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A review of Direct Power Control Technologies for Three-Phase Voltage PWM Rectifiers

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Abstract:
This article reviews the direct power control methods of three-phase voltage-type PWM rectifiers, including those based on virtual flux linkage (VF-DPC), model prediction (MP-DPC), and dual switch table. First, the basic topology of the three-phase voltage-type PWM rectifier is introduced, and its key role in the energy conversion process is explained. Subsequently, the implementation mechanisms, advantages and disadvantages of various direct power control strategies and their performance in practical applications are comparatively analyzed. Finally, the article looks forward to future development trends in three-phase voltage-type PWM rectifier direct power control technology, and points out directions for further research, including algorithm optimization, hardware implementation, and broader application promotion.
Keywords: PWM, DPC, Virtual flux, Model predictive, Dual-switch table

1. Introduction

In the realm of power electronics, rectifiers are key devices for AC/DC conversion. Since the 1980s, the focus has shifted to Pulse Width Modulation rectifiers, noted for their superior performance. This interest was ignited by advances in PWM techniques and self-commutating devices. In 1984, Akagi Hirofumi and colleagues introduced a PWM rectifier-based reactive power compensation strategy, foundational for early voltage-type PWM rectifiers [1]. By the late 1980s, further developments were made by A.W. Green and others who offered dynamic mathematical models for PWM rectifiers, utilizing coordinate transformation and sophisticated control strategies [2]. PWM rectifiers continue to be a prominent research topic, influencing fields like active power filters, HVDC transmission, and Unified Power Flow Controllers.

Recent years have seen a surge in interest in direct power control of three-phase voltage-type PWM rectifiers, known for its straightforward method, strong anti-interference capability, and excellent dynamic performance, which allows for decoupling control of active and reactive power [3]. This article will introduce the topology of the main circuit of the three-phase voltage-type PWM rectifier, analyze and compare the control strategy based on DPC, and on this basis, look forward to the control strategy of the PWM rectifier.

2. Topology of three-phase voltage PWM rectifier

Currently, for applications requiring lower power, emphasis has shifted towards reducing the number of power switches and enhancing direct current output characteristics [4]. In contrast, high-power applications predominantly concentrate on multilevel technology, combinations of converters, and soft-switching techniques [5].

Two-level and three-level PWM rectifier structures represent mature topologies with widespread adoption in industrial applications [6]. Figure 1 shows the three-phase half-bridge VSR topology [7]. During the working process, the working states of the two switching tubes of each bridge arm are exactly opposite and in a complementary state. The voltages u_{a0}, u_{b0} and u_{c0} at the midpoint of each phase bridge arm have two levels: 0 and U_{dc}.

The conventional two-level topology, limited by higher harmonic content at low switching frequencies, has been improved with a three-level VSR topology using midpoint clamping. This approach uses series-connected power switches and diode clamping to achieve three-level modulation, significantly reducing harmonic generation and suiting high-voltage applications. Figure 2 shows the topology of the three-phase three-level VSR main circuit. Each phase bridge arm is composed of four switching tubes and two clamping diodes. The voltages u_{a0}, u_{b0}

and u_{c0} at the midpoint of each phase bridge arm have three levels: $-\frac{U_{dc}}{2}$, 0 and $+\frac{U_{dc}}{2}$.

