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Research and Future Research Prospects of PWM Modulation Method of Inverter in New Energy Field and Harmonic Suppression

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Abstract:

With the increasing depletion of fossil fuels, the limitations on nuclear energy development, and the implementation of increasingly stringent environmental laws and regulations, the utilization of clean energy and the development of new energy vehicles have become crucial industries. Harmonic suppression in inverters is a key area of current research. This paper covers several Pulse Width Modulation (PWM) techniques, including single-pulse modulation, Sinusoidal PWM (SPWM), Selective Harmonic Elimination PWM (SHEPWM), harmonic injection SPWM, Space Vector PWM (SVPWM), Multi-carrier PWM, and Harmonic Optimal PWM (HOPWM). Through analysis of their fundamental principles and comparing harmonic suppression performance, the advantages and disadvantages of each modulation technique are identified, and their effectiveness in harmonic suppression is discussed. The research found that for different PWM modulation methods, the harmonic suppression effects vary greatly, SHEPWM, harmonic injection PWM, Multi-carrier PWM, and SVPWM enjoy a better performance. Based on these analyses, the future research prospects for harmonic suppression in PWM modulation are explored.

Keywords: Renewable Energies; PWM modulation; harmonic elimination; inverter

1. Introduction

Inverter is a power electronic device that converts DC current into AC current, it is widely used in various systems such as motor drives and DC microgrids Grid-Connected Inverter. Inverters will generate harmonics during operation, these harmonics are generated from inefficient PWM modulation approach and non-linearity of circuit components. Harmonics generated by the inverter may cause adverse effects on the grid and other electronic devices. Excessive harmonics will cause devices to overheat, and the iron loss of the electric motor increases even damage the electrical appliances. Therefore, for the reliability and highly efficient operation of an electric power system, it is vital to reduce the inverter harmonics. In inverters, PWM modulation is a useful and efficient method to control the switching components, PWM uses voltage pulses to control the conduction and shut-down time of switching devices, thus the inverter is capable of regulating output voltage easily, reducing low harmonics with advanced PWM technology. However, when applying with some specific PWM modulation method such as SPWM, higher switching frequency will be adopted. Under this condition, the inverter will result in increased inverter switching losses, reduced inverter efficiency, increased device stress, and increased heat dissipation requirements. So it is critical to select the appropriate PWM modulation method.

This paper focuses on PWM modulation methods of inverters and reviews the various PWM modulation methods used in inverters, including single-pulse modulation, Sinusoidal PWM (SPWM), Selective Harmonic Elimination PWM (SHEPWM), harmonic injection SPWM, Space Vector PWM (SVPWM), Multi-carrier PWM, and Harmonic Optimized PWM (HOPWM). In this paper, a variety of PWM modulation methods are studied and their basic principles and advantages and disadvantages are analyzed.

2. Inverter common PWM modulation mode

2.1 Single-pulse PWM Modulation

The single-pulse modulation single-phase inverter circuit is shown in Figure 1. It generates only one pulse within each switching cycle, and the control pulse width of the two switching component pair maintained at 180°. There are two pairs of switching components, one is Q_1 and Q_4 the other is Q_2 and Q_3, each pair of them conducts separately and synchronously, upper tube and the lower tube of same bridge arm is not allowed to conduct synchronously, otherwise causing short circuit. Single-pulse modulation regulates the output voltage of the inverter by altering the phase of conduction time between the two pairs of MOSFETs. Changing the phase difference also alters the phase of the output voltage, resulting in a technique known as phase-shifting modulation for voltage control in SPWM inverters. The waveform of single-pulse modulation is shown in Figure 2, assuming the load is purely inductive, during the interval from t_1 to t_2 , with Q_1 and Q_4 simultaneously turned on, the voltage across the load is the power supply voltage Uin, it is a positive polarity. From t_2 to t_3, Q_4 is turned off while Q_2 is turned on. For an inductive load, the current flows through the diodes D_2 and sustains the current direction, in this time interval, the energy stored in the inductor provides energy to the load. During t_3 to t_4, Q_1 is turned off and Q3 is turned on, maintaining the positive current direction due to the inductive energy stored. The current flows through D_2, D_3, and returns to the DC power supply. This time, the energy stored by inductor is feedbacked to DC power supply. At t_4, the output current decreases to zero, then Q_2 and Q_3 turns on. The output voltage U_o reverses, reaching $-U_i$, this is the part of negative half-cycle of the inverter output. Due to the inductive impedance hinders the current rise, the current rises gradually, the DC power supply is providing energy. From t_5 to t_6, when Q_4 turns off, the current continues to flow through D_3 and D_4, and the current direction maintains unchanged The output voltage remains at 0V.

