Research on harmonic suppression method of SPWM inverter circuit for photovoltaic power generation system

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Abstract. To effectively reduce and suppress the harmonics generated by single-phase inverter circuits, this paper mainly investigates the harmonic characteristics of single-phase Sinusoidal Pulse Width Modulation (SPWM) inverter in the output voltage and its suppression methods. According to the SPWM principle and Fourier series theory, the mathematical model and simulation of the output voltage of the SPWM inverter are established, and the harmonic characteristics of the SPWM inverter are analyzed. Secondly, the harmonic content and distribution of the output voltage under three different carrier control methods are investigated. Then, two effective methods for suppressing the harmonics of the output voltage of single-phase SPWM inverters are investigated: selecting the appropriate carrier ratio and injecting the proper number of harmonics. Finally, the study shows that a single-phase unipolar frequency doubling SPWM inverter can effectively filter out the high harmonics, making the output voltage waveform smoother and closer to the sinusoidal waveform. This study will have a certain positive impact on the future development of energy-saving power supply, high-quality power supply, and high-performance power supply technology in China, which can realize the efficient and low-pollution use of electric energy.

Keywords: SPWM, Fourier series theory, Carrier ratio, Harmonic suppression, Inverter.

1. Introduction

With the progress of industry science and technology, the power quality requirements are increasing, especially the low harmonic content of the inverter output, which sets strict requirements. As an important part of power electronics technology, inverter circuits are widely used in various fields such as photovoltaic power generation, DC power transmission, and wind power generation. Their main function is to convert DC power sources (e.g. batteries, dry cells, solar cells, etc.) into AC power to supply loads. In addition, inverter circuits play a key role in many power electronic devices, such as inverter speed controllers for AC motors, uninterruptible power supplies (UPS), inverters and stabilizers for induction heating and other power supplies, to support the effective control and conversion of electrical energy to meet the requirements of modern power systems for power quality, efficiency, and stability [1]. However, the problem of harmonics generated during the inverter process cannot be ignored. These harmonics can lead to a deterioration of the power factor in the grid as well as increased electromagnetic interference from surrounding electronic equipment and communication systems. Therefore, before connecting a PV system to the public grid, the harmonics generated by the inverter need to be effectively managed and controlled to ensure stable system operation, and compliance with grid requirements and to reduce the negative impact on the surrounding environment [2]. This includes the adoption of appropriate harmonic suppression measures, such as the use of modern modulation techniques (SPWM) to optimize the output waveforms of the inverter to reduce or suppress the generation of harmonics.

Taking the SPWM inverter circuit as an example, this paper establishes the single-phase SPWM inverter model under different carrier modes through MATLAB software. The harmonic characteristics of the inverter output voltage under unipolar, bipolar, and unipolar frequency doubling SPWM control strategies are specifically analyzed. By varying the carrier ratio method, it is investigated to achieve harmonic reduction and suppression to ensure that the output of the inverter meets the requirements of the grid and at the same time reduces the negative impact on the surrounding environment and other equipment. Effective reduction or suppression of harmonic components is critical to the overall performance and reliability of a PV solar panel system. By adopting appropriate design and control strategies, the efficiency, stability, and extended service life of a PV system can be maximized to better achieve the goals of clean energy utilization and environmental protection.

2. Photovoltaic solar panel principle and harmonic component generation mechanism

2.1. Photovoltaic solar panel working principle and inverter circuit principle

First, the photovoltaic panels absorb the sunlight and convert the solar radiation energy into direct current (DC). Then the PV inverter converts the DC power into AC power, and the generated power can be stored directly in the battery or fed into the grid via the inverter, finally, the grid is used to schedule the power.

PWM (Pulse Width Modulation) control is a technique whose basic principle is to synthesize the desired waveform signal by adjusting the pulse width of the signal [3]. The modulated waveform is synthesized by modulating sinusoidal and triangular waveforms, and its pulse width varies with the sinusoidal waveforms and is used to effectively control the insulated gate bipolar transistors (IGBTs) in the inverter circuit. This modulation technique is commonly known as Sine Wave Pulse Width Modulation (SPWM) [4]. In inverter circuits, SPWM is classified into voltage type and current type, with voltage type SPWM being the most commonly used control technique.

