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Design of Composite Repetitive Controller for Single-Phase Uninterruptible Power Supply Inverter Circuit

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WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Inverter systems widely use the state space averaging method to establish mathematical models. The state space averaging method is based on the fact that the output frequency is much smaller than the switching frequency, and by replacing the instantaneous value of the variable with the average value in a switching period to obtain a continuous state space averaging model.*
- *Single-phase uninterruptible power supply (UPS) is widely used in various important electrical equipment to ensure the smooth implementation of the power supply. Its core control goal is to make the harmonic distortion rate of the output voltage as low as possible.*

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ABSTRACT

Single-phase uninterruptible power supply (UPS) is widely used in all kinds of important electrical equipment to ensure the smooth implementation of power supply. The core part of the UPS is the inverter circuit, and the control of the output voltage of the inverter circuit is of great significance. This paper takes the single-phase full-bridge inverter circuit as the research object. First, the mathematical model of the system is obtained based on the frequency domain modeling method of the minimum phase system. Then, a composite controller composed of an inverse system and repetitive control is proposed. By expanding the repetitive controller transfer function, the inherent positive feedback term of the repetitive controller is found, and the inherent positive feedback term is overcome by a parallel proportional term. Using frequency domain analysis, the design process and parameter selection method of the complex repetitive controller are given. Finally, the effectiveness of the proposed control method is verified by experiments. When the inverter system is connected to the resistive load, the instantaneous output voltage error fluctuates within ±0.30 V and the total harmonic distortion rate is 1.28%. Compared with the traditional cascade control, the output voltage error fluctuates within ±1.10 V and the total harmonic distortion rate is 2.98%. The performance of the proposed control method is greatly improved, which indicates the engineering application value of the proposed inverter control scheme.
Index Terms— Harmonic distortion, inverter circuit, inverse system, repetitive control, uninterruptible power supply (UPS)

I. INTRODUCTION

With the continuous advancement of power electronics technology, the power supply industry has achieved unprecedented development, along with industries such as industrial control, medicine, communications, and transportation. In the actual power consumption process, the previous power supply methods have gradually failed to meet the power supply needs. To improve the power supply quality, uninterruptible power supply (UPS) has become the primary choice for power users. In order to ensure that UPS can work safely and stably, it is necessary to combine the actual power needs of power users and adopt efficient and feasible inverter control solutions to ensure the smooth and reliable implementation of power supply. At the heart of the UPS device is the DC–AC converter (inverter) in power electronics technology, which can synthesize sinusoidal AC voltage from a backup DC power supply [1].

A lot of studies focus on the control methods of inverter output waveform, which can be divided into the following four categories roughly: proportional–integral–derivative (PID) control [2–4], repetitive control [5–7], nonlinear control [8–10], and model-based feedback control [11–12].

Proportional–integral–derivative control is one of the earliest control strategies. It has been widely used in the control of various systems because of its very simple algorithm calculation process, high reliability, and good robustness. However, the parameters of the PID controller are mutually coupled, and the parameter setting method is complicated, resulting in poor

WHAT THIS STUDY ADDS ON THIS TOPIC?

- *A more accurate mathematical model of the inverter system is obtained based on the frequency domain modeling method of the minimum phase system.*
- *The positive feedback term of the repetitive controller is analyzed, and it is overcome by proportional control, and the feedforward control is added to improve the transient performance of the control system while reducing the harmonic distortion rate of the output voltage.*

control performance. These factors limit the application of PID control in complex systems and systems with high-performance requirements. When PID control is applied to inverter control, the biggest problem is that proportional control alone will produce static error when a sine signal is taken as the target value. Although the static error of the system output can be reduced by adding an integral control term, it will also cause phase lag. Differential control will lead to amplification interference and cause instability in the control system. Therefore, when PID control is applied to a frequency converter, it is difficult to improve the PID control accuracy.

