CONTROL DESIGN OF UPS INVERTER BASED ON SPWM CONTROL TECHNOLOGY

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Abstract - Currently, the distribution network is highly susceptible to lightning strikes, insulation damage, and operational accidents, causing severe fluctuations and instantaneous power outages in the power supply, resulting in chaos throughout the entire process, and even causing production equipment to shut down. The traditional uninterruptible power supply (Uniterruptible Power Supply, UPS) inverter control method has been unable to meet the real needs. In view of the problems of high harmonic distortion and poor stability of power equipment in traditional control methods, front sinusoidal pulse width modulation technology (Sinusoidal Pulse Width Modulation, SPWM) is introduced to significantly improve the harmonic composition of the output waveform and make the waveform closer to sine wave; then combined with the parameter setting of electronic filter (Lnductor Capacitor, LC), a new UPS inverter control system is designed to improve the overall performance of UPS inverter. It was found that the basic waveform of the proposed scheme was 217.2 V, which conformed to the basic principle, and its control output voltage harmonic distortion was better than traditional methods. Under nonlinear load conditions, the output voltage still maintained a stable sine waveform, and the total harmonic distortion of the inverter output voltage was 0.22%, which was relatively low and achieved the expected control target. The UPS inverter control algorithm proposed in the paper is practical and feasible, which can ensure that the device can still work normally in the event of abnormal power supply to the grid, and has certain practical application value.

Keywords: SPWM technology; Inverter; Control strategy; Filtering circuit; Unipolar; Bipolar.

1. Introduction

Driven by rapid economic development, the requirements for power quality of various electrical equipment are also constantly increasing. Especially in the fields of data centers, banking institutions, and medical institutions, there are higher requirements for the reliability of power supply. Due to power outages and other issues, it is difficult for the power system to supply power to important electrical equipment [1-3]. In such a specific environment, once the power system malfunctions, it will not only cause significant economic losses to people, but also endanger personal safety. Therefore, to ensure the normal operation of critical equipment, an Uninterruptible Power Supply (UPS) has emerged. UPS power supply is based on inverters as the core and contains energy storage batteries to provide uninterrupted high-quality electrical energy to electrical equipment. Its original intention is to continuously supply power to loads in case of sudden power outages [4].

At present, there is a higher demand for power quality in various application scenarios, so UPS also needs to incorporate functions to improve power quality. The control circuits of early UPS inverters were mostly implemented in an analog way. After several years of development and exploration, they have become quite perfect, but there are still many problems and shortcomings. For example, traditional Computer Numerical Control (CNC) systems have complex circuit structures, difficult maintenance, susceptibility to temperature and device characteristics, and many other problems. Using digital control methods can not only complete a large number of calculations, but also complete completely different operation modes from conventional linear adjustment, with great flexibility [5-6]. Based on this, a novel single-phase UPS inverter control system is proposed by innovatively introducing Sinusoidal Pulse Width Modulation (SPWM) method, aiming to provide reference for the safe and reliable operation of electrical equipment in various industries.

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2. Related Works

Considering the various characteristics of UPS inverters, researchers internationally have proposed various solutions. According to the number of circuits of the inverter power load, there are single circuit, double closed loop, and multiple circuit. At present, from the perspective of control algorithms, there are generally traditional Proportion Integration Differentiation (PID) control, triangular wave modulation method, hysteresis comparison control, repetitive control, fuzzy control, etc. In response to the current problem of high harmonic output from voltage sources, Yan et al. studied Single-phase Full Bridge Inverter (SFBI) circuits. A dual sliding mode surface continuous switching sliding mode controller was designed based on circuit principles. This method and dual closed-loop cascade control were applied to control the output waveform of the SFBI circuit. The maximum instantaneous voltage error and Total Harmonic Distortion (THE) were improved [7]. Seyedalipour et al. built a control approach for a three-phase four bridge arm Lnductor Capacitor (LC) filtered voltage source inverter for the application of UPS inverters. The control method reduced the steady-state error of the output voltage and had good control performance [8]. To maintain uninterrupted output voltage under instantaneous impulse load and reduce the distortion of UPS output voltage, He et al. proposed a control strategy to suppress UPS impulse current based on virtual synchronous generator theory. This method could suppress surge current, reduce output voltage distortion of UPS inverters, and ensure good performance of online UPS under surge loads [9].

The sensorless control method is actually a soft sensing technology that can reduce system costs and measurement related losses, especially for UPS, which can improve system reliability. Li et al. proposed a limited control set model predictive control scheme for a single-phase UPS inverter without load current sensors. The results showed that the system had smaller load current estimation errors and lower output voltage distortion, and its effectiveness was verified through simulation and experiments [10]. Choeung et al. proposed an optimal voltage control approach for three-phase inverters using linear matrix inequality method to address the power quality caused by unbalanced loads in UPS systems. Simulation experiments verified the effectiveness of the control scheme [11]. Rymarski et al. proposed a simple discrete control method for SFBI in low switching frequency UPS systems to address the higher output voltage distortion at low switching frequencies. The results showed that the method had good control performance [12]. The traditional equal distribution control of active and reactive power can ideally suppress Alternating Current (AC) circulating current, but cannot limit Direct Current (DC) circulating current. Therefore, He et al. used a nonlinear robust backstepping controller to eliminate DC circulating current in parallel UPS systems. The effectiveness in suppressing DC circulating current and tracking the ideal output voltage was verified [13]. The low energy efficiency of locally manufactured UPS equipment in underdeveloped countries puts pressure on the national power grid and increases the cost for residential consumers. Therefore, Ahmed et al. proposed a local UPS inverter powered by photovoltaics, which utilized photovoltaic energy to make existing UPS units more efficient without interrupting their uninterrupted power supply during load shedding. Compared with existing UPS inverters, the photovoltaic fed local UPS inverter had an average efficiency of 81.51% and a minimum THE of 1.29% [14]. To restore the system state in external road interference, Saoudi et al. proposed a deadbeat control algorithm suitable for single-phase inverter UPS. The control method required measuring the capacitor current and output voltage to maintain a sinusoidal output voltage. The simulation results were consistent with the PIL test results, proving the effectiveness of the controller [15,16].

