Design and control of a single-phase voltage compensator based on an AC Chopper

Diseño y control de un compensador de voltaje monofásico basado en un chopper AC

Projeto e controle de um compensador de tensão de fase única baseado em um chopper CA

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Abstract

Introduction: This paper is the result of the research "Design and control of a single-phase voltage compensator based on an AC Chopper" developed in the AD-AF Academy of Viet Nam in 2019.

Problem: This article develops the concept of power electronic devices based on AC choppers and provides a solution for voltage sag and deep fade in rural power grids.

Objective: Improve the quality of the electricity system in rural Viet Nam.

Methodology: With the improvement of power systems, power quality has become the major concern of customers and grid companies. Voltage sag has turned into a research priority because of its frequent occurence and resulting economic losses. Based on the rounded analysis of traditional voltage compensation devices, this article develops the concept of power electronic devices based on AC choppers and provides a solution for voltage sag and deep fade in rural power grids.

Results: On the one hand, it reduces the cost and space requirements of the device. On the other hand, it provides a solution for the short compensation time of UPS and DVR.

Conclusion: The trial operation proves that this single-phase low-voltage compensation device has obvious compensation effects for the most resistive loads and some inductive loads, less harmonic content, long continuous compensation time and stable performance.

Originality: This compensation device integrates the advantages of UPS and DVR, and also solves their shortcomings and deficiencies.

Limitations: The authors need to spend more time on the development and design of three-phase low-voltage compensation devices.

Keywords: voltage sag; AC chopper; voltage compensation, rural power grid.

Resumo

Introdução: Este artigo é o resultado da pesquisa "Projeto e controle de um compensador de tensão monofásico baseado em um cortador de corrente alternada" desenvolvida na AD-AF Academy do Vietnã em 2019.

Problema: Este artigo desenvolve o conceito de dispositivos eletrônicos de potência com base em choppers CA e fornece uma solução para queda e queda de tensão em redes elétricas rurais.

Objetivo: Melhorar a qualidade do sistema elétrico na zona rural do Vietnã.

6Metodologia: Com a melhoria dos sistemas de energia, a qualidade da energia se tornou a principal preocupação dos clientes e empresas de rede. A queda de tensão tornou-se uma prioridade de pesquisa devido à sua ocorrência frequente e às perdas econômicas resultantes. Com base na análise arredondada de dispositivos de compensação de tensão tradicionais, este artigo desenvolve o conceito de dispositivos eletrônicos de potência baseados em choppers CA e fornece uma solução para queda e desvanecimento profundo de tensão em redes de energia rurais.

Resultados: Por um lado, reduz o custo e os requisitos de espaço do dispositivo. Por outro lado, fornece uma solução para o curto tempo de compensação de UPS e DVR.

Conclusão: A operação de teste prova que este dispositivo de compensação de baixa tensão monofásico tem efeitos de compensação óbvios para a maioria das cargas resistivas e algumas cargas indutivas, menos conteúdo harmônico, longo tempo de compensação contínua e desempenho estável.

Originalidade: Este dispositivo de compensação integra as vantagens do UPS e DVR e também resolve suas deficiências e deficiências.

Limitações: Os autores precisam dedicar mais tempo ao desenvolvimento e projeto de dispositivos trifásicos de compensação de baixa tensão.

Palavras chave: queda de tensão; Chopper AC; compensação de tensão, rede elétrica rural.

Resumen

Introducción: este artículo es resultado de la investigación "Diseño y control de un compensador de voltaje monofásico basado en un convertidor AC" desarrollado en la Academia AD-AF de Vietnam en 2019.

Problema: este artículo desarrolla el concepto de dispositivos electrónicos de potencia basados en convertidores CA y proporciona una solución para la caída de voltaje y apagado de las redes eléctricas rurales.

Objetivo: mejorar la calidad del sistema eléctrico en las zonas rurales de Vietnam.

Metodología: con la mejora de los sistemas eléctricos, la calidad de la energía se ha convertido en la principal preocupación de los clientes y las empresas que ofrecen energía. La caída de tensión se ha convertido en una prioridad de investigación debido a su frecuente aparición y a las pérdidas económicas que conlleva. Con base en el análisis completo de los dispositivos tradicionales de compensación de voltaje, este artículo desarrolla el concepto de dispositivos electrónicos de potencia basados en convertidores CA y proporciona una solución para la caída de voltaje y el apagado de las redes eléctricas en el ámbito rural.

Resultados: por un lado, se reduce el costo y los requisitos de espacio del dispositivo. Por otro lado, se proporciona una solución para el corto tiempo de compensación de UPS y DVR.

Conclusión: la operación de prueba demuestra que este dispositivo de compensación de bajo voltaje monofásico tiene efectos de compensación obvios para las cargas más resistivas y algunas cargas inductivas, menor contenido de armónicos, tiempo de compensación continuo prolongado y rendimiento estable.

Originalidad: este dispositivo de compensación integra las ventajas de UPS y DVR, y también resuelve sus desventajas y deficiencias.

Limitaciones: los autores deben dedicar más tiempo al desarrollo y diseño de dispositivos de compensación trifásicos de baja tensión.

Palabras clave: caída de tensión; Helicóptero AC; compensación de voltaje, red eléctrica rural.

1. INTRODUCTION

In recent years, Viet Nam's rural areas have developed rapidly, rural electricity demand has increased, and electricity consumption has increased significantly, while rural power grids remain relatively simple. This is the cause of the voltage sag phenomenon, which is long-lasting, and deep fade over the rural power grid [1]. So, the improvement of power system operation efficiency and power quality has become the major concern of customers and grid companies in Vietnam's rural communities [2, 3].