A repetitive controller is a controller designed using the periodicity of the output signal. It generates a feedback signal to suppress interference by periodically recording the period and amplitude of the interference signal to eliminate the interference. Although the repetitive controller not only effectively suppresses periodic disturbances but also demonstrates minimal dependence on system parameters, its standalone application in inverter control reveals two limitations: compromised dynamic performance of the system and relatively limited capability in suppressing non-periodic disturbances.

A nonlinear controller is a controller that can handle complex dynamic systems. Common types of nonlinear controllers include adaptive controllers, fuzzy controllers, neural network controllers, and sliding mode controllers. When these nonlinear controllers are applied to the waveform control of the inverter, although they can enhance the system's dynamic performance and minimize the overshoot of the output voltage waveform, they also significantly heighten the complexity of implementing the controller. These methods are highly sensitive to parameter mismatches. In ref. [1], a sliding mode controller with double sliding surfaces and continuous switching is designed, which is composed of an inverse system and an improved sliding mode control. Double sliding surfaces are used to replace the traditional single sliding surface to reduce the output voltage chattering and improve the maximum instantaneous voltage error of the inverter output voltage and the total harmonic distortion rate of the output voltage. For the sinusoidal inverter voltage output with an amplitude of 12 V, the maximum error is 0.47 V when the load is resistive, and there is still room for improvement in the control performance.

The model-based control aims to describe the working characteristics of the controlled object with relatively accurate mathematical expressions and then design the corresponding algorithm control through the mathematical description of the controlled object. Although model-based transient feedback controllers offer adequate dynamic performance and controlled steady-state error, their effectiveness hinges on the precision of system structural parameters. Owing to the constrained gain of the control system loop under the inverter's AC output, achieving a high level of accuracy in the steady-state error proves challenging.

In addition, in the design of inverter structures, there are many literatures [13–15] on improving the number of switches in the circuit and synthesizing AC power by designing circuits to generate multiple levels. The paper [13] designed a new cascade H-bridge multi-level inverter with a small number of switches. The paper [14] designed an inverter circuit consisting of three capacitors and eight switches that can generate seven levels of output. The paper [15] proposed a strategy that combines the nearest level control technology with the Pulse–Width–Modulation (PWM) control technology on the cascade H-bridge multi-level inverter to achieve smooth and wider range output voltage control.

Repetitive control assumes that the output signal has already produced waveform distortion in the previous cycle. By comparing the reference signal and feedback signal of the controller, the information that needs to be adjusted is determined, and the adjustment information is superimposed on the initial input signal at the same time in the next cycle, thereby eliminating the waveform error generated after this cycle. The core idea of the repetitive controller is the internal model principle. Since the dynamic performance of the repetitively controlled inverter is poor, the ability to suppress aperiodic disturbances is weak. By analyzing the characteristics of the output signal of the repetitive controller, this paper proposes a composite repetitive controller combined with an inverse system for the output voltage waveform control of a single-phase inverter.

The article is structured as follows. Section II introduces the experimental setup and frequency domain modeling results of a single-phase full-bridge inverter. Section III details the structural design of the controller, the selection of control parameters, and the experimental results of the control system. The conclusion is presented in Section IV.

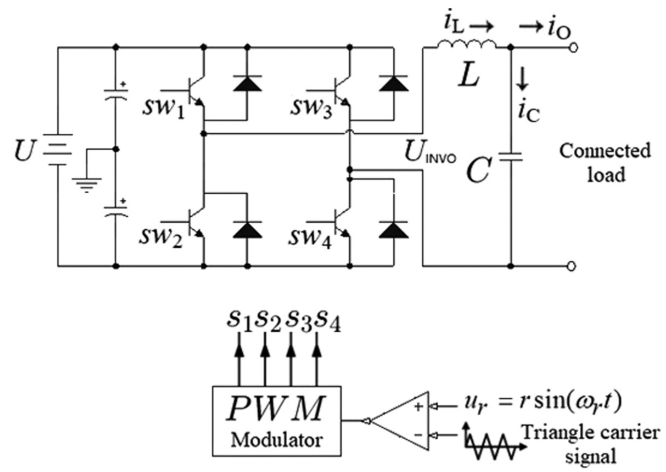

Fig. 1. Single-phase bridge synchronous inverter circuit.

