

## Analysis of Current Status and Development Trends of Voltage-Source PWM Rectifier Control (Postprint)

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### Abstract

For voltage-type PWM rectifiers that are currently widely employed in microgrids and industrial applications, this paper first presents a brief analysis of their fundamental principles and dual-loop control structure. The control systems are classified into two major categories based on the type of controlled variables: current and power. On this basis, traditional, modern, and intelligent control methods are comprehensively elaborated. Finally, the future development trends of voltage-type PWM rectifier control are discussed.

### Full Text

### Preamble

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## Analysis of Control Status and Development Trend of Voltage Source PWM Rectifier

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### Abstract

For voltage source PWM rectifiers that are currently widely used in microgrids and industrial fields, this paper first briefly analyzes their main principles and double closed-loop control structure. The control system is categorized into two major types based on the controlled quantity: current control and power

control. On this basis, traditional, modern, and intelligent control methods are comprehensively expounded. Finally, the development trend of voltage source PWM rectifier control is prospected.

**Keywords:** voltage source PWM rectifier, double closed-loop control, control method

## 1 Introduction

Traditional rectifier circuits are mainly composed of diodes (uncontrolled) and thyristors (phase-controlled), which generally suffer from large harmonic distortion, low power factor, and high energy loss [1]. With the rapid development of fully-controlled IGBT devices, PWM rectifiers have emerged, offering significant power factor correction and harmonic suppression effects. They are currently widely used in microgrid systems [2], active power filters [3], reactive power compensators [4], superconducting energy storage [5], AC drives [6], DC transmission [7], and unified power flow control [8]. According to the DC-side energy storage method, PWM rectifiers can be divided into voltage source rectifiers (VSR) and current source rectifiers (CSR). Due to its simple structure, low power loss, and fast dynamic response, VSR currently dominates PWM rectifier research, with its control technology being a key focus.

VSR control generally adopts a dual-loop structure with a DC voltage outer loop and an AC current inner loop, where the outer loop output serves as the inner loop command to achieve mutual control of DC voltage and AC current [9]. This paper classifies VSR control technologies based on the type of controlled quantity and reviews various VSR control techniques from three perspectives: traditional, modern, and intelligent control, while also discussing their development prospects.

## 2 VSR Dual-Loop Control Strategy

Control strategies have always been a key focus and hot topic in VSR research, mainly including two control objectives: first, stabilizing the DC-side output voltage of VSR; second, making the grid-side current sinusoidal and synchronized with the voltage phase to achieve unity power factor operation.

**(1) Current Control Strategy.** Current control strategies can be divided into indirect and direct approaches. The main representative of indirect current control is amplitude-phase control [10], which indirectly controls the current by controlling the fundamental amplitude and phase of the grid-side voltage. This approach is simple in principle, requires no current sensors, has low cost and good static characteristics, but poor robustness, and is prone to oscillation and large overshoot when disturbed. Direct current control, on the other hand, directly controls the current components in the three-phase stationary coordinate system or two-phase synchronous rotating coordinate system based on the VSR mathematical model. This approach is easy to implement with

clear physical meaning and has become the most widely used method [11]. The current response is fast, anti-interference capability is strong, and steady-state accuracy is relatively high. However, to achieve high-quality zero-error control, phase-locked and detection loops are needed to ensure accuracy.

**(2) Power Control Strategy.** Power control indirectly achieves control of VSR grid-side instantaneous active and reactive currents by controlling instantaneous active and reactive power [12]. It samples the grid voltage, estimates instantaneous power, and selects state variables from a pre-stored switching table to guide VSR bridge arm switching, thereby achieving rectification. This method eliminates the need for coordinate transformation, PWM generation, and current regulation, offering simple algorithms and good dynamic performance. However, the phase angle detection in voltage-oriented power control is susceptible to grid voltage harmonic interference. Building on this, reference [13] proposed a virtual flux-based strategy that treats the rectifier AC side as a virtual motor, effectively overcoming the influence of grid voltage harmonics on flux and ensuring control system accuracy. Estimating reactive and active power through virtual flux can also eliminate voltage sensors, reducing costs.

