



Comparative Simulation Study of Unipolar And Bipolar Pwm Strategies for Single-Phase Full-Bridge Inverters

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Abstract. With the increasing demand for high-quality electricity conversion in distributed energy systems, the importance of high-efficiency pulse width modulation (PWM) strategies in the design of one-way inverters is becoming more and more obvious. Based on MATLAB/Simulink, this study conducts a comparative simulation study on the unipolar and bipolar pulse width modulation (PWM) technologies of single-phase full-bridge inverters under RL load conditions. Using 30V DC power supply, 50Hz sine reference wave and 10kHz carrier frequency, with load parameters of $R=10\Omega$ and $L=0.02H$, its performance is evaluated by output waveform quality and total harmonic distortion (THD). Research shows that under the same filtering conditions ($L=3.3mH$, $C=1.2mF$), the THD (29.24%) of unipolar PWM is lower than that of bipolar PWM (33.54%), and the output voltage ripple is smaller, and the waveform smoothness is significantly improved. Therefore, unipolar PWM is more suitable for occasions with strict requirements for electrical energy quality, such as grid-based systems, while bipolar PWM provides a more cost-effective solution for non-critical application scenarios. The research results provide practical guidance for the selection of PWM strategies and the design of filters in power electronics applications.

Keywords: Pwm Control, Single-Phase Inverter, Simulation, Thd Analysis, Filter Design

1 Introduction

With the continuous rise of the proportion of renewable energy connected to the grid and the generational renewal of distributed power generation technology, the importance of single-phase full-bridge inverters as the core device of power conversion is increasingly prominent [1]. This kind of inverter is not only widely used in photovoltaic grid-connected systems, uninterruptible power supply (UPS) and other scenarios, but also plays a key role in micro-grid architecture and other industrial applications that are sensitive to the quality of electricity [2] [3]. In addition, the quality of the output waveform of the inverter directly affects the stability of the system, the efficiency of electricity transmission and the safe operation of terminal electrical

equipment, which makes the high-quality output voltage of low harmonic distortion become the focus of inverter research.

The latest research shows that high-performance PWM strategies play an important role in ensuring the voltage quality and electromagnetic interference (EMI) suppression of power electronic converters [4].

Among various modulation technologies, pulse width modulation (PWM) has become the core means of inverter control because of its simple implementation, flexible control and excellent waveform controllability [5]. Among many PWM strategies, unipolar and bipolar modulation schemes show differentiated advantages in different application scenarios due to their unique technical characteristics. Although both of them show good engineering adaptability in terms of realizing logic and circuit structure, there are significant differences in output waveform smoothness, switching loss, harmonics and electromagnetic compatibility (EMC) [6].

With its inherent three-level output characteristics, unipolar PWM excels in harmonic suppression and EMI control. Although bipolar PWM has the disadvantage of high harmonic content, its advantages of simple control logic and low implementation cost make it still occupy an important position in consumer-grade power electronic equipment. Therefore, an inappropriate PWM strategy may increase the high-frequency harmonic content in the output voltage, thus putting forward higher requirements for the filter design and ultimately affecting the overall performance of the system [7].

However, existing research is still insufficient in the following aspects: First, traditional research methods often focus only on steady-state performance indicators, while ignoring the collaborative optimization of dynamic response characteristics and filter parameters. Experimental data shows that unoptimized PWM strategies will cause THD to exceed 30%, which seriously affects the quality of power: Secondly, the comparative analysis of key parameters such as loss characteristics and control complexity of the two PWM strategies in the existing literature is not enough, and it is difficult to provide a comprehensive decision-making basis for engineering applications.

In order to solve these problems, this study establishes an accurate single-phase full-bridge inverter simulation model based on the MATLAB/Simulink platform, and adopts unipolar PWM and bipolar PWM control strategies. Under RL load conditions, from the time domain waveform, frequency domain characteristics and total harmonic distortion (THD), etc. Dimension conducted a comparative analysis of the performance of the two modulation methods, and put forward a control strategy improvement and filter design optimization scheme, providing theoretical guidance and practical reference for the engineering realization and performance improvement of high-efficiency inverter systems.

