

# Design and Simulation of Weak Current Measurement Circuit Based on System Proportional Measurement

Haiwei Mu, Chunhui Zhu \*

School of Electronics Science, Northeast Petroleum University, Daqing, 163318, China

\*Corresponding Author

**Keywords:** Plant physiological electrical signal, System scale measurement, Weak current measurement, Circuit design, Simulation

**Abstract:** In the field of plant electrophysiological signal measurement, it is necessary to accurately measure very weak current signals, usually ranging from 10<sup>-1</sup> to 10<sup>-15</sup>A. However, it is very difficult to directly measure the distribution characteristics of plant electrophysiological signals. In this paper, a non-contact weak current detection system is designed by system proportional measurement method, focusing on the research and improvement of the measurement circuit itself. In order to overcome the disadvantages of expensive instruments, large size and the inability of chips to directly measure current, a circuit which can be applied to the weak current vector detection of sensors is designed. We chose the operational amplifier current feedback method to design the circuit, improved the circuit design and reasonably determined the circuit parameters, and finally realized the automatic continuous monitoring of multi-channel plant physiological electrical signal parameters with a measurement accuracy of 1nA.

## 1. Introduction

In practical application, it is often necessary to detect some non-electric quantities, and these signals are weak current signals on the order of nA and uA and weak voltage signals on the order of mV and uV. Physiological signals are important parameters for understanding the mysteries of life, organisms and health conditions. The physiological process of plants under environmental changes is accompanied by changes in electrical signals [1]. Studying the changes of plant electricity can understand whether the physiological process of plants is in normal state, which is of great significance in the field of crop stress resistance [2]. In order to enable the measured data to be collected and processed by the computer, analog-to-digital conversion is also needed to make the generated frequency signal proportional to the measured input current. At present, in weak signal detection methods, lock-in amplifier circuit is widely used in precision instruments due to its advantages of stable center frequency, narrow passband and high quality factor [3].

At present, most of the commercial instruments are animal physiological signal acquisition devices used in conjunction with PC machines, and the number of channels is small, so the input impedance cannot meet the requirements of plant electrical signal detection, and it is difficult to meet the requirements of plant physiological signal acquisition. The author introduces a kind of plant physiological signal current measurement circuit based on high performance operational amplifier designed for system proportion measurement. It has the advantages of high precision, good stability, small volume and large measuring range, etc., and analyzes various factors affecting the circuit performance, and gives specific solutions.

## 2. The Overall Design of Measuring Circuit

### 2.1 Hardware Design of Measuring Circuit

#### 2.1.1 Constant Potential Circuit

The new constant potential circuit design in this paper is an improved circuit base on that traditional constant potential circuit, and its structure is shown in fig. 1. The signal generator inputs

the external excitation signal into the potential control circuit to act on the reference electrode, and measures the current value generated by the electrode reaction on the working electrode. In order to improve the accuracy of the excitation signal, this paper adopts the design of reference voltage source and adjustable resistor to compensate and adjust the input of the potential control circuit.

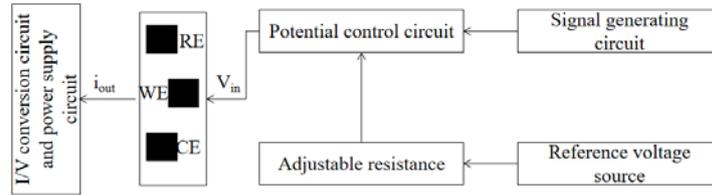


Fig.1 A New Constant Potential Structure

As shown in fig. 1, the signal generator inputs the external excitation signal into the potential control circuit to act on the reference electrode, and measures the current value generated by the electrode reaction on the working electrode. In order to improve the accuracy of the excitation signal, this paper adopts the design of reference voltage source and adjustable resistor to compensate and adjust the input of the potential control circuit.