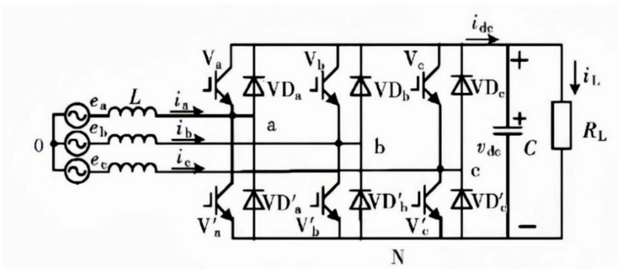

Figure 1: Three-phase half-bridge VSR topology

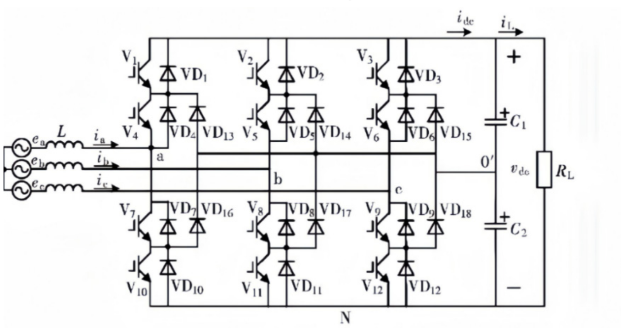

Figure 2: Three-phase three-level VSR topology

3. Direct power control method (DPC)

Direct Power Control(DPC) systems employ a dual-loop control strategy, the external loop maintains a stable voltage on the DC side, while the internal loop focuses on controlling instantaneous power. Within this framework, the aim of DPC PWM rectifiers is to precisely regulate the input currents by modulating instantaneous active and reactive powers, while keeping the AC side voltage constant. This methodology enables the rectifier to deliver the necessary power factor and direction of power flow, fulfilling the system's performance criteria [8].

3.1 Direct power control (VF-DPC) based on virtual flux linkage

The principle of the virtual flux control method is to treat the grid side of the PWM rectifier as a virtual AC motor [9]. The active power *P* and reactive power *Q* of the motor are determined by applying the voltage and current state variables of the motor, as well as motor parameters such as stator resistance R_s and inductance L_s, which are directly controlled. The system control block diagram of VF-DPC is shown in the Figure 3.

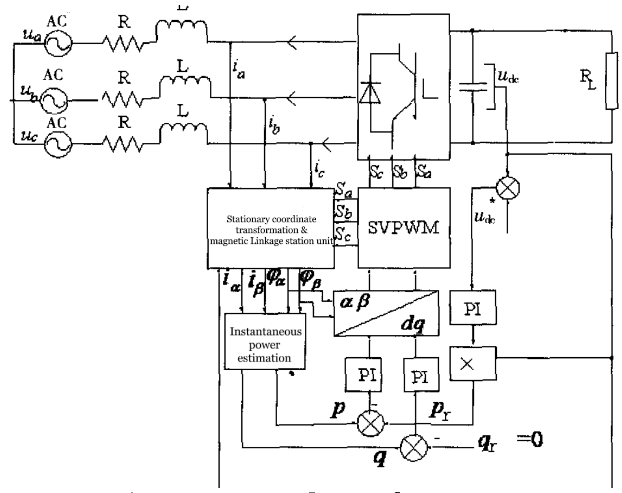

Figure 3: Topology of VF-DPC

The calculation model (1) of the flux linkage can be obtained by integrating the voltage equation and the time derivative term of the current.

$$\psi_{L\alpha} = \int \left(u_{s\alpha} + L\frac{di_{L\alpha}}{dt} \right) dt \tag{1a}$$

$$\psi_{L\beta} = \int \left(u_{s\beta} + L\frac{di_{L\beta}}{dt} \right) dt \tag{1b}$$

Furthermore, the reactive power Q and the active power P can be calculated by the following equations:

$$Q = -\frac{d\psi_\alpha}{dt} i_\beta + \frac{d\psi_\beta}{dx} i_\alpha + \omega\left(\psi_\beta i_\alpha - \psi_\alpha i_\beta \right) \tag{2}$$

$$P = \frac{d\psi_\alpha}{dt} i_\alpha + \frac{d\psi_\beta}{dt} i_\beta + \omega\left(\psi_\alpha i_\beta - \psi_\beta i_\alpha \right) \tag{3}$$

Because the grid voltage is a three-phase sinusoidal balanced symmetrical voltage, the amplitude of the flux linkage is constant, that is, $\frac{d|\psi|}{dt} = 0$. The calculation formula of instantaneous active and reactive power is:

$$P = \omega\left(\psi_{L\alpha} i_\beta - \psi_{L\beta} i_\alpha \right) \tag{4}$$

$$Q = \omega\left(\psi_{L\alpha} i_\alpha + \psi_{L\beta} i_\beta \right) \tag{5}$$

The virtual flux linkage-based direct power control (VF-DPC) strategy presents several advantages in the field of power electronics. This approach significantly reduces reliance on high sampling rates, which curtails data processing needs and facilitates system implementation. Additionally, it effectively minimizes total harmonic distortion of the current, enhancing power quality even under less-than-ideal grid voltage conditions. VF-DPC also simplifies control loop design by eliminating the need for traditional PI regulators, and it adapts well to voltage fluctuations, thereby enhancing system robustness.