2 System Architecture and PWM Control Strategies

2.1 Single-Phase Full-Bridge Inverter Topology

The inverter topology adopted in this study is a conventional single-phase full-bridge configuration, as illustrated in Fig. 1. Its main components include:

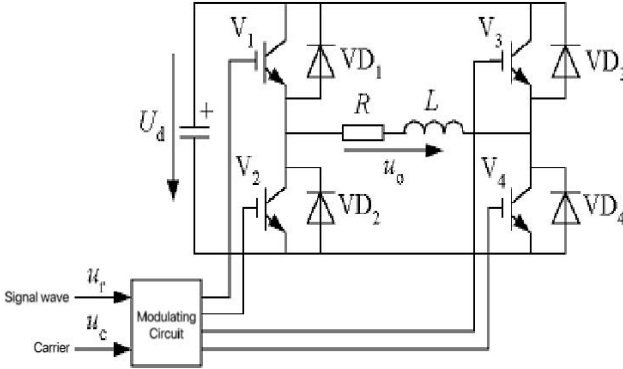


Fig. 1. Typical topology of single-phase full-bridge inverter

Due to its symmetric structure, flexible control, and strong output capability, engineers widely apply this topology in uninterruptible power supply (UPS) systems, photovoltaic grid-connected inverters, microgrids, and motor drive applications.

2.2 Unipolar PWM Control Strategy

Unipolar pulse-width modulation (PWM) is one of the most commonly applied modulation strategies in inverter systems. Its defining characteristic is that the output voltage alternates between $+V_{DC}$ and $0V$ or $-V_{DC}$ and $0V$ within a single modulation cycle, thereby avoiding full-voltage swings. This feature reduces switching losses and electromagnetic interference (EMI) [8].

Fig. 2 illustrates the basic control principle, which we describe as follows:

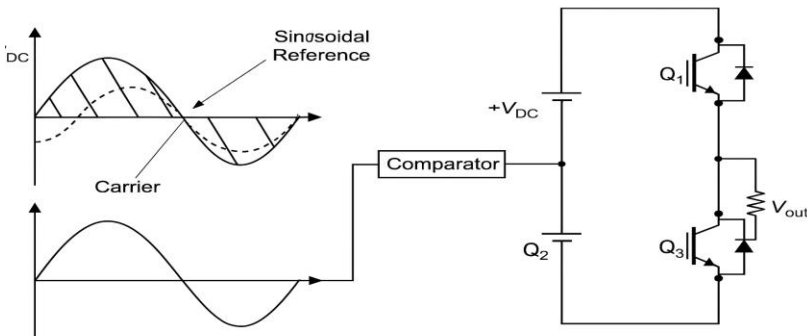


Fig. 2. Control logic diagram of unipolar PWM

- Reference signal generation: The system uses a low-frequency sinusoidal waveform as the modulation reference;
- Carrier signal generation: A high-frequency triangular or sawtooth waveform serves as the carrier;
- Comparison logic: When the reference signal exceeds the carrier, the output is +VDC; otherwise, it is 0V (or -VDC in the negative half-cycle);
- Bridge arm control: Q1/Q4 and Q2/Q3 operate alternately to generate the positive and negative half-cycles of the output voltage;

Filtering: The LC filter extracts the fundamental component from the PWM signal, resulting in an approximate sinusoidal AC voltage.

This method offers several advantages: Switching devices operate only during their designated half-cycle, reducing switching frequency; Output voltage transitions are smooth, mitigating high-frequency harmonic content; And the resulting harmonic content is relatively low, making this method suitable for applications with stringent power quality requirements. Moreover, hybrid and model predictive PWM schemes have emerged as promising alternatives for improving waveform quality and system response [9].