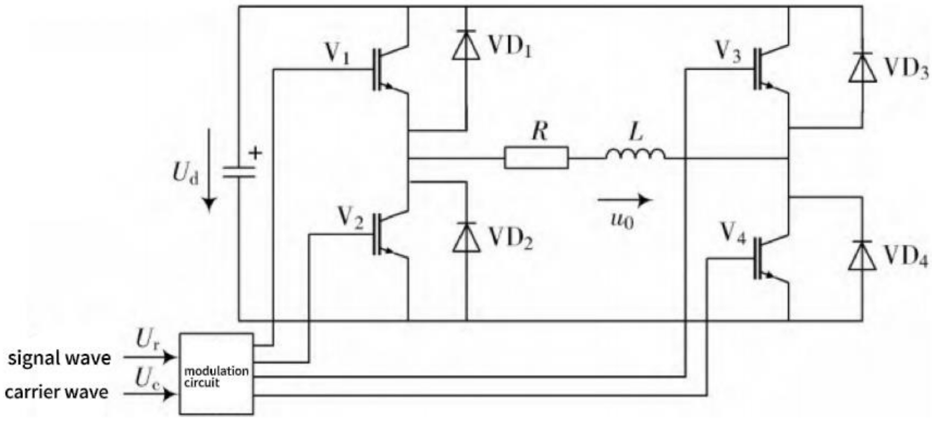

Fig.1 Phase-Bridge Voltage SPWM Inverter Circuit

The principle of the single-phase bridge voltage type SPWM inverter circuit used in this paper is shown in Fig.1. The DC signal is used as the voltage source U_d, the resistive load consists of a series-connected resistor R and inductor L, and the fully controlled IGBT power switches V1~V4 are connected in parallel with diodes VD1~VD4 to provide the feedback energy. In addition, the modulation circuit controls the switching on and off of the IGBTs to generate the signal Ur and carrier Uc to drive the four drive signals of V1~V4.

Modulation regime and carrier ratio are two important parameters in the SPWM (Sinusoidal Pulse Width Modulation) technique. The ratio of the amplitude of the sinusoidal modulating signal to the amplitude of the triangular carrier signal can be defined as the modulation depth M [5].

$$M = U_{rm}/U_{cm} \tag{1}$$

Here U_{rm} refers to the signal wave U_r appearing in chart 1 above, and U_{cm} refers to the carrier wave U_c.

The carrier ratio P is the ratio of the triangular carrier signal frequency fc to the sinusoidal modulation reference signal frequency fs, calculated as:

$$P = f_c/f_s \tag{2}$$

In practice, the fundamental output voltage of SPWM inverters is often calculated using a voltage-averaging model [6]. When the carrier signal frequency is much higher than the fundamental frequency of the output voltage and the modulation regime$M \leq 1$, the amplitude U_{1m} of the fundamental voltage is:

$$U_{1m} = MU_d \tag{3}$$

In the expression, the amplitude of the voltage source is U_d, a parameter that occupies a central position in the sinusoidal pulse width modulation technique. The amplitude of the output waves of the inverter circuit in this technique has a clear linear correlation with the modulation coefficient M, where the value of M is limited to the range from 0 to 1 and the carrier frequency f_c must be significantly higher than the fundamental frequency f_s. This relationship allows the frequency and amplitude of the output voltage of the inverter circuit to be flexibly and accurately manipulated by adjusting the modulation signal. Furthermore, the harmonic components of the output voltage of a voltage inverter are mainly concentrated around the octave point of other carrier frequency harmonic distribution is significantly affected by the carrier ratio P, and the variation of the value of P plays a dominant role in the magnitude of the harmonic components. Therefore, when designing and optimizing the SPWM inverter system, it is important to thoroughly understand these relationships and use them wisely to improve the system performance and reduce harmonic pollution [7].

2.2. Generation and effects of harmonic components

Harmonic generators, as a specific class of electrical equipment, can inject harmonic currents or voltages into the power system. During operation, due to their non-linear characteristics, these devices can generate periodic electrical waveforms, i.e. harmonics, that differ from the fundamental frequency, which in turn can potentially affect the power quality of the grid. In photovoltaic (PV) systems, the main source of harmonics is the PV inverter connected to the grid, and harmonics can directly affect the safety and reliability of PV system operation. Currently, the most commonly used power harmonic detection method is the Fast Fourier Transform (FFT). In addition, there are several major harmonic detection methods: analog filtered harmonic detection method, traditional power defined harmonic detection method, harmonic detection method based on instantaneous reactive power theory, harmonic detection method based on neural network, harmonic detection method based on adaptive offset principle, harmonic detection method based on wavelet analysis [8]. These methods have their advantages and disadvantages and applicable scenarios in practical applications to ensure that the harmonics generated by the inverter of the PV system can be controlled within a safe range, avoiding the adverse effects on the grid and surrounding equipment, so as to ensure the stable operation and long-term reliability of the PV system [2]. According to the working principle of the PWM (Pulse Width Modulation) technique, it uses a sequence of equal area pulses to simulate a continuous signal. According to the important conclusion of the sampling theorem, if narrow pulses of equal pulse area but different shapes are added to a process with inertia, they will produce essentially the same output response waveform [9]. This means that although the details of the waveforms may be different, the overall effect is similar in some applications.