Most modern power systems face many issues in power quality. All the power quality issues include problems that are related to voltage. The result of this voltage quality issue leads to the most frequent and common problem called voltage sag.

Voltage dip or voltage sag is the reduction in certain levels of voltage, which reduces the quality of power. Just as there can be voltage reductions there are also increases in voltage known as voltage swell [4]. The connection of non-linear loads in the system and short circuit faults are considered the major cause for the occurrence of voltage sag. This issue may collapse the entire system causing malfunction or failure of the equipment [5].

Many devices are used for compensating the voltage disturbances:

Uninterruptible power supplies (UPS) provide a number of benefits to both home and business use, keeping vital computer and electronics systems running through brief power outages and preventing damage from sudden power loss. Using a UPS also involves a number of disadvantages, especially in the upfront and maintenance costs. UPS batteries do not last forever. Like all rechargeable batteries, their capacity to hold a charge diminishes over time. In order to keep its batteries charged at all times, a UPS system must draw more power than the attached equipment requires [6].

Dynamic voltage restore (DVR) is a kind of FACTS device which is used for series compensation in distribution networks [7]. The DVR can mitigate voltage sag and improve power quality of the system [8]. The DVR is able to produce and absorb reactive power by controlling the series injected voltage (Vse) [9]. But to exchange active power with the system, the DVR needs the DC storage unit [10]. The DC storage unit saves a finite amount of energy, so it cannot support the critical load at the faulty condition for a long period of time. It is one of the worst deficiencies of DVR [11].

AC-choppers have been used for AC voltage regulation and voltage sag compensation as proposed in [12]. The AC-Chopper can be used to perform like an automatic voltage regulator as presented in [12]. The AC-chopper can offer a minimum energy injection using micro-SMES; as has clearly been verified in [13]. As can be seen, a developed PWM technique in [13] is for fast output voltage control for a conventional converter which can be utilized in AC-choppers with some modification. Hence, fast dynamic voltage response for AC-choppers can be achieved by using an instantaneous voltage control technique as presented in [14]. The simulation and experimental results have been reported and have been validated in [15] for single-phase AC-chopper applications.

This article develops power electronic devices based on AC choppers and provides a solution for long-lasting voltage sag and deep fade over rural power grids. This compensation device integrates the advantages of UPS and DVR, and also solves their shortcomings and deficiencies. On the one hand, it reduces the cost and space of the device. On the other hand, it solves the short compensation time of UPS and DVR.

2. CONTENT AND RESEARCH METHODS

2.1. Traditional Voltage Compensation Device [7, 9]

With its good dynamic performance, the dynamic voltage restorer (DVR) has become the most economical and effective way to solve the voltage sag problem.

However, the dynamic voltage restorer also has serious defects: The device requires battery energy storage to complete the voltage compensation function, in some areas where the voltage drops frequently, the device is prone to frequent charging and discharging, and the battery life is bound to be greatly shortened, thereby increasing its operating cost; The capacity of the energy storage element in the device is limited; After a voltage drop occurs, the device can only be dynamically compensated within half a cycle to a few cycles. Therefore, for areas with a long voltage drop duration, the device is not applicable.

2.2. Single phase voltage compensator based on AC Chopper [5]

After inheriting the advantages of the above voltage compensation devices, this paper designs the device circuit topology shown in Figure 1. The voltage compensation device is mainly composed of a series transformers, a filter, an AC chopper unit and a series compensation capacitor. Each part will be analyzed in detail below.

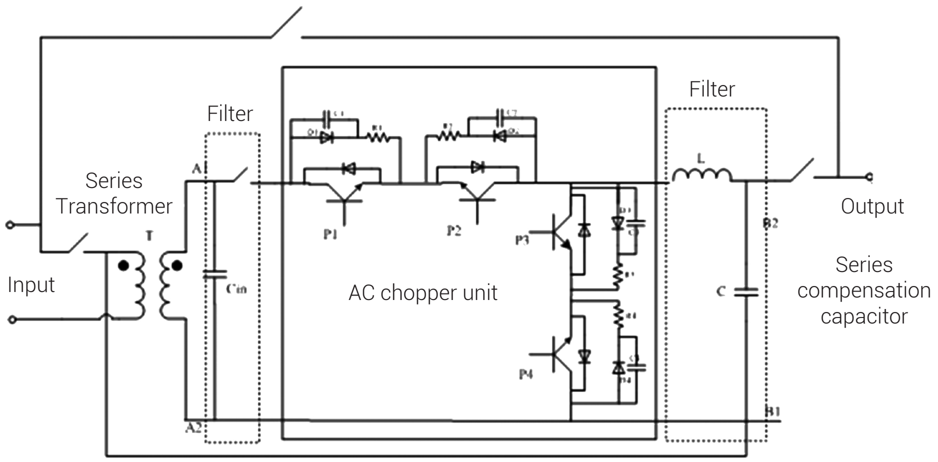

Figure 1. The topological structure of the device
Source: own work

AC chopper unit: The AC chopper circuit is the core part of the entire voltage compensation device and the basis for the realization of the voltage compensation function.

$$\begin{aligned} u_{o(t)} &= u_{i(t)} \times S(t) = U_m \sin \omega t [D + \frac{2}{\pi} \sum_{a=1}^{\infty} \frac{\sin \varphi_a}{a} \cos(a\omega_c t - \varphi_a)] \\ &= U_m D \sin \omega t + \frac{U_{Nm}}{\pi} \sum_{a=1}^{\infty} \frac{\sin \varphi_a}{a} \{\sin[(a\omega_c + \omega)t - \varphi_a] - \sin[((a\omega_c - \omega) - \varphi_a]\} \end{aligned} \quad (1)$$

It can be seen from Equation 1 that the modulated output voltage is composed of the fundamental wave and higher harmonics at the same frequency as the sinusoidal input voltage. So as long as the high-frequency harmonics are filtered out by the low-pass filter to make the output voltage $u_{o(t)} = DU_{i(t)} = U_m D \sin \omega t$, then the output voltage can be adjusted directly by adjusting the duty ratio D, that is, the output voltage can be linearly adjusted.