### 2.1.2 Weak Current Signal Acquisition and Amplification Circuit

The common method for measuring micro-current is to use current negative feedback DC amplifier to complete I-V conversion. However, this amplifier is in the first stage, and the noise it brings will affect the measurement results, so the noise reduction of this stage is the key problem [4]. Amplifier noise is caused by many factors, but it is mainly caused by the active of arithmetic unit and thermal noise of circuit. The total noise output is expressed as:

$$\overline{v_{no}^2} = G_{en}^2 \overline{e_n^2} + G_{in}^2 \overline{I_n^2} + 2YG_{en}G_{in} \overline{e_n I_n} + \overline{e_f^2} \quad (1)$$

Where  $\overline{e_f^2}$  is the equivalent thermal noise of the feedback resistor.  $\overline{e_n^2}$ ,  $\overline{I_n^2}$  is the equivalent series and parallel noise of the operational amplifier.  $G_{en}G_{in}$  is the transfer coefficient of series and parallel noise.  $Y$  is the correlation coefficient of series and parallel noise.

Since  $\overline{e_f^2}$ ,  $\overline{e_n^2}$ ,  $\overline{I_n^2}$  are both stable and random processes independent of each other and conform to the law of Gaussian distribution, the average noise voltage is 0[5]:

$$\overline{V_{NO}} \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T v_{no} dt = 0 \quad (2)$$

The most important part of current integration unit of potentiostat is potentiostat, and the core of potentiostat is operational amplifier. The noise performance of the circuit will directly affect the sensitivity and stability of the circuit, so it is particularly important to de-noise the circuit. The feedback signal is an AC signal with the same frequency as the excitation signal, and the amplitude varies with the position of the moving parts. Compared with common signal conditioning circuits, weak signal detection circuits should have the characteristics of low noise, low temperature drift, large dynamic response range, fast response, high sensitivity and the like [6]. In the acquisition system, ADC basically converts the voltage signal into a digital signal. Therefore, a preamplifier is needed to convert the current signal output by the detector into a voltage signal, and then filter and amplify the voltage signal to obtain a voltage signal convenient for measurement. The design of the current amplifier is shown in fig. 2.

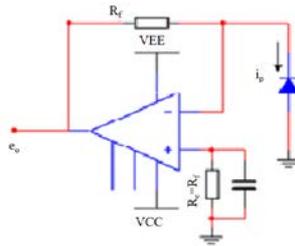


Fig.2 Matching I/ V Current Amplifier Scheme

### 2.1.3 I-V Conversion Circuit

The I/V circuit has a relatively simple structure, solves the contradiction between bandwidth and gain well, and can have higher bandwidth and higher gain at the same time, which provides a good idea for the later improved circuit. The circuit for detecting weak current signals firstly collects and processes the generated weak current signals. The selected scheme is to adopt the high input impedance method of I/V conversion method. The key component of high input impedance method is operational amplifier. The output voltage after I-V conversion with  $R_f=20M\Omega$  is 20mV. This voltage needs further amplification to meet the needs of subsequent processing such as filtering and A/D conversion. We perform two-stage voltage amplification after the first-stage I-V conversion. Experiments show that the SNR is the highest when the magnification is 10 times [7]. For the operational amplifier with JFET structure, the input bias current is only on the order of pA. If the gain is on the order of megawatt without matching resistor, the DC bias voltage brought to the output is only on the order of microvolt. Based on the above analysis, the phase compensation I/V type is adopted. The schematic diagram of the designed circuit is shown in fig. 3.

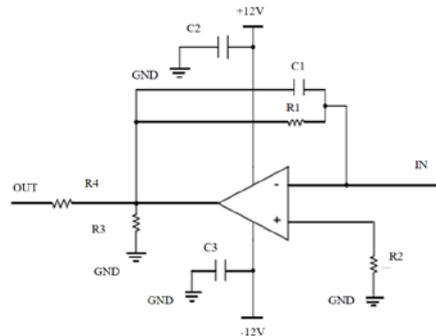


Fig.3 Schematic Diagram of Weak Current Signal Detection

### 2.1.4 The Design of Signal Conditioning Circuit

Because many signals have relatively small amplitudes, amplifiers are needed to improve the measurement accuracy. The amplifier achieves the purpose of improving the measurement resolution by matching the signal level with the measurement range of the A/I converter. For 50Hz, which is widely existing in natural environment. Power frequency interference has strong suppression. The A/D conversion bits of analog signals reach 24 bits, which can realize the detection of microvolt level changes of signals, and is especially suitable for data acquisition modules of exploration instruments.



