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High-performance Single-phase AC Electronic Load Design based on Active PFC and SPWM Control Strategy

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Abstract: Aiming at the problems of low simulation accuracy, slow dynamic response speed and poor grid-connected current quality in the current single-phase AC electronic load, this design deeply studies the efficient main power topology and load simulation strategy with fast dynamic response and low steady-state error. Based on the STM32F103C8T6 single-chip microcomputer platform, the system adopts the active power factor correction (APFC) dual-loop control strategy and unipolar modulation method to significantly improve the response speed of the system and reduce the steady-state error. In order to achieve adjustable power factor (PFC), this design adopts AC-DC-AC conversion topology. Among them, the front-end circuit is responsible for simulating the load characteristics, and a one-cycle control technology is used to ensure high-precision load simulation; the energy feedback unit of the latter stage uses the hysteresis current control technology, which effectively reduces the harmonic components in the input current, thereby improving the power factor. Through simulation analysis and actual circuit test verification, this design scheme shows significant improvement in simulation accuracy and dynamic response compared with traditional methods. Specifically, the 60 W single-phase AC electronic load constructed according to the above scheme can be flexibly adjusted in the power factor range of 0.70 to 0.94 under the condition that the input voltage U1 is 30 V and the current I1 is 2A, and the efficient feedback of electric energy to the power grid is realized. This design not only improves the overall performance of the single-phase AC electronic load, but also provides a feasible technical path for the effective utilization of energy, which has a good engineering application prospect.

Keywords: AC Electronic Load; Active Power Factor Correction; Power Factor Adjustment; Closed-Loop Control; Energy Feedback.

1. Introduction

With the development of power electronics technology, single-phase AC electronic load plays an increasingly important role in testing and evaluating power supply performance. However, some existing single-phase AC electronic loads have problems such as low simulation accuracy, slow dynamic response speed, and poor grid-connected current quality, which limit their effectiveness and reliability in practical applications. In order to solve these problems, this design is based on STM32F103C8T6 single-chip microcomputer platform, using active power factor correction[1] (APFC) dual-loop control strategy and unipolar modulation method, aiming at improving the response speed of the system, reducing the steady-state error, and improving the power factor by reducing the input current harmonics.

This paper will introduce a new design scheme of single-phase AC electronic load in detail. The design adopts AC-DC-AC[2] conversion topology, in which the front-end circuit is responsible for accurate load characteristic simulation[3], and one-cycle control technology is used to ensure high precision. The energy feedback unit of the latter stage uses the hysteresis current control technology[4] to effectively reduce the harmonic components in the input current, thereby improving the power factor of the overall system. In addition, the design scheme also includes the selection and demonstration of the main control chip, rectifier circuit, load characteristic analog circuit and energy feedback circuit to build an efficient and stable system architecture.

Through simulation analysis and actual circuit test verification, this design scheme shows significant improvement in simulation accuracy and dynamic response compared with traditional methods. Specifically, under the condition that the input voltage U1 is 30 V and the input current I1 is 2A, the designed 60 W single-phase AC electronic load can be flexibly adjusted in the power factor range of 0.70 to 0.94, and the efficient feedback of electric energy to the grid is realized. This design not only improves the performance index of single-phase AC electronic load, but also provides new ideas and technical support for the effective utilization of energy.

The following chapters will discuss in detail the technical selection of each functional module and the theoretical basis behind it, including the selection of the main control chip, the design of the rectifier circuit, the load characteristic analog circuit and the specific implementation plan of the energy feedback circuit. These contents together constitute a comprehensive and in-depth design guide, which provides a solid foundation for subsequent research and practice.

2. System Design and Scheme Demonstration

This chapter aims to discuss the design idea of single-phase AC electronic load and the selection basis of each component in detail. According to the design requirements, the system is mainly divided into four functional modules: filtering, rectification, power factor correction (PFC) and inverter.

The first part uses LCL filter to filter out high-frequency harmonic signals.

In the second part, the input single-phase alternating current is rectified to convert it into direct current.