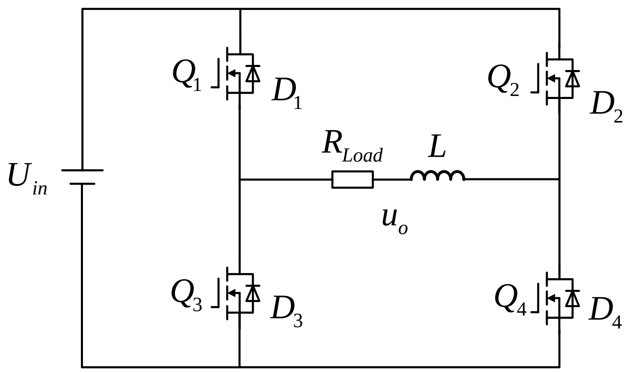

Fig. 1 Single-pulse modulation single-phase inverter circuit

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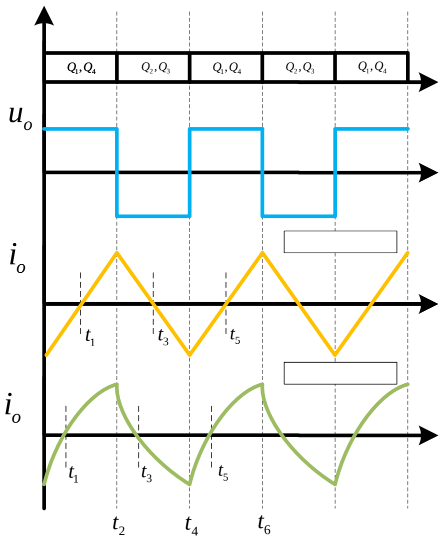

Fig. 2 Single-pulse modulation output voltage and current waveform

Since the AC voltage generated by the inverter has only one pulse per switching cycle, the voltage waveform is approximately square wave, and the Angle of conduction time lag between Q_2 and Q_1 is defined as θ, and the output voltage can be expressed by Fourier series.

$$u_o = \sum_{n=1}^{\infty} \frac{4U_{in}}{n\pi} \sin\frac{n\theta}{2} \sin n\omega t \tag{1}$$

When adopting single-pulse modulation, the output voltage contains significant odd harmonic. Since the output voltage has no even harmonics. The high proportion of harmonics in output voltage and the distortion in output waveform causes various damages. For motor, transformer, and other inductive loads, the presence of numerous harmonics generates additional eddy current losses and hysteresis losses, thus resulting in increased heat generation and decreasing efficiency. For the motor, this will also lead to torque pulsation. In power grids, the power quality will be degraded by harmonics. In systems with a neutral line, if the load is unbalanced, the third harmonics will add on the neutral line, leading to an increase in the neutral current and potential overheating. To sum up, the single pulse width modulation output waveform quality is poor, and it has large voltage distortion. It is not suitable for practical application.