When these response waveforms are analyzed by Fourier transform, it can be seen that they are very close in the lower frequency bands, while there may be some slight differences in the higher frequency bands. This conclusion indicates that the waveforms generated after PWM modulation are basically similar to the original sine wave, but not exactly the same. This is because in PWM technology, the sinusoidal signal is modulated by the carrier waveform to produce harmonics relative to the carrier frequency at the output of the inverter, and the specific frequency distribution of the harmonic components and their corresponding amplitude magnitudes are one of the key considerations when evaluating the performance of a PWM inverter circuit. Accurate measurement and analysis of these parameters are essential to fully understand the output characteristics of the inverter, optimize system performance, and meet specific application requirements. Therefore, a thorough study and proper control of the harmonic components is an important way to improve the overall performance of PWM inverter circuits [5]. Harmonic analysis can help determine the level and characteristics of harmonics in the inverter output, which is essential to ensure grid acceptance of the inverter output, reduce electromagnetic interference, and improve system efficiency. Therefore, harmonic analysis of the PWM waveforms is essential, especially detailed harmonic analysis of the unipolar frequency-doubled SPWM inverter output voltage.

3. Design Strategies for Reducing Harmonic Components

3.1. Circuit Simulation & Analysis

In order to investigate the harmonic characteristics in-depth and verify the relevant theoretical models, this paper designs the corresponding inverter circuit and relies on simulation technology to interpret and analyze the experimental results. The simulation of the unipolar SPWM inverter circuit, the simulation of the unipolar frequency-doubling SPWM inverter circuit, and the influence mechanism of the main parameters on the harmonic characteristics of the unipolar SPWM inverter circuit are mainly included. In addition, to further optimize the output quality of the inverter, this paper also explores the strategy of installing a harmonic filter at the output of the inverter or at the grid access point and analyses the influence of adjusting the carrier frequency and modulation ratio (or modulation index) in the SPWM technique on the harmonic suppression effect. The SPWM modulation technique controls the fundamental frequency and harmonic distributions of the output waveform of the inverter and tries to make the output as close as possible to the ideal sinusoidal waveform. Harmonic filters filter out the high-frequency harmonics generated by the SPWM modulation from the output voltage, particularly those harmonics that can cause interference to the mains and surrounding equipment. SPWM modulation is often used in PV inverters because it produces a near-sinusoidal output and reduces the generation of high-frequency harmonics compared to other PWM techniques. By adjusting the carrier ratio and modulation frequency of SPWM, the output waveform is optimized, and harmonic components are reduced. The use of SPWM can produce outputs that are closer to sinusoidal and usually reduces the generation of high-frequency harmonics compared to other PWM techniques.SPWM controls the amplitude of the output voltage by adjusting the width of the pulses and can optimize the quality of the waveforms by using an appropriate carrier frequency and modulation index.

Unipolar: As the carrier ratio increases, the lowest harmonic is further away from the fundamental and is easier to filter, so the quality of the output voltage improves as the carrier ratio increases. However, the higher the carrier ratio, the higher the losses in the switching devices and the more difficult the hardware implementation [10].

Unipolar frequency doubling: The lowest harmonic of the inverter output voltage under unipolar frequency doubling control is 2N-3, and the highest harmonics are N-1 and N+1 harmonics; regardless of whether the carrier ratio N is even or odd, the output voltage contains only the odd harmonics; with the increase of the carrier ratio and the modulation waveform, the THD gradually decreases, and the output current waveform tends to be more similar to the sinusoidal waveform. The output harmonic performance of this modulation method is equivalent to a single-phase unipolar SPWM with twice the carrier frequency, but the frequency of the switching tubes is not doubled, so the losses of the switching tubes do not increase; in the same case, it is stronger than the unipolar and bipolar control strategies in terms of harmonic suppression capability.