The third part is the chopper part (PFC switching power supply) will not filter the pulsation of the positive half cycle voltage as the power supply of the chopper, because the chopper of a series of do ' switch ' work pulsation of positive voltage and current waveform is discontinuous, the envelope and voltage waveform are the same, and the envelope and voltage waveform phase in phase.

The fourth part is the energy feedback part, which is mainly for DC-AC conversion

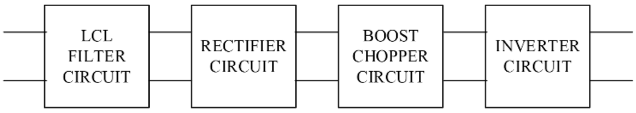

Fig 1. AC electronic load system block diagram

2.1. The Demonstration and Selection of the Main Control Chip

In this design, in order to achieve efficient control of single-phase AC electronic load, it is necessary to select a master chip with superior performance and suitable for application requirements.

In order to ensure the efficient operation of the system, we compared and analyzed two main control chips : STM32F103C8T6 and MSP430G2553. The STM32F103C8T6 has abundant on-chip resources, including 64 KB Flash memory and 7 timers. It supports dual 12-bit 1 µS ADC and two high-speed SPI interfaces and other peripherals. It has good data acquisition stability and transmission independence. In addition, its low power consumption characteristics make it an ideal choice for power control applications. In contrast, although MSP430G2553 also has the advantages of low power consumption, it is inferior to STM32F103C8T6 in terms of running speed and programming flexibility. Therefore, after comprehensive consideration, STM32F103C8T6 is selected as the main controller of this design.

2.2. Demonstration and Selection of Rectifier Circuit

In the design of single-phase AC electronic load, the selection of rectifier circuit directly affects the efficiency and economy of the system. Rectifier circuit is an important part of the system. We compare two schemes of fully controlled bridge rectifier circuit and uncontrollable bridge rectifier circuit [5]. The full-controlled bridge rectifier circuit can accurately control the output voltage through PWM technology, but the cost is high and the control system is complex. On the contrary, the uncontrollable bridge rectifier circuit has a simple structure, high efficiency and economical benefits. Although the output voltage of the DC side cannot be flexibly adjusted, the application scenario of the fixed input voltage is sufficient to meet the demand. Therefore, the uncontrollable bridge rectifier circuit is finally selected as the rectifier unit.

2.3. Demonstration and Selection of Load Characteristic Analog Circuit

In order to achieve efficient load characteristic simulation, we evaluated two schemes of single-phase voltage source PWM converter and active PFC circuit. Although the former can realize bidirectional power transmission and accurately control the AC side current and power factor, its complex design requirements and technical challenges are large. The active PFC circuit can effectively eliminate the current waveform distortion, keep the voltage and current phase consistent, and solve the problems of power factor and electromagnetic compatibility[6]. Therefore, considering the design difficulty and actual effect, the active PFC circuit is selected as the infrastructure of the load characteristic simulation unit.

2.4. Argumentation and Selection of Energy Feedback Circuit

The design of energy feedback circuit is very important to improve the overall performance of the system. We choose the unipolar SPWM single-phase bridge inverter circuit as the optimal solution. Compared with the bipolar modulation method, the higher harmonic component generated by the unipolar modulation is smaller, which is more suitable for applications that require high-quality output voltage [7]. In addition, the unipolar SPWM circuit also has the advantages of wide output voltage adjustment range and simple control, which is helpful to improve the overall performance of the system. The system block diagram is shown in Fig 2.

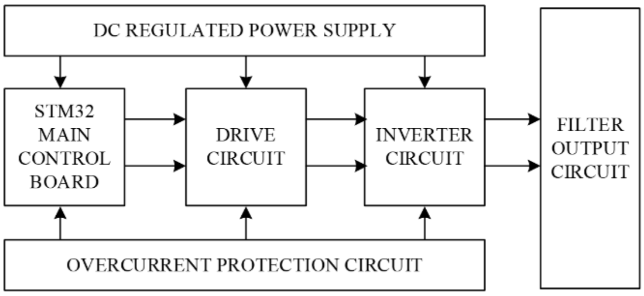

Fig 2. unipolar SPWM single-phase bridge inverter circuit diagram

In summary, through the detailed analysis and trade-off of each key component, an efficient and reliable single-phase AC electronic load design scheme is finally determined. The following chapters will introduce the specific hardware design and software implementation process in detail to build a comprehensive and in-depth design guide and provide a solid foundation for subsequent research and practice.