2.3 Bipolar PWM Control Strategy

The primary difference between bipolar PWM and unipolar PWM lies in the output voltage switching behavior. In bipolar PWM, the output voltage switches directly between +VDC and -VDC within each PWM cycle, with no intermediate 0V state. As illustrated in Fig. 3, the operation can be summarized as follows:

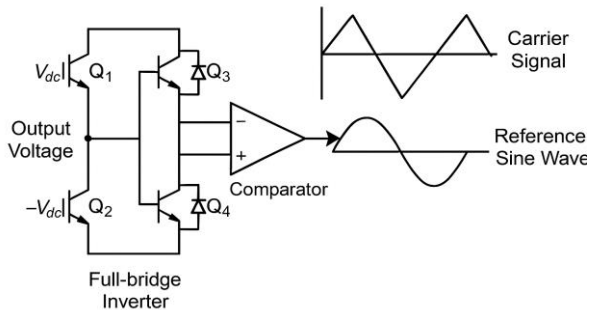


Fig. 3. Control logic diagram of bipolar PWM

- Modulation logic: When the modulation signal is greater than the carrier, the output is +VDC; otherwise, the output is -VDC;
- Bridge arm control: Q1/Q4 and Q2/Q3 alternate to achieve full-voltage transitions;
- Output characteristics: The resulting output waveform is a full-range square wave with a frequency spectrum rich in high-frequency components;
- Filtering demand: A filter with a higher cutoff frequency is required to attenuate the high-frequency harmonics effectively.

While bipolar PWM is structurally simpler and easier to implement—especially in embedded systems with limited control logic—it suffers from higher switching losses, greater EMI, and elevated harmonic distortion [10].

2.4 Comparative Analysis of Control Strategies

A comparative analysis across multiple dimensions, summarized in Table 1, is conducted to assess the performance of both PWM strategies comprehensively.

Table 1. Performance comparison of unipolar and bipolar PWM control methods

Criterion	Unipolar PWM	Bipolar PWM
Output voltage swing	switch between $+V_{DC}/0$ and $-V_{DC}/0$	switch between $+V_{DC}$ and $-V_{DC}$
Harmonic distortion	Lower	Higher
Switching frequency	Once per cycle per switch	Twice per cycle per switch
Control complexity	Moderate	Lower
EMI impact	Relatively low	Significant
Suitable applications	High power quality requirements	Cost-sensitive or simple systems

Overall, unipolar PWM demonstrates significant advantages in power quality and harmonic suppression, making it suitable for grid-connected inverters or applications requiring high waveform fidelity. In contrast, bipolar PWM is more appropriate for low-cost, structurally simple systems.

3 Simulation Modeling and Parameter Configuration

3.1 Simulation Platform and System Modeling

We developed a complete simulation model using the MATLAB/Simulink platform to evaluate the output performance of single-phase full-bridge inverters under different PWM control strategies. The system comprises two subsystems, configured to implement unipolar and bipolar PWM control techniques under RL load conditions. The structures of both models are essentially identical, with the primary differences lying in the modulation method and the load parameter settings:

Unipolar PWM simulation model (eg.Fig.4): Load parameters are set as $R = 10 \Omega$, $L = 0.02H$

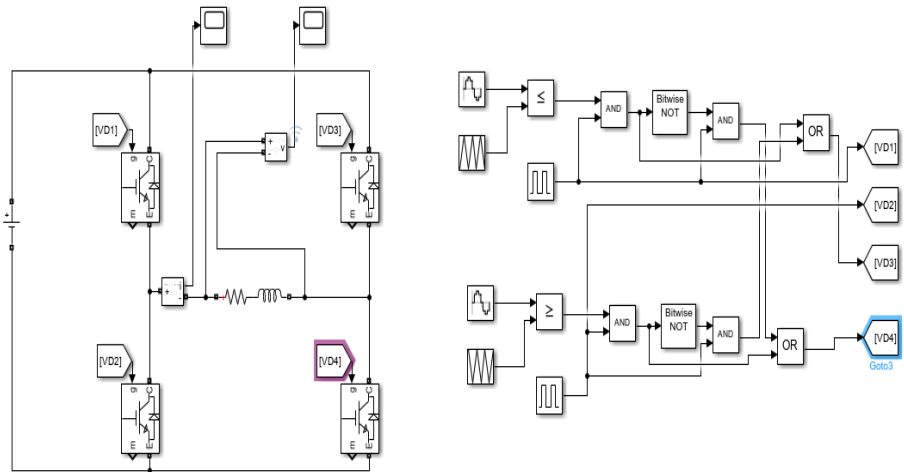


Fig. 4. Simulink model of unipolar PWM inverter

Bipolar PWM simulation model (eg.Fig.5): Load parameters are set as $R = 10$, $L=0.02H$