In summary, there are various control methods for UPS inverters both domestically and internationally, but each method has its own advantages and disadvantages. Although these algorithms have high accuracy, their robustness is not strong. Therefore, this paper innovatively introduces SPWM control technology into motor control and selectively combines it together to form a novel motor variable frequency speed control algorithm. This method can complement each other's strengths and weaknesses, which is more in line with the requirements of UPS inverter power supply. The rest of the paper is organized as follows: Section 3 mainly describes the design of UPS inverter control model based on SPWM modulation control technology, and expounds its related methods. Section 4 mainly simulates the paper-designed UPS inverter control system to verify the effectiveness and superiority of the research method. Part 5 is to summarize the full text, summarize the existing limitations of the research, and propose future research direction.

3. Design of UPS inverter Control Model based on SPWM Control Technology

3.1. Construction of Mathematical Model for UPS Inverter

At present, the rapid conduction and turn off switching elements can change the magnitude and direction of the output voltage and current, which has become the foundation of various power electronic converters and inverters. However, this scheme adopts a relatively simple approach, which generates AC current in a square shape and produces many harmonics, and the amplitude is difficult to adjust [17,18]. This paper applies SPWM method to power switching circuits, effectively overcoming the above problems and ensuring stable output of the inverter power supply. In the power grid, an inverter power supply is a power electronic device similar to other power electronic devices, used to convert DC electrical energy into AC electrical energy. The UPS inverter topology selected for this paper is a SFBI with LC filter. Its phase full bridge inverter topology structure is shown in Figure 1.

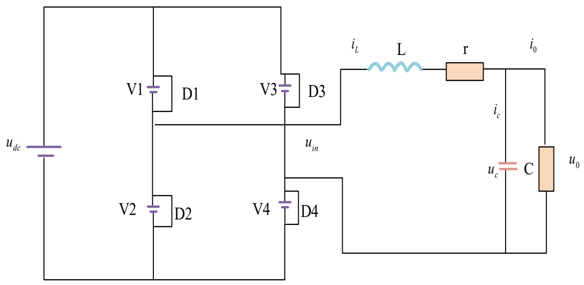


Figure 1: Topology diagram of single-phase full bridge inverter

In Figure 1, u_{dc} represents the DC bus voltage. r represents the comprehensive equivalent resistance. u_{in} represents the output pulse voltage. V1, V2, V3, and V4 all represent power switching devices IGBT. Among them, i_L is the induced current. u_c is the voltage at the capacitor terminal. i_c signifies the current of the capacitor. i_0 signifies the load current. u_0 is the output of the inverter.

When power switches V1 and V4 are turned on and V2 and V3 are turned off, the output of the converter load is positive. When switching between V2 and V3, the load of the converter will have a negative polarity when V1 and V4 are disconnected. If a specific switching frequency is set and two sets of switching states are continuously switched, the transition from DC to AC can be achieved. Due to the fact that all four power switching devices in the SFBI switch during operation, the circuit exhibits strong nonlinear characteristics. The state space method is applied to solve the equivalent circuit of a single-phase inverter power supply. The inverter full bridge is equivalent to a proportional connection. That is to say, when the frequency of the output voltage of the single-phase inverter is much lower than the switching frequency of the system, Kirchhoff's voltage law and current law are adopted [18]. The induced current and capacitor voltage can be regarded as state variables of the system, and a new voltage equation can be obtained. The description equation obtained after Laplace transform is shown in equation (1) [11].

$$\begin{cases} u_{in}(s) - u_0(s) = i_L(s)(Ls + r) \\ u_c(s) = i_c(s)\dfrac{1}{sC} \\ i_L(s) = i_0(s) + i_c(s) \end{cases} \tag{1}$$

In equation (1), i_L represents the inductor current of the system. u_{in} represents the pulse voltage output of the system. u_0 represents the output voltage. In the low-pass filter of the single-phase inverter LC, the state equation of the output filter segment of the SFBI is obtained through this transformation. The equivalent space model of the SFBI is displayed in Figure 2.