3. System Design and Implementation

3.1. Design of Load Characteristic Simulation Module

The system needs to be able to simulate resistive, inductive and capacitive loads, and in the case of input voltage U1 = 30V and input current I1 = 2A, the input side power factor cosφ1 can be adjusted in the range of 0.50 ~ 1.00.

3.1.1. Parameter Calculation and Key Component Selection

This design uses a DC boost chopper circuit [8] (Boost Converter) to adapt to the application scenarios that need to increase the DC voltage. The working principle of the circuit is shown in Fig 3. When G1 is on, the current forms a loop through the boost inductor L and the field effect transistor G1, so that the inductor L stores energy. When G1 is turned off, the back electromotive force generated by the inductance is superimposed on the DC power supply voltage, thereby obtaining a voltage higher than the power supply on the load side. Choosing the right components is essential to ensure the stability and efficiency of the system. For example, considering the safety margin, the rated voltage of the field effect transistor should be 2 to 3 times the peak voltage, so the P75NF75 model MOSFET is selected, with a rated voltage of 75V and a rated current of 75A. The freewheeling diode is HFA25TB60, with a rated voltage of 600V and a rated current of 25A. The specific selection is shown in Table 1.

Table 1. Component selection table

COMPONENTS	MODEL	U_d/V	I_d/A
FIELD-EFFECT TRANSISTOR	P75NF75	75	75
RECTIFIER DIODE	B20200G	200	20
FREEWHEELING DIODE	HFA25TB60	600	25
FAST RECOVERY DIODE	STPS20S100CT	100	10

3.1.2. Hardware Circuit Design and Implementation

The hardware circuit design includes power filter, rectifier and active PFC circuit design. The power supply filter (common mode filter) is composed of L01, LF01 and C01, which is used to eliminate the conduction interference of DC-DC and DC-AC working in high frequency state. The half-wave sinusoidal pulsating voltage output by the rectifier is processed by the active PFC circuit, which eliminates the current waveform distortion and phase change caused by capacitor charging, and ensures that the power supply line exhibits pure resistive load characteristics. The DC voltage then supplies power to the back-stage Boost circuit, and efficient energy conversion and feedback are achieved through SPWM control.

