International Journal of Control and Automation
Vol.7, No.3 (2014), pp.333-348
http://dx.doi.org/10.14257/ijca.2014.7.3.32

High-voltage Isolation Current Sensor by using Signal Modulation Method

Ping Chen [1, 2,3,a], Ling Wang[2,a], Xingyi Wu[2,a] and Sheng Lu [2.3,a,†]

[1] State Key Laboratory of Automotive Safety and Energy, Qinghua University, Beijing100084, China
[2] Institute of Pattern Recognition and Application, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
[3] State Key Laboratory of Vehicle NVH and safety Technology, Chongqing Chang an, Chongqing 401120, China

[a] lusheng@cqupt.edu.cn

† Corresponding - Author: Sheng Lu

Abstract

The signal processing circuit of shunt type current sensor is directly coupled with the high voltage electric circuit so that the common-mode interference signal conditioning becomes a problem. This paper proposes a high-voltage isolation current sensor employs modulation and demodulation which is based on shunt output signal. There is an electrical isolation is set between the high voltage and the low voltage to solve the poor anti-interference ability of shunt type current sensor. The test results show that the current measurement accuracy of the proposed sensor is 0.4%.

Keywords: *Current sensor, Modulation-demodulation, Shunt type, Current detection*

1. Introduction

One of the most popular current measurement methods is using current sensor which can be used to intelligently detect and control systems. However, with the increasing of the high-low voltage couple applications in electrical system, conventional current sensors have been unable to meet their development requirements, exposing some defects, like difficult signal conditioning, large common-mode disturbances and so on [1]. For the solution of these problems, there are two options can be selected: First, it can use new materials and new methods to develop new current detection techniques, and then using these new technologies to develop new current sensor; Second, it can overcome the shortcomings of conventional current detection technology, then make the new design adapt to new requirements.

Large current measurement includes DC (Direct Current) current measurement, Transient large current measurement, and Pulse current measurement [2]. Among them, the DC current measurement is the most urgent problem to be solved; it has a significant impact on improving product quality, saving energy and so on. DC current is used in many industrial fields. Such as industrial aluminum, new energy vehicles, electric utilities, *etc.* [3]. DC current measurement methods are: DC current transformer, Hall element and Shunt. Each of these measurement methods has their own advantages as soon as disadvantage; their characteristics are shown in Table 1.

ISSN: 2005-4297 IJCA

According to the Table 1, it is not difficult to find that shunt has obvious advantages in measuring current. Shunt-based current sensors have good linearity, and they are accurate, reliable, stable and simple [4]. However, the traditional shunt current sensor is directly in series with measured loop. The high voltage measured circuit has a great common-mode interference affecting the output signal quality in low voltage section, greatly reducing the signal to noise ratio. If the two major problems can be overcome, then the shunt current sensor will have a higher practical value.

Table 1. Comparison of the current measurement methods

	DC current transformer	DC current comparator	Hall element	Shunt
Response speed	Relatively low	Low	Relatively fast	Fast
Measuring range	Hundreds kA	Hundreds kA	Wide	Less than 10 kA
Accuracy	Relatively bad	High	Bad	Relatively high
Temperature effect	Relatively little	Relatively little	Relatively large	Relatively little
Power consumption	Relatively large	Relatively large	Relatively large	large
Auxiliary power	Have	Have	Have	No
High voltage insulation	Relatively bad	Relatively bad	Relatively bad	Good
External magnetic field effects	Vulnerable	Little influence	Vulnerable	No
System complexity	Relatively easy	Relatively complicated	Relatively easy	Easy
Short-time overload	Relatively bad	Relatively bad	Relatively bad	Relatively good

This paper introduces a method of modulation-demodulation for shortcomings of conventional shunt current sensor. Electrical isolation is formed between the primary circuit and the secondary circuit, avoids strong electricity part influencing the weak part, ensures the system work stably so that the secondary circuit can better process signal, thereby obtain a output signal with lower noise and higher accuracy so that the follow-up system is able to accurately monitor and control. Some previous studies also are designed to solve the problem by modulation-demodulation. In the literature [5], A/D (Analog/Digital) chip is used to modulate the analog signal into a digital signal. The signal is demodulated into analog signal by a D/A (Digital/ Analog) chip in low voltage portion. The high-voltage part and the low voltage part of the design both need external power supply. The collected voltage signal noise is high, and then the value of the accuracy of measurement of the A/D chip is low. In the literature [6], an isolated operational amplifier is used as electrical isolation; modulation and demodulation are integrated in the operational amplifier. The design has a simple structure, high accuracy and non-linearity is less than 0.01%. Isolation amplifier requires two external power supplies. In the literature [7], the circuit comprises a signal acquisition circuit composed by two micro-transformers and a chopper circuit, and a data processing circuit. The high voltage and low voltage are isolated by read transformer and command transformer. The command transformer controls the chopper circuit. In chopper circuit, the collected signal is modulated into an AC (Alternating Current) wave signal. Then, the signal passes through the read transformer to be put into the data processing section to the low-voltage. The advantage is the high-voltage part does not require a power supply, only the low-voltage part need an external power supply. The disadvantage is that the accuracy is relatively low, and two miniature transformers are required.

