Review of Low Carrier Ratio Converter System*

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Abstract: With the rapid development of new energy power generation and high-power traction technology, the voltage and power levels of converter devices have been continuously improved, and the application of high-power converters is becoming increasingly widespread. However, high-power converters are affected by switching losses and heat dissipation, meaning they are not suitable for high carrier conditions. Therefore, research of low carrier ratio converter systems has received increased attention. Based on existing research, the problems of large current harmonics, low observation accuracy, and poor stability that may occur at low carrier ratios are explained. In addition, the topologies, modulation strategies, and control methods of the low carrier ratio converter system are analyzed and classified. Finally, future research directions of low carrier ratio converter systems are proposed.

Keywords: Converter, low carrier ratio, modulation strategy, control method

1 Introduction

With the continuous growth of new energy power generation capacity, high-power converters are increasingly being used in new energy power generation and associated grid connection technology [1-5]. However, high voltages and currents require better switching loss performance from converters in high-power applications. Consequently, converters must work at a lower carrier ratio.

High-speed motors have the advantages of small size, high-power density, and excellent dynamic response. Therefore, they are widely used in modern electric locomotives, aerospace, and other fields [6-10]. However, they are limited by conditions such as heat dissipation and losses. The switching frequency of power switching devices cannot be set too high, which means the system should work at a low carrier ratio. If a traditional converter topology and modulation strategy are selected, the harmonic content of a system will increase under low carrier ratio conditions, affecting the performance of high-speed motors [11-13]. If filter circuits are added to meet the harmonic requirements of the system, the volume and cost of the converter will increase, and affect the working efficiency of the system [14]. Traditional position sensors have the disadvantages of large size, high cost, and poor anti-interference ability. Therefore, high-speed motors usually use sensorless control to reduce the cost of the system. The theory of sensorless control is well developed under high carrier ratios [15-17]. However, the observer accuracy of the system will decrease, and the system stability will worsen in the case of low carrier ratios [18]. Moreover, the system's steady-state performance and dynamic performance need to be improved in the case of low carrier ratios. Moreover, it has been difficult to achieve a breakthrough in power switching device manufacturing technology. Therefore, it is particularly important to discuss the topologies, modulation strategies, and control methods of the converter under low carrier ratios.

This paper presents a survey of the topologies of low carrier ratio converter system, the related modulation techniques, and control methods. The performance of the low carrier ratio converter system has been analyzed in detail. The paper is organized as follows: Section 2 summarizes and analyzes the topology of related applications. Section 3 describes the low carrier ratio modulation strategies from pulse width modulation, space vector modulation, and other special modulation strategies. Section 4 presents the control methods under various low carrier ratio conditions. Section 5 proposes the development of a low carrier ratio converter system. Section 6 concludes the paper.

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2 Topologies

2.1 Traditional PWM converter topology

The traditional pulse width modulation (PWM) converter topology, as shown in Fig. 1, is currently mature in both application and research. It has the advantages of fast dynamic response, excellent input current waveform, and adjustable input current power factor [19]. However, this topology has high current total harmonic distortion (THD) and switching losses at low carrier ratios, and needs to be improved through modulation strategies and control methods.

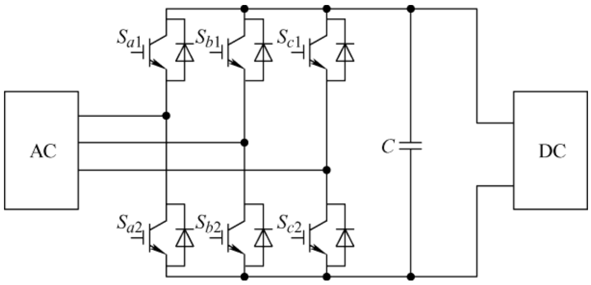


Fig. 1 Traditional PWM converter topology

2.2 Multilevel converter topology

Fig. 2 shows a multilevel converter topology. The increase in the number of levels improves the output waveform of the multilevel converter. Therefore, the multilevel converter can obtain the same THD output voltage waveform at a lower switching frequency than the two-level converter at a high switching frequency. This reduces the switching loss of the multilevel converter improves the working efficiency [20-23]. Each power switching device of the multilevel converter only needs to withstand a single stage voltage. Therefore, the low-voltage devices can be used to achieve a high voltage and high-power output. However, the multilevel converter has disadvantages too, such as unbalanced capacitor voltage, high cost, and difficult controllability.

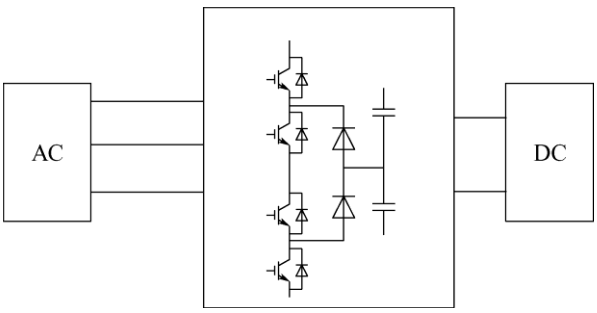


Fig. 2 Multilevel converter topology

2.3 Impedance source converter topology

Fig. 3 shows an impedance source converter topology. The impedance source converter not only implements the functionality of a traditional PWM converter, but also the buck-booster conversion of the input voltage. It has a common ground structure for the input and output. This structure makes assembly easy and reduces electromagnetic interference. Its unique impedance source network and the matching of the inverter bridge arm are equivalent to a straight state, which makes it possible to increase the equivalent switching frequency of the system. Moreover, the impedance source inverter is more reliable [24-27].