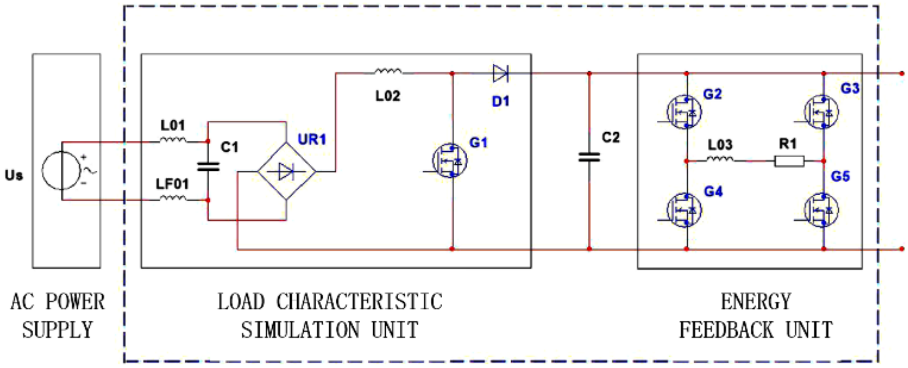

Fig 3. System circuit diagram

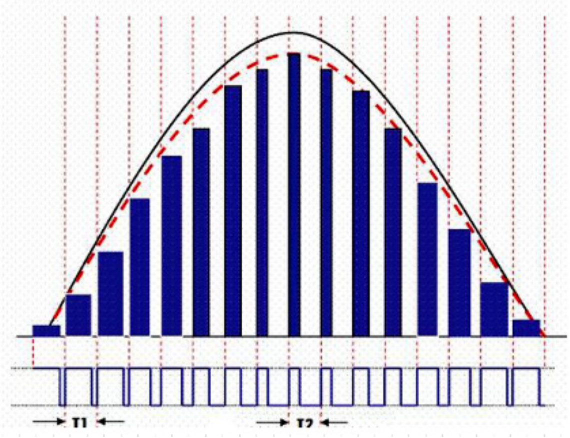

Fig 4. Chopper voltage amplitude diagram

3.1.3. Software Design and Control Strategy

Based on the control principle of BOOST chopper circuit, the corresponding SPWM control program is designed by using STM32F103C8T6 single chip microcomputer. SPWM control is the technology of modulating the width of the pulse, that is, by modulating the width of a series of pulses, the required waveform can be obtained equivalently. The key of PWM control technology lies in the principle of area equivalence, that is, the required waveform is obtained by modulating a series of pulse widths [9-10]. This design uses SPWM method to control IGBT, so as to realize the DC-AC inverter process. The principle block diagram of the control circuit is shown in Fig 5, and the corresponding waveform is shown in Fig 6.

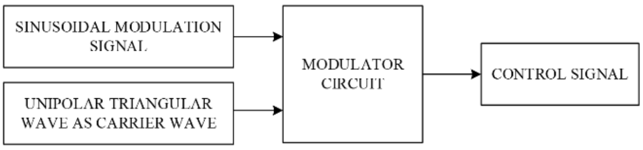

Fig 5. Control circuit principle diagram

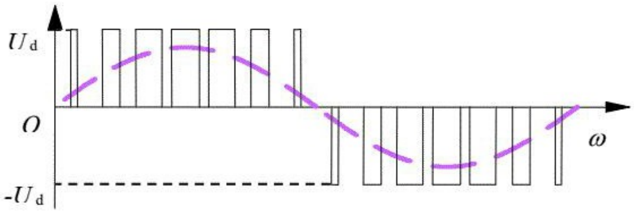

Fig 6. Control circuit waveform diagram

In the actual operation : First of all, through a current sampling to control the input current is 2A ; secondly, the zero-crossing point is obtained by the sliding filter algorithm, and the phase difference of the voltage and current is controlled by changing the starting point of the sine table, so that the current and voltage are forward or backward by 90 °. Change the starting point of the sine table to control the PFC ; the software controls the starting point of the sinusoidal meter, thereby controlling the phase difference of the voltage and current to make it a resistive load ; then the Boost circuit controlled by SPWM is filtered by large capacity electrolytic capacitor and sent to DC-AC circuit. The PFC control program flow chart is shown in Fig 7, and the overall system design flow is shown in Fig 8.