User side filter: It can be seen that the output voltage is mainly composed of the fundamental wave component and the higher harmonic component, so in order to ensure that the output voltage distortion rate is low, the higher harmonic contained within must be removed. Because the harmonics contained in the output voltage are mainly composed of $\sin[(a\omega_c + \omega)t - \varphi_a]$ and $\sin[(a\omega_c - \omega) - \varphi_a]$, which ω_c is determined by the carrier cycle T_c, that is $\omega_c = \frac{2\pi}{T_c}$, the carrier cycle T_c is determined by the carrier ratio $K = T / T_c$, so selecting the parameters of the band-reject filter should be based on the carrier frequency of the AC chopper.

Transformer secondary filter: Since the grid inevitably contains harmonics, a filter must be installed in front of the AC voltage regulation unit to optimize the input voltage waveform.

2.3. Voltage compensation strategy

2.3.1. Full compensation method [6]

This method can not only solve the drop of voltage amplitude but also solve the problem of voltage phase shift, and can make the compensated voltage fully recover to levels before the drop. However, this strategy also has serious disadvantages:

The implementation of this method needs to rely on a considerable system capacity, which requires having a large enough capacitance value to achieve it, which increases the difficulty and cost of system implementation; This method is almost impossible to achieve in the case of a large voltage drop depth or a large phase shift.

2.3.2. In-phase compensation method [8]

The basic principle is to ensure that the compensation voltage vector is in phase with the system voltage vector after the drop, so that the compensated voltage amplitude returns to the normal level. The main advantage of this method is that the compensation voltage that the device needs to provide is always the minimum value, and the control method is simple and easy to implement.

The main disadvantage of this method is that the output power is not controlled, and the phase jump problem caused by voltage sag is not solved.

2.3.3. Minimum energy compensation method

Using this method compensates for the sag by injecting minor real power to the system. The minimum energy compensation method has the least active power output, but the output voltage is large.

2.3.4. Improved minimum energy compensation method

In the voltage tolerance method with minimum energy injection, a small drop in voltage and small jump in phase angle can be tolerated by the load itself. If the voltage magnitude lies between 90%-110% of nominal voltage and 5%-10% of the nominal state, the operation characteristics of loads will not be disturbed. Both magnitude and phase are the control parameters for this method, which can be achieved by small energy injection.

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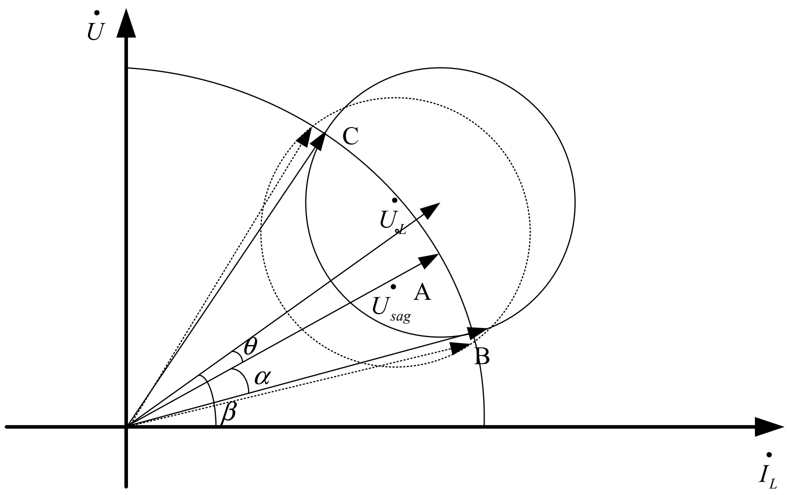

Figure 2. The diagram of the principle of the improved minimum energy compensation method
Source: own work

2.4. Research on Control Strategy of Voltage Compensation Devices [10-11]

In terms of system control strategy, open-loop control is simple and easy to implement, but its stability is poor; the closed loop control system is absolutely stable. Therefore, closed-loop control is selected.

In closed loop control, the control action from the controller is dependent on feedback from the process in the form of the value of the process variable. A closed loop controller, therefore, has a feedback loop which ensures the controller exerts a control action to manipulate the process variable to be the same as the "Reference input" or "set point". For this reason, closed loop controllers are also called feedback controllers.

Closed loop control is preferred due to its strong dynamic behaviour compared to open loop. The control scheme of closed loop is presented in Figure 3.

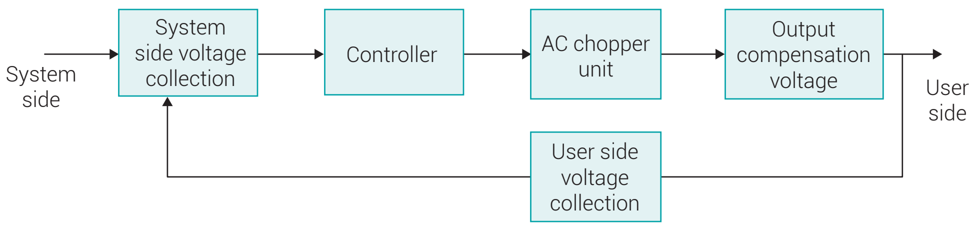

Figure 3. Schematic diagram of the closed-loop control system
Source: own work

3. RESULTS

3.1. Hardware and software design and simulation

This paper is based on the power system simulation software PSCAD /EMTDC V4.20 to simulate the basic structure of the voltage compensation device and detection and control methods.