II. INVERTER DEVICE AND FREQUENCY DOMAIN MODELING

The single-phase full-bridge inverter circuit is generally composed of three parts: DC voltage source, PWM inverter bridge and Inductor–Capacitor (LC) filter circuit, and the structure diagram is shown in Fig. 1.

In Fig. 1, *U* is a DC voltage source, and sw_1, sw_2, sw_3, and sw_4 are power switching tubes, which form an inverter bridge. *C* is the filter capacitor, and *L* is the filter inductance. According to the comparison result between the triangular carrier signal and the modulation signal u_r, the PWM modulator generates a pulse signal with an appropriate width to control the on–off of the power switch tube groups sw_1, sw_2, sw_3, and sw_4 and drives the inverter bridge to output the required AC voltage. The whole experimental device of the single-phase full-bridge inverter circuit is shown in Fig. 2 [1].

The DC voltage source is RIGOL's DP832 linear DC power supply. In the PWM inverter bridge and LC filter circuit, the triangle carrier signal is generated by the precision oscillator integrated device ICL8038. The drive chip is the isolated gate drive element IR2109, and the switching device is the power field-effect transistor IRF3205. It has very low on-resistance and a very fast slew rate. The AD and DA conversion modules in the dSPACE DS1104 card are used as ADC/DAC, and the MATLAB software in the host computer containing the dSPACE DS1104 card is programmed to realize the control law. The parameters of the main components of the circuit are measured by the high-precision LCR tester LCR-819 of GWinstek Company. The specific parameter values are filter inductor 7.38 mH, filter capacitor 23.05 μF, load resistance 78.69 ohms, and switching frequency 61 kHz. The inverter circuit adopts a regular sampling SPWM algorithm.

Neglecting the high-frequency small-amplitude ripple in the output voltage brought by the SPWM process, the dynamic characteristics of the inverter mainly depend on the LC filter circuit, so it can be well described by the second-order linear model. The damping ratio of the inverter or the size of the resonance peak is very important to the design of the repetitive controller, but there are many damping factors in the inverter, and the mechanisms of their influence are complex and different, which is it makes it difficult to determine the high-precision parameters of the inverter model based on theoretical analysis. Since the SPWM inverter model is a second-order linear model, although the exact values of its damping ratio and cutoff frequency are still to be determined, the model has neither poles nor zeros in the right-half plane of the *s* domain. That is to say, the SPWM inverter is a minimum phase linear system. For this system, its amplitude–frequency characteristics and phase-frequency characteristics are not independent, and there is a unique correspondence between its amplitude–frequency characteristics and phase-frequency characteristics, so it is possible to avoid the cumbersome measurement of phase frequency characteristic curves and directly measure the amplitude frequency characteristics of SPWM inverters, and then compare the measured amplitude–frequency characteristic curve with the standard second-order system frequency characteristics, which can easily determine the damping ratio and the size of the natural oscillation frequency. Then, a high-precision mathematical model of the inverter is obtained.

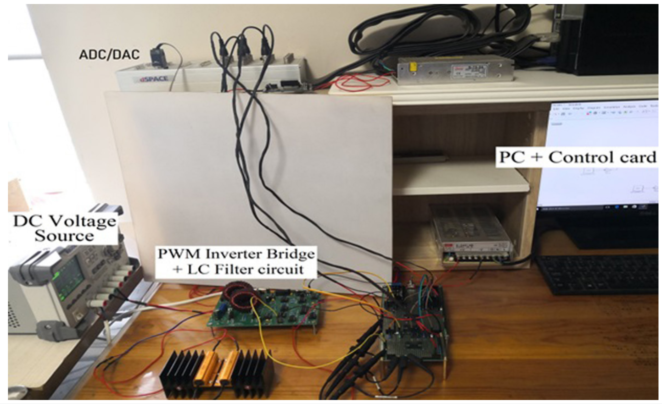

Fig. 2. Schematic of the entire experimental device [1].