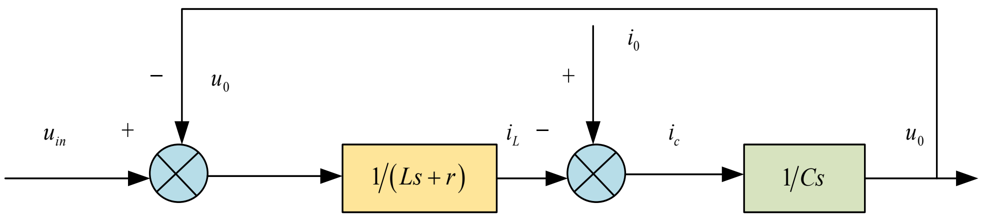


Figure 2: Equivalent space model of single-phase full bridge inverter

The state space equation of the output filtering part of the SFBI system is displayed in equation (2) [12].

$$\begin{cases} x' = Ax + Bu_{in} + Di_0 \\ y = Ex \end{cases} \tag{2}$$

In equation (2), A represents a state transition matrix. E represents a positive output matrix. B represents an input matrix. D represents an interference input matrix. Due to the low damping and severe oscillation of single-phase inverter power supply in no-load state, it is usually necessary to refer to no-load control when controlling single-phase inverter power supply. In the no-load state, the load current i_0 is 0, and the conversion function $G(s)$ between the pulse of the SFBI power supply and the inverter power supply is finally calculated, as shown in equation (3) [15].

$$G(s) = \frac{u_0(s)}{u_{in}(s)} = \frac{1}{LCs^2 + rCs + 1} \tag{3}$$

3.2. Parameter Selection of Filtering Circuit based on SPWM Control Technology

After constructing the mathematical model of the UPS inverter, the filtering circuit parameters based on SPWM control technology is selected to eliminate high-frequency harmonics in the load of single-phase inverter power supply. SPWM method is currently a mature PWM method, which is widely used in UPS inverters. The basic idea of PWM is to use the area equivalence method, which generally refers to small pulse areas as pulse waves. If pulses with equal cross-sections are applied to it, similar reaction waveforms can be obtained. Especially in a very small system, this difference is difficult to detect. When it is elevated, this difference becomes even more significant [20-21]. The SPWM method usually decomposes a sine wave into multiple pulses with different amplitudes and equal widths. The principle is shown in Figure 3.

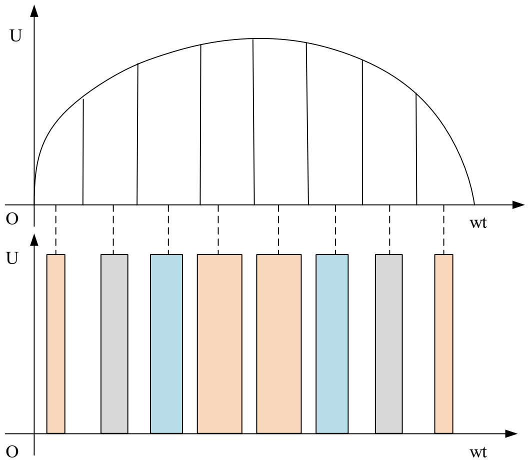


Figure 3: SPWM schematic diagram

In Figure 3, a sine wave is divided into N components, which can contain N pulses. From the Figure 3, the pulse widths of each component are equal and the amplitudes are different, while the top fluctuates sinusoidally with the waves. At this point, it is replaced with pulses of the same size but different width to obtain a new set of pulse waveforms. The area surrounded by each segment of the original segment of the new pulse waveform is the same as the new pulse area. The paper refers to the replaced pulse waveform as SPWM wave. In UPS inverters, as the switching frequency increases, the carrier ratio also increases, thereby reducing the distortion rate of the inverter's load output voltage. Therefore, the paper adopts interval synchronous modulation method to solve this problem. According to the different PWM methods, unipolar and bipolar can be selected. However, the currently studied SPWM control method is based on high-frequency modulation, and there are many high-frequency harmonics in the load of single-phase inverter power supply. To address this issue, a second-order LC filter is applied to process the high-frequency harmonics. The cut-off frequency f_a of the LC filter is shown in equation (4) [18].

$$f_a = 1/2\pi\sqrt{LC} \tag{4}$$

As long as the cut-off frequency f_a is lower than the switching frequency and higher than the fundamental frequency f_1, high-frequency harmonics can be greatly suppressed, while low-frequency components smaller than f_a can completely pass through the LC filter. The cut-off frequency of the LC filter must comply with F. In SPWM technology, the cut-off frequency of $10f_1 < f_a$ is usually selected within the range of 1/10-1/5 of the carrier frequency. Since the carrier frequency is 20 KHz, 1/10 is chosen for research, and $f_a = 2KHz$. Therefore, the description for LC parameters obtained is shown in equation (5)[19].

$$\begin{cases} i_0 = \dfrac{p}{u_0} \\ L = \sqrt{\dfrac{\dfrac{\varphi_1^3 u_0^2}{\varphi_C^2} + \dfrac{\varphi_1^3 u_0^2}{\varphi_C}}{\varphi_1 I_0^2}} \\ C = \dfrac{1}{\varphi_C^2 L} \end{cases} \tag{5}$$

In equation (5), φ_1 represents the fundamental angular frequency of the LC filter. p represents the rated power of the UPS inverter. φ_C represents the cut-off angular frequency. u_0 represents the effective load output voltage of the UPS inverter. This paper selects a 2mH inductor and a 470μF filter. However, LC filters can seriously affect the output voltage quality of inverter power supplies. Usually, when there is no load or the frequency is high, for some high-order harmonics, the total impedance of LC filters is approximately 0. Now, LC filter is regarded as a resonant circuit, whose expression is shown in equation (6) [20].

$$G(S) = \frac{\varphi_n^2}{s^2 + 2\varphi_n \varepsilon s + \varphi_n^2} = \frac{\dfrac{1}{LC}}{s^2 + \dfrac{r}{L}s + \dfrac{1}{LC}} \tag{6}$$

In equation (6), φ_n is the frequency of the resonance angle. ε is the damping rate of the system. In logarithmic amplitude characteristic maps below 0.7, resonance spikes are most likely to occur. However, in engineering, the attenuation of the inverter is very low, generally not greater than 0.707, so the entire system is a second-order under vibration reduction, with poor dynamic characteristics. The ultimate goal of this paper is to suppress harmonics and spikes through active damping technology to increase the damping coefficient of the system and suppress resonant spikes. The active damping method can add additional feedback signals to the control chain of the system. This scheme is applicable to devices of various power levels without additional losses, and its advantages are obvious. To optimize the vibration reduction effect of the system, the state feedback of the system is generally adopted.