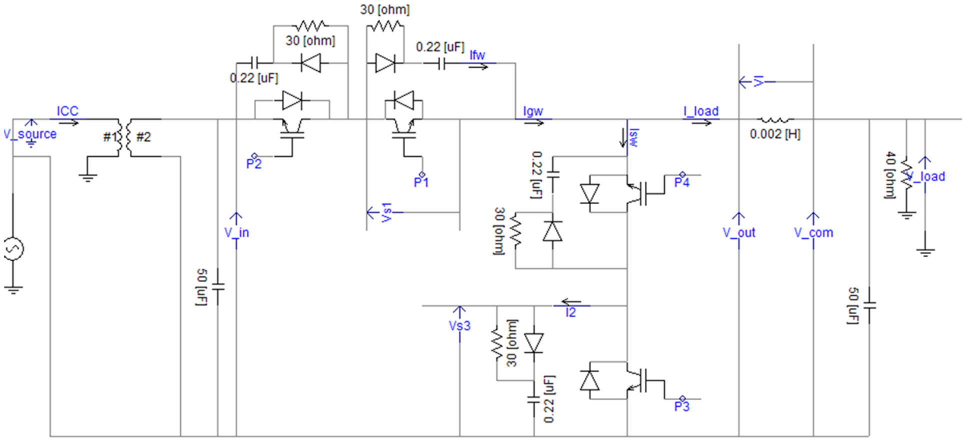

Figure 4. Topological simulation model of device's main circuit
Source: own work

In Figure 4, the ratio of the series transformer is set to 1:1, the input side low-pass filter capacitor is set to 50μF, the IGBT drive signal of the AC chopper unit is controlled by P1, P2, P3, P4, and the 40-ohm load resistor.

The voltage detection method used in this simulation is the effective value detection method. This method is simple and easy and has good accuracy. The simulation structure is shown in Figure 5 below.

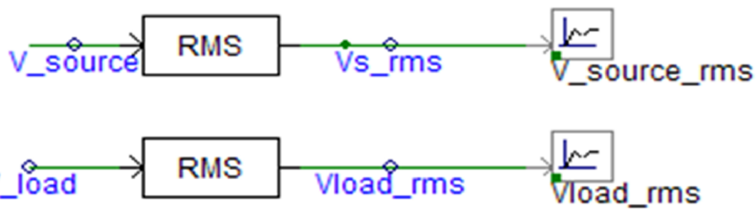

Figure 5. Simulation model of effective value detection method
Source: own work

In Figure 5, V_source is the system-side voltage, V_load is the load-side voltage, Vs_rms is the effective value of the system-side voltage, and Vload_rms is the effective value of the load-side voltage. The system-side voltage value is with the standard voltage value 220V to calculate the duty ratio of AC chopping. The duty ratio is calculated in Equation 2.

$$D = \frac{220 - Vs\_rms}{Vs\_rms} = \frac{220}{Vs\_rms} - 1 \quad (2)$$

Simulation results of the voltage compensation device: In the simulation, the voltage value of the system is adjusted to achieve the low voltage effect. The system voltage adjustment module is shown in Figure 6 below.

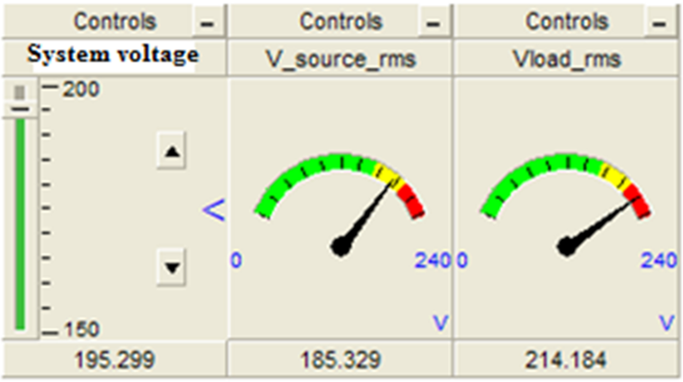

Figure 6. System voltage regulation module
Source: own work

In the simulation process, we will irregularly adjust the system voltage between 200V~150V to test whether the voltage compensation device simulation model, voltage detection method, AC chopping drive pulse generation, etc. are effective. The simulation results are shown in Figure 7 below. It can be seen that the effective value of the system voltage fluctuates continuously with the adjustment of the system voltage regulation module, and the effective value has always been below 200V, and the load voltage has been stable between 200V~220V. It can be seen that the effective value detection method, Non-complementary AC chopping methods to deal with long-term voltage instability, is very obvious.