2. Fundamental Principle

The modulation-demodulation current sensor circuit includes signal acquisition module, control module, signal processing module, power converter (DC-DC) and output module. An electrical isolation, which is made up with optocoupler and current transformer, is designed between high-voltage side and low-voltage side. This design can avoid the impact of high-voltage magnetic field on signal processing. According to Ohm's law, the measured current is converted to a weak voltage signal. Before the collected signal is imported into signal processing module, it needs to be modulated into an AC signal in order to pass through the electrical isolation. After some processing like amplification, detecting and filtering, the signal is restored into a DC signal by the demodulation circuit. Then it is output. It has a good linear relationship between the output value and the measured circuit value. The schematic diagram of current sensor has shown in Figure 1.

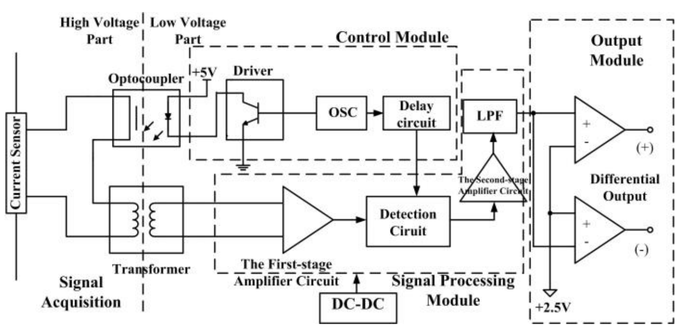

Figure 1. The current sensor schematic diagram

Signal acquisition module will achieve the current signal perception and conversion. According to Ohm's law, the measured current is converted to a weak voltage signal. The reason why the signal is weak is that its amplitude less than 100mV, and mixed with a lot of noise. This portion contains much noise, but with a greater intensity of the filter, so that the signal attenuation is too large, it becomes more weak signals, it can only be an appropriate filtering.

The control module is the heart of the system; the system provides a clock signal to control the frequency of the entire system. On the one hand, it will service for the modulation signal, on the other hand it will complete the signal detection work. Without the control module, these two works cannot be completed. The control module includes a control signal generating circuit, a drive circuit and a delay circuit.

Signal is modulated by switching manner. Modulation is completed by the control module in collaboration with the signal acquisition module. Optocoupler is the modulation table. The control module is responsible for the modulation frequency. The modulation signal has the same frequency with the control signal. With this method electrical isolation is achieved.

The signal processing module will amplify signal, detect signal and filter signal. Finally signal is restored by the demodulation circuit into a DC signal. The signal amplification factor is close to 100 times. In such large multiples, only one amplification circuit is hard to keep the linearity of the sensor. So there are Two-stage amplification circuits in design. The purpose of the detection circuit is to distinguish the measured signal is a charge or discharge. When the measured current is discharging, the detection circuit will be retained in the positive half-wave, the output voltage is positive; when the measured current is charging, the detection circuit will retain the negative half-wave detection circuit, the output voltage is negative. Filtering problem is the key in the signal processing circuit design. The design of filter circuit will be a key issue. The solution to filtering problem is: avoiding noise be introduced into the circuit loop. It is very necessary to select the low-noise devices. Then designing appropriate filter circuit to filter signal.

Differential output module is made up with a signal output part and a reference voltage part. After signal is demodulated, the output range of the sensor voltage is -2V ~ 2V. Signals may be a value close to 0, such a weak voltage is very unstable and easily missing, which is not conducive to transmit. So a 2.5V reference voltage is introduced to make the output of the two differential output voltage be between 0.5V to 4.5V. Reference voltage will not affect the differential output. The output value of the differential voltage will be a linear relationship with the measured current. Differential transmission is a signal transmission technology, different from the traditional transmission with one signal wire and one ground wire. The differential transmission transmits signal in both two wires, these two signals have opposite phase and equal amplitude. The main advantages of differential output are the following three points: First, the differential output signal can easily identify little signal. Second, the differential output has a high resistance to external electromagnetic interference (EMI). Third, in single-supply systems, differential output can output bipolar signals.

3. Modulation and Demodulation

In precision measurement, the output signal of the sensor often contains various kinds of noise [3]. The sensor output signals are generally very weak. How to avoid the noise being introduce into the processed signal, and how to separate the noise signal are important tasks in the detection circuit design. Modulation and demodulation is one of the effective ways to solve the appeal problem. Modulation and demodulation processing is shown in Figure 2, the collected DC signal is modulated into the AC signal by the switch way, and then the signal is imported into signal processing section through an electrical isolation. Such a design can effectively prevent the high-voltage part from causing interference to the signal processing, and facilitate the separation of signal and noise. After amplification and other processing, the measurement signal reflecting the measured value is extracted from the processed signal, *i.e.*, demodulation. Finally the output value and the measured value are in a linear relationship.