2.2 Sinusoidal PWM (SPWM)

Three-phase bridge inverters are widely used in photovoltaic grid-connected inverters and motor driver inverters. The basic circuit diagram of such inverters is shown in Figure 3. The three-phase inverter contains three arms. Three-phase output is connected to three midpoints of the three arms. The phase-to-phase voltage is measured across the 3 line-to-line voltage. The arms are driven by three pairs of MOSFETs. Each MOSFET contains body diode as a bypass route and can prevent the MOSFET from working under reverse voltage, thus protecting the MOSFET from damage. SPWM is a kind of simple PWM modulation method used in an inverter that can generate approximately sinusoidal AC voltage. The SPWM wave is generated by comparing a triangular carrier wave and a sinusoidal modulating wave. The comparison result is used as a control signal. The modulation index (M) is the ratio of the amplitude of the sinusoidal reference wave to the amplitude of the triangular carrier wave. In practical applications, altering the modulation index M is able to regular the amplitude of inverter output voltage. In the method of SPWM modulation, the on-off time of the switching device is determined by the intersection of the triangular carrier wave and the sinusoidal modulated wave, and the carrier wave frequency is several times of the sinusoidal reference wave, therefore there are more than one switching pulse in every switching period. Due to the higher switching frequency, it allows SPWM modulation to trace sinusoidal waveform more accurately [1]. Compared with PWM modulation, the low-order harmonics and high-order harmonics of SPWM modulation are significantly reduced. The higher the harmonic order, the greater the reduction. Meanwhile, SPWM modulation has more optimization degrees of freedom than single pulse width modulation. Since the main harmonic components are concentrated near the switching frequency [2], to suppress the low-order harmonics, a higher switching frequency could be adopted, then only a low-cost low-order filter is needed to obtain a good harmonic filtering effect. SPWM modulation is very simple and does not require a microcontroller to perform complicated mathematical operations, so it also has certain advantages in low-cost applications. In spite of this, the output waveform of the SPWM modulation inverter still has a large distortion, which is not capable of the stable operation of electrical appliances.

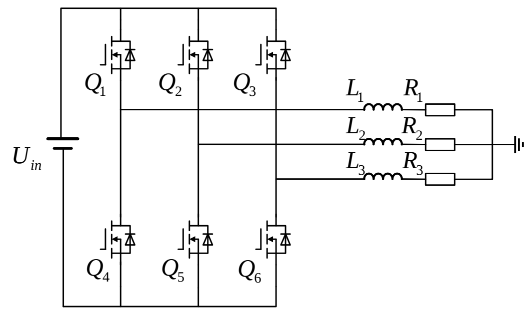

Fig. 3 Circuit diagram of three-phase bridge inverter

2.3 Selective Harmonic Elimination PWM

The single-pulse modulation and SPWM modulation mentioned above both have the disadvantage of large lower-order harmonics, Essam Hendawi brought out a PWM modulation method to suppress low-order harmonics in single phase full bridge inverter, and the high-order harmonics in output waveform can be easily filtered by simple passive filter. Thus, all harmonic components of the output voltage can be reduced. This method determines the amplitude and phase of each harmonic by Fourier decomposition of the inverter output voltage. The bipolar two-level output voltage waveform of a single-phase full-bridge inverter can be expressed by the Fourier series.

$$U_0(t)=\sum_{n=1}^{\infty}\left[a_n\sin(n\omega t)+b_n\cos(n\omega t)\right] \tag{2}$$

$$a_n=\frac{1}{\pi}\int_0^{2\pi}U_0(t)\sin(n\omega t)d(\omega t) \tag{3}$$

$$b_n=\frac{1}{\pi}\int_0^{2\pi}U_0(t)\cos(n\omega t)d(\omega t) \tag{4}$$

Where n=1,2,3,5... In the formula, since the output voltage waveform is symmetric about π/2 and symmetric about [π,0]. The DC component, even sine component and cosine component in the Fourier series are 0, and the Fourier coefficient can be simplified to

$$\begin{cases} b_n=0, n=1,2,3,\cdots \\ a_n=0, n=2,4,6,\cdots \\ a_n=\dfrac{4E}{n\pi}\left[-1-2\sum_{k=1}^{N}(-1)^k\cos\left(n\alpha_k\right)\right], n=1,3,5,\cdots \end{cases} \tag{5}$$

Then, the a_n corresponding to the harmonic order that needs to be eliminated should be 0, and the switch Angle can be calculated. To eliminate N harmonics of the specified order requires solving N+1 nonlinear equations [3]. Therefore, the implementation of this method is complicated, and the amount of calculation required is very large, which is not conducive to real-time calculation. In practice, the method of lookup table is often used to store the pre-calculated switch angle in the memory of the microcontroller for calling, but this method increases the requirement for storage space. Despite the above shortcomings, SHEPWM modulation can effectively eliminate low-order harmonics and allow the output voltage to be controlled, thus becoming an effective PWM modulation mode.