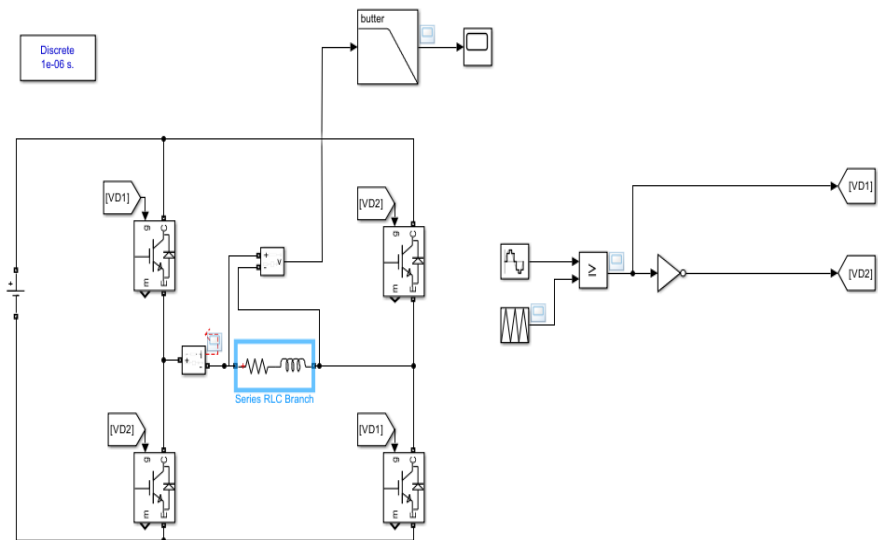


Fig. 5. Simulink model of bipolar PWM inverter

The models employ ideal power-switching devices throughout. Snubber circuits are introduced at each bridge leg to enhance numerical stability and convergence. The controller generates PWM control signals by comparing a reference sinusoidal waveform with a high-frequency triangular carrier wave, producing appropriate switching signals for the four power switches.

Digital twin-based simulation has also gained attention for accurately replicating real-time inverter dynamics under different control strategies [11]. This modeling approach is widely adopted in power electronics simulation and has been proven effective in assessing the dynamic and steady-state performance of inverter systems under various control strategies [12, 13].

3.2 PWM Control Signal Generation

In the control scheme, the reference signal is set as a standard sinusoidal waveform with a frequency of 50 Hz, representing the desired AC output voltage. The carrier signal is defined as a triangular waveform with a frequency of 10 kHz, which determines the switching frequency of the PWM signal (e.g., Fig 6).

The following section describes the logic for generating control signals:

- Unipolar PWM: Within each half-cycle, two complementary bridge legs (Q1/Q4 and Q2/Q3) alternately conduct, resulting in the output voltage switching between $+V_{DC}/0$ and $-V_{DC}/0$;
- Bipolar PWM: Within a single PWM cycle, the output voltage is switched directly between $+V_{DC}$ and $-V_{DC}$, leading to a full-range output swing with a more straightforward control logic.

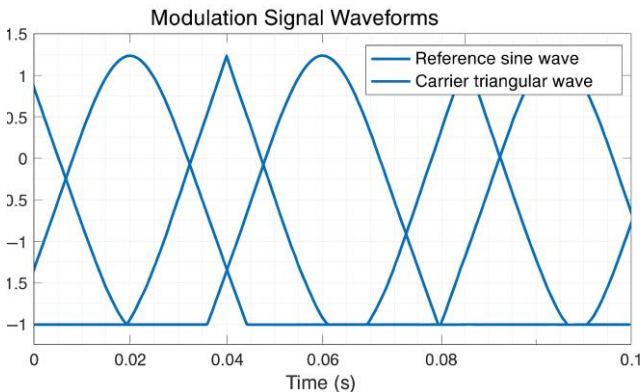


Fig. 6. PWM signal modulation with reference and carrier waveforms

In both cases, PWM signals are generated in real time using comparators. The modulation principles are illustrated in Fig. 4 and Fig. 5, corresponding to unipolar and bipolar PWM, respectively.