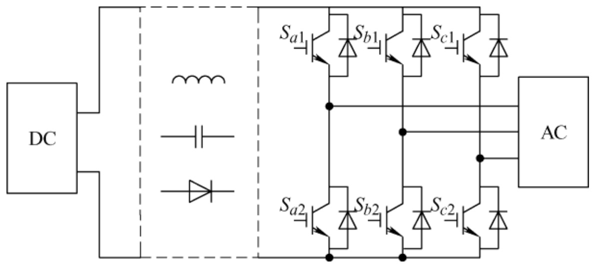


Fig. 3 Impedance source converter topology

2.4 MMC topology

Fig. 4 shows a modular multilevel converter (MMC) topology. This topology effectively avoids the dynamic and static voltage equalization problems caused by the direct series and parallel connection of power switching devices. Moreover, the modular power sub-module is easier to layout in engineering. It has the advantages of low switching frequency, small output voltage change rate, and excellent system

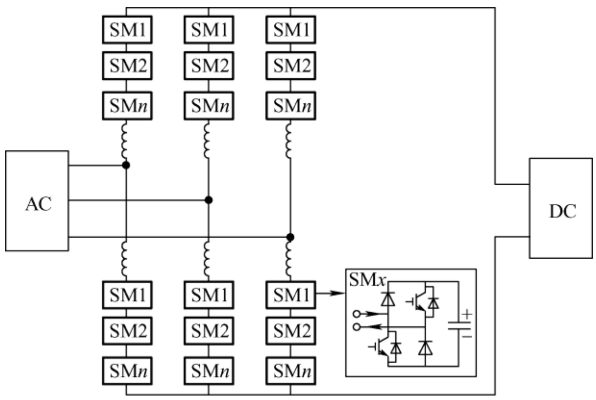


Fig. 4 MMC topology

electromagnetic compatibility [28-29]. It also has the disadvantages of circulating current suppression, interphase circulating current suppression, and sub-module capacitor voltage equalization.

2.5 SWISS rectifier topology

Fig. 5 shows a SWISS rectifier topology. This topology can achieve unit power factor operation, and has the advantages of small switching loss, low switching stress, and low current harmonic distortion. This topology is a buck topology. Compared with the boost system, it can realize a wider output voltage control range and can start directly [30-31]. However, the disadvantage is that the energy of this topology is unidirectional and the control method is complicated.

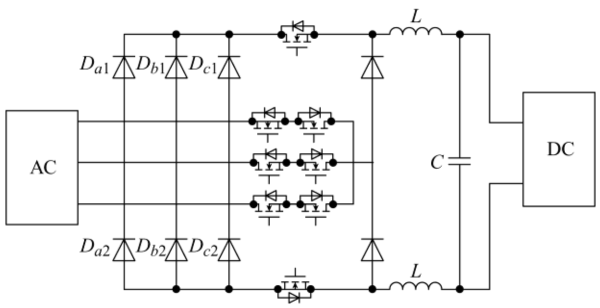


Fig. 5 SWISS rectifier topology

2.6 Improved PWM rectifier topology

Ref. [32] presented an improved PWM rectifier topology with a low carrier ratio, as shown in Fig. 6. This topology improves the equivalent switching frequency of the rectifier by replacing the single tube of the traditional PWM rectifier with a simple series-parallel approach, which makes it easy to filter high-frequency harmonics while the sinusoids of the input current are also good. However, the control of this topology is relatively complicated, the generation of driving signals being particularly difficult.

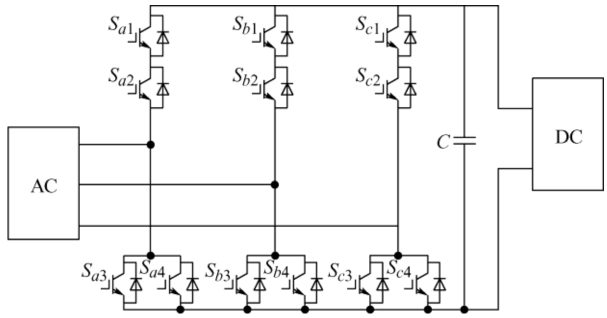


Fig. 6 Improved PWM rectifier topology

This section lists several different topologies for low carrier ratio converter systems. There are advantages and disadvantages to each of them, but the most widely studied and applied at present is the traditional PWM converter topology. The other topologies are based on the improvement of the traditional PWM converter topology. The topologies mentioned in Refs. [20-23, 28-32] reduce the switching frequency by increasing the number of switch tubes. The impedance source converter topologies mentioned in Refs. [24-27] generally increase the degree of freedom of the system by adding a passive network.

3 Modulation strategies

Modulation strategies affect the power switching on and off. They are the main factors of harmonic generation in converter system, and directly affect the working state of converter systems with low carrier ratios. They are a key technology related to the operating performance of converter systems with low carrier ratios.

3.1 Pulse width modulation

3.1.1 Hybrid pulse width modulation strategy based on current harmonic optimization

The traction drive systems of rail vehicles have characteristics of high power, low switching frequency and a wide speed range. Ref. [33] proposed a hybrid pulse width modulation strategy for current harmonic minimum pulse width modulation (CHMPWM), as shown in Fig. 7. This strategy first used a combination of a genetic algorithm and a numerical iterative method to optimize the switching angle. Then, based on the calculation results of the switching angle, the hybrid pulse width modulation strategy of “asynchronous modulation +15 frequency division common synchronous modulation +9, 7, 5, 3 frequency division CHMPWM + single pulse modulation” was used to improve the output characteristics of the converter. The overall optimization of the current harmonics used by CHMPWM makes the switching between modes less affected by harmonics. It also exhibits good working performance at low switching frequencies with a lower current total harmonic distortion rate.