3.3. UPS Inverter Control Design

After selecting the parameters of the filtering circuit based on SPWM control technology, to improve the output voltage quality of the inverter power load in practical operating environments, a modular main function interrupt control method is applied to efficiently control it. Based on the system's interruption, the various loop parameters to be collected are effectively sampled through ADC, and then processed by DSP. Based on this, efficient control of the entire UPS inverter system is achieved, as displayed in Figure 4.

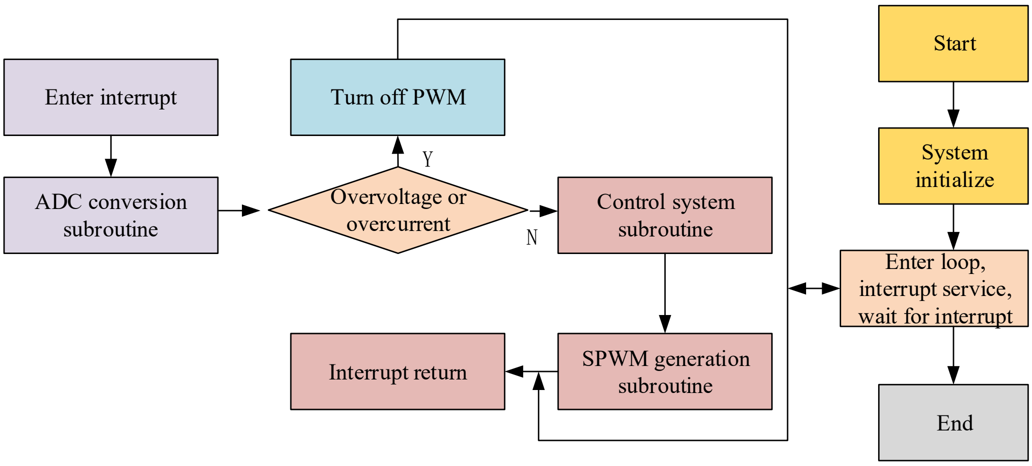


Figure 4: UPS inverter control system flowchart

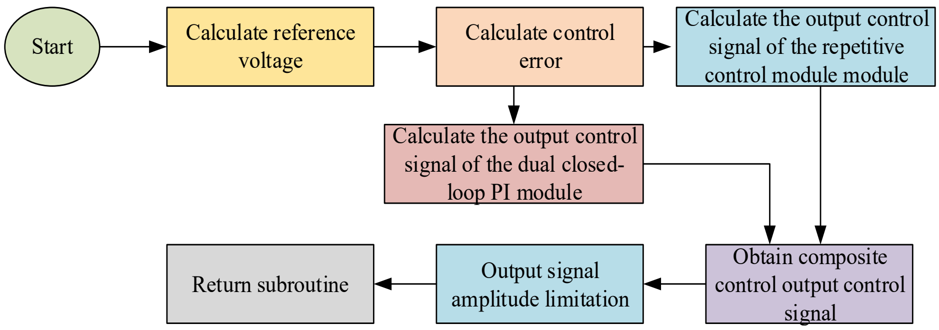


Figure 5: Integrated control system flow chart

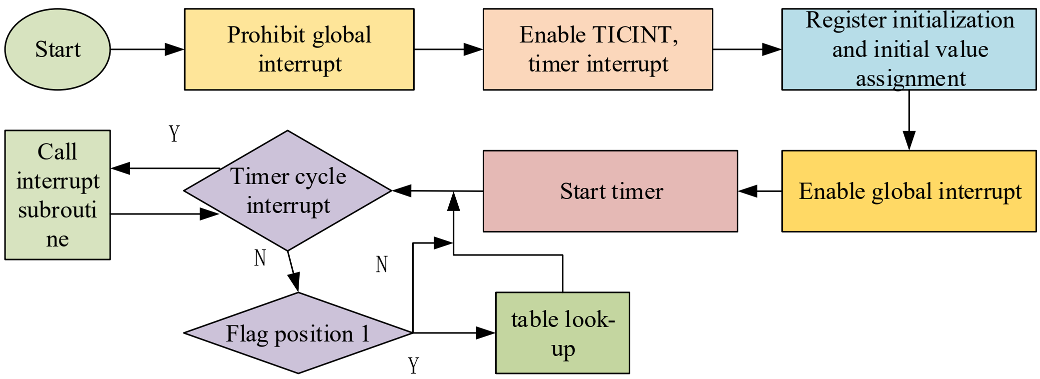


Figure 6: SPWM switch drive signal generation process

After powering up the UPS inverter system, the system performs a self-test and begins initialization work. A pin is passed to an interrupt register to initiate an interrupt service. Before performing interrupt handling, it is necessary to confirm the working status of the line. When overvoltage, overcurrent and other phenomena occur, the controller will immediately cut off the driving signal of the device. Under normal working conditions, the controller triggers a control algorithm to determine the number of controlled objects and adjusts the required amplitude modulation wave based on the state of the controlled objects. Finally, the tuned sine wave is input into the SPWM excitation circuit. At this point, the interruption work of the inverter has been completed, and its control system will return to its original function and issue a new interference request. In the combination control module of UPS inverter system, after the system completes sampling, the collected data parameters are subjected to system operation, and the obtained values are compared with the values in the timer. Finally, in order to control the proposed UPS inverter system, the corresponding PWM waveform needs to be used for interrupting the IGBT tubes. The comprehensive control steps proposed this time are shown in Figure 5.

