The reactive power output of an SVG can be calculated using the following formula:

$$Q_{\text{SVG}} = \frac{U_s U_{\text{SVG}} \sin \theta}{X_s}$$

where Q_{SVG} is the reactive power output of the SVG, U_s is the system voltage magnitude, U_{SVG} is the SVG output voltage magnitude, θ is the phase difference between the two, and X_s is the equivalent reactance. This formula provides a quantitative basis for setting control parameters, enabling precise regulation by adjusting U_{SVG} and θ . In practical applications, comprehensive detection and protection modules must be configured to monitor system and device operating states in real time, ensuring stable responses under fault conditions or sudden load changes.

2.2 Dynamic Regulation Technology of Static Synchronous Compensators

Static Synchronous Compensators (STATCOMs) are implemented based on voltage source converters and offer advantages such as fast response, high regulation accuracy, and relatively low losses. They are highly

effective in addressing reactive power fluctuations caused by the integration of renewable energy sources into power grids. Core technologies involve converter control strategies and energy management. By adjusting the magnitude and phase of the output voltage, bidirectional reactive power exchange is realized. The key to dynamic regulation lies in enhancing response speed and disturbance rejection capability. Commonly adopted control strategies include model predictive control (MPC) and sliding mode variable structure control. Model predictive control constructs a mathematical model to predict output states and selects optimal control commands to achieve precise regulation, offering excellent dynamic performance and robustness. Sliding mode variable structure control maintains system operation in a sliding mode by designing appropriate sliding surfaces and control laws, ensuring insensitivity to parameter variations and external disturbances. On the DC side, capacitors are used for energy storage, and appropriate voltage control strategies must be applied to maintain stability and prevent voltage fluctuations from affecting regulation accuracy^[3]. In renewable energy power station applications, STATCOMs operate in coordination with generating units to compensate in real time for reactive power components caused by power fluctuations, thereby ensuring voltage stability at the point of grid connection and enhancing power accommodation capability.

2.3 Coordinated Reactive Power Regulation Technology Implemented by Unified Power Flow Controllers

As a core device of Flexible AC Transmission Systems (FACTS), the Unified Power Flow Controller (UPFC) is capable of simultaneously regulating active power, reactive power, and voltage. Reactive power regulation is mainly realized through the shunt-side converter, which operates in coordination with the power system. The shunt-side converter adopts a voltage-source structure and achieves reactive power absorption and injection by regulating the magnitude and phase relationship between its output voltage and the system voltage, thereby maintaining node voltage stability.

The core of the coordinated technology lies in the coordinated control of the shunt-side and series-side converters, ensuring that reactive power regulation

does not interfere with the efficiency of active power transmission. A hierarchical control architecture is commonly adopted. At the bottom layer, device-level control is implemented to achieve precise tracking of current and voltage. The middle layer employs station-level control to accomplish predefined objectives of reactive power and voltage regulation. The top layer performs system-level coordinated control to realize cooperative operation with other devices. With a response speed at the millisecond level, UPFCs can be effectively applied in complex power flow optimization and voltage stability control in power grids ^[4].

3. Reactive Power Coordinated Control Technologies and Optimization Strategies

3.1 Coordinated Control Technology of Multi-Source Reactive Power Regulation Devices

With the increasing variety of reactive power regulation devices in power systems, independent regulation by single devices can no longer meet the requirements of complex system operation. Coordinated control of multi-source reactive power regulation devices has become a key technology for improving overall regulation performance. The core objective of coordinated control is to establish a unified control framework that enables information sharing and coordinated actions among different reactive power regulation devices, thereby preventing conflicts in regulation and functional redundancy. At present, the mainstream coordinated control architecture is hierarchical and distributed. The bottom layer consists of device-level control units, which are responsible for collecting operational status information of equipment and executing upper-level control commands. The middle layer comprises regional coordination control units, which aggregate operational data within a region and formulate regional reactive power regulation measures. The top layer is the system-level optimization control unit, responsible for monitoring global operating conditions and developing overall regulation strategies. During the design of coordinated control logic, devices should be assigned priorities according to their response speed and regulation characteristics. Fast-response devices, such as SVGs and STATCOMs, are suitable for handling high-frequency, small-amplitude reactive power fluctuations, while slow-response devices, such as shunt capacitor

banks and synchronous generators, are mainly used to address low-frequency, large-amplitude reactive power variations. Through reasonable priority assignment and action sequence coordination, complementary advantages of different devices can be fully utilized.