### 3.1 Traditional Control Methods

When designing control systems, VSR is often treated as a linear system, but its essence belongs to dynamic systems. Adopting nonlinear control technology can improve robustness and adaptability, so mature linear control is often combined with nonlinear theory.

Hysteresis current control is widely used in rectifier control due to its simple principle and convenient design [14], but it has no fixed switching frequency, making filter design relatively difficult. Subsequently, the triangular carrier comparison method [15] emerged, fixing the switching frequency and overcoming the shortcomings of hysteresis current control, but it suffers from current deviation. PID control [16] later appeared, greatly improving control system performance and is currently widely used in the control field, but parameter tuning always requires repeated trial and error. Proportional resonance control [17] eliminates the coordinate transformation link and directly controls AC quantities, but controller design still cannot avoid the tedious trial-and-error process. The above control methods currently require computer digital implementation, and sampling and calculation inevitably introduce delays. Although several predictive control techniques for compensating delays have been proposed subsequently, such as predictive current, deadbeat, one-cycle, repetitive, and model predictive control [18-22], they are generally sensitive to parameter variations and require high mathematical precision.

### 3.2 Modern Nonlinear Control Methods

The above linear control methods based on ideal models have undergone excessive simplification, resulting in limited control effects. Therefore, modern

nonlinear control theory has also been applied to PWM rectifier control.

To improve rectifier anti-interference capability, adaptive control was introduced into the control system [23]. This method can online correct its own parameters to adapt to object changes, improving robustness. However, model establishment and calculation are quite complex, and identification and correction consume time, making it difficult to apply to systems requiring high real-time performance and structural changes. Robust control [24] is an effective method for handling uncertain systems. It combines disturbance with system constraints to form an optimization problem, thereby improving system stability and controllability, but it relies too much on designer experience. Especially in high-order systems, the computation is excessive and control effects are limited. Subsequently, to solve time-varying parameter problems, variable structure control was introduced into rectifier control [25]. It can effectively reduce system order but requires high sampling frequency, making filter design difficult, and demands high parameter accuracy for each controller.

Feedback linearization decoupling control based on differential geometry [26] uses mathematical tools to transform complex nonlinear systems into linear systems. The current inner loop can achieve feedback linearization through a decoupling matrix to realize complete decoupling of active and reactive power. However, this method cannot directly limit active current, and the introduction of mathematical tools undoubtedly increases design difficulty. Based on this, inverse system control [27] was proposed without the constraints of differential geometry theory. It uses a given system to generate an auxiliary model, which is cascaded with the controlled object to form a pseudo-linear normalized system, further expanding the application range. However, this method requires the given system model to be precisely known and depends on the accuracy of the intermediate auxiliary model.

With further development of modern control theory, control methods based on Lyapunov energy function stability theory have also appeared in rectifier systems. Initially, reference [28] utilized the quantitative relationship between inductor and capacitor energy storage, as well as mathematical model and space vector constraints to derive new algorithms that solved large-scale stability problems. However, Lyapunov energy function establishment is not unique, and the optimal function is difficult to obtain. Subsequently, passivity-based control (PBC) [29] was proposed, transforming control theory from signal processing to energy processing. Based on the Euler-Lagrange (EL) mathematical model, it forces the system total energy to track the expected energy function through energy shaping and damping injection, achieving the goal of making the closed-loop control system passive. The entire design process eliminates the need to find Lyapunov functions, but constructing the storage function destroys the Lagrange structure and affects its stability. PBC control based on Hamiltonian systems [30] uses the port-controlled Hamiltonian (PCH) model to represent the system, utilizes the concept of energy dissipation to transform the introduced system into a port-controlled dissipative Hamiltonian system (PCHD),

and combines feedback stabilization principles to find feedback control, solving the problem of Lagrange structure destruction. However, variables such as the expected Hamiltonian function, interconnection, and damping matrix lack necessary physical meaning, computation is complex, and practical application is difficult. Finally, the backstepping control method [31] appeared, aiming at Lyapunov energy function convergence, decomposing complex nonlinear systems into several subsystems, using virtual control quantities for static compensation, and designing each subsystem recursively from front to back. The latter subsystems ensure the former subsystems reach positive definiteness, and the entire design ensures globally consistent asymptotic stability of the system, solving the construction problem of Lyapunov energy functions. It does not require nonlinear systems to satisfy matching conditions, expanding the application range, but requires high-precision object mathematical models, and parameter changes must also satisfy linearization conditions, greatly increasing computation and implementation difficulty.

