Research of Strain Sensor for Transmission Line Tower based on RFID

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Abstract. The change of foundation, line galloping and vibration will cause the change of the stress state of the tower. By monitoring the stress state of the tower, the accidents such as tower collapse and tower collapse can be forewarned in time. In view of the shortcomings of the existing tower stress monitoring device, such as inconvenient data collection and low measurement efficiency, this paper proposes a high-precision strain sensor chip and RFID technology-based strain sensor to monitor the tower strain. According to the characteristics of strain sensor collection unit and RFID technology, a low-power strain sensor for real-time monitoring of strain data of transmission towers was designed. It can be read and recorded by hand-held reader, which improves the collection efficiency of strain information of towers and reduces the manual operation. In view of the shortage of energy supply of transmission line sensors, the power consumption design extends the effective working time of the sensor.

1. Introduction
It is inevitable for transmission lines to pass through special areas such as goaf and hillside, which is prone to causing tower tilting, foundation cracking and deformation. In addition, the stress conditions such as tower tilting and conductor icing may lead to stress anomalies of tower foot components. In terms of macroscopic deformation, tower collapse, line fatigue and strand breakage due to conductor galloping also cause great hidden danger to the stable operation of the lines [1-4]. For this reason, the operation risk of the equipment can be grasped timely by effectively monitoring the deformation of power transmission and transformation equipment. The existing strain sensors are subject to the shortcomings such as manual zero setting, obtaining strain data by regular inspection, low measurement efficiency, etc.. In this paper, according to the demand of real-time monitoring of tower strain by transmission lines, the strain sensor based on high-precision strain sensing chip is applied to the strain monitoring of the tower. By using low power algorithm and optimizing the design of strain data acquisition circuit, the strain information can be collected in a quick, long-term and effective manner.

2. Total Design Scheme
This paper mainly involves the measurement of tower stress. Using a high-precision strain sensor, surface stress of tower foot can be accurately measured to complete the online monitoring of tower stress level, for which wireless data reading can be performed by means of RFID transmission module. Using a handheld mobile device, the stress level of the tower can be read directly during the inspection. The difference of stress changes between the tower feet can finally reflect the macroscopic deformation hazards such as tower tilting and settlement to meet the requirements for intelligent operation inspection.
The stress measurement method [5,6] based on RFID technology can be applied in the scenario of equipment deformation monitoring under the condition of partially replacing the stress-sensitive structure, thus greatly expanding the application range of strain sensor. The low-power strain sensor can be mounted at the four feet of the tower to be measured, to collect the strain information of the tower at fixed intervals (such as 12 hours), which stores the collected data in the non-volatile memory. When regularly holding the mobile device for inspection, the inspectors can read the historical information in the memory, and transmit the information to the master station server via 3G / 4G network. The server can acquire the change of tower stress through the strain algorithm [7] (see figure 1).

3. Design of Strain Measurement Circuit
The strain sensor is mainly composed of the following parts: strain sensing module mainly used for collecting the strain information of the tower; main control MCU used for executing low power algorithm, sensing data processing and forwarding; memory mainly used to store the historical data of stress; RFID communication module mainly used to complete the information communication, abstract the historical data from the memory and send it to the handheld mobile device; 3.6V lithium-ion batteries used for supplying power to main functional modules (see figure 2).

3.1. Design of Conditioning Circuit for Strain Sensor
The acquisition unit of strain sensor adopts a bridge circuit structure to improve the output sensitivity. Due to line loss, temperature drift and other factors, the initial strain signal may deviate from zero, and the diurnal temperature variation also may lead to the additional deformation of strain gauge, which leads to inaccurate strain measurement. In order to effectively control the reliable measurement range of strain signal, the performance balance must be carried out by using the conditioning circuit before the strain sensor is mounted on the transmission line tower, and the temperature drift error must be eliminated by bridge compensation.
As shown in Fig. 3, the strain test balance circuit is mainly of two types: series type and parallel type [8]. As shown in figure 3 (a), the series circuit can realize the bridge balance by adjusting the sliding rheostat \( R_P \) between \( R_1 \) and \( R_2 \). The value of \( R_P \) can be calculated by the following formula:

\[
R_{P_{\text{max}}} = \left| \Delta r_1 \right| + \left| \Delta r_3 \right| \cdot \frac{R_1}{R_3}
\]  