3.2. Simulation of Unipolar SPWM Inverter Circuit

In constructing the main circuit model of the unipolar SPWM inverter circuit, the basic framework is similar to that of the bipolar circuit model, but the main difference lies in the complexity of the unipolar control circuit model, which is shown in Fig.2.

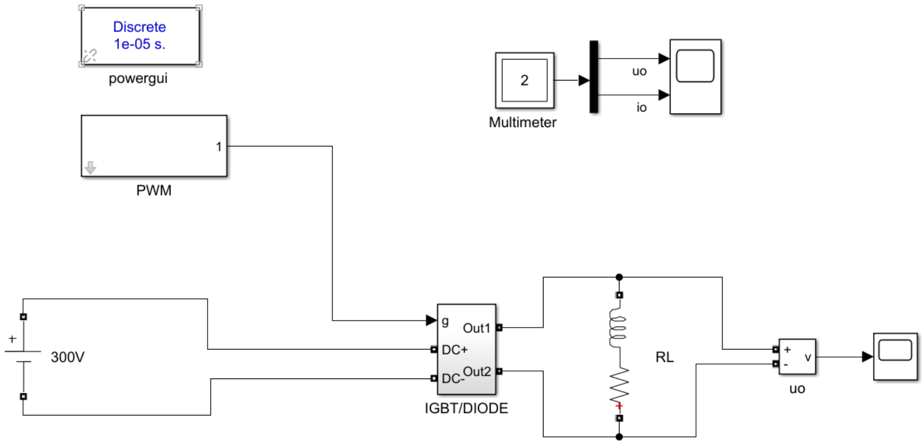

Fig.2 SPWM inverter circuit model

The key step in the model is the multiplication of the square pulse submodule with an isosceles triangular carrier, which is generated by multiplying the amplitude of the square pulse and superimposing a constant offset (e.g. constant 1). As for the other modules in the model, their parameter configurations basically follow the design principles of bipolar inverter circuits, maintaining a high degree of consistency.

This paper presents a novel approach to SPWM modulation, utilizing two-phase modulation signals (inverted one another) and carrier comparison to generate four-way (including complementary) control signals for the on-off control of four power devices. This is also a single-phase unipolar control method, which can be found in SIMULINK under the SPWM waveform generation schematic diagram in Fig. 3. In order to implement this method, the user must select the sinusoidal modulation frequency of 50Hz, the triangular carrier frequency of 1kHz, and the carrier ratio. Thus, the carrier frequency is 15 times 50 Hz or 750 Hz, and the modulation depth is 0.5. The following Fig. 3, depicts the unipolar SPWM waveform modulation circuit schematic diagram.

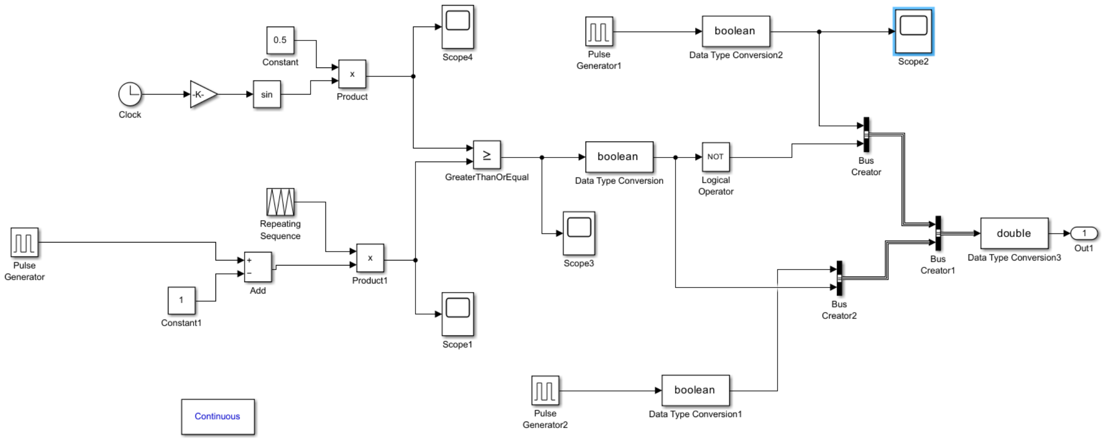

Fig.3 Unipolar SPWM Waveform Modulation Circuit Schematic Diagram

The unipolar modulation illustrated in Fig. 4 is distinguished by the fact that the output voltage of the inverter prior to filtering is a series of rectangular pulses, with amplitude width varying in accordance with the corresponding sinusoidal law. These pulses exhibit three distinct levels: Ed, -Ed, and O, which alternate with the positive and negative half-cycles of the sinusoidal wave.