3.2 Voltage–Reactive Power Coordinated Optimization Control Strategy

Voltage and reactive power exhibit strong coupling characteristics. Regulating voltage or reactive power alone is insufficient to achieve a globally optimal operating state of the power system. Therefore, voltage–reactive power coordinated optimization control has become an effective strategy for improving both economic performance and operational stability. The core idea of coordinated optimization control is to establish an optimization model with the objectives of ensuring qualified voltage levels and minimizing network losses, and then to determine the optimal reactive power regulation scheme using optimization algorithms. The objective function of the optimization model is generally set to minimize system network losses, while constraints include node voltage magnitude limits, reactive power source output constraints, and transmission line capacity constraints. Commonly used optimization algorithms include particle swarm optimization and genetic algorithms. Due to its fast convergence speed and strong robustness, particle swarm optimization has been widely applied in voltage–reactive power coordinated optimization. In practical implementation, online monitoring systems are used to track the distribution of node voltages and reactive power in real time, continuously updating the input parameters of the optimization model. Optimization algorithms are then applied to generate optimal control commands that guide the actions of various reactive power regulation devices. Considering the dynamic changes in system operating conditions, a rolling optimization approach is adopted, in which the optimization model is periodically updated and recalculated to ensure the timeliness and adaptability of control strategies. Voltage–reactive power coordinated optimization control can effectively prevent voltage abnormalities and increased network losses caused by unreasonable reactive power distribution, thereby enhancing the overall operational efficiency of the power system.

3.3 Adaptive Adjustment Technology for Reactive Power Regulation and Control Strategies

The operating state of power systems is characterized by strong randomness and uncertainty, making fixed control strategies difficult to adapt to dynamic changes. Adaptive adjustment technology has therefore become a key approach to improving system adaptability^[5]. Through self-tuning mechanisms, key parameters such as PI controller coefficients and regulation thresholds are automatically optimized based on identification results combined with predefined rules.

This technology is particularly important in scenarios with high penetration of renewable energy, as it can effectively respond to random power fluctuations and ensure the optimality of control strategies.

A strategy verification and correction mechanism is established to continuously optimize parameters by real-time monitoring of regulation effects, thereby enhancing control accuracy. **Table 1** presents a comparison of the performance of different reactive power regulation control strategies.

Table 1. Comparison of Performance of Different Reactive Power Regulation Control Strategies

Control Strategy Type	Response Speed	Regulation Accuracy	Applicable Scenarios	Operating Loss
Independent control of traditional devices	Medium–slow	Medium	Conventional load grids, small-capacity systems	Medium
Multi-source coordinated control	Relatively fast–fast	High	Complex grids, multi-power-source systems	Low
Voltage–reactive power coordinated optimization	Medium–relatively fast	High	Loss-sensitive grids, large-scale transmission systems	Low
Adaptive adjustment control	Fast	High	High renewable penetration grids, fluctuating load systems	Relatively low

Conclusion

The optimization and upgrading of reactive power regulation and control technologies in power systems are key supports for ensuring safe, stable, and economical system operation. From the perspectives of traditional equipment control, application of new power electronic devices, and coordinated optimization control, this paper systematically analyzes the implementation logic and key technical points of core technologies. Through formula derivation and tabular comparison, the technical advantages and applicable scenarios of different methods are clearly identified. The study shows that optimized control of traditional equipment provides a solid foundation, new devices enhance dynamic regulation capability, and coordinated adaptive control achieves global optimal performance. Future technological development will focus on digitalization and intelligent upgrading, integrating big data and artificial intelligence to further improve regulation accuracy. The technical measures and strategies discussed in this paper can provide reliable references for engineering practice and optimization upgrading, contributing to the overall improvement of power system operational performance.

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