The amplitude and frequency of the triangular carrier signal are fixed, respectively, a sinusoidal carrier with the same amplitude is added, and gradually the frequency is changed. The measured results are shown in Fig. 3. The small circles represent the measured results. A second-order system whose amplitude–frequency characteristic curve is closest to the above-measured data is as follows:

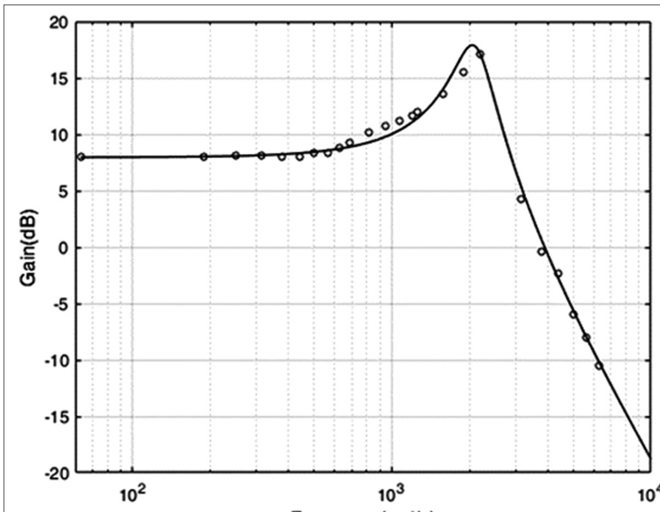

Fig. 3. Amplitude–frequency characteristics of inverter.

$$G_o(s)=\frac{1.1\times10^7}{s^2+674.9s+4.4\times10^6} \quad (1)$$

Its amplitude–frequency characteristic curve is drawn with solid lines in Fig. 3, which is in good agreement with the experimental data, it also fully shows that it is feasible to use the second-order linear model to approximately describe the dynamic characteristics of the inverter.

The sampling time of the system is 0.1 ms, by discretizing (1), and the discrete transfer function model describing the full-bridge inverter is

$$G_o(z)=\frac{0.0537z+0.0525}{z^2-1.892z+0.9347} \quad (2)$$

III. CONTROLLER DESIGN AND EXPERIMENTAL RESULTS

A. Controller Structure Design

According to the system modeling results, a composite repetitive control is designed as the control scheme for the inverter system. The control system structure is shown in Fig. 4.

The amplitude–frequency characteristic of the selected inverter circuit is shown in Fig. 3. Within the cutoff frequency, the amplitude of the amplitude–frequency characteristic of the inverter circuit has resonance, making it difficult to design a repetitive controller so that the system has a sufficient stability margin. Therefore, the following links $G_{CM}(z)$ are introduced:

$$G_{CM}(z)=\frac{z^2-1.892z+0.9347}{(0.0537z+0.0525)(z-0.4)} \quad (3)$$

After the introduction of the link $G_{CM}(z)$, the frequency characteristics of the equivalent-controlled object of the series system can be approximated as shown in Fig. 5.

Since the approximate frequency characteristic of the equivalent system remains almost constant within the cutoff frequency, and then the gain drops rapidly. This frequency characteristic is the most ideal controlled object characteristic in the repetitive controller design. Because the compensator is often composed of a low-pass filter and a phase advance compensation link, the amplitude–frequency response of the compensator remains constant within the cutoff frequency. If the controlled object of the repetitive controller remains constant within the cutoff frequency, then the controlled object after compensation is still constant within the cutoff frequency. By adjusting the repetitive control gain, the repetitive control system can have sufficient stability margin and faster convergence speed.