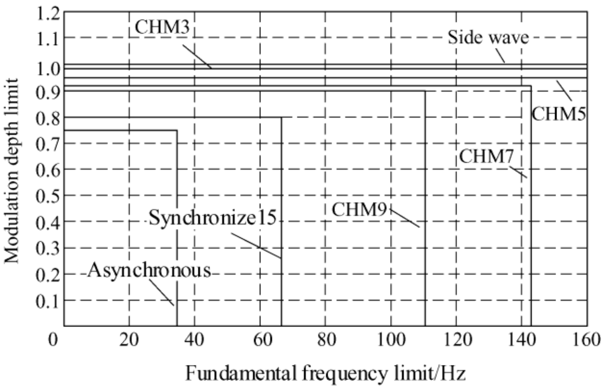
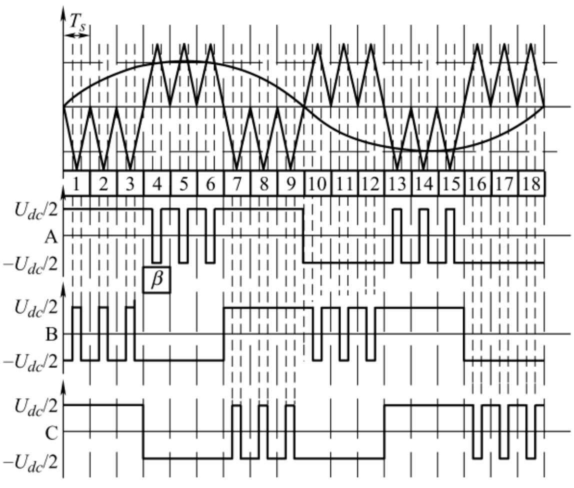


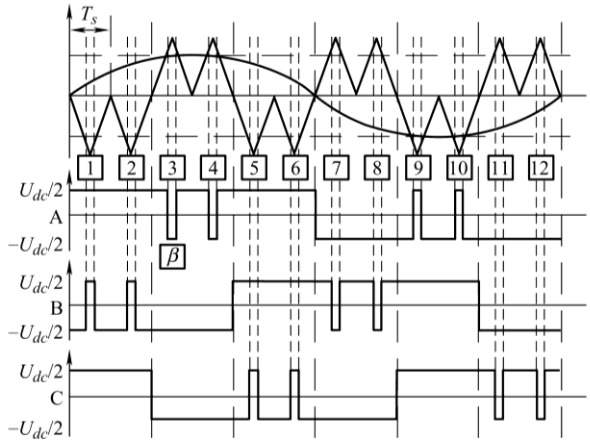
Fig. 7 Current harmonic minimum pulse width modulation

3.1.2 The central 60° synchronous modulation

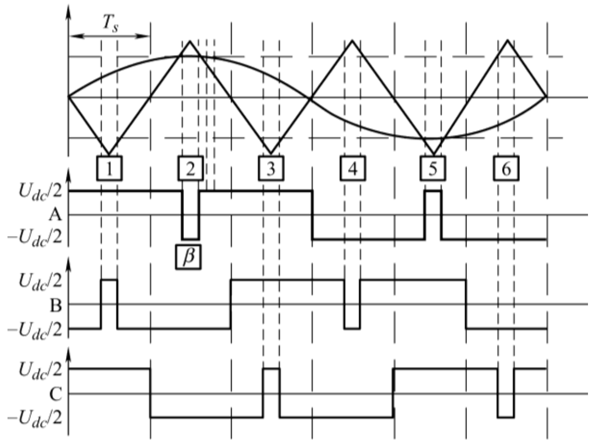
The central 60° synchronous modulation strategy is a non-optimized PWM applied to multi-mode pulse width modulation, as shown in Fig. 8 [34-35], where U_{dc} and T_s are the DC bus voltage and switching period, respectively. This strategy reduces the switching frequency by modulating 60° in the middle of the positive and negative half cycles of each modulation wave. It also increases the fundamental wave output voltage and maintains the output voltage symmetry. The traditional optimized PWM has the disadvantages of complicated switching angle calculations and difficult implementation. The realization of central 60° synchronous modulation is relatively easy and can be calculated in real time.



(a) Seven frequency division



(b) Five frequency division



(c) Three frequency division

Fig. 8 The central 60° synchronous modulation

3.1.3 Synchronous optimal PWM

Synchronous optimal pulse width modulation (SOP) is an emerging technology. It can reduce the switching frequency without affecting harmonic distortion. The switching angle is determined mainly by considering all possible low-order harmonic components, and is used as a variable to establish an equation to optimize it to keep the output voltage or current THD within a certain range. The SOP of the high-level inverter was realized in Ref. [36] using a generalized equation. It can operate at a very low switching frequency while maintaining the inherent DC link balance. Compared with the generalized SOP method, the SOP technology proposed in Refs. [37-38] further reduces the switching frequency of the device without affecting the current quality. Moreover, the SOP technology proposed in Ref. [39] overcomes the disadvantages of unequal switching frequencies of general SOP devices.

3.2 Space vector modulation

Space vector modulation (SVM) is a modulation technology that originated in a three-phase motor control system. Its principle is based on the basic voltage vector being formed by the power switching device of the three-phase rectifier. The desired voltage vectors are combined to approximate the ideal circular path of the magnetic flux [40]. SVM has the advantages of good harmonic suppression effects at a certain switching frequency. It is also easy to realize digitally.

3.2.1 Non-dead-time space vector modulation strategy

Ref. [41] proposed a non-dead-time SVM strategy based on a three-phase PWM rectifier, as shown in Fig. 9, where S_{a1}^{**}, S_{a2}^{**} are two complementary driving signals, respectively, output by the SVM. S'_{a1}, S'_{a2} are the upper and lower bridge arm blocking signals, S_{a1}^{*}, S_{a2}^{*} are the final driving signals of the upper and lower arms, and the shaded parts indicate high-frequency pulses. Compared with the continuous SVM strategy, the average switching frequency of this discontinuous SVM strategy is reduced. The setting without a dead zone can avoid the negative impact brought about by the setting of the dead zone, which can improve the working efficiency of the rectifier to a certain extent.