2.4 Harmonic Injection SPWM

The harmonic injection method is another effective modulation method to eliminate low-order harmonic. It utilizes a microcontroller to calculate and extract then output the amplitude and phase of the low-order harmonics. Then calculate and generate a control signal that can generate harmonics with opposite phase. Finally, add them to the original control signal. Thus, the low-order harmonics are cancelled. Jiangbo Chen et al. [4] proposed a harmonic current injection method in d-q coordinate system. The configuration of this system is shown in Figure 4. By converting abc three-phase voltage into two d-q components, the 5th and 7th harmonics are extracted in d-q coordinate system, filtered and then transformed into inverse coordinate transformation to achieve inverse harmonic injection. Compared with the grid-connected inverter without harmonic current injection, the 5th and 7th harmonics are reduced by 95.3% and 97.9% respectively, and the 3rd and 4th harmonics are also slightly reduced, and the single-phase grid-connected current THD is reduced from 9.07% to 1.82%. It can be seen that the control system of photovoltaic grid-connected inverter based on harmonic current injection method can effectively reduce the harmonic content. Although coordinate transformation is used to reduce the computational complexity, the complexity of control strategy puts forward higher requirements for the operational performance of microcontroller.

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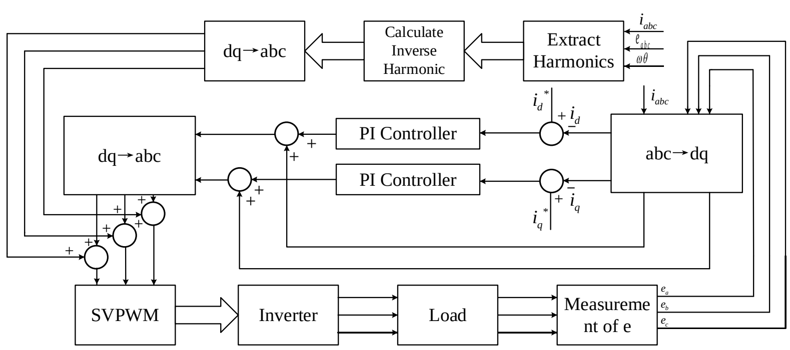

Fig. 4 System Block diagram of SPWM modulation inverter with harmonic injection method[4]

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2.5 Space Vector PWM (SVPWM)

SVPWM mainly focuses on the formation of circular rotating electromotive force, and forms 8 basic voltage vectors as shown in Figure 5 by changing the inverter switching state. Eight basic voltage vectors include six non-zero vectors and two zero vectors. By transforming the given ABC three phase voltage using the Clark transform into a rectangular coordinate system. Then get two components in the alpha-beta right coordinate system. After that, the phase angle of the three-phase synthetic voltage vector is calculated by the arctangent function, and the sector is judged according to the phase Angle. Then the switch combination is selected. Because of its better ability to form a three-phase symmetrical voltage, SVPWM is more suitable for forming a circular rotating stator magnetic field. Therefore SVPWM is widely used in induction motor drive inverters.

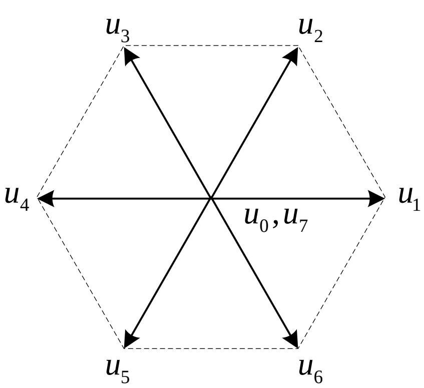

Fig. 5 Basic voltage vector of SVPWM

Compared with SWPM, SVPWM eliminates the step of switching state calculation because SVPWM use space vector selection to generate output waveform. By using the appropriate selection and distribution of the zero voltage vector, the switch loss and the PWM waveform symmetry can be reduced. SPWM has a better total harmonic distortion (THD) compared to SPWM, 60°PWM, and 3rd Harmonic Injiection PWM[5]. The SVPWM inverter with microcontroller control has less than 1% THD [6]. The optimal performance of SVPWM makes it extremely suitable in transmission systems. Compared to SPWM modulation, SVPWM has a higher DC bus voltage utilization. Compared with the general SPWM, the output voltage of the SVPWM control method can increase by 15%. The waveform of current is much smoother when adoping SVPWM, and less harmonics are gennerated, which is beneficial to reduce the energy loss and heating inside the motor. At the same time, the noise generated on the coil is also reduced. However, the SVPWM control algorithm is more complex. It is more computational intensive, and requires higher performance of the controller.