(1)

In the above formula, \( \Delta r_1 \) is the deviation between \( R_1 \) and \( R_2 \), and \( \Delta r_3 \) is the deviation between \( R_3 \) and \( R_4 \). As shown in figure 3 (b), the parallel circuit also can realize the bridge balance by adjusting \( R_P \). Adjusting ability of the zeroing circuit depends on \( R_b \), and the value range of \( R_b \) is calculated according to the following formula:

\[
R_{b_{\text{max}}} = \frac{R_1}{\Delta r_1 + \Delta r_3} \cdot \frac{R_1}{R_3}
\]  

(2)

In addition, the temperature drift caused by temperature change can be calibrated using a compensated strain gauge. The working strain gauge \( R_1 \) is pasted on the surface of the tested piece, the compensated strain gauge \( R_B \) is pasted on the compensation block which is exactly the same as the material of the tested piece, and only the working strain gauge bears the strain. The output difference between the two is the strain value free of temperature error. In this paper, the effect of temperature compensation circuit is verified. As shown in figure 4, when the ambient temperature rises from 0°C to 55°C, the output fluctuation of circuit strain value after temperature compensation is much smaller than that before the temperature compensation.

**Figure 4. Comparison of strain values before and after temperature compensation**

### 3.2. Design of Automatic Balance Circuit

The traditional manual zero setting method of strain sensor needs to be manually operated by the personnel arranged in the measuring place, which consumes a lot of manpower and shows low operation accuracy and efficiency. In this paper, an automatic balance adjustment circuit of strain information is designed based on CC1110 chip and non-volatile digital potentiometer X9241, which is used to replace...
manual adjustment so as to meet the requirements for fast arrangement of test system on the transmission lines [9].

Fig. 5 shows the schematic diagram of the automatic balance measuring circuit for strain data, mainly including $R_1$-$R_4$ strain resistor, $R_w$ resistor, X9241 digital potentiometer, operational amplifier $U_1$, and microcontroller CC1110. The differential signal generated by the strain bridge composed of $R_1$ to $R_4$ is fine-tuned by the digital potentiometer X9241 and $R_w$ resistor and then transmitted to the operational amplifier $U_1$ for signal amplification and output of the $V_{out}$ signal. The CC1110 processor samples the $V_{out}$ output signal and performs DA conversion to determine whether the output voltage signal is within the specified null voltage range, and to process the deviation by adjusting the digital potentiometer to make the output voltage meet the requirements for the null voltage [10].

![Figure 5. Schematic diagram of automatic balance circuit](image)

The four resistances in an ordinary bridge are usually of the same value. According to the formula (3), the value of $R_w$ is small (usually tens of milliohms). The nominal value of digital potentiometer is usually much higher than the value of $R_w$, and the resulting current is much lower than the current through the bridge. In order to reduce this situation, $R_1$ and $R_3$ are used as strain gauges, $R_2$ and $R_4$ are used as fixed resistors, and $R_w$ and digital potentiometer X9241 are connected in parallel between $R_2$ and $R_4$. Under the condition, the bridge balance is in accordance with the following formula:

$$\frac{R_1}{R_1 + R_3} = \frac{R_2 + R_{pw}}{R_2 + R_{pw} + R_4}$$

(3)

Where, $R_{pw}$ is the value after the digital potentiometer X9241 is connected with $R_w$ in parallel. $W_a$ is the resistance value of Part a in X9241. If the rated value is greater than the rated value $R_p$, the value after parallel connection of $R_w$ and X9241 is approximately equal to $R_w$. Generally, $R_2$ and $R_4$ are greater than $R_w$. In such a case, the voltage at both ends of X9241 is relatively low. By adjusting the position of sliding contact in X9241, the voltage changes of $\mu$V ~ $mv$ level can be adjusted, and the static voltage value can keep equal to that of $R_1$ and $R_3$ connection points. Thus, the automatic balance of the circuit is realized [11]. The circuit board capable of automatic zero setting is shown in Figure 6. The bridge circuit capable of temperature compensation and automatic zero setting is in position of the red circle in the figure [12,13].