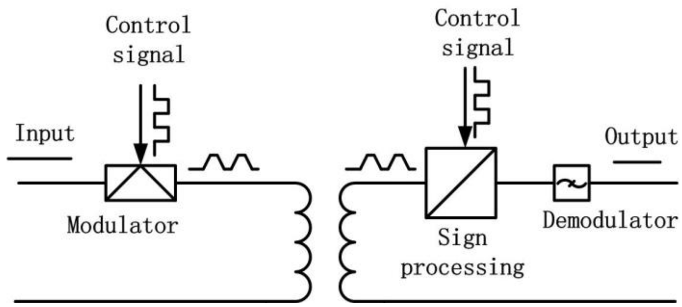

Figure 2. Modulation and demodulation processing

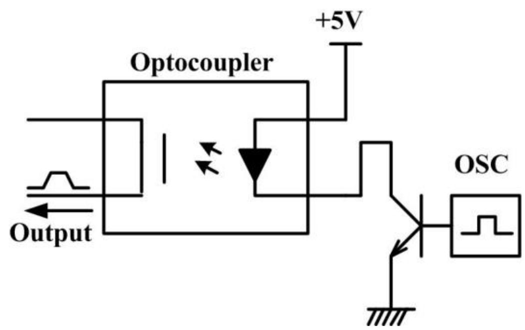

Figure 3. Modulation principle

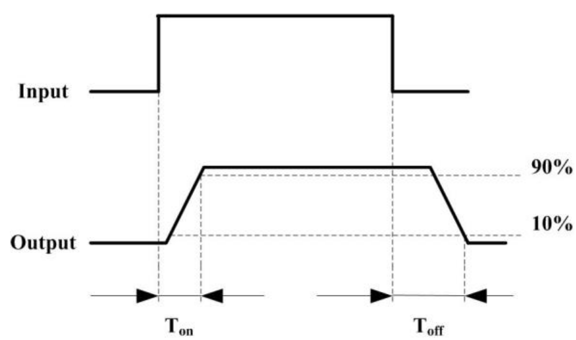

Figure 4. Operating waveforms

3.1. Modulation principle

The modulation circuit is made up with an optocoupler and a control signal generator. The optocoupler using Panasonic AQW216 shown in Figure 3, which uses light as media and transmits electrical signals, is an “electricity-light-electricity” conversion devices. It is composed of two parts, light emitting source and the light receiver. The light emitting source and the light receiver are assembled in a same closed casing. They are isolated with each other by a transparent insulator. Clock control signal is input from the light source side, whose duty cycle is D=T2/(T1+T2)=0.5 and operating frequency is 100Hz. The light off of the light-emitting diode can be controlled by the current change, so that the photosensitive MOSFET can be controlled. Due to the presence of the rise time (*Ton*), the fall time (*Toff*) and the delay time, the modulated signal is not a square wave signal, but the trapezoid wave signal, shown in Figure 4. AQW216 is MOS type optocoupler, which has a low turn-off voltage, a high sensitivity, a low off-leakage current and a low thermal emf.

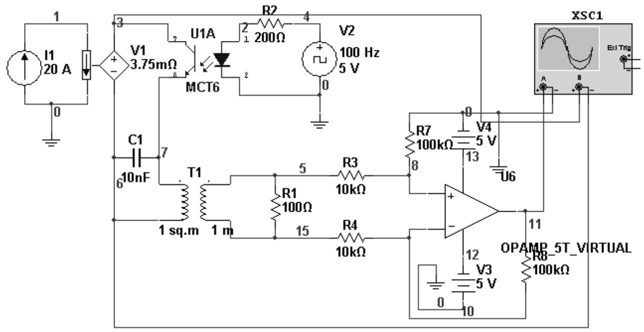

Figure 5. Signal modulation process and the first stage amplifier circuit simulation