2.6 Multi-Carrier PWM

In the method of SVPWM, to make the inverter output three-phase voltage as sinusoidal as possible, SVPWM uses the method of of voltage vector synthesis by selecting suitable voltage vector and zero vector distribution, so that the synthesized three-phase voltage can form circular rotating electromotive force. In this process, it is necessary to solve nonlinear equations, which is very computational intensive and requires high computational power, which is not conducive to real-time calculation. In order to reduce the harmonic of inverter output voltage and avoid the intensive operation process like SVPWM, multi-carrier PWM was born, which includes phase shift PWM, phase disposition PWM, phase opposition PWM and alternative phase opposition PWM. Compared to SPWM, multi-carrier PWM is characterized by having more than one triangular carrier compared to a reference sinusoidal modulated wave to generate a control pulse that controls the switching device.

2.6.1 Phase Shift PWM

Figure 6 represents the process of generating PWM waves using PSPWM method. PSPWM is a method that compares sinosodial reference waves with multiple triangular carrier waves with different pahse. For general seven-level inverters, this group of triangular carrier waves consists of three triangular carrier waves with equal amplitude and 120° phase difference. For an inverter with 2N+1 levels, then N triangular carrier waves are needed to compare with the sinusoidal modulated waves. These triangular carrier waves need to differ by 360°/N, while maintaining the same amplitude.

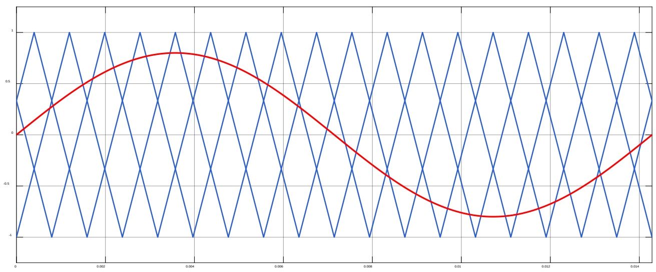

Fig. 6 Carrier waves and modulated wave of PSPWM

2.6.2 Phase Disposition PWM

PDPWM is the most widely used carrier shift modulation technology. As shown in Figure 7, PDPWM is formed by comparing one sinusoidal modulated wave with multiple triangular modulated waves. Different from PSPWM, the triangular carrier of PDPWM is not different in phase, but a DC offset between the carriers. In this paper, the triangular carrier wave with positive voltage is called positive carrier wave, the triangular carrier wave with negative voltage is called negative carrier wave. Triangular waves are called W1,W2,W3 and W4 from the top of the figure to the bottom. In PDPWM, W1,W2,W3 and W4 does not differ in phase. N-level inverters require (N-1) carrier waves to be compared with reference sinusoidal modulated waves. Taking a 7-level inverter as an example, PDPWM requires 6 triangular carriers with different amplitudes and phases, superimposed with positive and negative DC components. The modulation waveform of PDPWM is shown in Figure 7. The output line-to-line voltage of PDPWM has lower THD than PSPWM [7], and the three-phase NPC inverter based on PDPWM modulation has better THD performance than SVPWM in the switching frequency from 0.01Mhz to 1MHz [8].

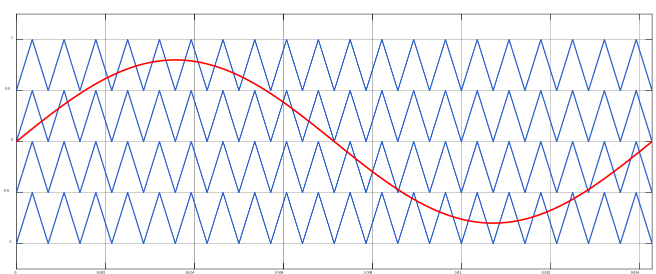

Fig. 7 Carrier waves and modulated wave of PDPWM

2.6.3 Phase Disposition PWM

PODPWM is roughly the same as PDPWM, the waveform of PODPWM is as shown in Figure 8. The difference is that the phase of a triangular carrier with a negative voltage (W3, W4) differs 180° from that of a triangular carrier with a positive voltage (W1, W2). This phase inversion reduces specific harmonics, resulting in a less distorted output waveform. POD-PWM is suitable for various multilevel converters, especially in modular multilevel converter (MMC).