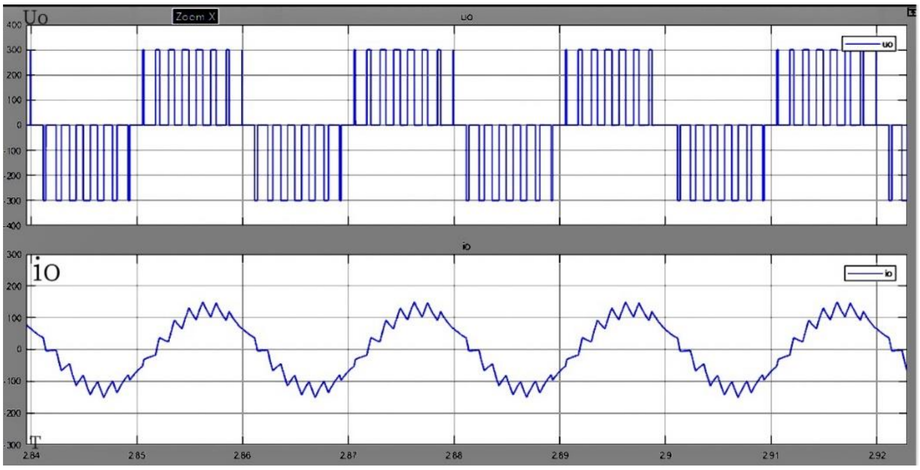

Fig.4 Unipolar modulation [11]

The amplitude of the fundamental voltage of the unipolar inverter circuit, as determined by FFT analysis of the output voltage, is 151.4 V. This value is in close proximity to the theoretical value predicted by Eq. (3), which indicates that the amplitude of the fundamental of the output voltage is in a linear relationship with the modulation system "M" [1]. It can be demonstrated that the output voltage waveform of the inverter contains harmonics that are integer multiples of the carrier frequency and its vicinity. When the modulation depth M is less than one, the highest amplitude and the most influential harmonic component is the N±1, while the lowest harmonic component that warrants consideration is the N-3. Conversely, when the modulation depth M is equal to one, the highest amplitude is the N±3, while the lowest harmonic component that requires attention is the N-5. These findings are supported by the literature [10-12]. As the modulation depth and carrier frequency increase, the relative value of the amplitude decreases. When the carrier ratio is even, the output voltage harmonics contain only odd harmonics. Conversely, when the carrier ratio is odd, both even and odd harmonics are present. Irrespective of whether the carrier ratio is odd or even, the output voltage harmonics do not contain harmonics that are integer multiples of the switching frequency (carrier frequency). As the carrier ratio is increased, the frequency of the lowest harmonic moves away from the fundamental frequency, thereby facilitating a more efficient and straightforward filtering process. This, in turn, contributes to the optimization and improvement of the output voltage quality. Nevertheless, an increase in the carrier ratio entails a trade-off: it will exacerbate the energy consumption issue of the switching elements and introduce further challenges and complexity to the implementation of the hardware system [10]. Therefore, when seeking to enhance the quality of the output voltage, it is essential to consider the potential impact on system efficiency and the design of the hardware. Fig. 5 illustrates the harmonic analysis of the output voltage.