![Figure 6. PCB with auto zero function](image)
When the strain test is carried out, the microcontroller CC1110 may perform AD conversion by acquiring the value of $V_{out}$, and determine how to adjust the digital potentiometer by analysing the size of $V_{out}$. In addition, it issues the adjustment instruction to the potentiometer. After a period of time, the circuit re-outputs the new $V_{out}$, and the microcontroller continues to judge whether its voltage value is zero. After many cycles, the signal conditioning circuit outputs zero voltage and the state of the digital potentiometer under the condition is stored before finishing the zero setting [14, 15].

The procedure flow chart is shown in Figure 7.

![Figure 7. Procedure flow chart](image)

3.3. Design of RFID Antenna
The strain sensor needs to be laid on the metal structure of the tower. If the monopole antenna is used, the low radiation resistance of the antenna may result in poor radiation efficiency. In this paper, the PIFA antenna is selected and designed to keep a distance from the circuit board so as to prevent the metal from causing attenuation to the RF signal.

The structure diagram of the designed PIFA antenna is shown in Figure 8.

![Figure 8 Model diagram of tag antenna](image)

The return loss diagram of the antenna is simulated using the HFSS. The simulation results are shown in Figure 9. It can be seen from the diagram that the return loss of the antenna is minimized with less signal loss at about 450MHz.
The 3D gain direction diagram of the antenna is shown in Figure 10. The simulation shows that the antenna can form a uniform field around and the receiver can effectively receive data from any direction.

3.4. RFID Circuit and Low Power Design
In this paper, the CC1110 module is used to realize RFID circuit. The CC1110 adopts multiple power supply working modes. In sleep mode, the current consumption is only 0.3uA, which is suitable for the application of low-power system and meets the needs of long-time condition monitoring of tower [16,17]. The chip is integrated with a high-performance wireless transceiver, showing good receiving selectivity and ultra-high sensitivity (−110dBm @ 1.2 kBaud).

The circuit diagram of RFID is shown in Figure 11.
Considering the application of strain sensor in the strain monitoring of transmission line tower, the higher requirements for the service life of the sensor are proposed. A low power design is adopted for the microcontroller to make full use of the power working mode of the RF microcontroller in order to reduce the power consumption by the alternate working mode of sleep-wake [18]. The power consumption test is shown in Figure 12. According to the test results, the sleep current of sensor is only 0.72uA.

![Figure 12. Power consumption test of strain sensor](image)

The RFID function of strain sensor mainly involves the following points: wireless modification of label ID, channel, configuration of acquisition sensor time, low battery alarm function, and wireless collection of label ID; designated label buzzing and flicker; wireless time calibration; storing initial deformation value of sensor; timing acquisition and storage of sensor deformation value; responding to wireless query instructions (such as querying the corresponding parameter configuration, sensor deformation values during a period of time, etc.).

4. Test Scenario
The test scenario is shown in Figure 13.

![Figure 13. Test scenario](image)

During the communication, the handheld device is used to connect with the strain sensor to obtain the data stored in the strain sensor memory chip. The display interface of the handheld device is shown in the figure below. Figure 14 shows the parameter setting interface of the handheld device, and Figure 15 shows the interface for reading the information of the strain sensor. The test results show that the data can be easily obtained using a handheld device 100 meters from the strain sensor.
5. Conclusions
In this paper, in order to meet the actual needs of strain monitoring for the transmission line tower, a low-power and high-precision strain sensor capable of wireless communication and automatic zero setting is designed and developed based on temperature compensation, automatic circuit balance and RFID technology. Relying on the wireless communication technology, the sensor shows the advantages such as simple fabrication, stable operation, low hardware cost and channel expansion. By means of program control, the temperature compensation of sensor can effectively improve the inspection efficiency of transmission line tower and greatly improve the convenience and real-time capability of stress-strain test. In the stress test of transmission line tower, the sensor obtained good application results to save the test time and improve the test efficiency.

6. References
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