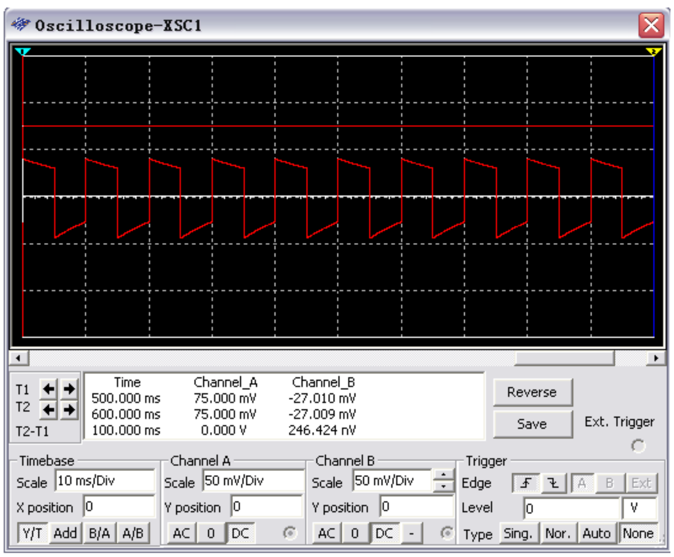

Figure 6. Signal modulation waveform

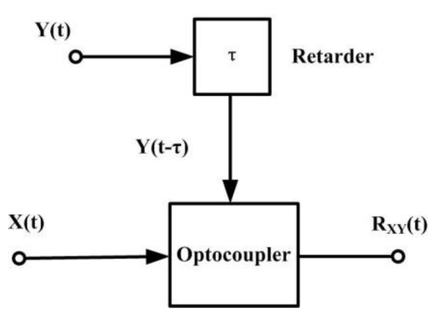

Figure 7. Detection principle

The signal modulation simulation circuit is shown in Figure 5. The simulation circuit is a discharge process, the discharge current of 20A. Current /Voltage converter power supply V1 represents current shunt. Multiplying the measured current with a shunt resistor, the voltage drop can be obtained. The control signal is replaced by a signal generating source. DC signal is modulated into AC signal to pass a current transformer. Simulations waveforms are shown in Figure 6, the virtual oscilloscope probe the simulation circuit in two locations. One is the signal input waveform which is 75mV DC signal; the other is the modulated waveform which passes through the transformer. According to the comparison of two signals, the modulation design process is reasonable and feasible.2.3 Detection circuit.

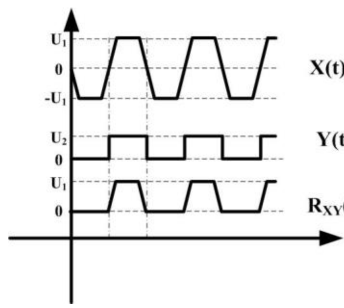

Figure 8. Operating waveforms

The main function of the detection circuit is to distinguish the polarity of the input signal, and to ensure the output signal and the measured current keep the same in polarity. Correlation detection includes autocorrelation detection and cross-correlation detection, the performance of cross-correlation detection is better, whose output signal-to-noise ratio is higher [5, 6]. In this design, use cross-correlation detection. The detection principle is shown in Figure 7, and Figure 8 is the operation waveform of the measured current for charging.

If the repetition frequency or the cycle of the input signal is known, the reference signal must have a same frequency with the input signal. Make the correlation calculation to the reference signal and the input signal mixed with noise. Optocoupler here is equivalent to an analog switch. When the switch turn on, the reference signal value is 1; when turn off, the reference signal value is 0. Related calculations are as follows:

$$R_{XY}(t) = X(t) \cdot Y(t - \tau)\begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{1}$$

Where: $X(t)$ is the input signal; $Y(t-\tau)$ is the reference signal; $R_{XY}(t)$ is the mixed signal.

The reference signal and the input signal cannot be completely the same frequency. It can assume that Δt is the error time between the reference signal and the input signal; T is the cycle time of the signal; D is the total charge within a cycle; U_1 is the former half cycle voltage; U_2 is the latter half cycle voltage.

$$D = \left(\frac{T}{2} - \Delta t\right)U_1 + \Delta t U_2 \tag{2}$$

Usually the absolute value of U_1 and U_2 are equal and opposite in sign, above equation can be simplified as:

$$D = \left(\frac{T}{2} - 2\Delta t\right)U_1 \tag{3}$$

Value D and the output voltage is related, as long as the error is sufficiently small, by adjusting the gain of the subsequent amplification circuit, the influence to the output results can be neglected.

Detector circuit simulation shown in Figure 9, the output waveform of the delay is in place of 100Hz, 5V clock signal generator. BIP signal generator in place of the detection signal. The optocoupler is detected table. The analog oscilloscope respectively probes the waveform of the detection signal before and after.

Detector circuit simulation results shown in Figure 10, a detection signal is initially alternating positive and negative waveform, if it is demodulated, the value will be 0, and can't reflect the size of the measured current. So it can only be reflected in the waveform of the positive half-wave or the negative half-wave. The phase of the reference signal is fixed. When the discharge of the circuit under test, the collected signal is positive and will retain the positive half-wave of the subject signal is demodulated after the signal is positive; when charging of the circuit under test, acquisition signal to a negative value, the subject negative half-wave of the signal will be retained, and the demodulated signal is negative. As shown below, to the circuit under test and discharge, the next wave for the detection of the waveform, on the wave of post-test waveforms. Waveform burr Note that the filter circuit when designing the circuit. Also, avoid isolated DC signal.