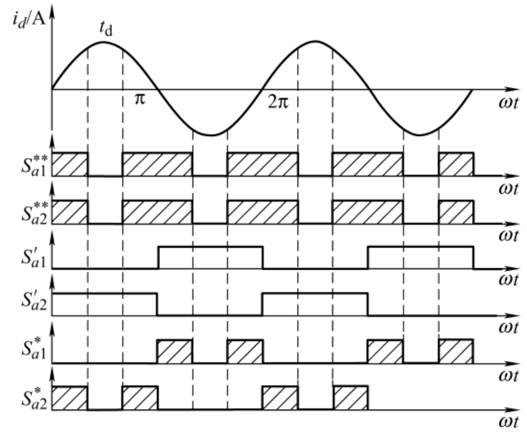


Fig. 9 Non-dead-time space vector modulation strategy

3.2.2 Synchronized space vector PWM for three level neutral point clamped

Ref. [42] proposed a synchronous space vector pulse width modulation (SVPWM) algorithm for a three-level neutral-point clamped (NPC) inverter with a low carrier ratio as shown in Tab. 1. The algorithm uses 1/4 period symmetry as an unnecessary condition and the output line voltage weighted total harmonic distortion as a performance evaluation index. A new switching sequence is designed to achieve better harmonic performance in some modulation sections.

The algorithm corresponds to a specific switching sequence for a specific reference vector. Each modulation algorithm keeps the output harmonic content at a low level while reducing the switching frequency.

Tab. 1 Switch sequence

Category	SN	θ_p/(°)	θ_v/(°)	Switching sequence
Syn2_1	2	30	[15, 45]	$V_sV_bV_m \to V_mV_bV_s$
Syn2_2			[0, 30]	$V_sV_b \to V_mV_bV_s$
Syn3_1	3	20	[10, 30, 50]	$V_sV_bV_m \to V_sV_m\,V_s \to V_mV_b\,V_s$
Syn3_2			[0, 20, 40]	$V_sV_b \to V_sV_bV_m \to V_mV_b\,V_s$
Syn4_1	4	15	[7.5, 22.5, 37.5, 52.5]	$V_sV_m\,V_b \to V_sV_bV_m \to V_mV_b\,V_s \to V_bV_mV_s$
Syn4_2			[0, 15, 30, 45]	$V_sV_b \to V_sV_bV_m \to V_sV_m\,V_s \to V_mV_b\,V_s$
Syn5_1	5	12	[6, 18, 30, 42, 54]	$V_sV_m\,V_b \to V_sV_bV_m \to V_sV_m\,V_s \to V_mV_b\,V_s \to V_bV_mV_s$
Syn5_2			[0, 12, 24, 36, 48]	$V_bV_sV_b \to V_sV_bV_m \to V_sV_m\,V_s \to V_mV_b\,V_s \to V_sV_bV_m$

3.2.3 Asymmetric space vector modulation

Ref. [43] proposed an improved asymmetric space vector modulation (ASVM) for a two-level voltage source converter with a low carrier ratio. This strategy reduces the output current THD by adding two switching pulses in a basic period near the zero crossing of each phase voltage. Compared with the traditional ASVM, the improved ASVM can significantly reduce the output current THD under a high modulation index.

3.3 Other special modulation strategies

3.3.1 Carrier phase shift modulation

The carrier phase-shifted modulation switching signal is generated by comparing a sine-modulated wave having a smaller amplitude than the triangular carrier with multiple triangular carriers. Fig. 10 shows the high-side switch signal of the carrier phase shift modulation in a five-level topology. It has the advantages of high equivalent switching frequency, good harmonic characteristics, simple control, and good output waveform quality [44].

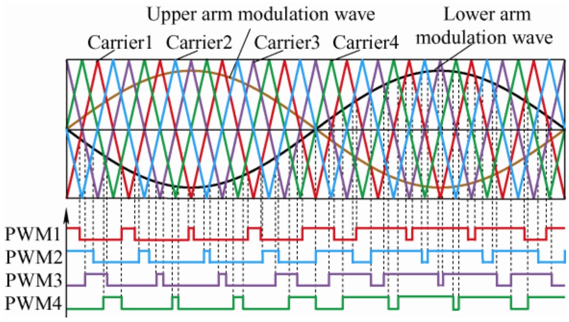


Fig. 10 Carrier phase shifting bridge arm switching signal

3.3.2 Specific harmonic elimination method

The specific harmonic elimination method (SHEPWM) obtains the magnitude of the fundamental wave by expanding the Fourier series of the voltage waveform. Then, it makes certain specific low-order harmonic amplitudes zero to obtain a set of nonlinear transcendental equations, after which the nonlinear phase equations are solved using the algorithm to obtain the pulse phase angle solution. Finally, the PWM pulse is generated to eliminate the specific low harmonics [45].

The output voltage of SHEPWM does not contain low-order harmonics and the current waveform exhibits good sineness. It can obtain good waveform quality at low switching frequencies and effectively reduce switching losses. Consequently, it is widely used in multilevel inverters [46-47]. The development of high-speed computer technology such as digital signal processing (DSP) and various new optimization algorithms are constantly proposed [48-49]. The possibility of solving nonlinear transcendental equations online makes online SHEPWM technology feasible.

3.3.3 Improved PWM strategy for minimum switching frequency

Ref. [27] proposed a PWM improvement strategy for the minimum switching frequency of a quasi-Z source rectifier, as shown in Fig. 11. This strategy keeps the two bridge arms in a fixed switch state within a sector. The other bridge arm operates at a high switching frequency to implement shoot-through interval control and output voltage regulation. Compared

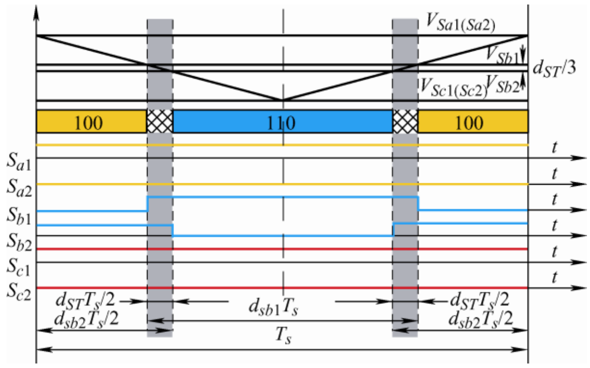


Fig. 11 Improved PWM strategy for minimum switching frequency

with the traditional impedance source rectifier PWM strategy, this strategy effectively improves the minimum intermediate link capacitor voltage and the equivalent switching frequency.