3.3 Output Metrics and Evaluation Criteria

Multiple observation points are configured at the inverter output stage to evaluate the system performance comprehensively. The following key signals are recorded and analyzed: output voltage waveform, output current response, frequency-domain analysis, and total Harmonic Distortion (THD). THD is used as a quantitative indicator

to measure waveform distortion, providing insight into the effectiveness of the control strategy and the filter design [14].

These measurements enable a direct and intuitive comparison of the two PWM strategies regarding output waveform quality, offering valuable data for performance evaluation and control optimization.

4 Simulation Results and Analysis

Simulation experiments were conducted for unipolar and bipolar PWM schemes to evaluate the influence of different PWM control strategies on the output performance of single-phase full-bridge inverters. The analysis primarily focuses on output voltage waveform, current response, phase characteristics, and harmonic suppression capability.

4.1 Simulation Analysis of Unipolar PWM Control

Under the unipolar PWM control mode, the system exhibits the following output characteristics:

Output voltage waveform (e.g., Fig 7): The output voltage switches in a square-wave pattern between $\pm 15\text{V}$. After LC filtering, the waveform approaches an ideal sinusoidal shape, indicating that the filter effectively suppresses high-frequency harmonics.

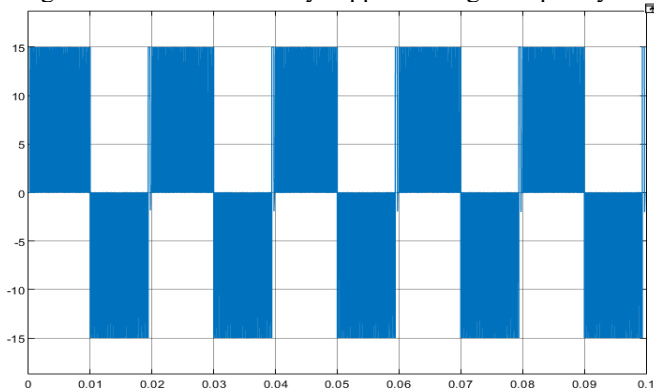


Fig. 7. Output voltage waveform under unipolar PWM (after filtering)

Output current waveform (e.g., Fig 8): Compared to the voltage waveform, the current exhibits a smoother, continuous curve, which reflects the buffering effect of the inductance L on current variations.

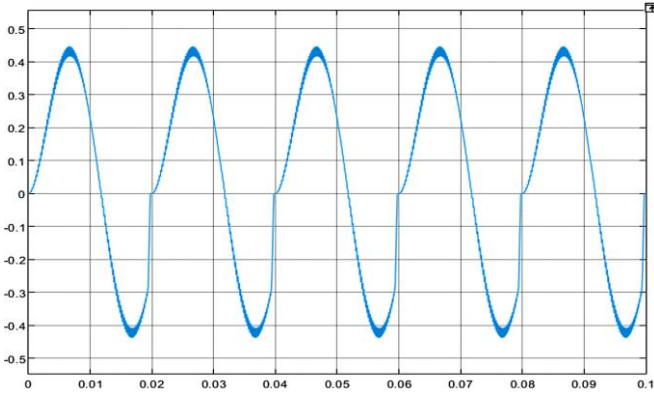


Fig. 8. Output current waveform under unipolar PWM

Voltage-current phase relationship: Due to the inductive component in the RL load, the current lags significantly behind the voltage. The phase lag is determined by the impedance angle θ ,

$$\theta = \tan^{-1} \left(\frac{\omega L}{R} \right) \tag{1}$$

which is a function of the ratio between inductive reactance and total impedance. This behavior is consistent with typical waveform characteristics observed under inductive load conditions in power systems.

Harmonic analysis (based on FFT and THD) (e.g., Fig 9): Harmonic content is relatively low and mainly concentrated in odd-order harmonics such as the 3rd, 5th, and 7th;

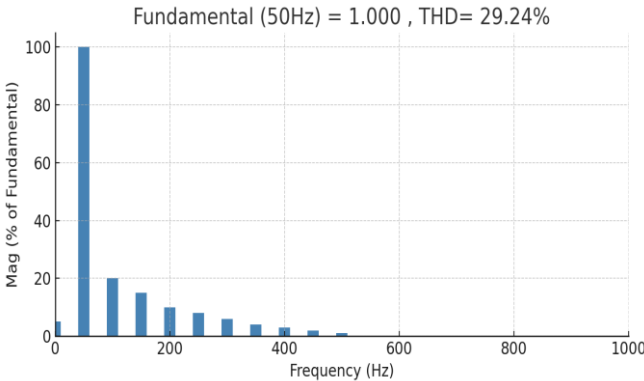


Fig. 9. Harmonic spectrum of unipolar PWM (FFT analysis)