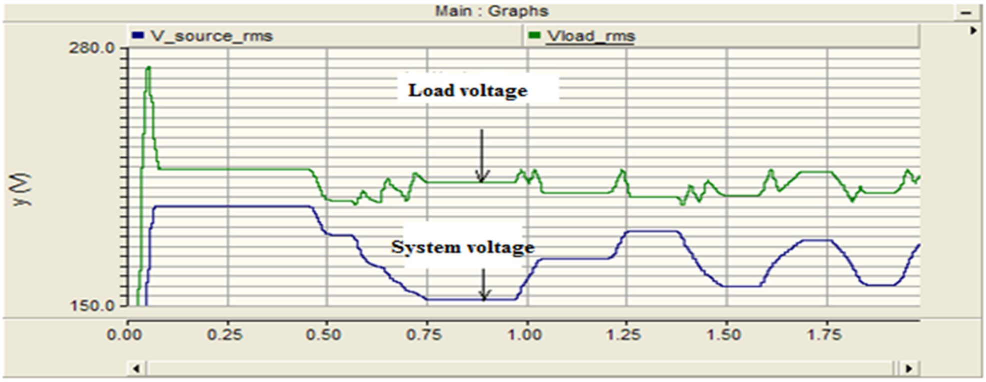

Figure 7. Input voltage and effective value of voltage after compensation
Source: own work

In addition, we made a simulation analysis of the stability of the device and the output voltage distortion and set the system voltage to the maximum amplitude of 255V. The simulated system voltage waveform, load voltage waveform and compensation voltage waveform are shown in Figure 8 below.

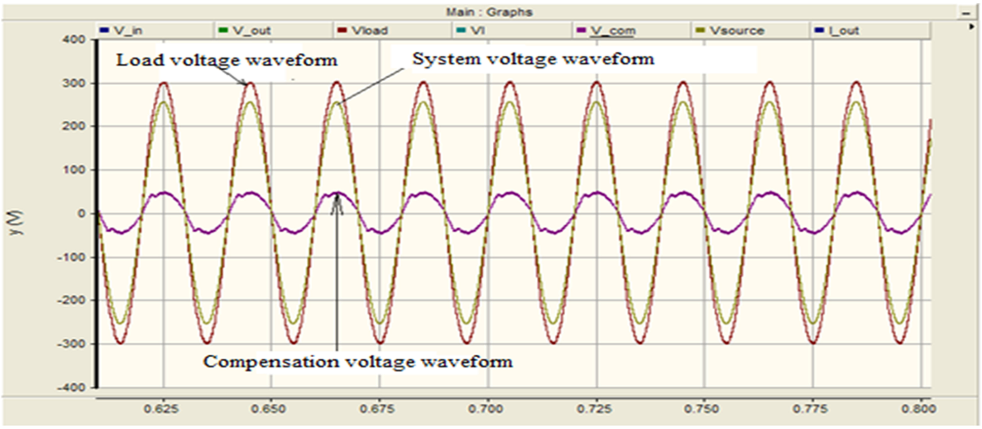

Figure 8. Input voltage and voltage waveform after compensation
Source: own work

It can be seen from Figure 8 that the output voltage waveform of the voltage compensation device is perfect, without harmonic interference, and the output voltage has the stable amplitude at 300V without fluctuation

In this simulation, corresponding to Figure 8, the results comparing the effective value of the system voltage and the effective value of the load voltage are shown in Figure 9. It can be seen that the effective value of the system voltage is 180V, the effective value of the load voltage is quite stable at 214V and there is no fluctuation.

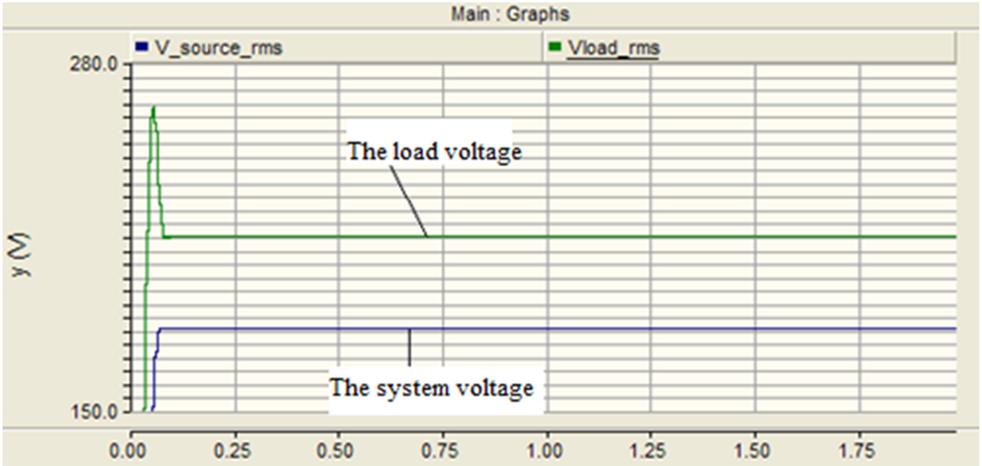

Figure 9. Comparison chart of long-term compensation stability
Source: own work

After the above simulation analysis, this device is feasible with regards to the circuit topology, voltage detection method, voltage compensation strategy, or in the application of AC chopping mode, and the compensation effect is very obvious. The output waveform is perfect, and it meets the standard voltage requirements.

3.2. Hardware implementation of the voltage compensation device

Its specific structure can be roughly divided into: main control circuit, output filter, AC chopper unit, buffer and drive protection circuit of AC chopper unit, circuit breaker, information collection and control circuit. The main hardware circuit block diagram is shown in Figure 10.