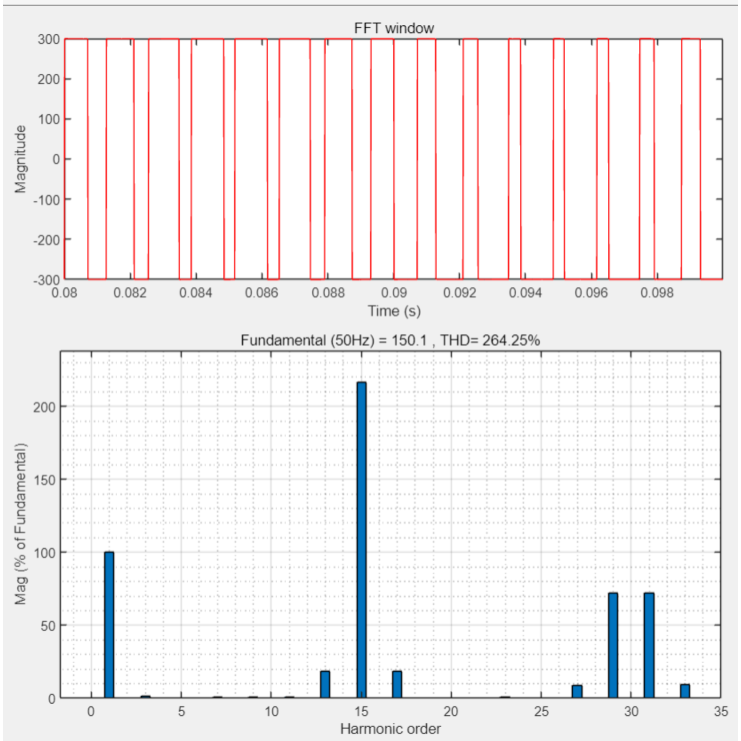

Fig.5 Harmonic analysis diagram of output voltage

The strategy for generating the octave SPWM control pulses is, in essence, analogous to the generation of bipolar SPWM. However, the crux of the matter lies in the introduction of two distinct strategies. One approach employs two reference sine wave signals of opposite phase (opposite polarity) in conjunction with a bidirectional (i.e., capable of varying in the positive and negative directions) triangular carrier. The intersection of these two signals is utilized to determine the drive signal for the power switch. An alternative approach employs a sine wave signal, with the triangular carrier waveform used for comparison being in the opposite direction during the rise and fall, thus generating control pulses of alternating polarity. Both approaches have been demonstrated to be effective in generating frequency-doubled SPWM control pulses [11].

3.3. Unipolar frequency doubling SPWM circuit simulation

A schematic diagram of the unipolar frequency-doubling SPWM waveform modulation circuit is provided in Fig. 6 for reference. At the same switching frequency, the harmonic order is increased, allowing for the reduction in the size of the filter.

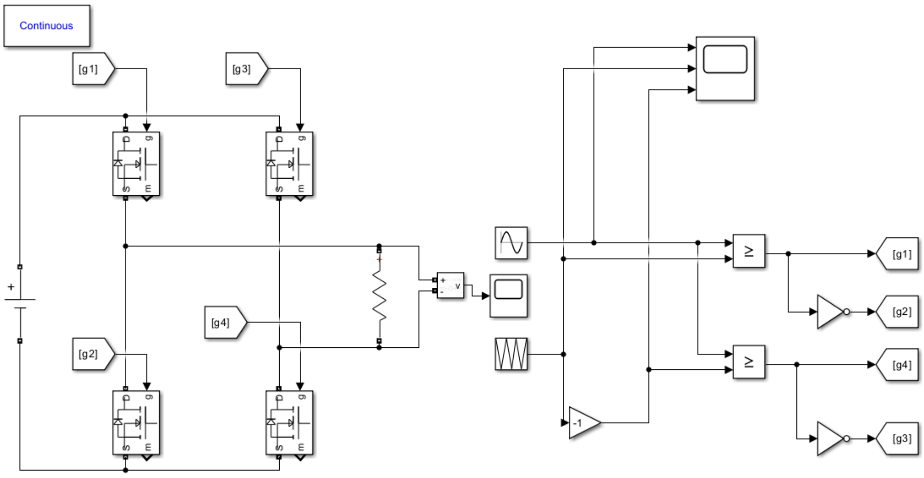

Fig.6 Single-phase frequency-doubled SPWM waveform modulation circuit schematic diagram

Fig.6 illustrates the output voltage waveform, which reveals that the output voltage of the inverter in an unfiltered state presents as a series of rectangular pulses. The amplitude and width of these pulses fluctuate in accordance with the corresponding sinusoidal law. In a manner analogous to the unipolar control strategy, there are only three levels: Ud, -Ud, and O, which alternate with the positive and negative half-cycles of the sinusoidal waveform. The Output Voltage Waveform is shown in Fig.7.