### 3.3 Intelligent Control Methods

The above traditional or modern control methods are all based on the mathematical model of PWM rectifiers, comprehensively considering various factors from different angles to control the system, with control strategies varying according to different control objectives. For some system models without strict mathematical description, lacking necessary physical meaning, and having no discernible patterns, existing control methods usually cannot be directly applied. Therefore, new intelligent control methods have emerged.

Currently, the most widely used intelligent control methods are mainly two: fuzzy control and neural network control. Fuzzy control imitates human thinking patterns, fuzzifying precise quantities, obtaining output through reasoning operations, and then using defuzzification to obtain deterministic output values [32]. It does not rely on the mathematical model of the controlled object, has strong adaptability to system parameter changes, and high robustness. However, its design accuracy is constrained by the quality of control rules, has significant subjective human factors, and makes optimal control difficult to achieve. Neural network-based control imitates the brain's information processing method, distributing function mapping relationships in network connection weights and node functions, setting input and output data as learning samples, adjusting connection weights of each layer, making the relationship between input and output arbitrarily approximate the expected nonlinear dynamic system [33]. It has strong self-learning ability and high fault tolerance, but lacks clear physical meaning, has no scientific theoretical basis, and requires high data signal processing during control.

Intelligent control methods each have their advantages and limitations and can be reasonably selected according to application scenarios. Currently, integrating the complementary advantages of various intelligent control methods into higher-intelligence solutions has become a new trend, such as fuzzy neural control

[34], which combines fuzzy control with neural network control, learning from each other's strengths to form more intelligent control solutions. This control philosophy will become the general trend for VSR intelligent control.

## 4 Research Prospects for VSR Control Technology

With the widespread application of PWM rectifiers, research on their control technology will continue to develop, mainly manifested in the following aspects:

**(1) Research on VSR Control Technology Under Unbalanced Grid Conditions [35-37].** When the grid is in an unbalanced state, the negative sequence component of voltage causes low-order harmonics in VSR grid-side current and DC-side voltage. Control technologies under balanced grid conditions are no longer applicable and seriously affect normal operation, so corresponding new control technologies need to be proposed. The main idea of current research is to introduce corresponding modules and algorithms to improve or suppress unbalanced factors, making them reach an equivalent balanced state.

**(2) Research on CSR Control [38].** The rapid development of superconducting technology has solved the efficiency problem of CSR with DC-side energy storage elements as inductors. Its control of current is more direct, dynamic response is faster, and volume and cost have been significantly improved. Therefore, CSR has broader application prospects in medium and high-power occasions, and its control technology research will also become a hot topic.

**(3) Research on New Control Methods.** With the rapid development of power electronics, microprocessors, computers, and other technologies, complex, cumbersome, and computationally intensive algorithms can be gradually implemented, making it possible to find new control methods and improve traditional control. It is difficult to solve many problems in practical applications with only one scheme, so integrating different types of control methods into comprehensive control strategies is also a new trend. For example, using neural network control on the grid side to offline train a controller to replace the hysteresis comparator not only maintains the robustness and rapidity of the hysteresis controller but also can limit the switching frequency of switching devices [39]. In summary, combining different methods' strengths, drawing on each other's advantages, and integrating them into more effective new control solutions is a development direction for VSR control technology.

## 5 Conclusion

This paper elaborates on the control methods of voltage source PWM rectifiers in detail, scientifically classifies them, and comprehensively analyzes the principles, advantages, and disadvantages of various methods. On this basis, it analyzes the development direction of VSR control in response to some unresolved problems and deficiencies. It is foreseeable that with the continuous development of the rectifier industry and digital technology, the application prospects of VSR will

be broader.

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