Key Technology of Reactive Current Sensor in Three Phase Circuit with Hall Effect

Yuzhong Chen*[1,a;2;3]

[1]Jiangsu Union Technical Institute Nanjing Branch, Nanjing Jiangsu 210019, China;
[2] Nanjing Technical Vocational College Engineering Inspection Co. Ltd., Nanjing Jiangsu, 210019, China;
[3]Otgontenger University, Ulan Bator, Mongolia

ABSTRACT

A method of reactive I-U (current voltage) conversion of three-phase circuit based on Hall effect is proposed, that is, the method and implementation of reactive current measurement of three-phase circuit based on Hall effect. Using the basic theories of three-phase circuits, RLC series parallel circuits, and integrated operational amplifiers, draw a Hall effect I-U conversion circuit diagram, conduct mathematical modeling analysis, design unit circuits, and configure parameters. Under the action of Hall elements, the phase current flowing through the load is added to the DC reference voltage source signal, and the resulting DC signal is superimposed.The phase voltage at both ends of the load is controlled by an input protection and square wave amplification circuit, which controls the conduction and cutoff of the transistor and outputs a switching signal. Two sets of signals jointly drive the core amplifier and filtering circuit to achieve I-U conversion. Based on the phase relationship of output I-U or the value of power factor angle φ, determine the nature of the load, calculate the parameters of the parallel capacitor, perform reactive power compensation, and improve the power factor $\cos\varphi$.

Keywords: Hall effect; three-phase circuit; Reactive current sensor; Power factor

1. INTRODUCTION

In industrial experiments and actual production, the power load of three-phase circuits is commonly seen as inductive loads, such as load circuits such as motors, transformers, fluorescent lamps, and electric arc furnaces. The power factor $\cos\varphi$ of these circuits is usually very low, which not only affects the effective output of the power supply equipment, but also increases the losses of the line and power supply equipment. To improve the above shortcomings, reactive power compensation is applied to the circuit load. The commonly used method is to connect a capacitor with appropriate capacity on each phase load in parallel, so as to reduce the reactive current provided by each phase inductive load on the side of the power grid and transmitted by the line, increase the active power, and thus effectively improve the power factor [1].

2. DESIGN STEPS OF SENSING CIRCUIT

Sensor technology is built on the basis of experiments, and the entire design process from basic conception to the launch of new products requires multiple iterations of calculation, analysis, and experimentation, including the structure, process, and experiment of the sensor. The design process is shown in Figure 1.

The International Conference Optoelectronic Information and Optical Engineering (OIOE2024), edited by Yang Yue, Lu Leng, Proc. of SPIE Vol. 13513, 135130E · © 2025 SPIE · 0277-786X · © The Authors.

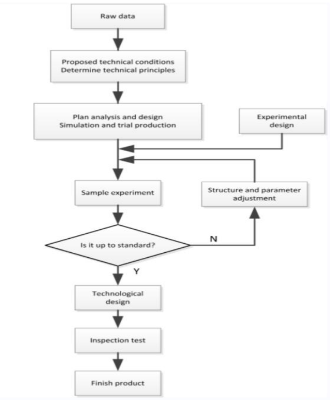


Figure 1 Sensor Design Process

The design process is divided into two stages. The first stage is the preliminary design stage: based on the working principle and environmental conditions, formulate design goals and expected technical conditions, analyze and compare performance and technology, draw circuit diagrams, establish mathematical models, design unit circuits, use computer and software tools for simulation optimization, configure parameters, and launch experimental sample development. The second stage is the correction and debugging stage: relying on research experiments to obtain data, analyze various error components, and correct and debug the original design and process conditions. Conduct environmental or destructive tests for performance testing, screening, calibration, and sampling. Ensure that the performance of the product is stable within the allowable range of technical specifications, and ensure the yield of the product [1].