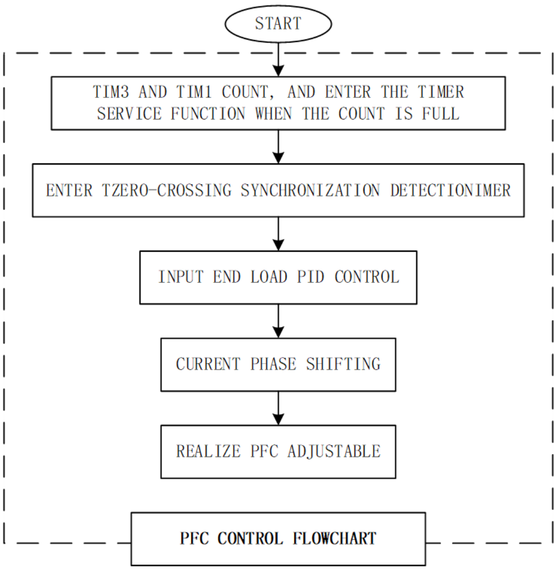

Fig 7. PFC control program flow chart

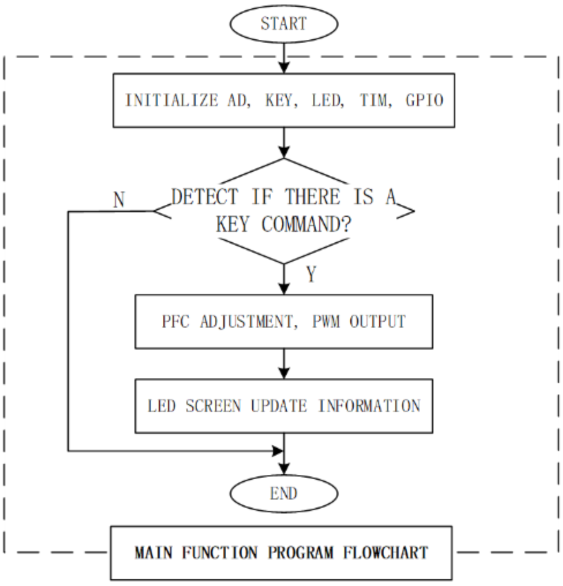

Fig 8. AC electronic load system control flow chart

3.2. Energy Feedback Module Design

As shown in Fig 9, the unipolar SPWM single-phase bridge inverter circuit using MOSFET as the switching device is the core part of the energy feedback unit. The basic working principle of the circuit is: V1 and V2 on-off state are complementary, and V3 and V4 on-off state are also complementary. The unipolar SPWM waveform can be generated by controlling the on-off of IGBT through the intersection of Ur and Uc. This process realizes an efficient inverter from DC to AC, and can efficiently feedback electric energy to the grid.

When the Ur of the signal wave is positive for half a week, V1 remains on and V2 remains off. When Ur > Uc, make V4 pass, V3 break, Uo = Ud. When Ur < Uc, V4 is broken, Vs is connected, Uo = 0.

When the signal wave Ur is negative half cycle, V2 remains on and V1 remains off. When UrUc makes V3 break, V4 pass, Uo = 0, the unipolar SPWM waveform is obtained.

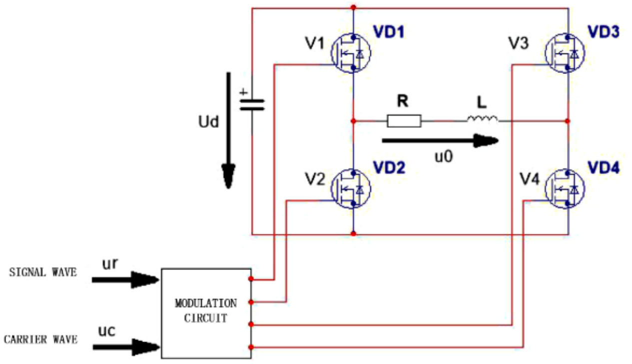

Fig 9. The schematic diagram of unipolar SPWM single-phase bridge inverter circuit

This chapter describes in detail the design ideas and implementation methods of each key module in the single-phase AC electronic load system, which provides a solid foundation for subsequent testing and optimization. The next chapter will introduce the specific test plan and its result analysis.

4. Test Scheme and Result Analysis

4.1. Test Scheme and Experimental Design

In order to verify the performance of the designed single-phase AC electronic load system, a detailed test scheme was developed. The scheme aims to provide a standard basis for power supply testing to ensure that the test can be carried out correctly and accurately. The test circuit layout is shown in Fig 10. The specific test requirements are as follows: in the case of input voltage U1 = 30V and input current I1 = 2A, the resistive, capacitive and inductive loads are simulated; the input side power factor cosφ is required to be automatically adjusted in the range of 0.50 ~ 1.00.