Conversely, VF-DPC faces certain challenges and limitations. It does not resolve the issue of unfixed switching frequencies, which could impact the system's electromagnetic compatibility and noise levels. The strategy's performance heavily relies on the accurate estimation of virtual flux linkages, necessitating robust algorithmic support. Furthermore, implementing VF-DPC requires complex control algorithms, increasing software development complexity and demanding higher processor capabilities, complicating its application and optimization in practical settings.

3.2 Direct power control based on double switch table

Traditional switch tables are designed for simultaneous control of active and reactive power, in order to balance P & Q using a single voltage vector [10]. However, in practice, the selected voltage vector might regulate active power more effectively than reactive power, which might impact the overall response speed of the system.

To address issues such as the reactive power deviation not being confined within the wide range of the hysteresis loop, an improved DPC method introduces a double switch table selection strategy. This method sets a deviation threshold for reactive power at M. For small reactive power deviation (| △ Q|<M), the traditional switch table I is used to minimize system switching losses. For larger deviations (| △ Q|≥M), switch table II that has a stronger reactive power adjustment capability, is employed to quickly confine the reactive power within the hysteresis loop's limits. Figure 4 shows the topology of double switch table based DPC.

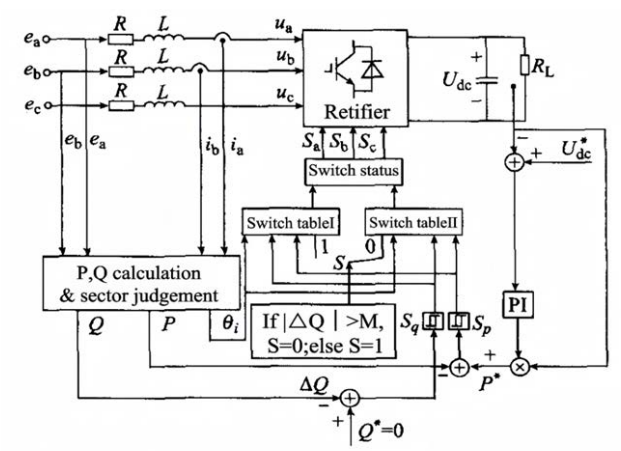

Figure 4: DPC topology based on double switch table strategy

This strategy proposes a new simplified method to determine the sector where the power supply voltage phasor $\dot{u}_s$ is located. This method only needs to determine the spatial position of $\dot{u}_s$ based on the detected two phase-voltages e_a and e_b (As shown in Figure 5) by analyzing their relationship with the phase voltage peak U_m, significantly simplifying the traditional calculation process.

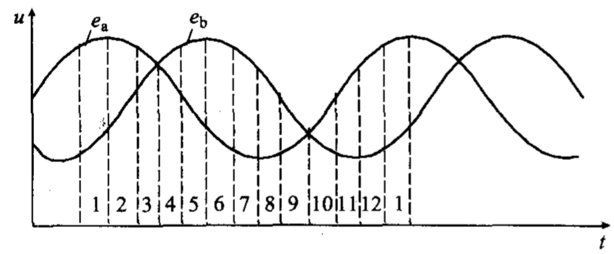

Figure 5: Phase voltage at alternating side

As shown in Table 1, the DPC improvement method proposed in this strategy directly determines the sector where the power supply voltage phasor $\dot{u}_s$ is located according to the method in Table 1.

Table 1: Sector division of power-source voltage vector

Voltages judgment	Conditions		Sector
$e_a \geqslant 0, e_b \leqslant 0$	$e_a + e_b \leqslant 0$	$e_a - e_b \leqslant 1.5U_m$	θ_{11}
		$e_a - e_b > 1.5U_m$	θ_{12}
	$e_a + e_b > 0$	$e_a - e_b > 1.5U_m$	θ_1
		$e_a - e_b \leqslant 1.5U_m$	θ_2
$e_a \geqslant 0, e_b > 0$	$e_a - e_b \geqslant 0$		θ_3
	$e_a - e_b < 0$		θ_4
$e_a < 0, e_b > 0$	$e_a + e_b > 0$	$e_b - e_a < 1.5U_m$	θ_5
		$e_b - e_a \geqslant 1.5U_m$	θ_6
	$e_a + e_b < 0$	$e_b - e_a \geqslant 1.5U_m$	θ_7
		$e_b - e_a < 1.5U_m$	θ_8
$e_a < 0, e_b \leqslant 0$	$e_a - e_b < 0$		θ_9
	$e_a - e_b \geqslant 0$		θ_{10}