3. WORKING PRINCIPLE

3.1 Basic Theory

Taking the widely used three-phase circuit in industrial production as an example, a scientific and systematic analysis and design of the circuit is carried out. By solving the special circuit of Y-type connection for three-phase four wire symmetrical loads, mathematical models are established, circuit parameters are calculated, and general circuit design ideas and methods such as Δ -type connection for three-phase symmetrical loads and Y-type or Δ -type connection for three-phase asymmetric loads are analyzed [2].Set the U phase as the reference phase line, and the effective value UVW of the line voltage is 380V. Each phase has the same load property (ZU=ZV=ZW=Z), and make a Y-type connection. NN' is the neutral line, which is a three-phase four wire symmetrical load Y-type circuit. As shown in Figure 2.

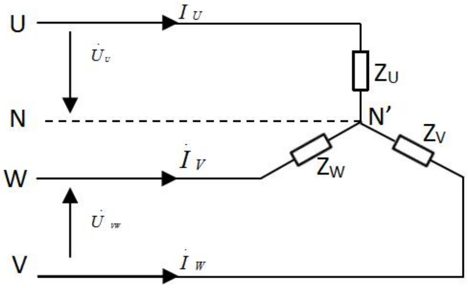


Figure 2 Schematic diagram of a three-phase four wire symmetrical load Y-type circuit

Based on the basic theory of RLC series parallel and three-phase symmetrical loads as Y-shaped connection circuits, the size and phase relationship of the I/U of each phase load are obtained. If the load is inductive, the phase current phase corresponding to the leading phase voltage at both ends of the load is (impedance angle, also known as power factor angle). The I-U phasor diagram of the inductive load is shown in Figure 3 (a).If the load is capacitive and the phase current flowing through the load leads to the corresponding phase voltage phase, the I-U phasor diagram of the capacitive load is shown in Figure 3 (b).

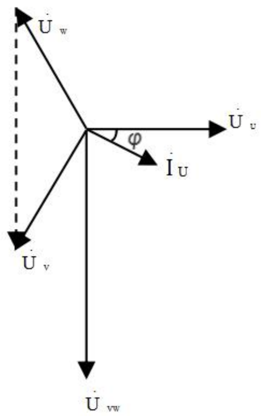


Figure 3 (a) Inductive load I-U phasor diagram

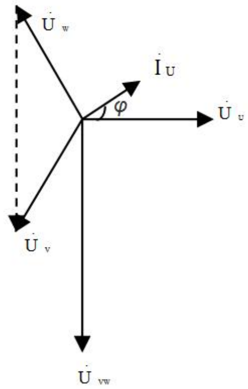


Figure 3 (b) Capacitive load I-U phasor diagram

3.2 Design Scheme and Working Principle

According to the general idea of sensor design, taking into account the static and dynamic characteristics of the sensor, a Hall effect I-U conversion circuit diagram is drawn, as shown in Figure 4. This circuit mainly consists of Hall elements, input protection circuits, square wave amplification circuits, adders, filters, inverting amplifiers, several amplifiers, as well as DC reference voltage sources, Hall element constant current sources, etc [3].

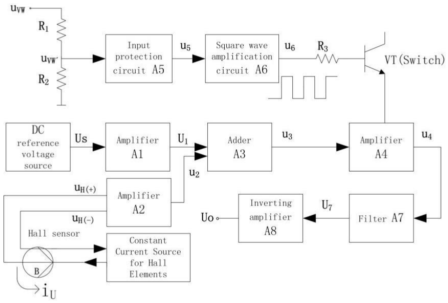


Figure 4 Hall Effect I-U Conversion Circuit Block Diagram

As shown in Figure 4, placing the U-phase load current of a three-phase symmetrical power supply in a high permeability iron core will generate a magnetic field line with a magnetic induction intensity of B. According to the definition of magnetic induction intensity and electrified carrier

$B\propto iU$, namely $B=KiiU$. (1)

In equation (1), Ki——Constant (determined by the shape of the carrier fluid, not repeated here).

When B⊥ i_U passes through the Hall element(θ= 90°), with an output Hall voltage of

$$uH=KHIHB\sin\theta=KiKHIHiU \qquad (2)$$

In equation (2), KH——The sensitivity of the Hall element; IH——Control current of Hall element.