In fact, in the real environment, various disturbance factors cause an increase in measurement errors, making the timer unable to work properly. In order to avoid system failure caused by excessively large superimposed signals, this paper adds restrictions to the superimposed signals. In the case of long-term operation at a sampling frequency of 20KHz in the system, there is a large amount of data stored in the control chip. The paper allocates 400 storage spaces for the composite control signal and error control signal, respectively. After sampling is completed, the two data spaces are updated in real time. The UPS inverter uses three different comparison elements, each generating three complementary PWM drive waveforms. The process of generating the SPWM switch drive signal is shown in Figure 6.

In Figure 6, first, a continuous comparison is made between the values of the comparison register and the time counting register in the digital signal processing program. When the comparison register and the timer count register have equal values, it is called the comparison matching method. At this point, when the interrupt allowance bit of the digital signal processor is also set to 1, an interrupt request will be immediately generated. When an interrupt request is sent, there will be a distortion in the TXPWM pin.

4. Simulation Analysis of UPS Inverter Control System

To verify the designed UPS inverter control system, firstly, the designed power supply is connected to various resistive loads, and its output voltage and current are measured. Then, capacitive loads of different capacities are connected to the power supply to test its output voltage and output current. The parameters selected are shown in Table 1.

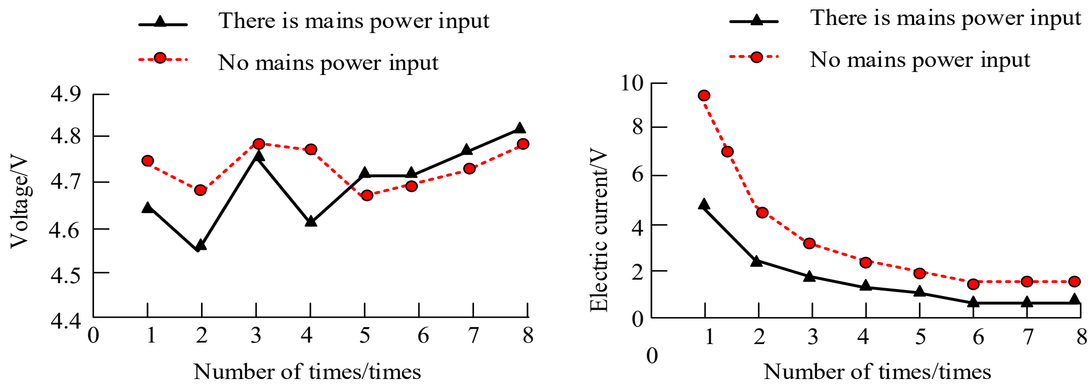
Table 1. Selection of experimental parameters

/	Parameter selection
Modulation signal frequency	50Hz
Modulation ratio	Constant: 0.74
DC bus voltage	300V
Carrier frequency	20KHz

Multiple sets of data are selected for comparison. The test results are shown in Figure 7.

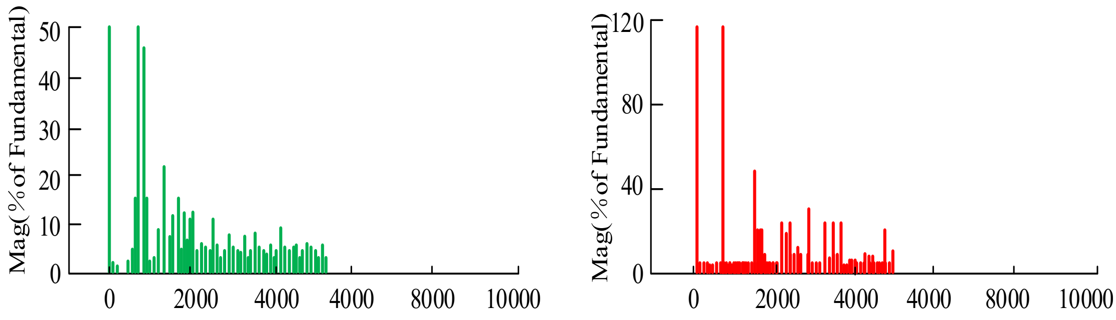
From Figure 7, regardless of whether the mains power was input or not, the curve direction of the output voltage and output current of the designed UPS inverter power supply was exactly the same, and the values of these two parameters were very close and basically the same between 6Ω and 8Ω, achieving the design specifications. Then, a Simulink simulation main circuit model for inverters based on traditional control methods and a Simulink simulation main circuit model for inverters based on SPWM control technology are built. The clock module, logic function module, and loading module are used to implement unit sine modulation, and Constant is selected to set the modulation rate. The repetitive sequence module generates a triangular carrier, which is compared with the sine wave to generate a SPWM control signal. Then, the inverse of it is obtained to obtain another SPWM control signal. The harmonic analysis results of the research method and the traditional method are obtained, as shown in Figure 8.