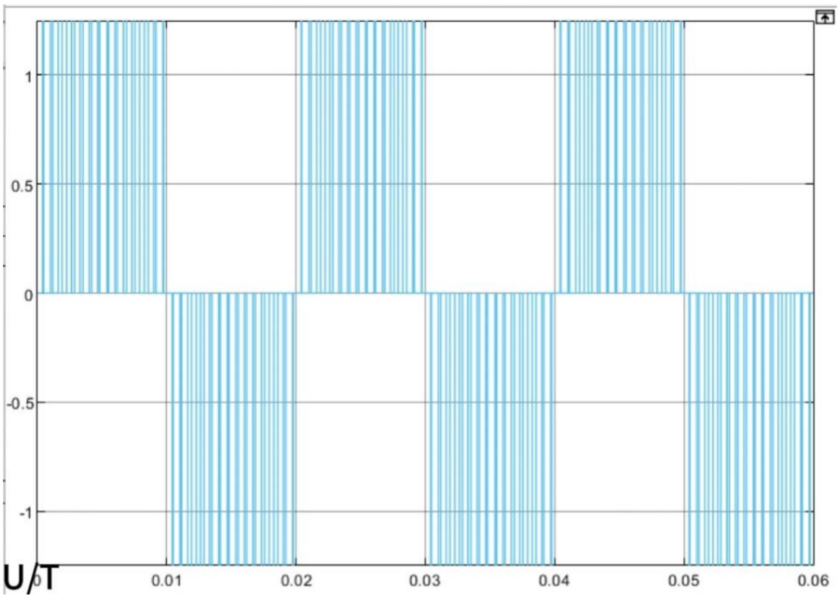

Fig.7 Output Voltage Waveform

Subsequently, the circuit components and state space equations were connected and transformed using the PowerGUI module in Specialised Power Systems. The output voltage was subjected to Fourier analysis through the FFT analysis function, and the results are presented in Fig. 8. In this figure, the modulation depth is 0.5, the fundamental frequency is 50 Hz, the carrier frequency is 1750 Hz (N=35) and the carrier ratio is P=15 [1].

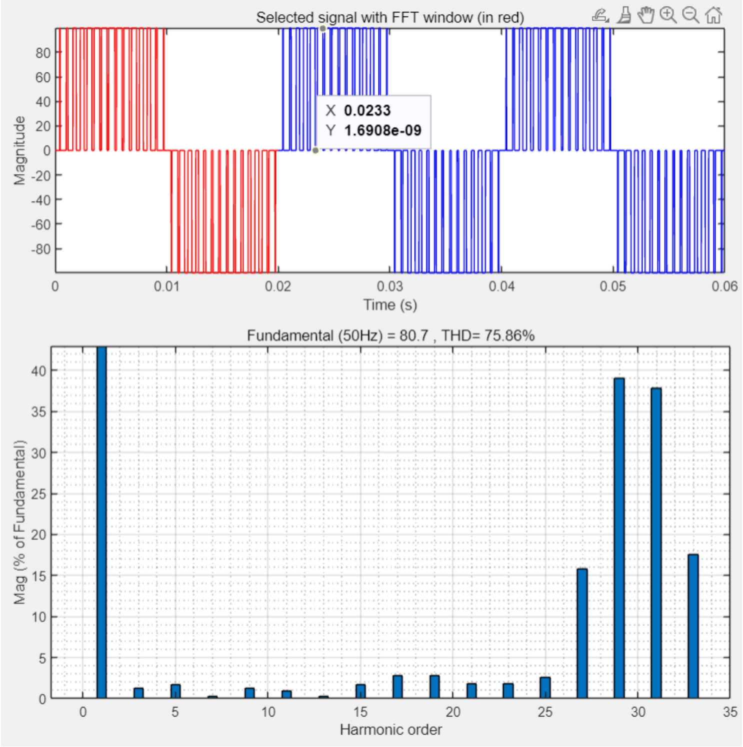

Fig.8 Harmonic analysis diagram of output voltage

In the context of unipolar frequency doubling and the control mode of the inverter, the lowest harmonic that warrants consideration is 2N-3. The highest harmonics are the N-1st and N+1st harmonics. This remains true regardless of whether the carrier ratio N is even or odd. In such a case, the output voltage will contain only the odd harmonics. As the carrier ratio and modulating waveforms increase, the total harmonic distortion (THD) will decrease gradually. This will result in the output current waveform becoming more similar to a sinusoidal waveform. In unipolar frequency doubling, the harmonic performance of the output is equivalent to twice the carrier frequency of single-phase unipolar SPWM. However, the frequency of the switching tube remains unaltered, preventing an increase in switching tube loss. Furthermore, the harmonic suppression ability of the unipolar control strategy is enhanced. This is a relatively straightforward enhancement that can significantly enhance performance, thereby demonstrating the practical value of unipolar frequency doubling as a technology.