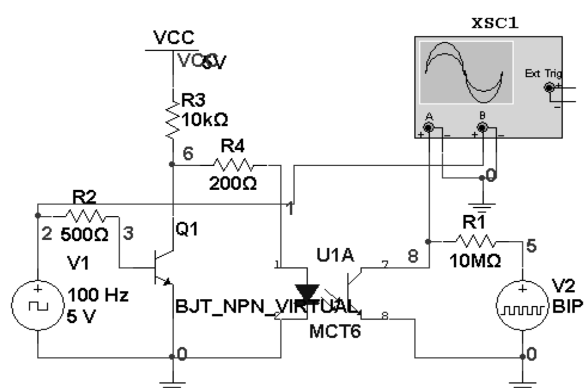

Figure 9. Simulation detection circuit

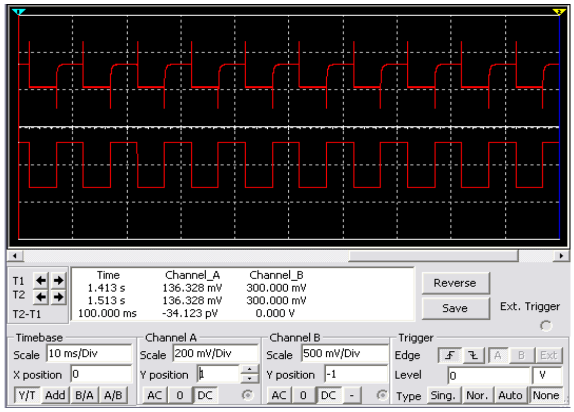

Figure 10. Detection circuit simulation results

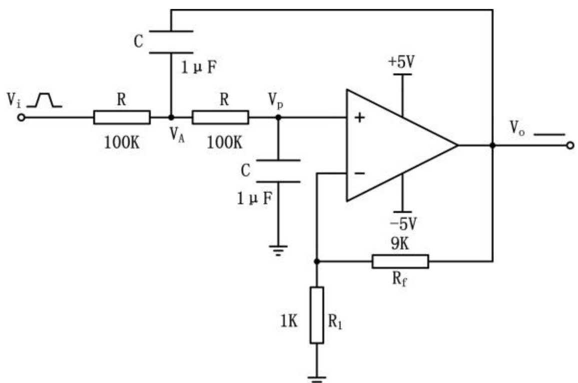

Figure 11. The demodulating circuit

3.2 Demodulation circuit

The demodulating circuit uses a second-order active low-pass filter. The filtering problem is the crux of the signal processing [8]. The circuit has shown in Figure 11. The voltage gain of the same relative proportion amplifier circuit is the pass band voltage gain of the low-pass filter. It is defined as:

$$A_0 = A_{VF} = 1 + \frac{R_f}{R_1} \tag{4}$$

The voltage relationship of the op amp's inverting input terminal is

$$A_{VF} = \frac{V_0(s)}{V_P(s)} \tag{5}$$

The relationship of $V_P(s)$ and $V_A(s)$ is

$$\frac{V_P(s)}{V_A(s)} = \frac{1}{1 + RCs} \tag{6}$$

KCL to node A relationship is

$$\frac{V_i(s) - V_A(s)}{R} = (V_A(s) - V_o(s))sC + \frac{V_A(s) - V_P(s)}{R} \tag{7}$$

Integrating these three equations, transfer function expression can be obtained as:

$$A(s) = \frac{V_o(s)}{V_i(s)} = \frac{A_{VF}}{1 + (3 - A_{VF})sRC + (sRC)^2} \tag{8}$$

$$A(s) = \frac{A_{VF}\omega_n^2}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2} \tag{9}$$

Where $\omega_n = 1/RC$, $Q = 1/(3 - A_{VF})$.

Frequency response:

$$20\lg\left|\frac{A(j\omega)}{A_{VF}}\right| = 20\lg\frac{1}{\sqrt{\left[\left(\frac{\omega}{\omega_n}\right)^2 - 1\right]^2 + \left(\frac{\omega}{\omega_n Q}\right)^2}} \tag{10}$$

Taking the parameters into Eq.7, when ω=100Hz, the attenuation is -40dB/decade. This attenuation meets design requirements.