The output voltage Us of the DC reference voltage source is amplified by amplifier A1 to output U1, and then added to the voltage u2 from amplifier A2 through adder A3 to output voltage u3. Using an oscilloscope to observe the waveforms of two sets of signals, u3 and U1+u2, should display as |u3|=|U1+u2| [4]. If the load is inductive, its waveform diagram is shown in Figure 5 (a). If the load is capacitive, the waveform diagram is shown in Figure 5(b).

The three-phase AC voltage uVW with sinusoidal changes is divided into attenuation circuit and input protection circuit A5 to obtain a sine wave signal u5. The square wave signal u6 is output by the square wave amplifier A6.The signal u6 is connected to the base of NPN type switch transistor VT to control the conduction or cutoff of VT. When the base level is high, VT conducts and amplifier A4 outputs an inverted signal u4H=-Av4Hu3. When the base level is low, VT is cut off, and amplifier A4 outputs an inverted and in-phase superimposed signal

$$u_{4L}=\sum_{i=1}^{2}A_{v4Li}u_3 \qquad (3)$$

In equation (3), A_{v4H}, A_{v4Li}——The voltage amplification factor of amplifier A4.

4. ESTABLISHING MATHEMATICAL MODELS

Calculate the frequency response characteristics of a stable constant coefficient linear sensor system using Fourier transform. It can be expressed as

$$\mathrm{H}(j\omega)=\frac{Y(j\omega)}{X(j\omega)}=\frac{b_m(j\omega)^m+b_{m-1}(j\omega)^{m-1}+...+b_1(j\omega)+b_0}{a_m(j\omega)^m+a_{m-1}(j\omega)^{m-1}+...+a_1(j\omega)+a_0}=\mathrm{H}_R(\omega)+j\mathrm{H}_I(\omega) \qquad (4)$$

In equation (4), HR(ω)——The real part of H(jω); HI(ω)--The imaginary part of H(jω).

The amplitude frequency characteristic (mode) of the sensor is $A(\omega)=|H(j\omega)|=\sqrt{[H_R(\omega)]^2+[H_I(\omega)]^2}$

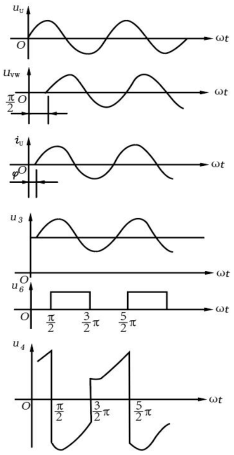


Figure 5 (a) uU leading iU (inductive load)

The phase frequency characteristic (phase angle) of the sensor is $\varphi=\arctan\frac{H_I(\omega)}{H_R(\omega)}$

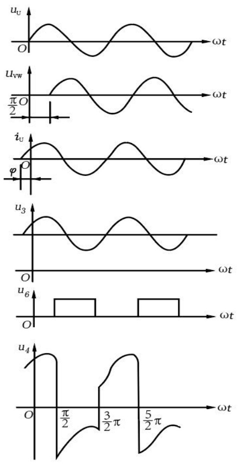


Figure 5 (b) uU lagging iU (capacitive load)

According to the waveforms shown in Figures 5 (a) and 5 (b), perform an integration operation on the output signal u4 of amplifier A4, and calculate the average value of [π/2, 5π/2] over a complete cycle, which is

$$\bar{u}_4 = \frac{1}{2\pi}\int_{\frac{\pi}{2}}^{\frac{5\pi}{2}} A_{v4} u_3 \mathrm{d}\omega t = \frac{1}{2\pi}\left[\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} A_{v4}(-U_1 - u_2)\mathrm{d}\omega t + \int_{\frac{3\pi}{2}}^{\frac{5\pi}{2}} A_{v4}(U_1 + u_2)\mathrm{d}\omega t\right]$$
$$= \frac{1}{2\pi}\left[\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} A_{V4}(-U_1 - A_{v2}u_H)\mathrm{d}\omega t + \int_{\frac{3\pi}{2}}^{\frac{5\pi}{2}} A_{V4}(U_1 + A_{v2}u_H)\mathrm{d}\omega t\right]$$
$$= \frac{1}{2\pi}\left[\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} A_{V4}(-U_1 - A_{v2}K_iK_HI_Hi_U)\mathrm{d}\omega t + \int_{\frac{3\pi}{2}}^{\frac{5\pi}{2}} A_{V4}(U_1 + A_{v2}K_iK_HI_Hi_U)\mathrm{d}\omega t\right]$$
$$= \frac{1}{2\pi}\left[\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} A_{V4}(-U_1 - K_Oi_U)\mathrm{d}\omega t + \int_{\frac{3\pi}{2}}^{\frac{5\pi}{2}} A_{V4}(U_1 + K_Oi_U)\mathrm{d}\omega t\right] \quad (5)$$

In equation (5), Av2——The voltage amplification factor of amplifier A2; KO——Constant (KO=Av2KiKHIH).