4. Harmonic SPWM inverter harmonic suppression method research

It has been demonstrated that the output voltage of a single-phase SPWM inverter invariably comprises a proportion of harmonics and that the output voltage does not exhibit a sinusoidal waveform, irrespective of the carrier control method employed. The active power factor corrector modulates the current waveform by regulating the switching devices within the circuit (e.g., IGBTs or MOSFETs) to minimize the phase difference between the voltage and the current, thereby reducing ineffective power loss. This optimization results in a reduction of the load on the inverter from the grid and an increase in system efficiency. An analysis of the harmonics present in the output voltage of a single-phase SPWM inverter reveals that they are distributed around integer multiples of the carrier waveform. This indicates that the magnitude of the carrier frequency has a significant impact on the harmonics of the output voltage of a single-phase SPWM inverter [1]. Consequently, in order to eliminate the low and some odd harmonics of the output voltage, it is necessary to select an appropriate carrier frequency, that is to say, a suitable carrier ratio.

By analyzing the output voltage harmonics of a single-phase SPWM inverter, it can be seen that the harmonics are usually distributed around integer multiples of the carrier frequency. Therefore, choosing the appropriate carrier frequency (i.e., carrier ratio) is critical to eliminate the lower and some odd harmonics. A higher carrier frequency will reduce the size of the filter by concentrating the major harmonics in a higher frequency band. The carrier frequency is generally required so that the carrier ratio is an integer and is capable of suppressing harmonics that are integer multiples of 3. Generally speaking, for an extra high power inverter, due to the poor performance of high power switching, and most of the cases work in the hard switching state, to get a higher inverter efficiency should be selected in the $N \leq 9$. For the large and medium power inverter with no dead zone, the performance of the switching device is better, and buffer circuits or soft-switching mode of operation of switching engineering to improve the inverter efficiency is not a lot of decline so that it can be selected as $9 \leq N \leq 21$. For small and medium power inverters with no dead zone, the switching performance is good, and the switching loss should be smaller due to the buffer circuit over the soft-switching mode of operation, so $N \geq 21$ can be selected, especially for the small power UPS working under the soft-switching state, $N \geq 100$ can be selected, and the switching frequency of the inverter can be increased to more than 20KHz. In this way, if you do not consider the reduction of loop current or short-circuit current filter parameters will become even smaller, sometimes as long as very small capacitors can be very effective in filtering out the high harmonics. When the switching frequency is increased above 20 KHz, the audible noise of the inverter is again eliminated. If the selected carrier ratio is very large, whether the carrier ratio is selected as odd or even does not have a great influence, so it can be selected at random. In this case, either synchronous modulation or asynchronous modulation can be selected. In another case, when the value of N is small, for example, when $N \geq 21$, the output frequency and the harmonic frequency of the side frequency are very close to each other, thus generating jumps, which will make the characteristics significantly worse and make it unusable.

In practice, the selected carrier frequency may deviate from integers or multiples of 3 due to errors, leading to SPWM synchronization modulation difficulties and the appearance of even harmonics. To reduce the carrier frequency error, synchronization of the carrier with the sinusoidal modulating waveform should be enforced so that the carrier frequency can be precisely achieved. However, although increasing the carrier frequency reduces the low harmonics and motor losses, it also significantly increases the switching losses of the inverter.

5. Conclusion

Different carrier ratios and modulation ratios affect the harmonic content and distribution of the output voltage of the SPWN inverter. With the gradual increase of carrier frequency and modulation index, the total harmonic distortion (THD) level of the output voltage shows a decreasing trend. Based on voltage-based SPWM inverter circuits, this study provides an in-depth analysis of the differences in harmonic characteristics between unipolar frequency doubling and standard unipolar modulation strategies through refined modeling and simulation techniques. The experimental results show that the unipolar modulation strategy exhibits superior harmonic suppression performance in the linear modulation region. Further, this study focuses on the two core parameters of modulation depth and carrier ratio. Both methods of choosing the appropriate carrier ratio and injecting appropriate harmonics can suppress the output voltage harmonics of single-phase SPWM inverters so that the THD value can be reduced, but both methods are limited and can only suppress the harmonics to a small extent. Their specific effects on the harmonic composition of the unipolar frequency doubling inverter circuit are systematically explored. The detailed simulation analysis not only verifies the accuracy of the proposed model, but also highlights the ease of implementation of the model in a software environment, its highly flexible configurability, and its intuitive operating experience.

Although the current circuit simulation model maintains a high degree of simplicity, it provides a wide scope for future component selection and parameter optimization based on practical application requirements, intending to explore and design the most optimal harmonic suppression strategy.

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