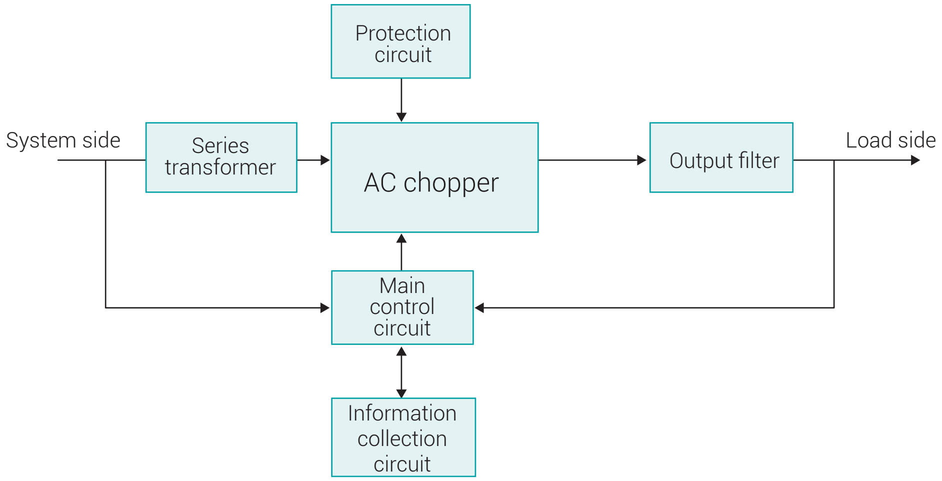

Figure 10. Device hardware structure diagram
Source: own work

The main control circuit plays the role of system side and load side voltage collection, voltage drop judgment, duty cycle calculation and AC chopping pulse output in the entire voltage compensation device. It is the core component of the entire device, mainly including the following parts: AD sampling conditioning circuit, system voltage zero-crossing comparison circuit, circuit breaker and IGBT status feedback, AC chopping pulse and dead zone control circuit, and watchdog module. The structure diagram is shown in Figure 11.

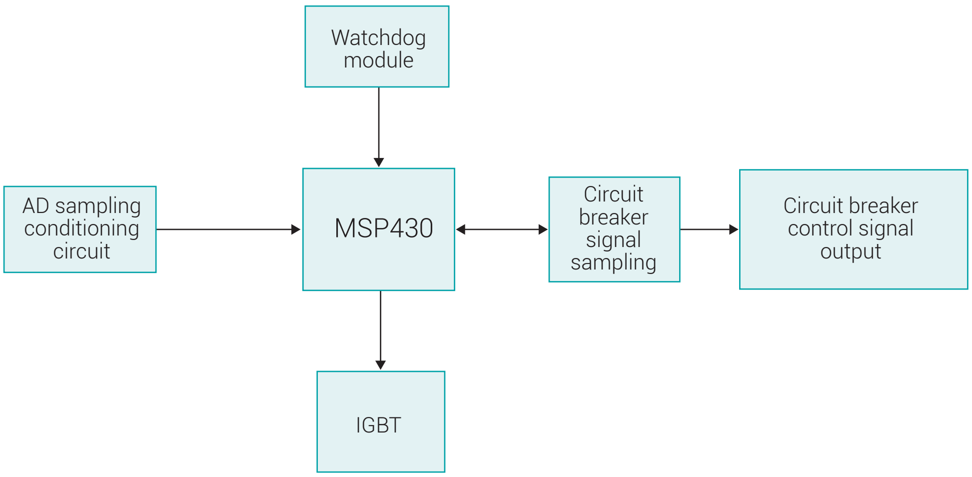

Figure 11. Main control circuit hardware structure diagram
Source: own work

The main board control circuit is shown in Figure 12 below.

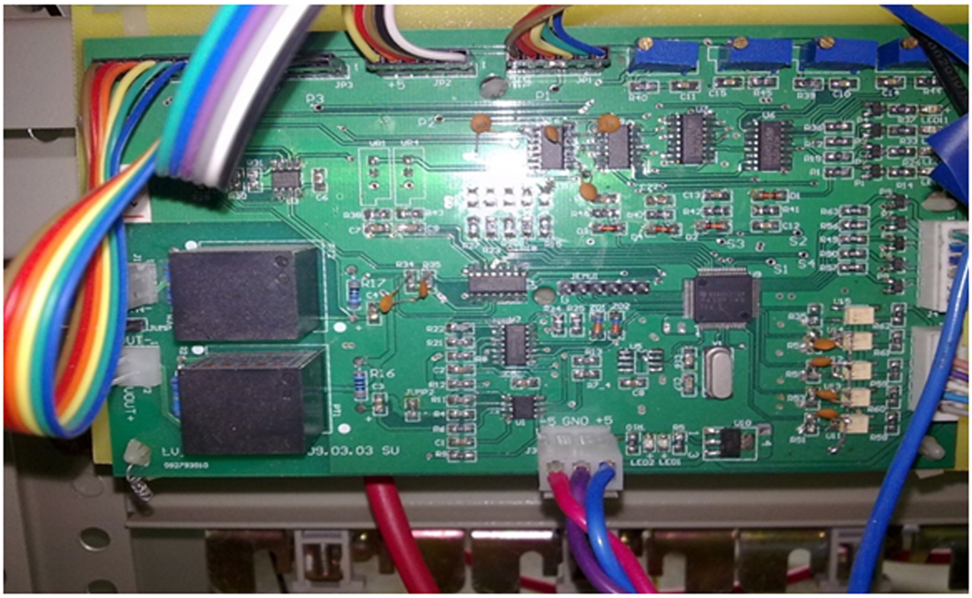

Figure 12. Main control circuit board
Source: own work

IGBT drive and protection circuit: IGBT is a device composed of a bipolar transistor and a MOSFET. It not only has the characteristics of fast switching of the gate voltage of the MOSFET, but also has the characteristics of high current handling capacity and low saturation voltage drop of the bipolar transistor. The IGBT drive and protection circuit of this voltage compensation device mainly use the FUJI EXB841 chip. The chip is a typical dedicated drive circuit suitable for IGBTs below 300A, and has the main characteristics of single power supply, positive and negative bias, over-current detection, protection, soft shutdown; the finished IGBT drive and protection circuit is shown in Figure 12.