4.1 Analysis of Inductive Load Model

$\dot{U}_U$ leads $\dot{I}_U$, as shown in Figure 2(a). $u_U = \sqrt{2}U_U\sin\omega t$, $i_U = \sqrt{2}I_U\sin(\omega t - \varphi)$, $u_{VW} = \sqrt{3}U_U\sin(\omega t - \frac{\pi}{2})$. Then equation (5) becomes [6]

$$\bar{u}_4 = \frac{1}{2\pi}\left\{\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} A_{V4}[-U_1 - K_O\sqrt{2}I_U\sin(\omega t - \varphi)]\mathrm{d}\omega t + \int_{\frac{3\pi}{2}}^{\frac{5\pi}{2}} A_{V4}[U_1 + K_O\sqrt{2}I_U\sin(\omega t - \varphi)]\mathrm{d}\omega t\right\}$$
$$= -A_{V4}K_O\frac{2\sqrt{2}}{\pi}I_U\sin\varphi \quad (6)$$

After voltage u4 passes through filter A7 and inverter amplifier A8, the output voltage UO$\propto \bar{u}_4$.

$$U_O = -A_{V8}u_7 = -A_{V8}K_7\bar{u}_4 = -A_{V8}K_7(-A_{V4}K_O\frac{2\sqrt{2}}{\pi}I_U\sin\varphi) = \frac{2\sqrt{2}}{\pi}K_OK_7A_{V4}A_{V8}I_U\sin\varphi = K_UI_U\sin\varphi$$
$$K_U = \frac{2\sqrt{2}}{\pi}K_OK_7A_{V4}A_{V8} \quad (7)$$

In equation (7), K7——The coefficient of filter A7; Av8——The voltage amplification factor of inverter amplifier A8;IUsin φ——Reactive current of the load.

From equation (7), it is not difficult to find tha UO$\propto$IUsin φ.With a digital voltmeter, the positive reactive current value can be displayed to verify that $\dot{U}_U$ is ahead of $\dot{I}_U$.

According to the impedance triangle, calculate the power factor angle through $\varphi = \arctan\frac{X}{R} = \arctan\frac{X_L - X_C}{R}$ based on the impedance triangle φ.

To improve the power factor cos φ ， When the DC resistance R and inductive reactance XL of the load remain unchanged, a capacitor with appropriate parallel capacity can increase the value of capacitive reactance XC, reduce reactance X, and power factor cos φ Increase, reduce reactive power Q=UUIUsin φ , and achieve reactive compensation.

4.2 Analysis of capacitive load model

$\dot{I}_U$ leads $\dot{U}_U$, as shown in Figure 2 (b).

Set $u_U = \sqrt{2}U_U\sin\omega t, i_U = \sqrt{2}I_U\sin（\omega t + \varphi）, u_{VW} = \sqrt{3}U_U\sin(\omega t - \frac{\pi}{2})$.

The analysis and calculation process is the same as 4.1 and will not be repeated.

After calculation, UO=-KUIUsin φ (8)

From equation (8), it can also be observed that UO$\propto$-IUsin φ. Using a digital voltmeter, the negative reactive current value can be displayed to verify that $\dot{I}_U$ is ahead of $\dot{U}_U$.

Similarly, calculate the power factor angle φ through $\varphi = \arctan\frac{X}{R} = \arctan\frac{X_L - X_C}{R}$ .To improve the power factor cos φ ， When the DC resistance R and inductive reactance XL of the load remain unchanged, a capacitor with appropriate parallel capacity can increase the value of capacitive reactance XC, reduce reactance X, and power factor cos φ Increase, decrease reactive power Q=-UUIUsin φ, and achieve reactive compensation.