Figure 8 (a) and Figure 8 (b) respectively show the harmonic analysis results using the research method and the traditional method. From Figure 8 (a), the fundamental amplitude of the voltage obtained by the research method was 217.2V, which met the principle requirement that the value of multiplying the DC node voltage by the modulation rate is the fundamental voltage amplitude. From Figure 8 (b), the voltage fundamental amplitude using the traditional method was 224.2V, which also conformed to the basic principle, but its control output voltage harmonic distortion was worse than the research method. Through the analysis of simulation results, the control scheme has better control effects than the traditional control scheme under the same parameter conditions. The steady-state time results of the research method and traditional method are shown in Figure 9.



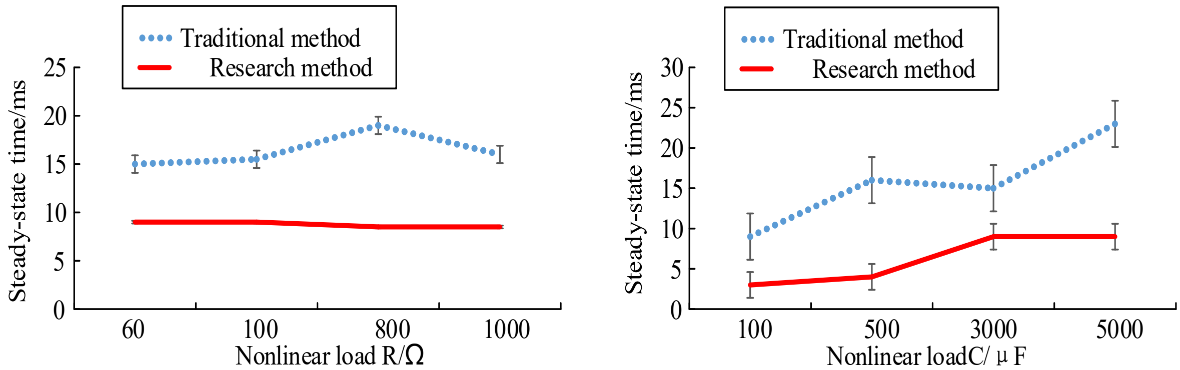
(a)Output voltage (b)Output current

Figure 7: Test results of UPS inverter control system



(a) Research method output voltage harmonics (b) Traditional method output voltage harmonics

Figure 8: Harmonic analysis of output voltage



（a）Control effect under different resistances （b）Control effect under different capacitors

Figure 9: Steady-state time comparison analysis

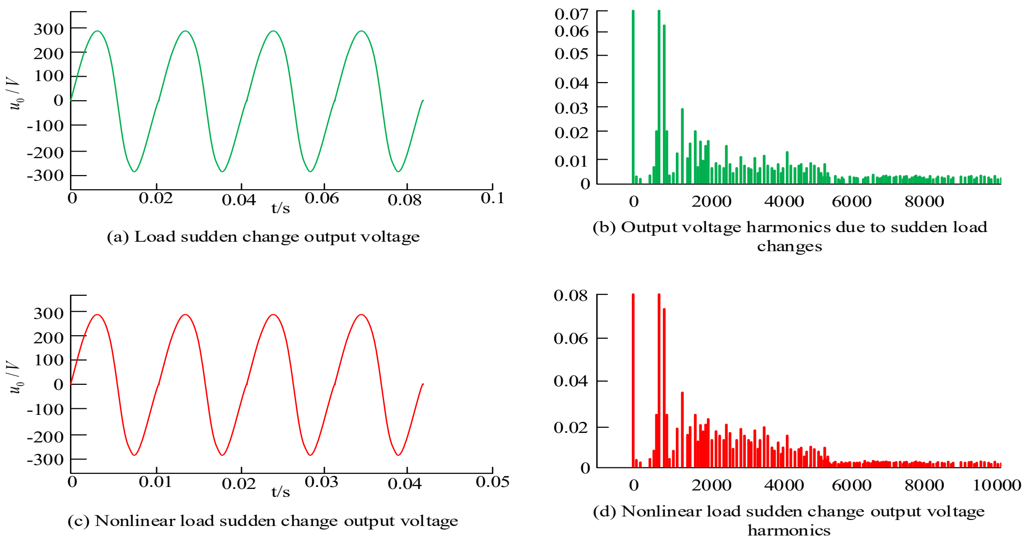
Figure 9 (a) shows the steady-state time comparison results of two methods under different resistances. Figure 9 (b) shows the steady-state time comparison results of two methods under different capacitances. From Figure 9 (a), under different resistances, the proposed control method had a shorter steady-state time, with a maximum improvement of 60.52% compared with the traditional method. From Figure 9 (b), under different capacitors, the research method took a shorter time to realize the steady-state. The results indicate that the control method performs better than the traditional method. By simulating factors such as sudden load changes and load nonlinearity in UPS inverters, the reliability and stability are verified. Under the same inverter parameters, the inverter load is set to sharply increase by 3.58Ω within 0.025s, and construct a load mutation simulation model. Simultaneously, a rectifier capacitor with 500μF, 1.2mH, and 24Ω is set to construct a nonlinear load simulation model. The output voltage and harmonic analysis results for these two scenarios are obtained, as shown in Figure 10.