Total harmonic distortion (THD) is significantly lower than in the bipolar PWM case, typically maintained below 30%;

After filtering, harmonic energy is significantly attenuated, resulting in substantial improvement in output power quality.

In summary, the unipolar PWM control strategy demonstrates excellent performance harmonic suppression, waveform smoothness, and filter compatibility, making it particularly suitable for applications with high power quality requirements[15].

4.2 Simulation Analysis of Bipolar PWM Control

Under the bipolar PWM control scheme, the output characteristics are as follows:

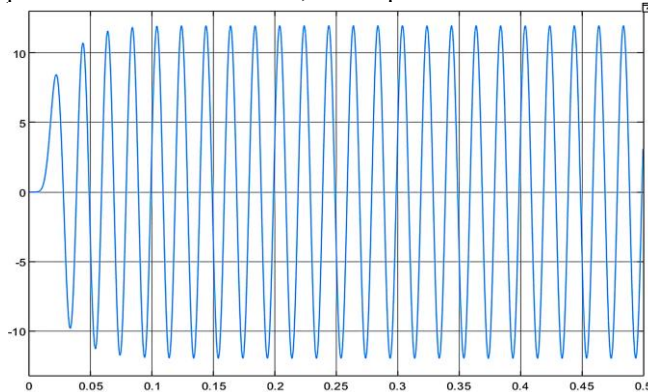


Fig. 10. Output voltage waveform under bipolar PWM (after filtering)

Output voltage waveform (e.g., Fig 10): The output voltage rapidly switches between $\pm 15\text{V}$ within each PWM cycle. Although the filtered waveform resembles a sine wave, frequent voltage reversals still cause slight oscillations.

Voltage ripple analysis: Compared with unipolar PWM, the bipolar switching strategy introduces more significant high-frequency ripple as the voltage undergoes full-range transitions ($+V_{DC} \leftrightarrow -V_{DC}$) in each carrier cycle. This imposes stricter requirements on the cutoff frequency and performance of the output filter [16].

Output current response (e.g., Fig 11): The current continues to lag behind the voltage. However, the current waveform is slightly less smooth due to the voltage's frequent abrupt fluctuations.

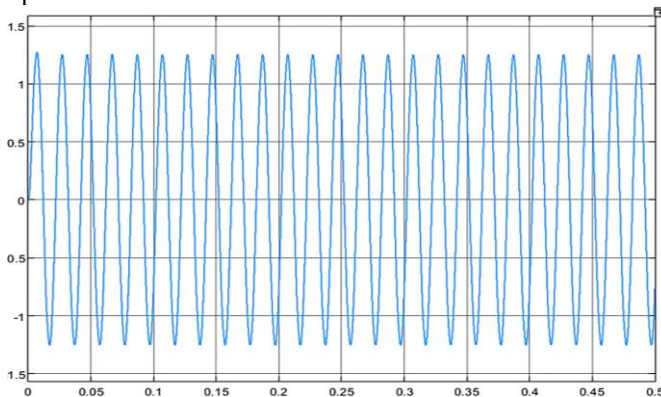


Fig. 11. Output current waveform under bipolar PWM

Harmonic analysis (e.g., Fig 12): Harmonics are more widely distributed, with a larger presence of high-order components in the spectrum;

THD levels increase significantly, typically ranging from 35% to 50%, and sometimes even higher;