The frequency domain expression of general repetitive control [16] is

$$G_{RC}(s)=\frac{k_{rc}e^{-sT}}{1-e^{-sT}} \quad (4)$$

where k_{rc} is the gain of the repetitive controller and T is the sampling period.

Expand e^{-ST} and we can get

$$G_{RC}(s)=k_{rc}\left(-\frac{1}{2}+\frac{1}{Ts}+\frac{2}{T}\sum_{i=1}^{\infty}\frac{s}{s^2+(i/T)^2}\right) \quad (5)$$

It can be seen from (5) that since the gain k_{rc} of the repetitive controller is greater than 0, the repetitive controller can be decomposed into negative proportional terms, integral terms, and multiple parallel resonant terms. Since the expansion of the repetitive controller contains a negative proportional term, the negative proportional term constitutes a positive feedback in the negative feedback, which produces a negative regulation on the error signal, which not only has an adverse effect on the dynamic performance of the system but also causes system instability. For this reason, proportional control is incorporated into the structure of the general repetitive controller. The proportional coefficient is selected to be greater than the gain $k_{rc}/2$ of the repetitive controller so that the control system does not contain positive feedback of the error. In addition, in order to ensure the stability of the entire control system, it is also necessary to introduce a zero-phase shift low-pass filter into the general repetitive controller. The specific design is given in the controller parameter selection. In order to improve the rapidity of the entire system, feedforward control is introduced here, and its structure is the inverse system of the controlled system after series connection $G_{CM}(z)$.

B. Controller Parameter Selection

The expected output voltage of the single-phase full-bridge inverter circuit system is

$$u_{od}(t)=10\sin(100\pi t) \quad (6)$$

According to the designed control system structure in Fig. 4, the expression of the output voltage error is

$$E(z)=\frac{1}{1+\left(K_p+G_{RC}(z)\right)G_{CM}(z)G_o(z)} \quad (7)$$

where K_p is the proportional control coefficient, $G_{RC}(z)$ is the improved repetitive controller, and is designed as

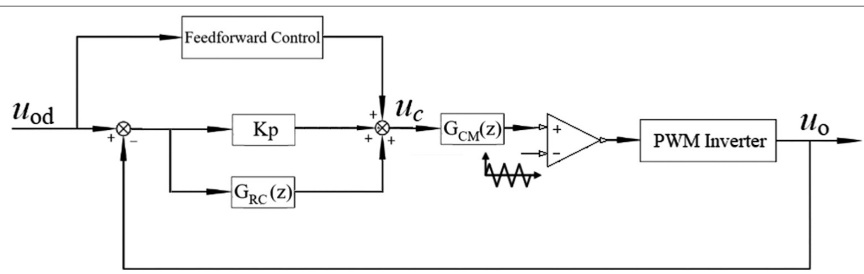

Fig. 4. Structure of inverter compound repetitive control system.

$$G_{RC}(z) = \frac{k_{rc} z^{-N} Q(z) z^{r}}{1 - k_u z^{-N}} \tag{8}$$

where k_{rc} is the gain of the repetitive controller, N is the number of delay cycles, $Q(z)$ is the designed zero-phase-shift low-pass filter, z^r is the time advance link, and k_u is the robust factor to be designed, which is less than 1.

Substituting (8) into (7), we can obtain

$$E(z) = \frac{1 - k_u z^{-N}}{1 - k_u z^{-N} + \left(k_p(1 - k_u z^{-N}) + k_{rc} z^{-N} Q(z) z^{r}\right) G_{CM}(z) G_o(z)} \tag{9}$$

In order to make the whole control system stable, the parameters should be selected to meet.

$$\left\| k_u e^{-Nj\omega} - \left(k_p(1 - k_u e^{-Nj\omega}) + k_{rc} e^{-Nj\omega} Q(e^{j\omega}) e^{rj\omega}\right) G_{CM}(e^{j\omega}) G_o(e^{j\omega}) \right\| < 1 \tag{10}$$

According to the internal model principle [17], the frequency components of all error signals can be attenuated to a minimum cycle by cycle as the operating cycle increases, thereby achieving stable operation of the inverter circuit and outputting high-precision voltage.