Figure 10 shows the simulation results of output voltage and harmonic analysis under load sudden changes and the nonlinear load sudden changes. From Figure 10 (a) and Figure (b), overall, under the load mutation, the output voltage remained a stable sine wave, while the THD of the inverter was only 0.24%, which well met the design requirements. Through in-depth research, when the load changed, if a 3.58Ω resistor is suddenly added within 0.025s and the increased resistance is removed within 0.05s, there will be no significant voltage waveform distortion. From Figure 10 (c) and Figure 10 (d), overall, under general nonlinear load conditions, the output voltage is still a very stable sine wave, and the output voltage THD is only 0.22%, with very little distortion, achieving the design purpose. At the same time, a comprehensive theoretical analysis is conducted. The harmonic distortion of its output is relatively small under nonlinear loads.

Finally, to verify the feasibility, a physical testing platform is established. In the experiment, a 200V DC bus, a 20KHz switching frequency, a 50Hz rated output, a 2mH filter, a 470uF filter, and a 110V output are selected. The instrument is connected to an oscilloscope, and the instrument is used to measure the SPWM driving waveform of the same bridge branch output by the DSP, thereby turning on the switching transistor of the inverter power supply and achieving complementary upper and lower power supplies. The research test results are shown in Figure 11.

From the load sudden change in Figure 11, within 0.5 seconds, the load suddenly increased by 3.58Ω, the output voltage showed no significant distortion, and the current jumping process was stable. The system has fast response capability and good control effect. To better test the performance of the UPS inverter during sudden load changes, a three-phase unbalanced resistive load is used in this paper, and load sudden change tests are conducted under this resistive load, including sudden unloading of 2.42Ω resistive load and sudden reduction of 6Ω resistive load to 2.42Ω. The waveform obtained from the experimental measurement is shown in Figure 12.

Figure 12 (a) shows the waveform of sudden unloading of a 2.42Ω resistive load. Figure 12 (b) shows the waveform of A-phase voltage and current when the 6Ω resistive load is suddenly reduced to 2.42Ω. From Figure 12 (a), when the 2.42Ω resistor load was suddenly unloaded, the phase voltage changed slightly and the amplitude increased slightly. However, after about 40ms of 2 cycles, the amplitude tended to stabilize again. From Figure 12 (b), when the load of 24KW suddenly increased by 60 KW, the phase voltage waveform of the UPS inverter did not change significantly, and the output phase voltage was relatively stable. At this time, the current also reached the predetermined speed. The fast response speed of the inverter to load changes proves that the dynamic performance of the UPS inverter control system is superior under resistive load conditions.



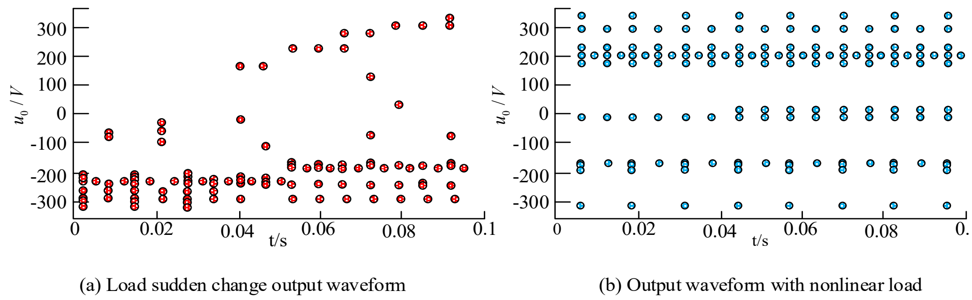
(a) Load sudden change output voltage

(b) Output voltage harmonics due to sudden load changes

(c) Nonlinear load sudden change output voltage

(d) Nonlinear load sudden change output voltage harmonics

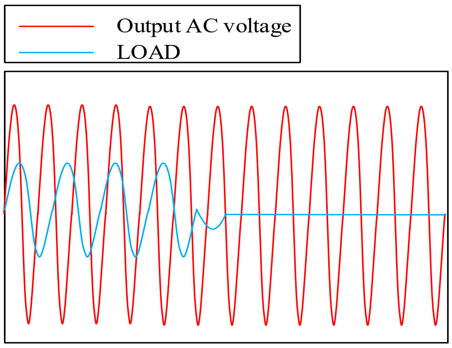
Figure 10: Analysis of output voltage and output voltage harmonics in load sudden change and nonlinear load sudden change



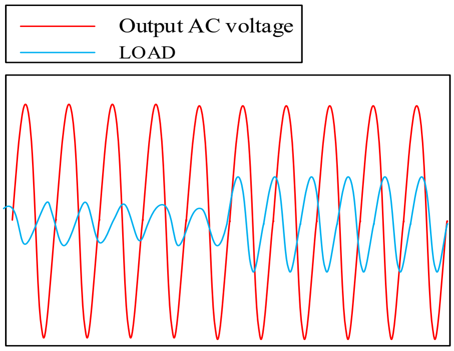
(a) Load sudden change output waveform

(b) Output waveform with nonlinear load

Figure 11: Output waveforms of load sudden change and nonlinear loads



(a) Waveform of sudden unloading of 2.42 Ω resistive load



(b) Waveform of phase a voltage and current when the load is suddenly increased from 24kw to 60kW