Fig.4 Structure Diagram of Signal Conditioning Circuit

In order to effectively suppress power frequency interference noise and amplification circuit noise, optimize the signal-to-noise ratio of signal conditioning circuit and improve the detection ability of weak signals in the later period of pulsed eddy current, the circuit structure and measures to improve the signal-to-noise ratio are mainly designed. The real-time performance of the signal is very strong, the number of channels is large, and the detection results are highly dependent on the

data. The signal conditioning circuit structure is shown in fig. 4.

## 2.2 Power Supply Circuit Design

The system needs to provide the operating voltage required by the operational amplifier in the analog input signal conditioning circuit and the 3.3V operating voltage required by the ARM7 processor. The external voltage is 24V. The noise of the power supply will be coupled to OPA 657 through the capacitive silicon photomultiplier, thus increasing the noise in the circuit and reducing the signal-to-noise ratio of the conditioning circuit. The advantages of serial single-point grounding method are simple grounding and convenient wiring, so it is widely used in circuits with low requirements on noise characteristics. The 24bit ADS1256 chip is used for signal sampling. The sampling frequency is 20kHz. The maximum sampling rate of the chip is 30ksps. The input voltage range is 0 ~ 5V. The output mode is SPI output and supports single-ended input and differential input. The frequency and amplitude of the flutter signal can be independently adjusted. Flutter signals are set in the software and superimposed on the control signals at the same time, and then the control current with the flutter signals is obtained through the power amplification circuit. The system amplifies and denoises the signal through hardware design to improve the anti-interference ability of the system, and uses lock amplification technology to detect the signal to improve the detection ability of the system.

## 2.3 Circuit Debugging and Pcb Processing

To debug the hardware circuit, we must first ensure that this preamplifier circuit can convert weak current signals into voltage signals independently without being controlled by the external system environment, and can achieve the required amplification factor. One-stage voltage following is added between the two-stage voltage amplification. The main function is to isolate the influence of the front stage and the rear stage, avoid the interference of the large signal circuit of the rear stage with the weak signal conversion circuit of the front stage, and improve the signal-to-noise ratio. The output of the following operational amplifier is added with low-pass filtering to suppress noise. In some cases, the input current may be positive or negative. For example, when the ionization chamber is powered by positive high voltage, its output current is positive, whereas when the ionization chamber is powered by negative high voltage, its output current is negative.

The signal finally detected by the phase-locked amplifier circuit is the difference frequency voltage between the input signal and the reference signal, so the band width of the low-pass filter can be made very narrow, while the difference frequency component of noise and the reference signal. According to the detection requirements, the current signals in different magnitudes are subjected to gear selection conversion, the upper limit and the lower limit of the voltage after each gear conversion are gear switching voltages, and the range is set as an embedded program automatic switching flag. Copper-clad grounding of PCB board provides very low inductance for return signal current. In this way, the grounding terminals of amplifier chip are connected with low impedance, thus reducing common path noise voltage.

## 3. Software Design of Measuring Circuit

After the hardware circuit platform of the system is built, the main work in this stage is the software design of the system. The main purpose of the software design is to reasonably schedule the hardware resources of the system so that each hardware module can be combined to realize the final requirements of the system. According to the constant current source parameters set by software, voltage and current setting instructions are sent to the constant current source at regular intervals. By sending inquiry voltage and current instructions, current voltage and current measurement values are inquired, and callback functions are used to continuously detect whether corresponding events occur. Therefore, the voltage comparator is restored to the initial state, that is, a new integration period is restarted, and the integration period is determined by the forward charging time and the reverse charging time of the current source current. It can provide a low impedance path between the power supply and the ground, i.e. a low pass filter, to filter out high

frequency current, stabilize the power supply voltage and reduce the interference caused by power supply fluctuation. This method of power supply by power supply chip is more stable than the method of voltage division power supply by resistor, because the resistance value will shift with the passage of time, causing the power supply voltage to also change.

After detection, receive the data, judge and analyze the data, and display the current voltage and current measurement values in real time in the test interface. see fig. 5 for the control flow chart.