Various modulation strategies are listed in this section. The modulation strategies proposed in Refs. [33-39, 44-45] can be used in various topologies. The modulation strategies in Refs. [26, 41-43] are proposed for a certain topology, but these strategies can be improved and optimized to be used in the other topologies. However, the topologies mentioned in Refs. [30-32] are unique and not widely used. As such, their modulation strategies need to be designed separately.

4 Control methods

The control method directly affects the dynamic performance and steady-state performance of low carrier ratio converter systems. Therefore, obtaining excellent dynamic and steady-state performance at low switching frequencies is the key to research of control methods for low carrier ratio converter systems.

4.1 Observer

4.1.1 Discrete-time synchronous frame full-order observer

Ref. [50] proposed a discrete-time synchronous frame full-order observer based on complex vectors for a low carrier ratio sensorless internal permanent magnet synchronous motor (IPMSM), as shown in Fig. 12, where $u_{\gamma\delta}$, $i_{\gamma\delta}$, and $e_{\gamma\delta}$ are the stator voltages, currents and extended back electromotive force (EMF) in the γ-δ axes. The symbol “^” denotes the estimated values. The observer is based on the establishment of the IPMSM complex vector discrete-time domain zero-order hold (ZOH) equivalent model, which uses direct pole placement in a discrete-time domain to ensure system stability and dynamic performance with a low carrier ratio. Compared with the discrete-time observer based on the Euler approximation [51], this system based on the accurate ZOH equivalent model performs better.

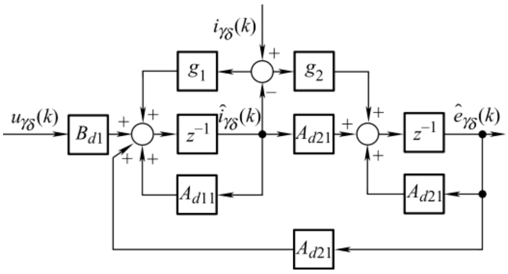


Fig. 12 Discrete-time synchronous frame full-order observer

4.1.2 Discrete-time Luenberger observer

Ref. [52] proposed a design method of an IPMSM discrete domain Luenberger observer in a static coordinate system. This design method firstly establishes a complex domain model of the discrete domain of the IPMSM. A mathematical model is constructed using the mathematical relationship between the given voltage and the detected current, combined with the precise discrete form of the back EMF. A feedback gain matrix is designed using the linear translation method in the discrete domain. This gives the observer good stability and fast convergence under low carrier ratios. This discrete domain Luenberger observer not only has the advantages of simple structure and high observation accuracy, but also has excellent steady state and dynamic performance at low carrier ratios. Compared with the discrete full-order observer, this design method avoids the tedious discretization process and has simpler discrete results.

4.1.3 Quasi-proportional-resonant controller based adaptive position observer

Ref. [53] proposed a quasi-proportional-resonant (QPR) controller based adaptive position observer for sensorless control of low carrier ratio permanent magnet synchronous motor (PMSM) drivers, as shown in Fig. 13, where u_α, u_β, i_α, i_β, e_α and e_β are α- and β-axis voltages, currents and back EMFs, respectively, and ω and θ are the rotor electric angular speed and

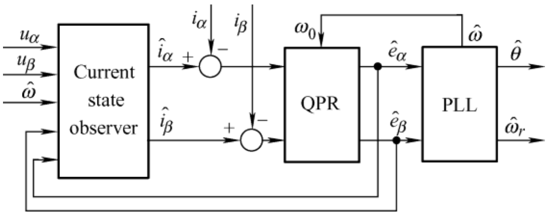


Fig. 13 QPR controller based adaptive position observer

position, respectively. This strategy tracks the actual current through a QPR controller instead of a symbolic function. It uses the frequency selection characteristics and adaptive harmonic cancellation capabilities to reduce chatter and harmonics. Compared with a sliding film observer, the QPR controller does not require a sliding film switching function and a low-pass filter. It can effectively improve the accuracy of position estimation and speed estimation at a low carrier ratio to provide good dynamic performance.

4.1.4 Dahlin controller

Ref. [54] proposed a fast and robust current control based on Dahlin's PMSM under low carrier ratios as shown in Fig. 14, where u_{dq} and i_{dq} are the stator voltages and currents vector in d-q axes, respectively. The parameter λ is used as a tuning factor and defines the behavior of the control. The symbol "*" denotes the reference values. This strategy extends a deadbeat control with integral parts, and uses this to compensate for model mismatches such as parameter changes, system nonlinearities, and saturation effects. Compared with the no-beat control and directly designed proportional-integral (PI) controller, the Dahlin controller has better steady-state performance and dynamic performance when high parameters are changed at a low carrier ratio.

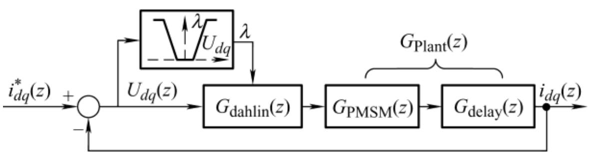


Fig. 14 Dahlin controller

4.2 Current regulator

4.2.1 Integral feedforward control strategy

Ref. [55] proposed an integrated feedforward control strategy for the IPMSM with a low carrier ratio, as shown in Fig. 15, where L_d and L_q are d- and q-axis armature winding inductance, respectively, and ψ_f and R_s are the rotor flux and armature winding resistance, respectively. Based on the integral feedforward control strategy, the strategy first uses the error integral of the given value and the feedback value to compensate the cross-coupled voltage. Then, it fully considers the effects of system delay and current error in the parameter calculation to improve the accuracy of decoupling. Compared with current feedforward and feed back decoupling, this integral feedforward control strategy enhances the current follow-up and effectively suppresses the saturation of the current regulator and voltage source inverter (VSI). It further improves the dynamic and static performance of the motor running at a low carrier ratio.