Figure 12: Waveform of load sudden change experiment

5. Conclusions

Affected by economic and technological development, the demand for power facilities in various industries is constantly increasing. However, due to the complexity of enterprise power supply systems, the power supply system is highly susceptible to damage. The drastic changes in power system and instantaneous power outages caused have led to chaos in the production process, and even resulted in equipment shutdown and personnel injuries, posing great harm to the production and safety of enterprises. To this end, a UPS inverter control model was designed based on SPWM control technology and LC filter parameter settings. The basic waveform of the designed scheme was 217.2V, which conformed to the basic principles. Its control output voltage harmonic distortion was better than traditional methods, with good performance. Under nonlinear loads, the harmonic distortion rate of the inverter power supply was significantly reduced to only 0.22%, achieving the expected control target. When the 2.42Ω resistor load was suddenly unloaded, the phase voltage changed slightly with a slight increase in amplitude, but after about 40 ms of 2 cycles, its amplitude tended to stabilize again. When the load suddenly increased by 60 KW from 24 KW, there was no significant phase voltage fluctuation, and the output phase voltage was relatively stable, with the current reaching the set value quickly. However, the UPS inverter control method based on SPWM control technology has only undergone relevant simulation tests in single-phase circuits, and the scope is relatively small. In the future, further research will be conducted in this area.

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Conflict of Interest

The author declares that the paper has no conflicts of interest and the author has full control of all primary data and that the author agrees to allow the journal to review data if requested.

References

[1] Li J, Sun Y, Li X. Observer-based adaptive control for single-phase UPS inverter under nonlinear load. IEEE Transactions on Transportation Electrification, 2022, 8(2): 2785-2796.

[2] Peng Y, Sun W, Deng F. Internal model principle method to robust output voltage tracking control for single-phase UPS inverters with its SPWM implementation. IEEE Transactions on Energy Conversion, 2020, 36(2): 841-852.

[3] Lu J, Savaghebi M, Zhang B. Distributed dynamic event-triggered control for accurate active and harmonic power sharing in modular on-line UPS systems. IEEE Transactions on Industrial Electronics, 2021, 69(12): 13045-13055.

[4] Anwar M R, Paramyta N, Fitriani E. Perancangan Sistemswitching Supply Power dan Monitoring Perangkat pada UPS Berbasis Mikrokontroler. Jurnal Pendidikan Tambusai, 2024, 8(1): 10078-10086.

[5] Tang H, Choeung C, Srang S. Robust Voltage Control of a Single-Phase UPS Inverter Utilizing LMI-Based Optimization with All-Pass Filter Under System Uncertainty. International Journal of Robotics and Control Systems, 2024, 4(2): 910-928.

[6] Mohamad Rawi M S, Baharom R, Mohd Radzi M A. Uninterruptible Power Supply Topology Based on Single-Phase Matrix Converter with Active Power Filter Functionality. Energies, 2024, 17(14): 3441-3464.

[7] Yan G. Continuous switching sliding mode controller design for single-phase UPS inverter circuit. Electrical Engineering, 2024, 106(2): 1265-1273.

[8] Seyedalipour S S, Shahparasti M, Hajizadeh A. Model-based control of four-leg inverter for UPS

applications considering the effect of neutral line inductor. IET Power Electronics, 2021, 14(8): 1468-1479.

[9] He G, Zhao L, Dong Y. A Novel VSG Control Strategy for UPS Voltage Source Inverter with Impulsive Load. Energies, 2022, 15(13): 4702-4729.

[10] Li P, Tong X, Wang Z. Sensorless Model Predictive Control of Single-Phase Inverter for UPS Applications via Accurate Load Current Estimation. Sensors, 2023, 23(7): 3742-3771.

[11] Choeung C, Soth P, Tang H. A Linear Matrix Inequality Approach to Optimal Voltage Control of a Three-Phase UPS Inverter under Unbalanced Loads. Engineering Proceedings, 2023, 56(1): 87-105.

[12] Rymarski Z. Simple discrete control of a single-phase voltage source inverter in a UPS system for low switching frequency. Energies, 2023, 16(15): 5717-5749.

[13] He G, Zhou Z, Dong Y. Design and analysis of robust backstep controller for DC suppression of parallel UPS inverter system. IET Power Electronics, 2023, 16(10): 1683-1695.

[14] Ahmed T, Khan F A, Waqar A. Design and Implementation of PV Fed Local UPS Inverter. Pakistan Journal of Engineering and Technology, 2021, 4(4): 1-8.

[15] Saoudi M, Benguesmia H, Chouder A. Processor-in-the-loop validation of an observer current-based dead-beat control for a single-phase UPS inverter. Engineering, Technology & Applied Science Research, 2023, 13(1): 10158-10164.

[16] Romasevych Y, Loveikin V, Bakay B, Rudko I. Optimal tuning of belt conveyor soft-starter via PSO-ROT-RING method. UPB Scientific Bulletin, Series D: Mechanical Engineering, 2023, 85(2): 73-84.

[17] Soth P, Noun S, Tang H. Robust power stabilizing control of a grid-connected inverter using linear matrix inequality. Sigma Journal of Engineering and Natural Sciences, 2024, 42(5): 1367-1377.

[18] Lee B K, Lee H S, Lee K B. Phase current control to reduce unbalanced outputs in paralleled inverters. Journal of Power Electronics, 2024, 24(10): 1628-1638.

[19] Albakri M, Darwish A, Twigg P. A Comprehensive Review of dc/ac Single-Phase Differential-Mode Inverters for Low-Power Applications. Electronics, 2024, 13(13): 2474.

[20] Issa W, Sharkh S, Abusara M. A review of recent control techniques of drooped inverter-based AC microgrids. Energy Science & Engineering, 2024, 12(4): 1792-1814.

[21] Rymarski Z. The Influence of Switching Frequency on Control in Voltage Source Inverters. Energies, 2024, 17(17): 4508.