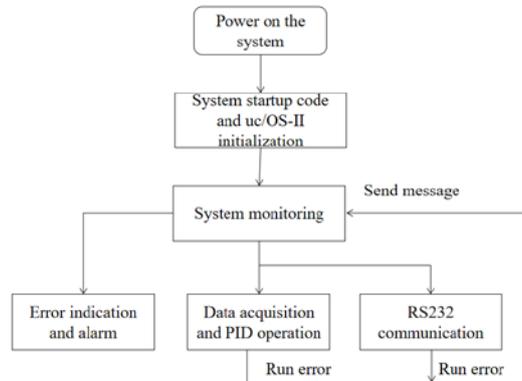


Fig.5 General Block Diagram of Control System Software

As shown in fig. 5, after the proportional flow valve controller is powered on, an operating system starts the program and performs initialization settings. The uc/OS-II operating system sets the monitoring task to the highest priority level, the data processing task to the second level, and the communication task to the lowest priority level. The storage of digital signals is realized, and information exchange can be carried out with the upper computer, so as to finally detect weak physiological electrical signals of plants. The cut-off frequency of the filter should be as close to the signal frequency as possible to achieve the best filtering effect. The generated weak current reaches the picoampere level weak current, and finally the ammeter for detecting the weak current signal is adopted for verification, and the picoampere level weak current can also be achieved by building the circuit on the bread board.

#### 4. Testing and Verification of Measuring Circuit

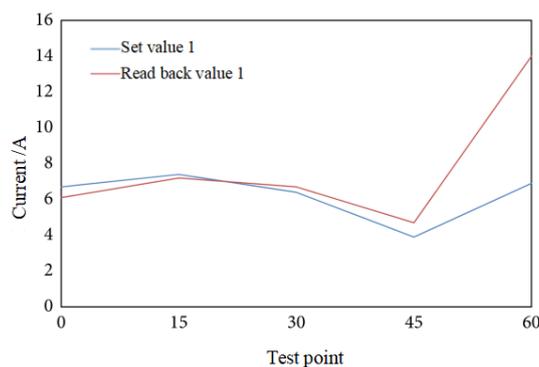


Fig.6 Sensor Current Readback

In this experiment, the changes of plant physiological electrical signal were observed by burning leaves to verify the stability and accuracy of the instrument. Calomel electrode was used in plant electrical test. The calomel electrode is filled with saturated KCl solution, and the circuit path with plants is realized by overlapping conductive cotton threads. In order to ensure that the maximum value of the output voltage of the I/V conversion circuit is always kept constant in different sections or different measurement ranges, i.e. 0.05 or 0.1V set, this requires that the feedback resistance  $R_f$  also varies with the measurement range. The voltage amplification factor adjustment range is 1-50 times; The time constant adjustment range of the low pass filter is  $1 \mu s \sim 100 ms$ . In order to reduce the influence of noise, the PCB board interface uses BNC to connect signals to [8]; In the case of

testing DC current, fig. 6 is a result diagram obtained by connecting a resistor of 10m to a given DC power supply voltage of 5V to 2V, and then passing the generated current through the preamplifier. when the feedback resistance of the preamplifier is 10m, theoretically the result of the output voltage generated should be equal to the value of the power supply voltage signal provided by the weak current.

After repeatedly confirming various functions of the system, fig. 6 shows that the contrast error between the measured value of the set current and the set value is  $\pm 0.1\text{mA}$ , and the three return trip set values are consistent with the measured value. The low frequency voltage gain of the operational amplifier is about 60 dB and the phase margin is about 50. This shows that the amplifier has higher gain and better stability. There is no obvious difference in noise and bandwidth, indicating that for PCB board design, there is little difference between multi-point grounding method and single-point grounding method, mainly because the bandwidth of the signal belongs to low-frequency signal. The current sensing range of the sensor is about 20pA-20 Can, i.e. the dynamic range is 120 dB. The potentiostat has a wide dynamic response range. However, the circuit board is small in length, and the ground loop impedance of single-point grounding and multi-point grounding is approximately 0.