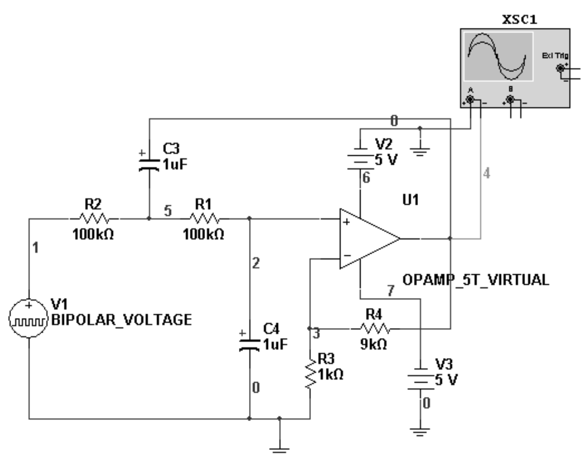

Figure 12. Demodulation circuit simulation

The demodulation circuit simulation of the circuit shown in Figure 12, the demodulation circuit is composed mainly by a second-order low-pass filter. The signal is demodulated into a DC signal, and completes the secondary amplification signal as well. Because of the limit of optocouplers cutoff frequency, the operating frequency of the sensor can only be controlled at about 100Hz, which makes the delay time is greatly increased. The MOS (Metal, Oxide and Semiconductor) type optocoupler cutoff frequency is much lower relative to the BJT (Bipolar

Junction Transistor) type. But the MOS type has a lower threshold voltage than the BJT type. So the MOS type is hard to be replaced by the BJT type.

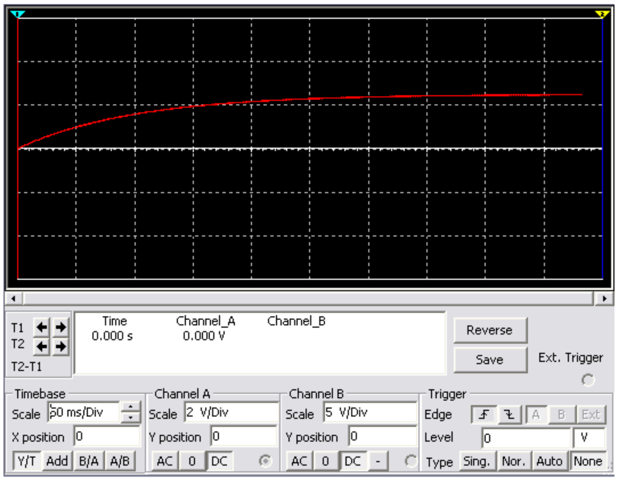

Figure 13. Demodulation circuit output signal simulation

The demodulated signal has shown in Figure 13. Signal rising steadily, but the rise time spends too long, the response time is not ideal, which is also one of the problems to be solved in the present design.

4. Experiment and Analysis

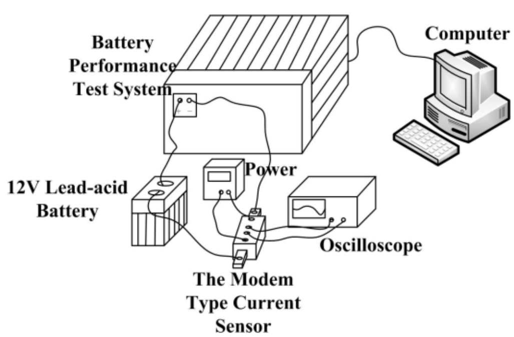

Figure 14. Experiment platform

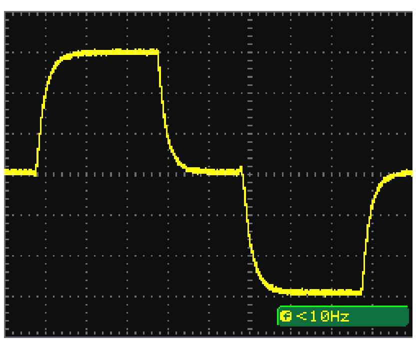

Figure 15. The working performance of current sensor

The test platform of the sensor is shown in Figure 8. The platform includes a high-precision battery performance test system, computer, 12V lead-acid batteries, power supplies, multimeter, oscilloscope, and modulation-demodulation type current sensor prototype. 12V lead-acid battery positive and negative terminals respectively connect to the positive and negative terminals of the battery performance test system, the current sensor string into the positive terminal of the battery. The oscilloscope respectively positive and negative probe head connect to the positive and negative output of the current sensor for detecting modulation-demodulation of the current sensor output waveform. The multimeter is used to record the output signal values in accuracy test experiment. The computer and the battery performance test system are connected by the communication cable. The software which control the battery performance test system is installed in the computer.

By setting the parameter in the software, the battery performance test system can control charge and discharge working of the lead-acid battery. The current size and working time are controllable. In the experiment, the charging and discharging process is: charging 20s pending 10s, discharging 20s, stopped. The oscilloscope probe current sensor output voltage is shown in Figure 14.

Seen in Figure 15, the actual working conditions of the sensor are consistent with the simulation results, the better the stability of the work of the sensor. From its work state you can see, the test prototype response time is very slow, reaching 3s. Most of the reason is more serious because the sensor inside the RC delays. Selected shunt slower response time is also one of the reasons.