Double switch table DPC systems solve the problem of periodic fluctuations in reactive power inherent in traditional DPC strategies, optimizing efficiency and minimizing switching losses by utilizing different switching phasors that suit the system's active and reactive power needs. This strategy enhances the starting transient by reducing fluctuations in DC-side voltage and power during motor starting, thus mitigating dynamic instability. It also optimizes steady-state performance by effectively suppressing DC voltage fluctuations under load interference and improves power tracking speed and enhances control immediacy by independently adjusting active and reactive power.

However, integrating an additional switch table increases complexities and potential drawbacks. The enhanced control scheme demands more complicated algorithm design and places higher demands on switching devices due to frequent state changes needed for independent power adjustments. Additionally, this independent regulation of power can lead to potential control delays, especially under rapidly changing power conditions, posing challenges for maintaining system stability and responsiveness.

3.3 Direct power control based on three-vector model prediction

Model Predictive Control (MPC) utilizes a precise mathematical model of the pulse width modulation rectifier to predict key electrical parameters. This control strategy develops an objective function tailored to meet the specific requirements of the system. By optimizing this objective function, MPC accurately determines the optimal electromotive force vector [11].

When integrated with Direct Power Control (DPC), it forms Model Predictive Direct Power Control (MP-DPC) [12]. This approach redefines the objective function to minimize the error between the actual and target instantaneous power values. Unlike traditional DPC, MP-DPC does not use a preset switching table. Instead, it selects the electromotive force vector by optimizing the objective function. The three-vector MP-DPC algorithm employs two adjacent non-zero vectors and one zero vector within a control cycle, enhancing the sinusoidal quality of the grid-side current and reducing instantaneous power ripple while maintaining a fixed switching frequency [13]. Figure 6 illustrates the MP-DPC control block diagram.

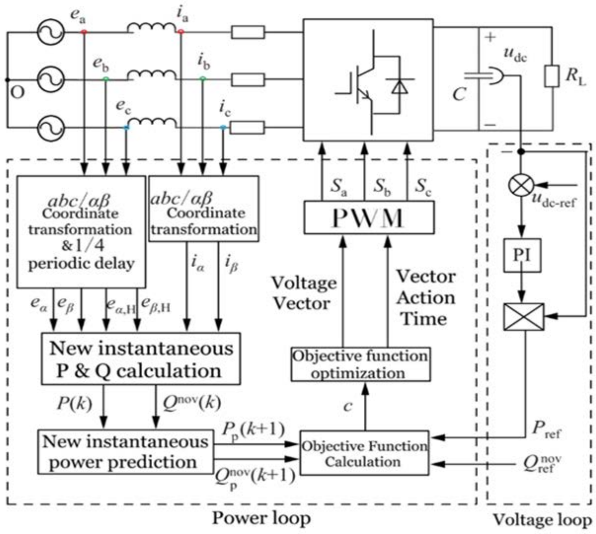

Figure 6: Control diagram of MP-DPC

If the power grid is unbalanced and only the fundamental wave component of the grid electromotive force is considered, E can be expressed in the dq coordinate system as:

$$E = e^{j\omega t}E_{dq}^{P} + e^{-j\omega t}E_{dq}^{N} \tag{6}$$

According to the new instantaneous power theory, the expression of the new instantaneous power in the two-phase stationary αβ coordinate system is equation (7) and the change rate of the new instantaneous active and reactive power can be expressed as equation (8).