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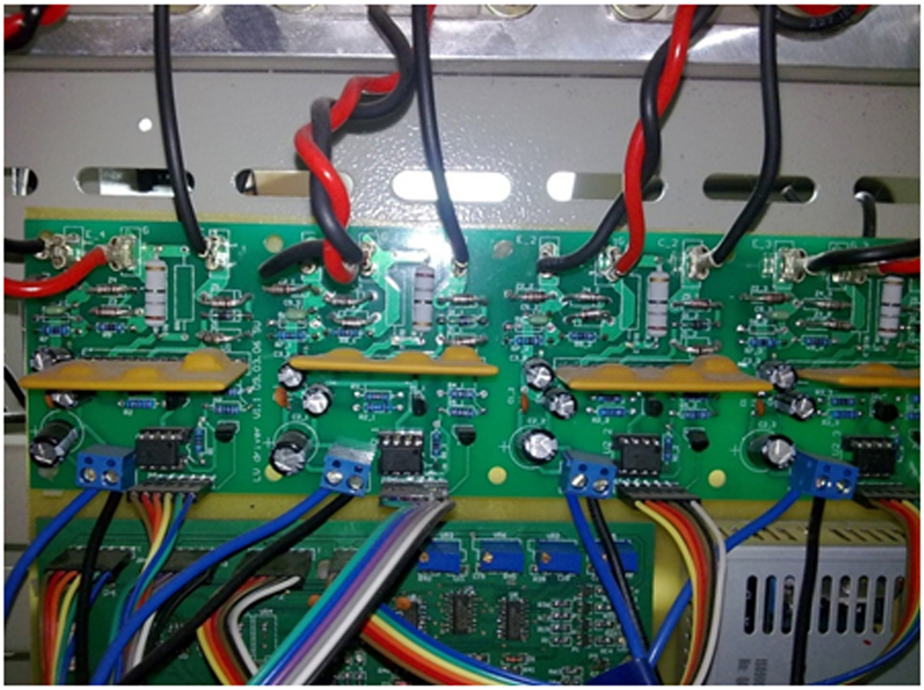


Figure 12. IGBT drive and protection circuit products
Source: own work

AC chopper unit: The AC chopper unit is the core component of the entire voltage compensation device. Finished power module in this voltage compensation device is shown in Figure 13 below.

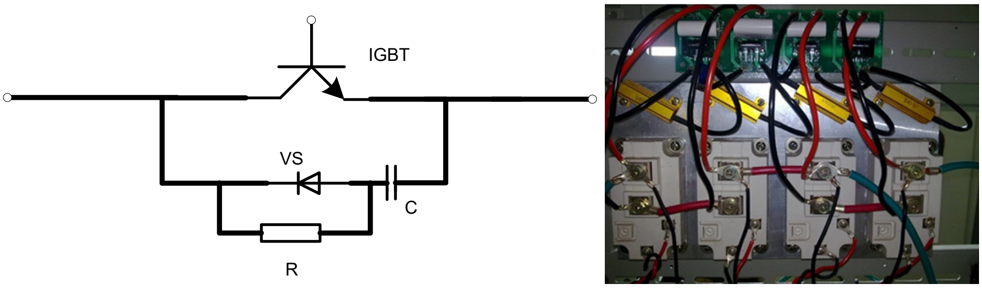
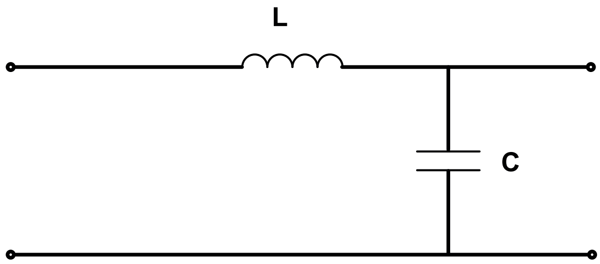


Figure 13. Finished power module
Source: own work

Output filter: The basic schematic diagram of the LC filter, and finished product of low-pass filter on output side of voltage compensation device is shown in Figure 14 below:



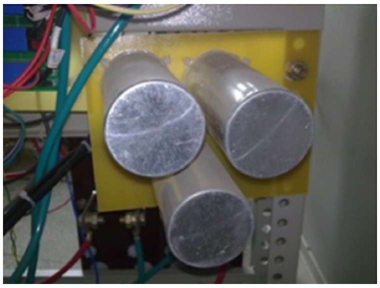


Figure 14. Finished LC low-pass filter
Source: own work

3.3. Actual test results of the device on the Oscilloscope

The load uses was a 1.5 hp air conditioner. Figure 15 is the waveform of the input voltage and input current of the device at the instant of air conditioning startup. From the figure, it can be seen that at the instant of air conditioning startup, the effective value of the input voltage is dropped approximately 100V. The effective value of the input current is increased approximately 200A.