4.1 Test data

The output precision experiment use high-precision digital multimeter measure. The experiment carry out three times [9, 10]. The first and the third sets of data measured from 20A to -20A, the second set data measured from -20A to 20A, the interval width of the test data is 2A. The measurement results are indicated in Figure16. From the experiment data, the maximum error value of the sensor is 0.15A, full-scale error is 0.4%, and the offset voltage is 600nV. Meanwhile, comparing above three groups, the proposed sensor has a good repeatability and a good delaying.

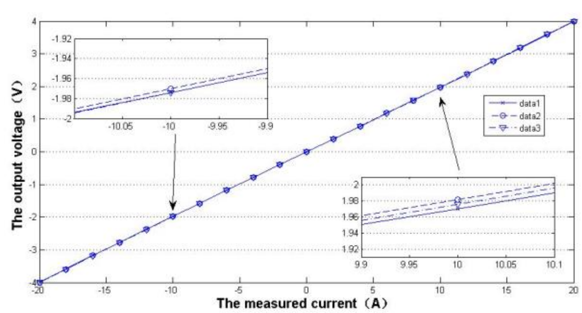

Figure 16. The measurement results

From the error sources, the sensor itself has a major error. Simultaneously measuring error of the instrument, the error in the battery management system and environmental factors also affect the measurement data. The following will analyze the sources of generated errors in the process of modulation and demodulation type current sensor measurement.

Shunt used as a measurement tool itself has a certain error. Shunt error sources include: resistance stability of the error, the current uneven distribution of errors due to errors caused by the connection of the equipotential bonding conductor, the thermopower error and load error. The shunt sensor design precision alpha 0.5 V to 75mV full-scale, maximum absolute error is calculated shunt.

$$d = \alpha \times V = 0.375mV \tag{11}$$

The unilateral maximum range of the sensor S is 20A, the maximum absolute error is

$$D = \frac{S \times d}{V} = 0.1A \tag{12}$$

In order to reduce the error generated by the shunt, when the shunt is selected, choose a higher accuracy.

After the Sensor is corrected, residual error is still inevitable to exist. This error is proportional to the measurement results, and the effect would be relatively small. When the sensor is corrected, these errors can be reduced by selecting the higher accuracy instruments.

The error caused by multimeter is decided by the accuracy and the display digits of the multimeter. The experiment use a 20V DC voltage stalls to measure. The multimeter display digits are four and a half, the measurement data to two decimal places. The multimeter maximum absolute error is 0.02V. The maximum absolute error may be to the sensor measurement is 0.1A.

Test loop current is not necessarily equal to the current default, but the accuracy of the battery test system, very close to the loop current and default, the error is very small, about 10-5.

In working condition, with the temperature of the resistance increases, the resistance decreases. It may lead to the drift error. Equipment such as battery performance test systems and computer will produce external heat; the heat will affect the ambient temperature. Especially the resistance and capacitance in the processing circuit will be significantly affected.

By the above method, it is impossible to eliminate the systematic error, but it can minimize or eliminate the impact of the systematic errors on the measurement accuracy.

4.2 Curve fitting

Based on the above three sets of measurement data, the average one is obtained by using the arithmetic mean method. Using the least squares method, the fitting curve of the measured current value and the actual output value can be obtained.

$$y_0 = 0.1988x + 0.0004 \tag{13}$$

The sensitivity of the sensor is known 0.1988V/A.

4.3 Nonlinearity error [9]

The non-linearity is the degree of linear relationship between the output and input of the sensor, the larger value indicates a worse linearity [10]. The sensor ideal input - output characteristic should be linear, *i.e.*, the non-linearity of 0, but the actual sensor input - output are nonlinear.

Non-linearity:

$$\gamma_L = \pm \frac{\Delta L_{\max}}{Y_{FS}} = 0.305\% \tag{14}$$

Where, $\Delta L_{\max}$ is the maximum difference of the fitting curve and the ideal curve, Y_{FS} is the full-scale output value.

4.4 Hysteresis

Hysteresis, also called return error is under the same measurement conditions, corresponding to the same size as the input signal, the sensor is the output signal of the stroke (input amount is increased by small), trans (input amount is reduced by the large) is not equal to the size of (errors) phenomenon [10]. The causes of this phenomenon are: the sensor mechanical part will present gap, loose, friction, dust, caused by energy absorption and consumption.

Hysteresis error of the sensor Hm is calculated as follows:

$$Hm = \frac{\Delta H}{I_N} \times 100\% \tag{15}$$

Formula: ΔH - the stroke of 3 times the rise and fall of each measuring inventory increase of the maximum value of the average of the difference of the average of the measured values with the descending stroke of the stroke Found. Calculated using Eq.15 data, the available sensor hysteresis is 0.4%.

4.5 Repeatability

Repeatability sensor input in the same direction for multiple testing of the full scale when the input - output characteristic curve of degree [10]. Actual characteristic curve of non-repetition causes hysteresis.