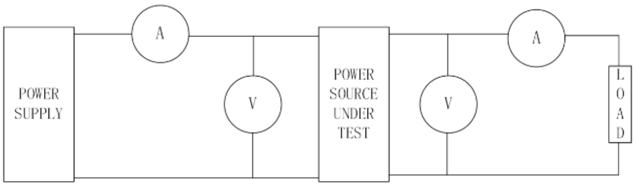

Fig 10. Test circuit diagram

4.2. Test Conditions and Equipment Configuration

In order to ensure the accuracy of the test data, a variety of high-precision measurement equipment are selected. All tests are carried out in a standard laboratory environment to ensure that the influence of environmental factors such as temperature and humidity on the test results is minimized. The specific configuration is as follows :

Table 2. Test equipment summary table

EQUIPMENT	MODEL	EQUIPMENT	MODEL
Digital Multimeter	DM3058	Power Analyzer	ANJ-JKG
Dual - trace Oscilloscope	SDS1202X-C	Electronic Load	IT8511+
Digital Clamp Meter	UT200B	Student Power Supply	DP832
Voltage Regulator	TDGC2	Isolation Transformer	BK-200

4.3. Test Results and Data Analysis

4.3.1. Overview of Test Data

According to different load types and set power factors, several tests were carried out, and the corresponding voltage, current and power data were recorded. The following is a summary of some key test data:

Table 3. Test data table of voltage and current under resistive load

INPUT VOLTAGE U1 /V	30.10	30.15	29.95	29.89
INPUT CURRENT I1 /A	2.03	2.01	2.01	1.98
INPUT VOLTAGE U1 /V	30.10	29.99	29.98	…
INPUT CURRENT I1 /A	2.01	1.99	1.99	…

Table 4. Test data table of voltage and current under inductive load

SET INPUT-SIDE POWER FACTOR COSΦ1	0.70	0.76	0.82	0.85	0.89	0.91	0.94
INPUT VOLTAGE U1 /V	30.10	30.15	29.95	29.89	30.10	29.99	29.98
INPUT CURRENT I1 /A	2.03	2.01	2.01	1.98	2.01	1.99	1.99

Table 5. Test data table of voltage and current under capacitive load

SET INPUT-SIDE POWER FACTOR COSΦ1	0.71	0.74	0.85	0.88	0.90	0.92	0.94
INPUT VOLTAGE U1 /V	30.09	30.12	29.98	29.88	30.04	29.97	30.01
INPUT CURRENT I1 /A	2.02	2.00	2.01	1.99	1.99	1.99	2.01

Table 6. Resistive load power test data table

SET INPUT-SIDE POWER FACTOR COSΦ1	INPUT POWER P1 /W	OUTPUT POWER P2 /W	POWER LOSS ΔP /W	LOSS RATIO %
0.92	55.2	42.6	12.6	22.83%
0.93	55.8	43.4	12.4	22.22%
0.92	55.2	43.4	11.8	21.38%
0.92	55.2	43.3	11.9	21.56%
0.91	54.6	42.5	12.1	22.16%
AVERAGE	55.2	43.1	12.1	21.92%

4.3.2. Load Test Data Analysis

Through the analysis of the test data, the following conclusions can be drawn:

(1) When simulating the resistive load, the input voltage of the electronic load is set to U1 = 30V, and the input current level I1 = 2A is required. The actual measurement is shown in Table 4-2. The current input voltage is 30.01V, the input current is 2.00A, and the power factor is close to 1, which is in line with expectations.

(2) In analog inductive load, when the electronic load input is U1 = 30V, I1 = 2A, the input side power factor cosφ1 can be automatically adjusted in the range of 0.50 ~ 1.00 according to the digital setting. The measured results are shown in Table 4-3.When the inductive load is simulated, the current input voltage is 30.01V and the input current is 2.00A, the power factor can be adjusted in the range of 0.70 ~ 0.94.

(3) In analog capacitive load, when the electronic load input is U1 = 30V, I1 = 2A, the input side power factor cosφ1 can be automatically adjusted in the range of 0.50 ~ 1.00 according to the digital setting. The actual measurement is shown in Table 4-4. When the capacitive load is simulated, the current input voltage is 30.00V and the input current is 1.99A, the power factor can be adjusted in the range of 0.71 ~ 0.94.

(4) When simulating the resistive load, the electronic load input is U1 = 30V, I1 = 2A. The input power P1 and feedback power P2 of the electronic load are measured, ΔP = P1-P2, and the smaller the ΔP is, the better. The actual measurement is shown in Table 4-5. When the resistive load is simulated, the current input voltage is 30.01V, the input current is 2.00A, the input active power is 55.2W, the output side feedback power is 43.1W, and the average ΔP is 12W. In the case of simulated resistive load, the power loss of the system is about 21.92 %.