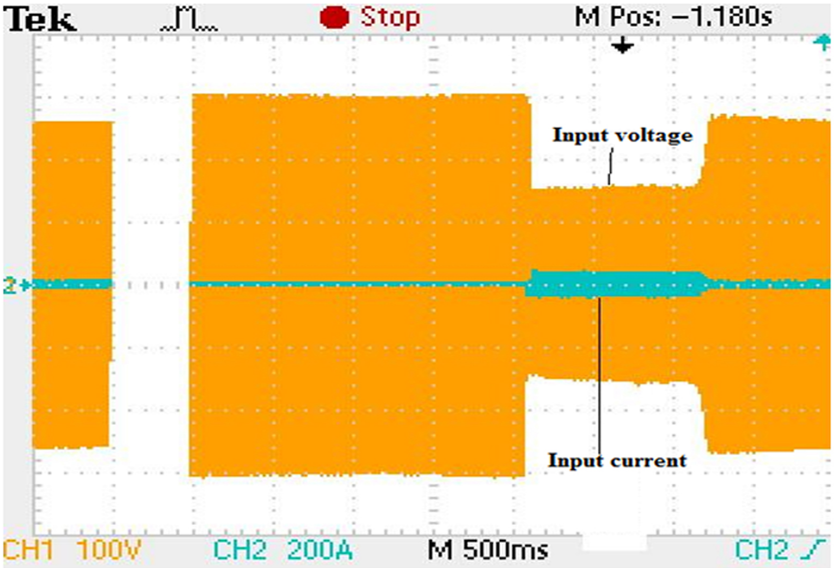


Figure 15. Voltage and current waveform at the instant of air conditioning startup without compensator
Source: own work

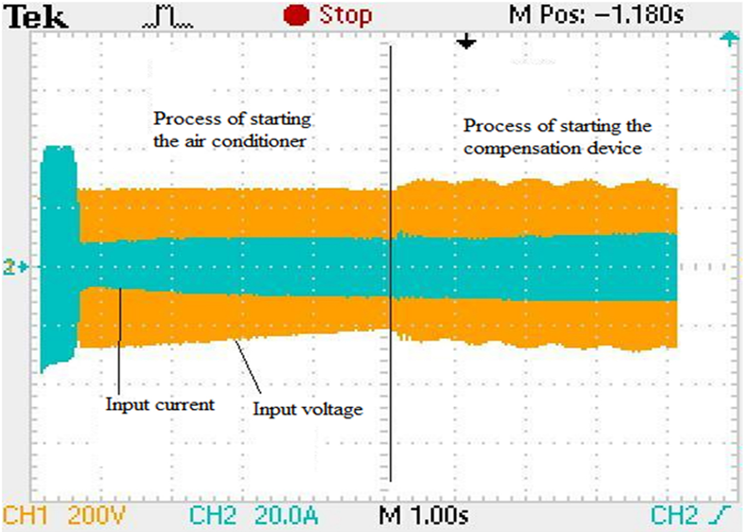


Figure 16. Voltage and current waveform from air conditioning startup to the start of compensation
Source: own work

Figure 16 shows the input voltage and input current waveforms of the device from air conditioning startup to the start of compensation. The left side of the black line in the figure is the whole process of starting the air conditioner, and the right side of the black line in the figure is the whole process of starting the compensation device.

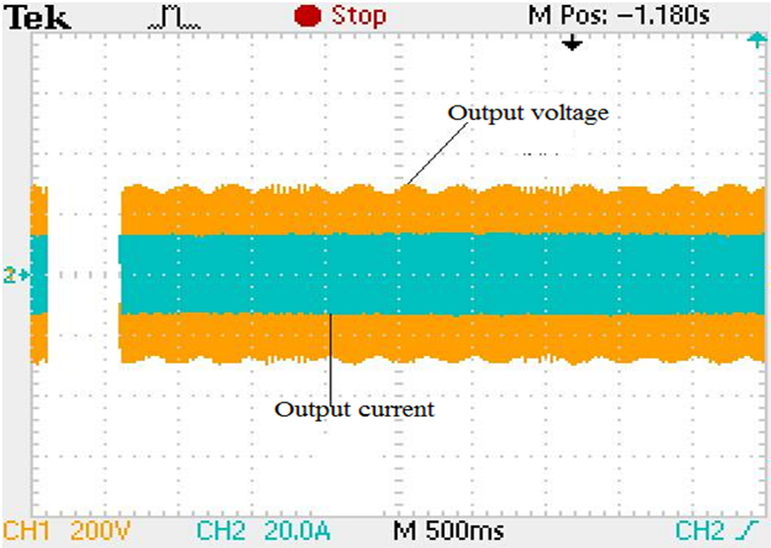


Figure 17. Voltage and current waveform at the instant of air conditioning startup with compensator
Source: own work

The trial operation proves that this single-phase low-voltage compensation device has obvious compensation effects; the effective value of the output voltage is approximately 200V, the effective value of the input current is approximately 20A.

4. DISCUSSION AND CONCLUSIONS

Firstly, this article puts forward the circuit topology of the voltage compensation device, and introduces the main functions of each part and the principle of AC choppers. Then, this paper makes the contrast between AC choppers with AC-DC-AC converters, and analyzes the major superiority of the circuit topology proposed by this paper.

This paper expounds the basic principle of voltage detection algorithms, and comprehensively analyzes the advantages and disadvantages of them. Then, this paper chooses RMS detection as the detection method of our compensation device, and proves the feasibility of it by emulation.

This paper intensively studies several voltage compensation strategies and provides a comparative analysis of the pros and cons of them, proving their feasibility by emulation. Meanwhile, this paper introduces several control strategies, analyzes their basic principles and compares the practicability of them.

Finally, this paper briefly describes the software and hardware for the voltage compensation device, the results of trial operations, and improvements based on operations. The operations prove the correctness and effectiveness of the circuit topology and algorithms. The trial operation proves that this single-phase low-voltage compensation device has obvious compensation effects for the most resistive loads and some inductive loads, less harmonic content, long continuous compensation time and stable performance.

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