4.3 Calculation of parallel capacitors

Taking inductive loads as an example, if there are no capacitors connected in parallel at both ends of the circuit load, the angle of $\dot{U}_U$ leading $\dot{I}_U$ is φ 1.After parallel capacitance, the angle of $\dot{U}_U$ leading $\dot{I}_U$ is φ 2.Because φ 2< φ 1, therefore cos φ 2>cos φ 1.It can be seen that the power factor of the entire circuit has been improved after parallel connection of appropriate capacitors, but the current flowing through the load itself, as well as the active power and power factor of the load, have not changed [6].

In general, it is hoped that after parallel capacitors are connected, the power factor compensation will be around 0.9, rather than higher. If the compensation is close to 1, the larger the required capacitance, the higher the economic value paid, and the lower the cost-effectiveness. It should be noted here that whether it is an inductive load or a capacitive load, the capacity of the load parallel capacitor must be appropriate, otherwise it will increase the |X| value and power factor angle φ Increase, IUsin φ increase, power factor cos φ Decreasing makes the reactive current "reverse" increase. So how much capacitance does it need to be connected in parallel to be suitable?

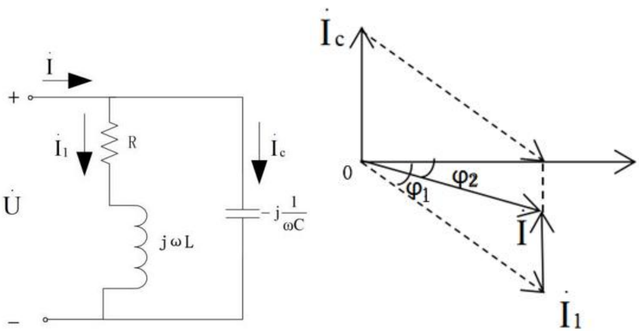


Figure 6 Circuit diagram and current voltage phasor diagram before and after parallel capacitors

Before parallel capacitance,P=UI1COS φ 1, $I_1 = \frac{P}{U\cos\varphi_1}$

After parallel capacitance,P=UICOS φ 2, $I = \frac{P}{U\cos\varphi_2}$

$$I_C = I_1\sin\varphi_1 - I\sin\varphi_2 = \frac{P\sin\varphi_1}{U\cos\varphi_1} - \frac{P\sin\varphi_2}{U\cos\varphi_2} = \frac{P}{U}(\tan\varphi_1 - \tan\varphi_2) \tag{9}$$

$$I_C = \frac{U}{X_C} = \omega CU \tag{10}$$

$$C = \frac{P}{\omega U^2}(\tan\varphi_1 - \tan\varphi_2) \tag{11}$$

In equation (9), I1——The total current value of the circuit before the parallel capacitor (which is also the current flowing through the resistor and inductor series branch);I——The total current value of the circuit after parallel capacitance.

The calculated value of equation (10) is the appropriate size of capacitors that need to be connected in parallel in the inductive load circuit to improve the power factor of the circuit.

5. UNIT CIRCUIT DESIGN AND OVERALL DEBUGGING

In this circuit, the decisive factors affecting the circuit are the "input protection circuit A5 module" and the "amplifier A4 module". The reasonable parameter design of these two modules directly affects the accuracy and precision of the circuit.

5.1 Input protection circuit A5 module

According to the functional requirements of the circuit, the input protection circuit module can be designed as the circuit shown in Figure 7.

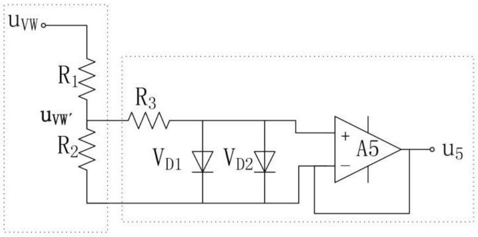


Figure 7 Input protection circuit

Use the AC voltage range of a multimeter to check if uVW is consistent with the value of uVW·R2/(R1+R2). If consistent, it can be determined whether the uVW' signal has received reliable attenuation. Assuming that for some reason, the line voltage of the three-phase power supply has missed the attenuation network and is directly connected to the current limiting resistor R3, use the AC voltage range of a multimeter to detect whether the voltage at both ends of R3 is close to uVW [6]. If close, it can be determined that the input protection circuit is normal. At this point, diode VD1 and amplifier A5 are conducting to ground. The current flowing through R3 in Figure 7