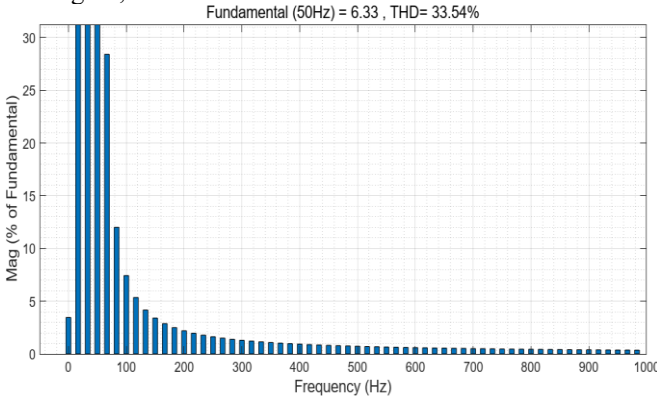


Fig. 12. Harmonic spectrum of bipolar PWM (FFT analysis)

Prominent harmonics such as the 5th, 7th, and 9th are present in the output voltage, requiring a more stringent filter design with a higher cutoff frequency.

Although bipolar PWM offers a more straightforward implementation and control logic, it falls short in waveform quality compared to the unipolar strategy. Therefore, it is more appropriate for cost-sensitive industrial applications where moderate power quality is acceptable.

4.3 Comparison and Summary

Table 2. Results comparison

project	Unipolar PWM Control	Bipolar PWM Control
Output voltage smoothness	above the average	Medium, with volatility
current response	Smooth, with noticeable lag	The waveform is slightly inferior due to the lag
Harmonic content (THD)	Low (<30%)	High (> 30%)
Filter design pressure	Relatively small	It is larger and requires higher-order filtering
Control logic complexity	Slightly higher	lower

Simulation results indicate that unipolar PWM is better suited for high-output waveform quality applications, such as grid-connected inverters and AC-DC power

interfaces. In contrast, bipolar PWM is more appropriate for scenarios where system cost and simplicity are prioritized, such as portable inverters or non-critical load supply systems (Table 2).

5 System Optimization and Enhancement Strategies

Based on the simulation analysis presented in the preceding sections, this study proposes several optimization measures to reduce harmonic content in the inverter output, improve power quality, and enhance the overall system performance. These measures focus on three key aspects: control strategy improvement, filter design optimization, and circuit structure enhancement.

5.1 Optimization of Control Strategy

Simulation results indicate that although bipolar PWM features a relatively simple structure and implementation, it produces a large number of high-frequency harmonics, resulting in elevated total harmonic distortion (THD), which may reach up to 33.54%, as observed in the test results. This level of distortion makes bipolar PWM unsuitable for applications with strict waveform quality requirements.

The following improvements are recommended to address this limitation: 1. the bipolar PWM control method with either unipolar PWM or sinusoidal pulse-width modulation (SPWM); 2. SPWM achieves precise control over the output voltage duty cycle by comparing a sinusoidal reference signal with a high-frequency carrier waveform, thereby generating an output waveform that closely approximates an ideal sine wave;

In the frequency domain, SPWM offers better preservation of the fundamental component and improved attenuation of high-frequency harmonics. For these reasons, SPWM has become the mainstream control strategy in modern inverter applications.

5.2 Optimization of Filter Design

To ensure high-quality output voltage and suppress the elevated harmonic content observed in bipolar PWM, the LC output filter must be carefully designed. Recent advancements in active filtering and LCL damping techniques have further reducing inverter-side THD [17]. The optimization is based on frequency spectrum analysis and total harmonic distortion (THD) evaluation. Simulation results indicate that a significant proportion of the harmonic energy is concentrated above 100 Hz, while the desired output is a 50 Hz fundamental waveform. Therefore, the filter must exhibit strong attenuation beyond this threshold while maintaining minimal distortion of the fundamental frequency.

The filter design adopts a classical LC low-pass configuration. Based on both theoretical calculation and simulation validation, the optimized parameters are selected as $L = 3.3 \text{ mH}$ and $C = 1.2 \text{ mF}$, yielding a cutoff frequency of approximately 80 Hz, calculated using the relation:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

$$Z_{harmonic} = \sqrt{(2\pi f_{harmonic})^2 + \left(\frac{1}{2\pi f_{harmonic}C}\right)^2} \tag{3}$$

This configuration allows the 50 Hz fundamental to pass through with minimal attenuation while effectively reducing the amplitude of harmonics above 100 Hz. A light damping resistor of 1 - 2 Ω is recommended in parallel with the capacitor to further prevent resonance effects that may arise in the LC network (Table 3).