To satisfy (10). Here, we select $k_u = 0.98$, $k_p = 0.26$,

$k_{RC} = 0.4$, $Q(z) = \dfrac{z + 6 + z^{-1}}{4}$,

$r = 1$, and the Nyquist curve of

$$k_u e^{-Nj\omega} - \left(k_p(1 - k_u e^{-Nj\omega}) + k_{rc} e^{-Nj\omega} Q(e^{j\omega}) e^{rj\omega}\right) G_{CM}(e^{j\omega}) G_o(e^{j\omega})$$

at this time is shown in Fig. 6. It can be seen from Fig. 6 that the selected parameters meet the controller design condition (10). Note that it is a non-causal link in the form $Q(z)z^r$, and the error data of the previous cycle has been obtained, so the non-causal link $Q(z)z^r$ can be realized.

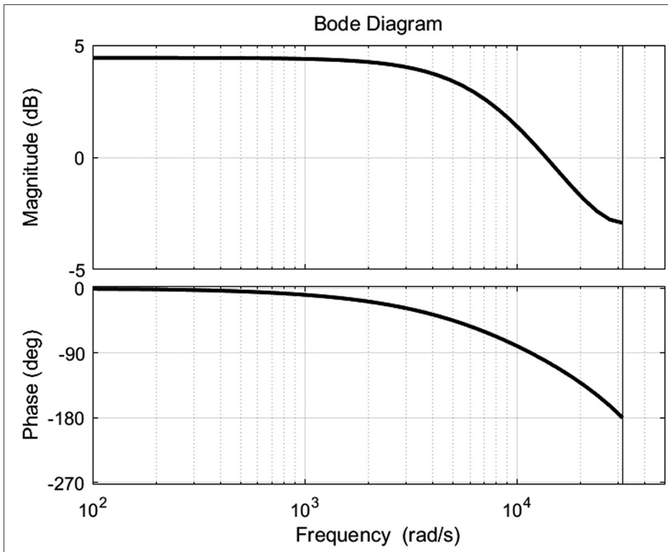

Fig. 5. Approximate frequency characteristics of the controlled system after series connection $G_{CM}(z)$.

C. Experimental Results

The experimental results shown in Fig. 7 illustrate the error in the inverter output voltage under composite repetitive control. Fig. 8 displays both the inverter output voltage and its harmonic distortion rate. By using harmonic analysis, the results show that the output voltage's harmonic distortion rate is a mere 1.25%.

For comparison, (3) continues to be employed for the given signal, opting for the extensively utilized dual closed-loop cascade controller to generate the system's control signal. Fig. 9 illustrates the general architecture of the dual closed-loop cascade control system, where the inner loop employs proportional control for the capacitor current, and the outer loop utilizes proportional–integral (PI) control for the output voltage.

Through the experiment, the proportional coefficient KI_P of the inner loop is determined first, and then the proportional coefficient KO_P