$$\begin{bmatrix} P \\ Q^{nov} \end{bmatrix} = 1.5\begin{bmatrix} e_\alpha & e_\beta \\ e_{\alpha,H} & e_{\beta,H} \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{7}$$

$$\begin{cases} \dfrac{dP}{dt} = 1.5\left(\dfrac{de_\alpha}{dt}i_\alpha + e_\alpha\dfrac{di_\alpha}{dt} + i_\beta\dfrac{de_\beta}{dt} + e_\beta\dfrac{di_\beta}{dt}\right) \\ \dfrac{dQ^{nov}}{dt} = 1.5\left(\dfrac{de_{\alpha,H}}{dt}i_\alpha + e_{\alpha,H}\dfrac{di_\alpha}{dt} + i_\beta\dfrac{de_{\beta,H}}{dt} + e_{\beta,H}\dfrac{di_\beta}{dt}\right) \end{cases} \tag{8}$$

Under the condition of unbalanced power grid, the differential form of vector E is:

$$\frac{dE}{dt} = j\omega E_{dq}^{P}e^{j\omega t} - j\omega E_{dq}^{N}e^{-j\omega t} \tag{9}$$

Putting equation (6) into equation (9), equation (10) can be derived. From Equation (10), the rates of change of the α and β components of the vector E in the αβ coordinate system can be derived. By combining Equations (8), (11) the differential expression (12) for the novel instantaneous power can be obtained.

$$\frac{dE}{dt} = -\omega E_H \tag{10}$$

$$\begin{cases} \dfrac{de_\alpha}{dt} = -\omega e_{\alpha,H}; \\ \dfrac{de_\beta}{dt} = -\omega e_{\beta,H} \end{cases} \tag{11}$$

$$\begin{cases} \dfrac{2dP}{3dt} = \dfrac{1}{L}\left(e_\alpha^2 + e_\beta^2 - e_\beta e_\beta\right) - \dfrac{R}{L}R - \omega Q^{nov}; \\ \dfrac{2dQ^{nov}}{3dt} = \dfrac{1}{L}\left(e_\alpha e_{\alpha,H} + e_\beta e_{\beta,H} - v_\alpha e_{\alpha,H} - v_\beta e_{\beta,H}\right) - \dfrac{R}{L}Q^{nov} + \omega P \end{cases} \tag{12}$$

This strategy offers several practical advantages, including low harmonic content, which improves power quality by reducing the harmonic component of the grid-side current. It also minimizes instantaneous power pulsations, enhancing system stability, and maintains a fixed switching frequency, which simplifies driver design and reduces costs. Additionally, it is well-suited for unbalanced power grid conditions, demonstrating strong adaptability.

Correspondingly, the complexity of MP-DPC control is higher than that of traditional methods, demanding increased computing resources and necessitating enhancements to the control system. This complexity also leads to higher initial implementation costs due to the need for high-performance hardware. Furthermore, the system's effectiveness heavily relies on accurate models and parameters, making it sensitive to model errors and parameter uncertainties. These aspects underscore the need for ongoing development and refinement of control strategies for three-phase rectifiers.

4. Prospects of direct power control

As industrial systems increasingly require higher power quality and system efficiency, traditional direct power control (DPC) strategies are being rigorously re-evaluated and optimized. Recent research on DPC strategies for three-phase rectifiers has focused on several promising areas. To address issues like high current harmonics and power fluctuations under unbalanced grid conditions, new model predictive control strategies are being developed. These strategies optimize the objective function to select the optimal voltage vector. Additionally, the application of nonlinear control strategies is becoming an important trend. Although nonlinear control theory is still immature, its potential for providing accurate linearization models and decoupling active and reactive power components is promising. Furthermore, sensorless control technology, which uses current observers to estimate grid-side current, has gained attention for its ability to enhance dynamic performance and reduce costs. Finally, integrating intelligent control technologies such as fuzzy logic and neural networks can create more effective control schemes. These techniques leverage the intelligent reasoning of fuzzy logic and the self-learning capabilities of neural networks to potentially further improve rectifier performance.

5. Conclusion

In summary, the development of direct power control for three-phase PWM rectifiers has evolved from basic approaches to more complex and efficient strategies that meet dynamic performance requirements and power quality standards. Innovations such as virtual flux linkage-based DPC, model prediction-based DPC, and dual-switch table-based DPC have brought significant improvements, including reduced harmonic distortion and enhanced system responsiveness. These developments highlight the critical role of precise control and optimization algorithms in modern power electronics technology. Looking ahead, future research may focus on improving control algorithms, integrating with renewable energy sources, and enhancing higher power system applications to ensure that DPC technology can continue to meet the growing needs of industrial systems.

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