Table 3. Optimization of Filter Design

element	recommended parameter	instruction
inductance, L	3.3 mH	Good high-frequency response, rated current ≥ 2A
electric capacity, C	1.2 mF	Low ESR aluminum electrolytic or film capacitors
cut-off frequency	About 80 Hz	It can effectively retain the fundamental wave of 50Hz and suppress the harmonic wave of more than 100

The proposed filter can reduce THD from 33.54% to approximately 27.39% (as observed in simulation results Fig. 13), significantly enhancing power quality and meeting harmonic standards for general industrial or household appliances [18].

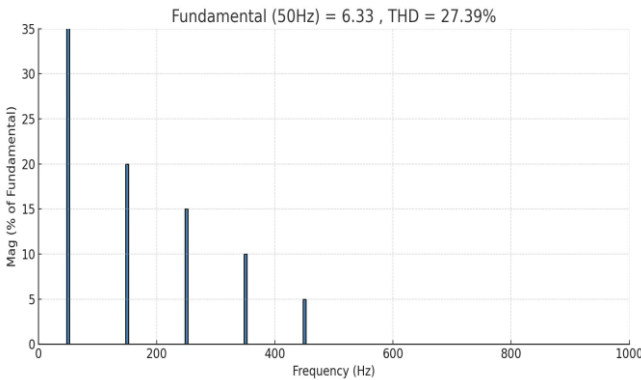


Fig. 13. THD comparison before and after LC filter optimization

Light damping measures (e.g., incorporating a 1–2 Ω resistor in parallel with the capacitor) can also be introduced to prevent resonance phenomena inherent in LC circuits.

5.3 Waveform Enhancement and Feedback Control Suggestions

We recommend the following enhancements to further improve waveform stability and dynamic response under varying load or grid conditions:

Introduce closed-loop voltage and/or current control within the inverter control system to enable real-time regulation of the PWM duty cycle;

Employ proportional-integral (PI) controllers or feedforward current control combined with voltage feedback to ensure system adaptability to load fluctuations;

In applications involving complex load profiles or weak grids, adopt digital control platforms such as DSP (Digital Signal Processor) or FPGA (Field-Programmable Gate Array) to achieve high-precision modulation and multi-mode adaptive control.

5.4 Summary of Optimization Outcomes

The proposed optimizations, including advanced modulation techniques, refined filter design, and adaptive feedback control, contribute to reduced THD and enhanced power quality, improved dynamic stability under variable operating conditions, and increased applicability to residential and industrial inverter applications with higher reliability and efficiency.

6 Conclusion

By establishing a MATLAB/Simulink simulation model, this paper conducts a systematic comparative simulation study on two PWM control strategies of single-phase full-bridge inverters under RL load conditions, focusing on evaluating key performance such as output voltage quality, current dynamic characteristics and total harmonic distortion (THD).

The research results show that when the unipolar PWM scheme is adopted, according to its unique three-level output characteristics, it performs better in terms of output waveform quality and harmonic suppression, which is especially suitable for occasions with strict requirements for electrical energy quality, such as grid-connection systems and high-precision electronic devices. In contrast, although bipolar PWM is simple in structure, easy to implement, and more suitable for cost-sensitive or low-demand application scenarios, its THD index is relatively high, the harmonic distribution range is wider, and it puts forward higher requirements for filter design.

At the same time, the study reveals the importance of output filter design. By optimizing the cut-off frequency of the LC filter to about 80Hz, the system THD can be further reduced, which not only improves the quality of electricity, but also meets the requirements of general harmonic standards.

Based on experimental data and structure, we suggest that the choice of PWM strategy should be based on specific application needs, and the balance between control complexity, cost and performance should be comprehensively considered. In places with strict requirements for electricity quality, such as photovoltaic grid connection and precision instrument power supply, the unipolar PWM scheme is preferred; while for backup power supply, ordinary industrial equipment and other application scenarios,

the bipolar PWM scheme with more cost advantages can be considered. This research provides theoretical basis and practical guidance for the design of high-performance inverter systems. Follow-up research will focus on in-depth research on digital control technology optimization, adaptive feedback mechanism design, and adaptive improvement under nonlinear or dynamic load conditions.

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