The sensor repeatability error r_m is calculated as follows

$$r_m = \frac{\Delta r}{I_N} \times 100\% \tag{16}$$

Wherein: Δr - the same stroke, the measured values of 3 measurements in each measuring point the difference between the maximum values. Using Eq.16 to calculate the data the duplication degree sensor can be obtained as 0.15%.

4.6 Sensitivity

The sensitivity is the change of the sensor output value on the ratio of the change of the input value in the steady state [10], S_n , *i.e.*:

$$S_n = \frac{\Delta U_{out}}{\Delta U_{in}} = \frac{dy}{dx} \tag{17}$$

For the linear sensor, its sensitivity is its slope of static characteristics; the sensitivity of the non-linear sensor is a variable. The sensitivity is actually a magnification; it reflects the ability of a significant change in the sensor on the measured small signal amplifier into an output signal, i.e. the sensor sensitive to small changes in input variables. Usually the slope of the fitting line is used to represent the average sensitivity of the system. In 3.2, the resultant fitting curve shows the sensor sensitivity is 0.1988V / A.

4.7 Study compared

Literature [11] proposed a probe current sensor used for auto detection. This sensor can be used for both DC and AC, has fast response time and low temperature drift. The modulation and demodulation current sensor has higher precision than the probe current sensor. The modulation and demodulation current sensor only need a single voltage supply has a lower manufacturing cost. In terms of the measurement range, the probe current sensor is able to measure the highest 1000A current. The modulation and demodulation current sensor in test can measure only ±20A, but by replacing the current shunt, a higher current can be measured.

5. Conclusion

The proposed current sensor is designed to achieve high-isolated current sensing. From the actual measurement data, the current sensor has high accuracy, good linearity and good repeatability. The current sensor can avoid the impact of the high-voltage part to the low-voltage part, and preferably achieve signal processing. As is known from the above, another disadvantageous point of the proposed sensor is the low response time.

Acknowledgements

This work is supported by the Natural Science Foundation Project of CSTC2011BB4145 and cstc2013yykfC60005.

References

[1] Budovsky, H. Sasaki and P. Coogam, “AC-DC transfer comparator for the calibration of thermal voltage converters against Josephson alternating voltage standards”, IEEE Trans on Instru & Meas, vol. 52, Issue 2, **(2004)**, pp. 538-541.

[2] R. Shiyan, “A 100000 - A high precision on-site measurement calibration device for heavy direct current”, IEEE Trans on Instru. & Meas, vol. 39, Issue 1, **(1990)**, pp. 19-22.

[3] M. Kang, P. N. Enjeti and I. J. Pitel, “Analysis and Design of Electronic Transformers for 150 Electric Power Distribution System”, IEEE Trans. on Power Electronics, vol. 2, **(1997)**, pp. 1689-1694.

[4] S. A. Boggs, G. J. Fitzpatrick and K. Jinbo, “Transient errors in a precision resistive divider”, IEEE International Symposium on Electrical Insulation, vol. 2, **(1996)**, pp. 482-485.

[5] A. Bouabana and C. Sourkounis, “A modulated interface for a low-cost Current Sensor in comparison with its simulated model”, Electrotechnical Conference (MELECON), 2012 16th IEEE Mediterranean, **(2012)**, pp. 455-458.

[6] F. Haifeng, Z. Yiming and W. Xuhong, “Design of Current Sensor Based on HCPL-7840 Isolation Amplifier”, Micromotors, vol. 45, Issue 5, **(2012)**, pp. 19-22.

[7] F. Rothan, H. Lhermet and B. Zongo, “A ±1.5% Nonlinearity 0.1-to-100A Shunt Current Sensor Based on a 6kV Isolated Micro-Transformer for Electrical Vehicles and Home Automation”, Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2011 IEEE International, **(2011),** pp. 112-114.

[8] D. W. Braudaway, “Behavior of resistors and shunts: with today's high-precision measurement capability and a century of materials experience, what can go wrong”, IEEE Trans. on Instru. & Meas, vol. 48, Issue 5, **(1999)**, pp. 889-893.

[9] W. T. Chung and A. K. David, “Development of a laboratory AC-DC simulator for on-line control study”, Electric Power Systems Research, vol. 46, no. 1, **(1998)**, pp. 27-33.

[10] P. Zenghui and Y. Xiaoxian, “Research on data processing method of dynamic force test and error analysis”, Guti Huojian Jishu/Journal of Solid Rocket Technology, vol. 31, no. 5, **(2008)**, pp. 539-542.

[11] K. Ogawa, S. Suzuke, M. Sonehara and T. Sato, "Optical probe current sensor module using the Kerr effect and its application to IGBT switching current measurements", 2011 Fifth International Conference on Sensing Technology (ICST), **(2011)**, pp. 594-598.