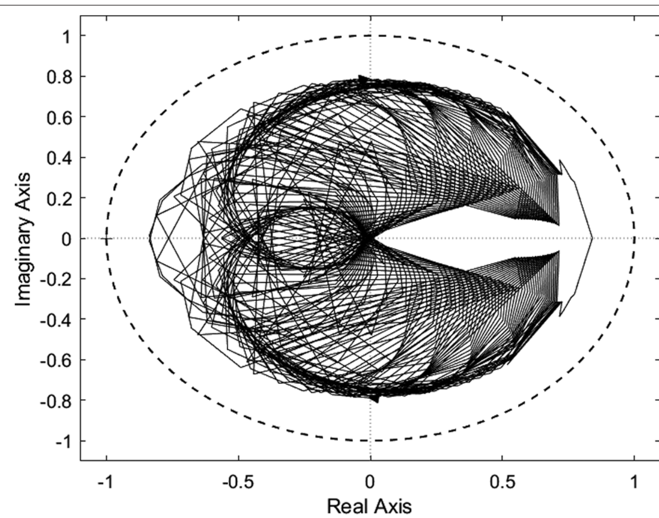

Fig. 6. Nyquist curve of $k_u e^{-Nj\omega} - \left(k_p(1 - k_u e^{-Nj\omega}) + k_{rc} e^{-Nj\omega} Q(e^{j\omega}) e^{rj\omega}\right) G_{CM}(e^{j\omega}) G_o(e^{j\omega})$.

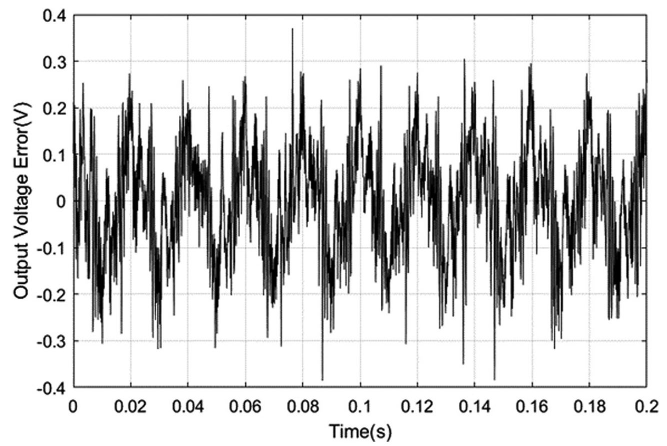

Fig. 7. Output voltage error of the inverter system of composite repetitive control.

and integral coefficient KO_I of the outer loop are determined. The criterion is that under the condition that the system does not produce oscillation, taking the minimum error as the basis for selecting the control parameters, KO_P = 1.3, KO_I = 0.004, and KI_P = 2.1 can be obtained. At this time, the output voltage error and the harmonic distortion rate of the output voltage of the inverter control system are shown in Fig. 10.

Although the dual closed-loop cascade control method uses current error and voltage error information to generate control signals, its control performance is worse compared to the composite repetitive control method proposed in this paper, including the instantaneous error of output voltage and the quality of the output waveform. In addition, the cascade control method requires two sensors, while the composite repetitive control method only uses one sensor, which increases system costs and reduces the reliability of the control system.

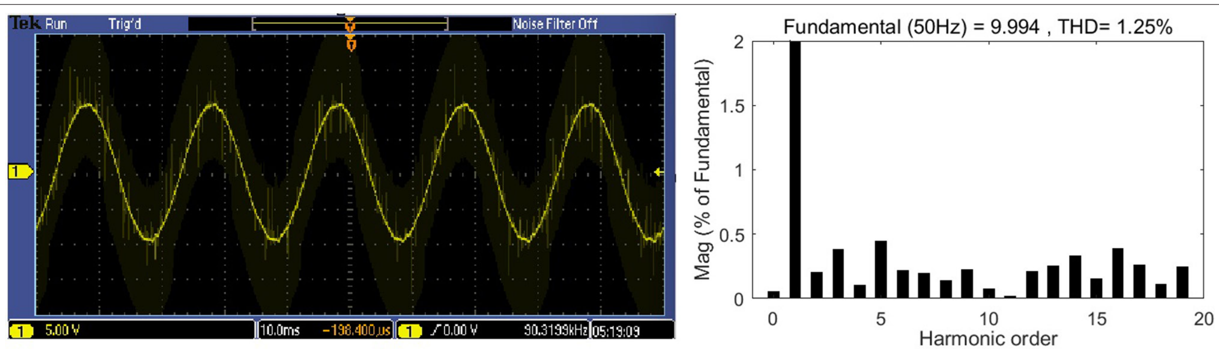

Fig. 8. Output voltage and its harmonic distortion rate under compound repetitive control.