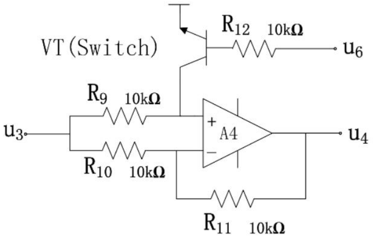
$$I=\frac{u_{VW}}{R_3+R_{VD1}+r_o} \qquad (12)$$

In equation (12), RVD1——Forward conduction resistance of diode VD1; Ro——Output resistance of amplifier A5.

Due to R3≫RVD1 and R3≫ ro, $I=\frac{u_{VW}}{R_3}$. According to the known condition uVW=380v and R3 taken as 200kΩ, then I is approximately 1.9mA, which meets the basic requirements of the input protection circuit.

5.2 Amplifier A4 module

Draw the amplifier A4 module in the Hall effect I-U conversion circuit diagram of Figure 4 into a circuit diagram, as shown in Figure 8 (a).



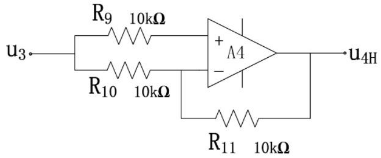
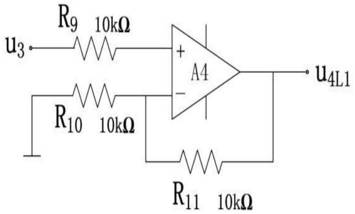


Figure 8 (a) Amplifier A4 Figure   Figure 8 (b) Vb High Level (Inverting Amplifier)



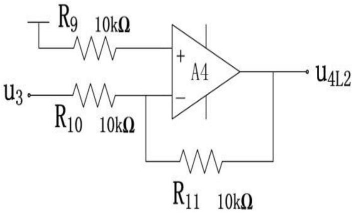


Figure 8 (c) Vb low level (In-phase amplifier)   Figure 8 (d) Vb low level (Inverting Amplifier)

1.When the base potential Vb of the square wave signal u6 input switch transistor VT is high, VT is in a conduction state. Figure 8 (a) can be equivalent to Figure 8 (b).According to the concept of virtual short, uP≈uN=(u4H-u3)R10/(R10+R11)+u3=0 .

After calculation, when the VT base potential Vb is high, the output voltage u4H of amplifier A4 is u4H=AV4Hu3=-(R11/R10)u3,if R11=R10,u4H=-u3,AV4H=1 .

At this point, amplifier A4 is equivalent to an inverting amplifier with an amplification factor of -1.

2.When the base potential Vb of the square wave signal u6 input switch transistor VT is low, VT is in the cut-off state. According to the superposition theorem, figure 8 (a) can be equivalent to the circuit superposition of figure 8 (c) and figure 8 (d).

Similar to the calculation principle of (1), the output voltages u4L1 and u4L2 in Figures 8 (c) and 8 (d) are respectively

$$\begin{cases} u_{4L1}=(1+R_{11}/R_{10})u_3 \\ u_{4L2}=-(R_{11}/R_{10})u_3 \end{cases}$$

After calculation, when the VT base potential Vb is low, the output voltage u4L of amplifier A4 is

$$u_{4L}=\sum_{i=1}^{2}A_{v4Li}u_3=[(1+R_{11}/R_{10})-(R_{11}/R_{10})]u_3=u_3, A_{v4L}=1$$

At this point, amplifier A4 is equivalent to an amplifier with an amplification factor of 1, also known as a voltage follower [6] .

Other amplifiers, filters, and adders can be designed according to general rules, or use Multisim circuit simulation software to simulate and adjust reasonable parameters.

5.3 Debugging steps

1.Add the line voltage uVW of the three-phase power supply to the attenuation network and verify whether uVW′=uVW·R2/(R1+R2) is established.