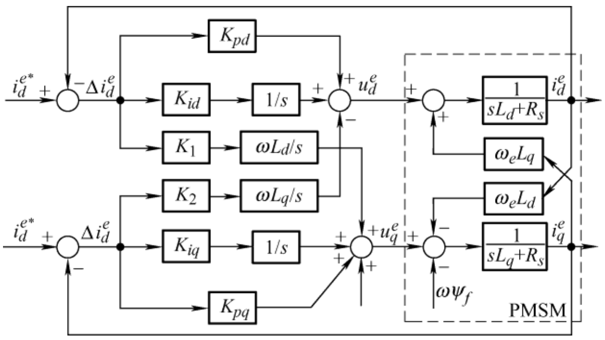


Fig. 15 Integral feedforward control strategy

4.2.2 Digital controller based on pole-zero cancellation

Ref. [56] proposes a digital controller, as shown in Fig. 16. This strategy is based on the discrete characteristics and digital delay of a digital control system, and is designed using the principle of zero-pole cancellation to obtain good control performance. Compared with the voltage feedback decoupling and the complex vector decoupling, this integral feedforward control strategy enhances the current follow-up and effectively suppresses the saturation of the current regulator and VSI. It further improves the dynamic and static performance of the motor running at a low carrier ratio.

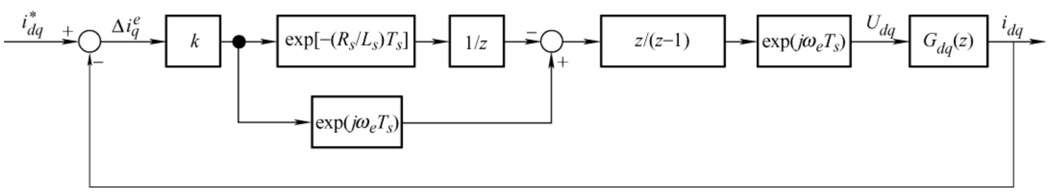


Fig. 16 Control block diagram of digital controller

4.2.3 Low carrier ratio PMSM digital current regulator

Ref. [57] proposed a design scheme of a PMSM digital current regulator with a low carrier ratio, as shown in Fig. 17. On the one hand, this solution uses a digital current regulator with a predictive active damping term to stabilize the current regulation loop. On the other hand, it compensates the sampling error by considering the first-order delay in the output of the regulator to improve the dynamic performance of the current. Compared with the direct digital current regulator, this low carrier ratio PMSM digital current regulator effectively enhances the dynamic and static characteristics of the current loop at a low carrier ratio.

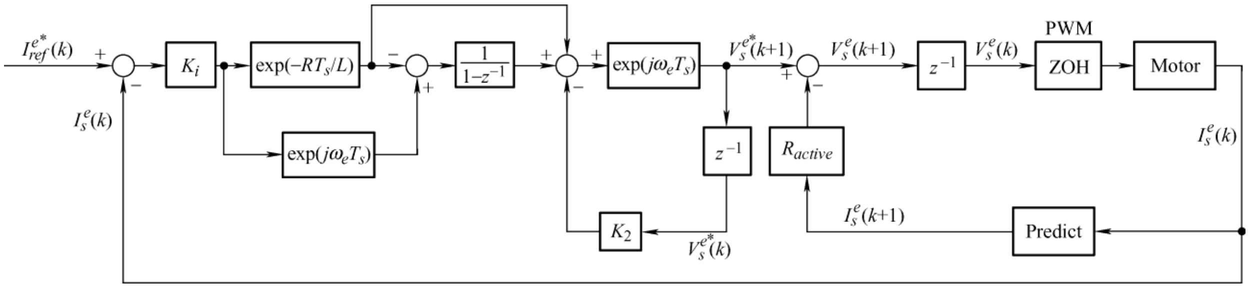


Fig. 17 Low carrier ratio PMSM digital current regulator

4.2.4 Complex coefficient PI controller with angle compensation

For problems in which the current loop control of a permanent magnet synchronous motor is easy to destabilize under a low carrier ratio or high-frequency operation, Ref. [58] proposed an improved complex coefficient PI controller with angle compensation, as shown in Fig. 18. This strategy analyzes the effect of impedance coupling and digital control delay on the operation of permanent magnet synchronous motors with a low carrier ratio. Then, it adds an angle delay compensation amount before the digital control delay in the complex coefficient PI decoupling method to solve the problem of current loop instability by compensating the influence caused by digital control delay. Compared with the current feedback decoupling method and the complex coefficient decoupling method, this improved complex coefficient PI decoupling method with angle compensation has better decoupling performance. It can solve the current loop instability caused by coupling in high-frequency operation or a low carrier ratio permanent magnet synchronous motor.

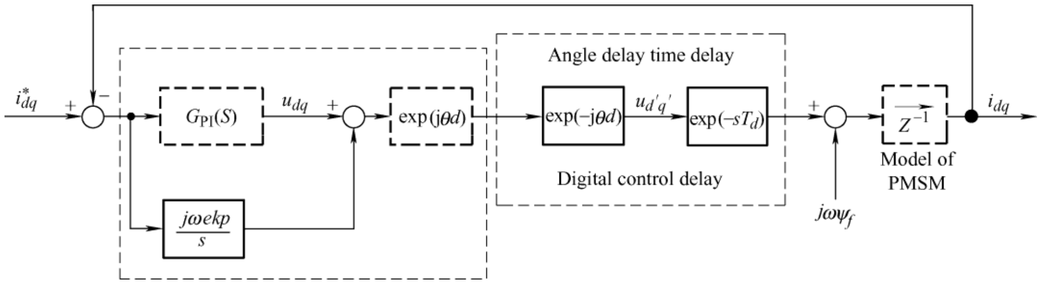


Fig. 18 Complex coefficient PI controller with angle compensation

4.3 Predictive control

Predictive control is a non-linear predictive control method suitable for dealing with nonlinear constraints [59]. It discretizes the mathematical model of the system, then predicts the future state of the system according to the equation. Therefore, predictive control does not require pulse width modulation and directly generates the drive signal of the converter, making it is easier to reduce the non-linear constraints.