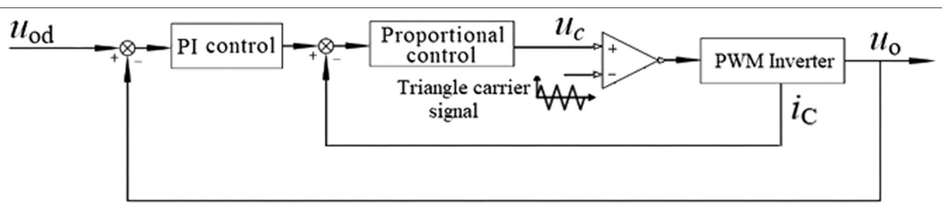

Fig. 9. Structure of double closed-loop cascade control system.

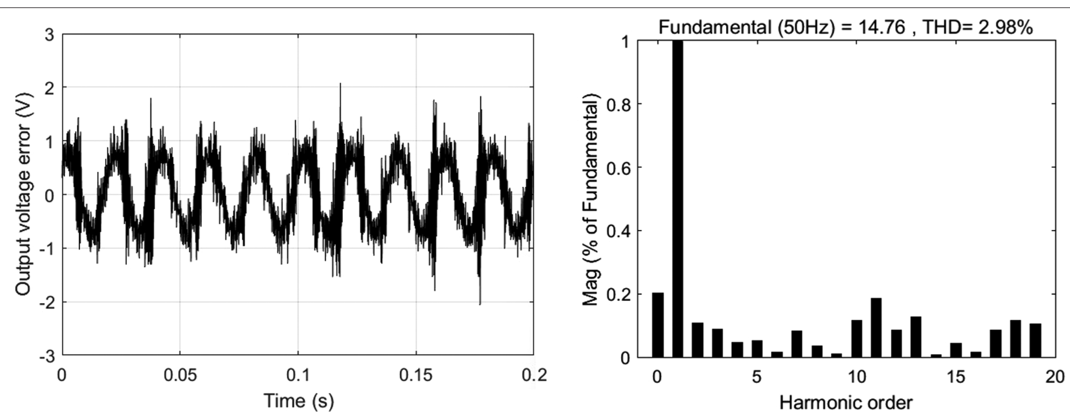

Fig. 10. Output voltage error and the harmonic distortion rate of the output voltage using cascade control.

IV CONCLUSION

This paper designs a composite repetitive controller for the selected single-phase full-bridge inverter system through frequency domain modeling. Combined with the inverse system feedforward control, it can improve the rapidity of the inverter circuit output. The repetitive control can improve the control accuracy of the output. The series of the repetitive controller is expanded, and the positive feedback term of the repetitive controller is analyzed. It is overcome by the parallel proportional link. The design process of the controller is given by frequency analysis. The experimental results confirm the practicality of the proposed composite repetitive control method. At the same time, the proposed control method has a simple structure, high reliability, a convenient design process, and is easy to apply in engineering. The proposed control method only needs to use the output voltage sensor and does not need to measure other variables such as inductor current or capacitor current. Sensors reduce the cost of the UPS inverter circuit and the complexity of the device and are easy to implement with low cost and high reliability. Further optimization of the design parameters to achieve the best performance is an issue that needs to be discussed in depth. At the same time, combining other types of control methods to improve the dynamic response of the system is also a very meaningful research direction.

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – G.Y.; Design – G.Y.; Supervision – G.Y.; Resources – G.Y.; Materials – G.Y.; Data Collection and/or Processing – K.X.; Analysis and/or Interpretation – G.Y.; Literature Search – K.X.; Writing – G.Y.; Critical Review – G.Y.

Declaration of Interests: The authors have no conflict of interest to declare.

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