In summary, through the actual circuit test, the design scheme has significantly improved the simulation accuracy and dynamic response compared with the traditional method, especially in the aspect of power factor adjustment, which can realize the efficient feedback of electric energy to the power grid. These results not only verify the effectiveness of the design, but also provide valuable data support for subsequent research and application.

5. Conclusion and Prospect

The purpose of this study is to solve the problems of low simulation accuracy, slow dynamic response speed and poor grid-connected current quality in the current single-phase AC electronic load. Based on the STM32F103C8T6 single-chip microcomputer platform, a new design scheme using active power factor correction (APFC) dual-loop control strategy and unipolar modulation method is proposed. The design realizes efficient load characteristic simulation by using one-cycle control technology in the front stage, and applies hysteresis current control technology for energy feedback in the back stage, which effectively reduces the input current harmonics and improves the power factor.

The experimental results show that when the input voltage U1 is 30V and the input current I1 is 2A, the designed 60W single-phase AC electronic load can accurately adjust the power factor of the input side to the range of 0.70 ~ 0.94, and realize the efficient feedback of electric energy to the grid. Specifically, the system exhibits about 21.92 % power loss, which means that about 78.08 % of the input energy is successfully converted and fed back to the grid, which verifies the high efficiency and reliability of the system.

Compared with the traditional method, this design shows significant improvements in simulation accuracy and dynamic response. In addition, through detailed hardware circuit design and software implementation, the stability and efficiency of the system are ensured. This study not only solves the key technical bottleneck of the existing single-phase AC electronic load, but also provides valuable design ideas and technical references for future related applications.

Future research can further optimize circuit design to reduce power loss, improve overall efficiency, and explore broader application scenarios, such as testing and evaluation of new energy power generation systems. Through continuous technological innovation, it is expected to promote the progress and development of power electronics and promote the efficient use of energy. In summary, this study provides an effective solution to improve the performance of single-phase AC electronic load, which has important theoretical value and practical application prospects.

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References

[1] Zhang Mingcun. Research on AC-DC Conversion Circuit with Controllable Power Factor Based on MATLAB[J]. Journal of Ningxia Normal University, 2024, 45(01): 39-45.

[2] Shen Yadong. Research on Hybrid Control Type Two-Stage AC/DC Converter[D]. North Minzu University, 2025.

[3] Zhang Jun. Research on AC Electronic Load Considering Dead-Time Effect[D]. China Jiliang University, 2022.

[4] Zhao Yue. Research on Double Closed-Loop Control of PWM Inverter Based on Current Hysteresis Tracking[J]. Electronic Science and Technology, 2016, 29(12): 51-54.

[5] Ma Yong, Li Zicheng, Luo Xuefang, et al. Modeling and Performance Analysis of Single-Phase Bridge Fully Controlled Rectifier Circuit[J]. Electronics World, 2020, (18): 86-90.

[6] Wu Chengjian. Research on DCM Buck-Buck/Boost PFC Converter with Segmented Fixed Duty Cycle Control[D]. Nanjing University of Science and Technology, 2020.

[7] Xu Ruiting, Wang Shunliang, Liu Xiaolin, et al. Analysis and Suppression of Parallel Circulating Current in Unipolar SPWM Inverters[J]. Journal of Power Supply, 2023, 21(01): 64-73.

[8] Liu Hongxi, Wang Lixuan, Wang Dan, et al. Research on Boost DC Chopper Circuit in Power Factor Correction Circuit[J]. Electronic Technology, 2018, 47(08): 33-35.

[9] Wang Jifeng. Power Electronics Technology[M]. Chongqing University Press: January 2019. 204.

[10] Shi Jingcong. Research on Overcurrent Suppression Technology of PWM Rectifier Based on Double Closed-Loop Control[J/OL]. Power Electronics, 1-9 [2025-07-02].