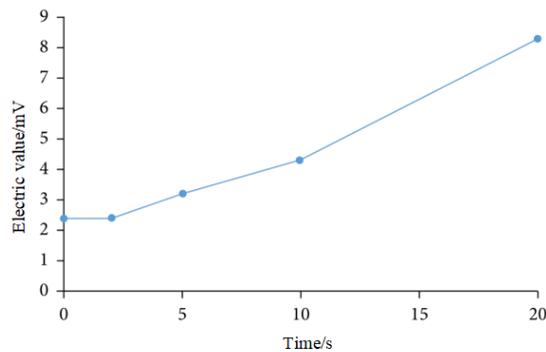


Fig.7 Results of Plant Leaf Burn Stimulation Experiment

The weak current signal obtained when the given power supply voltage is 3V and the connection resistance is 10M is -3.01V through the pre-I/V conversion circuit. Fig. 7 is the result of burn stimulation experiment on plant leaves. From the potential curve, it can be concluded that the signal curve is relatively stable when the plant is in a resting state. When the plant leaves are burned, the signal has obvious variation amplitude. In the integration time of each cycle, the output voltage on the integration capacitor has a high output swing, and the integration curve has a high linearity for each output current of the microbial sensor chip. In the hardware circuit of the system, components with excellent performance are adopted to ensure the reliability of the hardware. The power supply of each chip is filtered by bypass capacitor. The digital signal of the communication part is isolated from the analog signal to improve the anti-interference performance of the whole circuit. In the actual experimental test, the shell of the instrument and the shell of the preamplifier are connected to the ground to reduce the noise of the environment to the experimental environment.

## 5. Conclusion

In weak current signal measurement, the circuit is easily affected by the outside or the circuit itself. The purpose of this system is to continuously measure and monitor the changes of environmental and multi-channel plant physiological electrical signals, and to realize the portability of the system. Using weak signal detection technology, the signal amplifier with high gain and high bandwidth, which is required by the experiment, is well realized and has good stability. The principle of electromagnetic compatibility is applied to PCB design, overall circuit wiring, circuit shielding and grounding. After a repeated debugging process from design and debugging to field application, the problems of interference and inconvenient operation are overcome, and the whole process of system design is completed. The simulation results show that the measurement accuracy of this circuit is 1n A, reaching the design goal.

## References

- [1] Hu Hongqian, Gao Qifeng, Shen Shanshan. (2016). Design of a new weak current detection preamplifier circuit. *Nuclear Electronics and Detection Technology*, vol. 036, no. 008, pp. 847-851.
- [2] Yu Xiangqian, Chen Hongfei, Zou Hong, et al. (2015). Design of a very weak quasi-DC current signal measurement circuit. *Instrument Technology and Sensors*, no. 08, pp. 74-76.
- [3] Song Ningfang, Kang Ti, Jin Jing, et al. (2018). Design of weak atomic fluorescence light field measurement system. *Semiconductor Optoelectronics*, vol. 039, no. 001, pp. 91-94,117.
- [4] Gao Meirong. (2018). Design and Simulation of Ultrasonic Ranging Alarm System Based on Single Chip Microcomputer. *Foreign Electronic Measurement Technology*, vol. 037, no. 007, pp. 107-111.
- [5] Wang Ge, Liu Jia, Qiao Caiying, et al. (2018). Design and Simulation of Welding Loop Impedance Measurement System. *Hot Processing Technology*, vol. 47, no. 23, pp. 210-213.
- [6] Cui Zhijun, Liu Hong. (2018). Design of a Lock-in Amplifier for Detecting Weak Light Current Signal. *Computer Measurement and Control*, vol. 026, no. 004, pp. 143-147.
- [7] Cheng Zhi, Dong Dengfeng, Zhou Weihu, et al. (2016). High-precision laser position detection system based on position-sensitive devices. *Progress in Laser and Optoelectronics*, vol. 053, no. 008, pp. 146-154.
- [8] Dong Ming, Yin Gaofang, Zhao Nanjing, etc. (2018). High sensitivity and large dynamic range detection technology and application of weak fluorescence signal. *Journal of Quantum Electronics*, vol. 035, no. 004, pp. 395-401.