4.3.1 Model predictive control based on hysteresis

Ref. [60] proposed a finite control set and hysteresis-based model predictive control, as shown in Fig. 19, where ω_r is the electrical rotor speed. This strategy uses angular displacement compensation, delay compensation, and predictive control of the current to maintain the system's dynamic performance under low carrier ratio conditions. Compared with the finite control set model predictive control, the hysteresis-based model predictive control (MPC) has a lower switching frequency and better current THD at low carrier ratios.

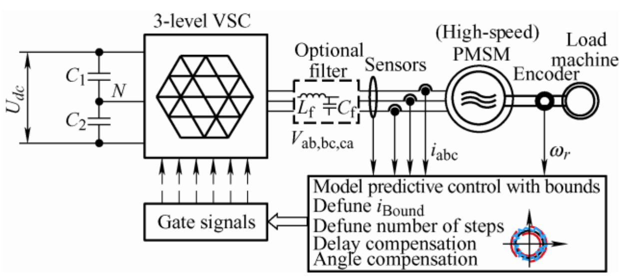


Fig. 19 Model predictive control based on hysteresis

4.3.2 Improved MPC based on two vectors

Traditional finite control set model predictive control (FCSMPC) has only one control cycle and high-power ripples. The introduction of zero vectors in combination with non-zero vectors can improve the steady-state performance of FCSMPC in one control cycle, but fixed vector combinations are not optimal solutions in terms of minimizing power errors. Therefore, Ref. [61] proposed an improved dual vector-based MPC, as shown in Fig. 20, where e_a, e_b, e_c, i_a, i_b, and i_c are the grid voltage vector and grid current vector, respectively, and R and L are the equivalent series resistance (ESR) and inductance of grid filter, respectively. In this method, the vector combination is decomposed into two arbitrary voltage vectors for control. It achieves good steady-state

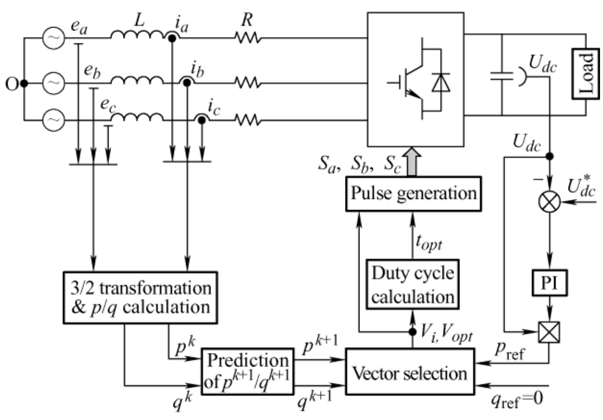


Fig. 20 Improved MPC based on two vectors

performance without affecting the dynamic response. Compared with the previous improved MPC using a fixed vector combination, this method can effectively reduce the average switching frequency and the switching loss.

4.3.3 Model predictive direct power control

Ref. [62] proposed a model predictive direct power control (MPDPC) based on low switching frequency, as shown in Fig. 21. This control method uses two different cost functions for steady state and transient state respectively, so that the system can obtain a low switching frequency in steady-state operation while maintaining fast dynamic response. Compared with other MPCs based on low switching frequency and their complicated weighting factor adjustment, the weighting factors of this low switching frequency based MPDPC are determined by mathe- matical rules. While avoiding repeated tests, it can significantly reduce steady-state fluctuations without affecting fast transient performance. It also exhibits superior steady-state performance.

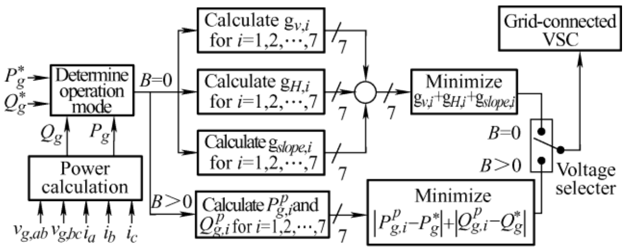


Fig. 21 Model predictive direct power control

4.3.4 Low complexity model predictive direct power control

Traditional low complexity model predictive direct power control (LC-MPDPC) using one or two vectors within a sampling interval will generate many current harmonics and high-power ripple [62-63]. To solve this situation, Ref. [64] proposed an LC-MDPC for PWM rectifier without voltage sensor, as shown in Fig. 22. This control method is based on the symmetrical optimization application of three voltage vectors, making full use of advanced pulse width modulation technology. On this basis, a control scheme based on virtual magnetic flux is proposed to realize the control of voltage-free sensor. This method retains all the advantages of a traditional LC-MPDPC, and it can also achieve excellent steady-state performance at low switching frequencies.

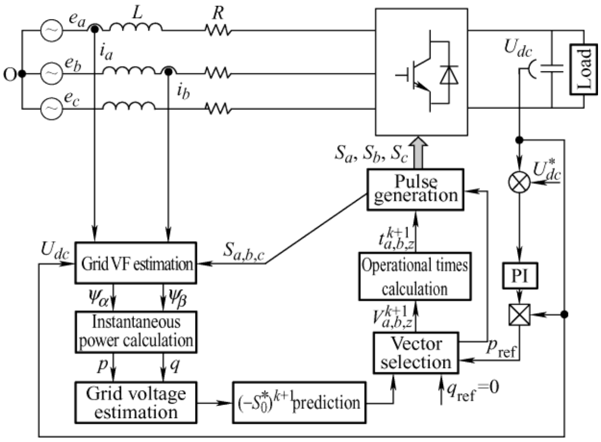


Fig. 22 Low complexity model predictive direct power control

4.3.5 Sensorless model predictive control for low switching frequency

Ref. [65] proposed a low switching frequency sensorless MPC, as shown in Fig. 23. This strategy reduces the weighting factor in the cost function by reducing the error between the applied voltage vector and the reference voltage vector. It also includes the neutral point potential fluctuation and switching frequency in the cost function. This achieves a balance between high and low DC voltage and lower switching frequency. This MPC extends the flux linkage control to weaken the magnetic field by adjusting the torque and stator flux linkage parameters online. It effectively widens the speed range of flux control. And it has excellent dynamic performance and steady-state response.