2.According to Figure 6, debug the input protection circuit A5 and test the voltage uR3 at both ends of resistor R3. If uR3=uVW′=uVW·R2/(R1+R2), it indicates that the circuit has a certain degree of attenuation and may not necessarily meet the basic requirements of the protection circuit [7] ; If uR3=uVW, it indicates that the circuit has not decayed and the input protection circuit can operate normally.

3.After the sine signal uR3 passes through the square wave amplifier A6, the square wave signal u6 should be output. Use a dual channel digital oscilloscope to detect u6 and determine whether it is a square wave.

4. Use a high-precision digital multimeter with an accuracy level of 1.0 to measure the output voltage Us of the DC reference voltage source and whether the output voltage U1 of amplifier A1 is a high stability DC voltage.

5. Debug the Hall element, use a dual channel digital oscilloscope to verify whether the current iU changes proportionally with the output voltage uH, and determine whether their waveforms are in phase.

6. Use a dual channel digital oscilloscope to observe the changes in U1 and u2, and verify whether u3=U1+u2 is valid.

7. According to Figure 8 (a) (b) (c) (d), when the base potential Vb of VT is input to high and low levels respectively, detect the relationship between the input voltage u3 and output voltage u4 of amplifier A4, and debug amplifier A4. Namely, Vb is low level, verify that u4=-u3; Vb is high level, verify u4=u3.

8. Use a multimeter to measure whether the output voltage Uo and reactive current IUsin φ Proportional.

6. CONCLUSION

Taking three-phase four wire symmetrical load as an example for Y-connection, this paper systematically analyzes the logic relationship of Hall effect I-U, establishes mathematical model, designs circuit parameters, effectively collects important data such as reactive current and power factor angle, calculates the capacity of parallel capacitors, and achieves the purpose of improving power factor. The DC reference voltage source involved in the circuit should be chosen as a precision power source with high stability as much as possible. The Hall element is made of gallium arsenide material, which is a sensitive and stable linear element. The constant current source of the Hall element should also be able to output a stable current source. These are important indicators that determine the stability and accuracy of the circuit. The analysis method, working principle, design concept, and calculation process of other general circuits with Y-type connection for non three-phase four wire symmetrical loads are consistent with the steps given in the article. However, it is necessary to analyze the load properties of each phase of these circuits separately, and reactive current, power factor angle and other data must be calculated separately, which is more complex than a single symmetric circuit.

7. ACKNOWLEDGMENTS

Topic: Phase Achievements of the Fifth Jiangsu Vocational Education Teaching Reform Research Project "Application Research of the ‘Split Classroom’ Teaching Model in the Teaching of Modern Communication Technology Major Group Platform Courses in Five Year Vocational Education" (No. ZYB548, Hosted by Jinlong Feng and Yuzhong Chen)

8. REFERENCES

[1] Liu Shaoqiang, Zhang Jing. Sensor Design and Application Example [M]. China Electric Power Press. 2008

[2] Bai Naiping. Fundamentals of Electrical Engineering (Fourth Edition) [M]. Xi'an University of Electronic Science and Technology Press, 2017

[3] Xie Huan. Current reconstruction and model predictive control of T-type three-level grid connected converter [D]. Zhengzhou University of Light Industry. 2023

[4] Wu Yanfei, Li Weichao, Zhang Shaorui et al. Design of Hall effect sensors [J]. Micromotor 2022,55 (07): 94-98

[5] You Jianzhang, Guo Moufa. Comprehensive Compensation Method for Asymmetric Distribution Networks with Four Arm H-Bridge Converters [J]. Journal of Electrical Engineering. 2022,37 (11): 2849-2858

[6] Li Jinsong, Chen Jiandong, Yang Baoqi, et al. Research on single-phase reactive current detection method for voltage sag control in distribution networks [J]. Electrical Measurement and Instrumentation. 2022,59 (09): 140-145

[7] Xie Zhiyuan, Cui Wenxu, Yang Rui. Design of a Digital Hall Current Sensor Based on Hall Elements [J]. Instrument Technology and Sensors. 2023 (09): 17-22