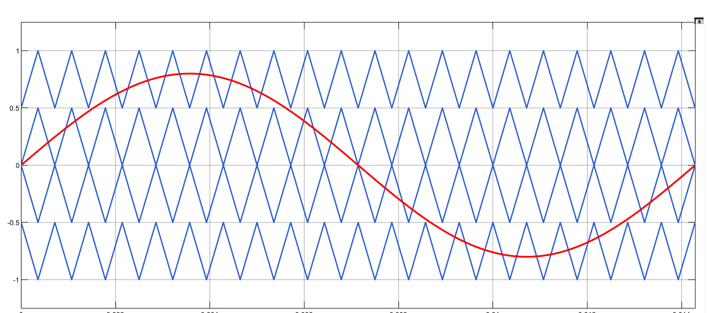

Fig. 8 Carrier waves and modulated wave of PODPWM

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2.7 Harmonic Optimal PWM

HOPWM was put forward by Giuseppe S. Buja and Giovanni B. Indri in 1977 [9], and its basic working mode is similar to SHEPWM, which decomposes the output voltage into Fourier series. Different from SHEPWM, HOPWM is optimized for current harmonics. By obtaining the Fourier series form of output current, it uses linear approximation method, neural network method, wavelet analysis and other methods for linear optimization, so as to obtain multiple switching angles. This method aims at THD optimization and solves the switching Angle by numerical analysis, which can reduce the harmonic distortion to the maximum extent, but it also has the shortcomings of excessive calculation [10].

3 Comparison and Analysis of Different Modulation Methods

It is of great significance for inverters to pursue lower THD. For motor driver inverters, excessive harmonics will produce more losses in the stator windings, resulting in motor heating and reduced efficiency, and high harmonics will cause torque pulsation and worsen motor NVH; For grid-connected inverters, the harmonic current exceeding the limit value will pollute the power grid, affect the power quality and endanger the safety of the power grid. PWM technology is the most widely used technology in inverters. It is used to control the switching devices to output sinusoidal AC waveform. At the same time, the use of PWM technology can make output voltage adjustment easier and can effectively reduce low-order harmonics. In this paper, 8 kinds of inverter PWM modulation techniques are analyzed, among which single pulse width modulation and SPWM output waveform with large distortion, high harmonics, large switching device loss caused by high switching frequency and increased system heat dissipation pressure. Although SPWM technology does not require complex mathematical calculations, its waveform quality is distorted and therefore it has not been widely used. SHEPWM, harmonic injection method, and HOPWM can effectively reduce harmonics by Fourier decomposition of output current and reducing harmonics through mathematical operations. However, these modulation techniques were rarely used in the early years due to insufficient computing power of microcontrollers. In recent years, with the development of microcontrollers, these technologies will be further developed and expanded. SVPWM is the most widely used PWM modulation technology, which is often used for asynchronous motor driver inverters. This PWM technology reduces the harmonics by forming a circular rotating voltage. And the calculation amount is moderate, therefore the SVPWM technique is relatively mature. By adopting this PWM modulation method, the harmonic in output is reduced. Compared to the SPWM technique, the DC bus voltage utilization rate is higher, therefore Improve inverter efficiency. Multi-carrier PWM technology can output a waveform similar to SVPWM and provide good output harmonic distortion at lower computational complexity.

4 Conclusion

This paper discusses the important role of various PWM modulation modes in harmonic suppression. SVPWM technology is mature, although it needs to rely on high-performance microcontrollers to select voltage vector, but the harmonic suppression effect is excellent. Multi-carrier PWM has less computation and can achieve harmonic suppression effect similar to SVPWM. With the increasing maturity of artificial intelligence technology in recent years, the future PWM modulation technology may focus on complex optimization algorithms based on artificial intelligence, such as real-time harmonic prediction and suppression, adaptive harmonic compensation, multi-objective optimization of THD and switching loss, etc., and subsequent research may focus on FPGA verification of complex optimization algorithms, IP core construction and other work.

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