Various control methods in the case of a low carrier ratio are mentioned in this section. The observer proposed in Refs. [50-54] and the current regulator proposed in Refs. [55-58] can be combined with various modulation strategies mentioned in Section 3 and applied to various control methods. The predictive control proposed in Refs. [61-65] is mainly aimed at the traditional PWM converter topology and cannot be directly used for the control of other topologies. Observers can be optimized for predictive control to improve the performance of a low carrier ratio converter system. And predictive control does not require a modulation strategy to reduce the nonlinear constraints of the converter system more effectively. Therefore, the study of predictive control for PWM topology will be a development direction.

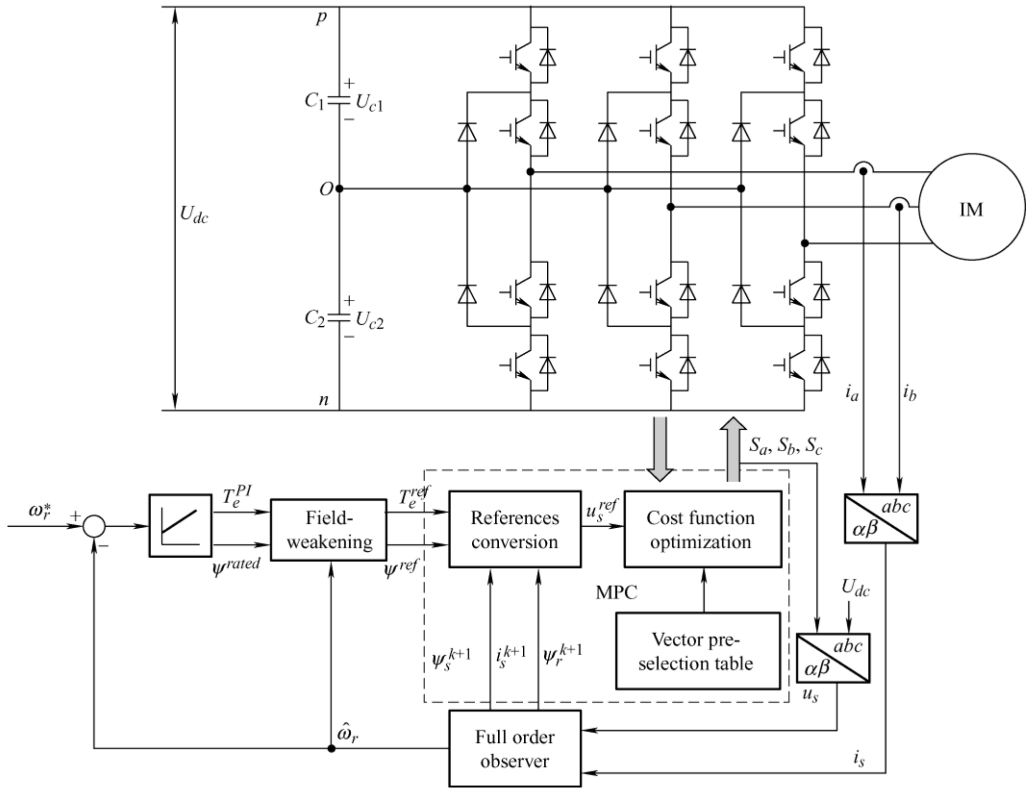


Fig. 23 Sensorless model predictive control for low switching frequency

5 Prospect

The research of a low carrier ratio converter system can effectively solve the problems of heat generation and harmonic pollution in the presence of high-power converters in modern industrial life. It has wide application value in high-power uses such as new energy generation and modern electric locomotives. Currently, domestic and foreign scholars have made some progress in low carrier ratio converter systems. This paper analyzes and summarizes the research status of low carrier ratio converter systems and proposes that future research can be carried out from the following aspects to promote the development of a low carrier ratio converter system.

(1) Optimization of the topologies. The topologies affect the working efficiency and output quality of the converter. Increasing the equivalent switching frequency without affecting the input current and output voltage quality will be an important research direction.

(2) Research on modulation strategies. At present, the modulation strategies of low carrier ratio converter systems are mainly for the research of traditional PWM converters and three-level converters. The research into the modulation strategies for five-level (or more) converters is considerably less. So, the optimization of switching frequency and voltage harmonics can be used to study other multilevel converters and MMC modulation strategies.

(3) Research on control methods and observers. The current research on low carrier ratio control methods is immature. The decoupling of the current loop and the improvement of the observer accuracy under low carriers are problems that need to be solved. Improving the dynamic performance and steady-state performance of the whole system through the improvement of control methods remains a subject of further study.

6 Conclusions

This paper summarizes the topological structures of a low carrier ratio converter system. Through a detailed analysis of the modulation strategy and control method of a low carrier ratio converter system, the following conclusions can be drawn.

(1) The main methods to reduce current harmonics at a low carrier ratio are to improve the equivalent switching frequency of the system through the improvement of topologies and modulation strategies.

(2) Real-time feedforward compensation and rolling optimization are the main methods to improve observer accuracy and the system's steady and dynamic performance at low carrier ratios are.

Low carrier ratio converter technology has very bright prospects. With deepening research of the low carrier ratio converter systems, the system's dynamic performance, power factor, and equivalent switching frequency will be further improved.

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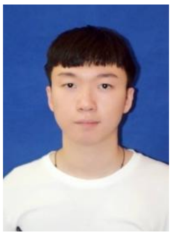

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