Design of Range Sensor for Transmission Line Fault Detection in Covered Conductor Overhead Grid

Haitao Wang 1,2, Yuan Cheng 1,2*, Zandong Zhou 1,2, Huangxu Ge 3 and Yifan Guo 3

1 NARI Group Corporation Ltd, Nanjing, Jiangsu, 210003, China
2 Wuhan NARI Limited Liability Company, State Grid Electric Power Research Institute, Wuhan, Hubei, 430000, China.
3 State Grid Zhejiang Electric Power Company Jiaxing Power Supply Company, Jiaxing, Zhejiang, 314033, China

*Corresponding author’s e-mail: chy0410@qq.com

Abstract. As an important detection means of partial discharges, range sensor is widely used in power system in China. Due to the complex and open environment around covered conductor overhead distribution networks, misjudgement and leakage in long-distance of traditional ultrasonic sensors often occur. Aiming at this problem, an range sensor with high sensitivity and directivity is designed in this paper. In this paper, the theoretical model of the ultrasonic screening can is established by COMSOL simulation software, and the structure of the screening can is designed reasonably by analyzing the concentration and directivity of the sound field of the model. In addition, based on the ultrasonic characteristics generated by partial discharge of overhead insulation wire, the ultrasonic probe with a central frequency of 40kHz was selected, and an amplification and filtering circuit was designed to reasonably improve the signal-to-noise ratio of ultrasonic detection signal. The results of laboratory test and field application show that the sensor can accurately detect and locate the partial discharge of covered conductor overhead distribution networks.

1. Introduction

With the continuous development of social economy, the demand and quality requirements of electric power are gradually increased. Therefore, it is very important to improve the stability and safety of distribution network[1]. As a bridge between substations and power users, distribution lines are an important part of the distribution network. Its running condition is directly related to the user's use of electricity [2]. Insulated overhead lines in the distribution network have been widely used due to their high stability, good safety, low construction costs and low maintenance costs [3-5]. In the use of overhead insulated lines, the weather, external branches and external stress may cause deterioration of insulation. Further, the entire insulation fails and a power outage occurs. Therefore, the detection of the insulation state of overhead insulated lines is of great significance [6]. Partial discharge is an early phenomenon of insulation degradation. When a partial discharge occurs, it is accompanied by temperature rise, chemical changes, ultrasonic phenomena, and electromagnetic wave phenomena [7-10]. In the past few years, China's power sector has used ultrasonic sensors to conduct discharge detection and positioning of overhead insulated wires. The results show that the ultrasonic detection method can effectively find the insulation fault on the distribution network [11].
At present, the most widely used ultrasonic sensors in domestic power systems are ultrasonic sensors such as EA Technology in the UK and MSI in Korea. Their common feature is the ability to accurately detect and locate short-range ultrasound sources. However, as the distance between the sensor and the ultrasound source increases, its detection sensitivity and directivity decrease significantly. For the partial discharge ultrasonic inspection of insulated overhead lines, workers often only perform ultrasonic testing at distances of several tens of meters from the line. In this case, the above sensor has been difficult to detect and locate the ultrasound source. Therefore, ultrasonic sensors used for overhead insulated wires should have high sensitivity and directivity.

Aiming at the above problems, an ultrasonic sensor suitable for the partial discharge detection of insulated overhead lines is designed to improve the sensitivity and directionality of ultrasonic detection under long distance.

2. Ultrasound screening can design
Ultrasound screening can have three main functions: First, it acts as a wave concentrator to improve the intensity of ultrasonic testing. The second is to shield the external interference. The third is to ensure that the ultrasonic sensor has directionality and achieve the positioning of the ultrasonic source.

Through simple mathematical analysis, it can be proved that when the inner surface of the ultrasonic screening can is parabolic, all the normal incident parallel ultrasonic waves can be concentrated to the focal point of the parabola through the reflection of the inner wall of the ultrasonic screening can. Therefore, the surface of the ultrasonic screening can is set to a parabolic shape, which can maximize the wave collecting performance of the ultrasonic sensor, as shown in Figure 1. depends on the size of the piezoelectric crystal. The plane of the piezoelectric crystal must be above the parabolic focus. The size of the reference ultrasonic probe d2 is 1cm. Other screening can parameters are shown in Table 1.

| Parameters | Parameter values |
|------------|------------------|
| d1         | 5cm              |
| d2         | 1cm              |
| h          | 28cm             |
| Material   | Carbon fiber (smooth surface) |

All normal incident ultrasound waves from screening can will converge on the surface of piezoelectric crystals. Therefore, the expression of the amplification factor $\beta$ of the signal amplification capability of the ultrasound screening is as follows:
As can be seen from the formula, the signal amplification capability of the ultrasound screening can depends on the ratio of the ultrasound screening can entrance to the square of the radius of the upper surface of the piezoelectric crystal.

The ultrasonic screening can simulation model corresponding to the parameters of Figure 1 was established by using COMSOL finite element simulation software. The internal space medium of the ultrasonic sensor is air. The inner wall is a smooth carbon fiber material, and the entrance is a plane wave radiation condition. The incident parallel ultrasound frequency is 40kHz and the direction is inward. The pressure amplitude is set to 0.2 Pa. It is assumed that the ultrasonic waves that reach the surface of the piezoelectric crystal are all converted into electrical energy. Therefore, the piezoelectric crystal surface is set as the absorption boundary, that is, ultrasound wave does not reflect on this surface. The cloud diagram of sound pressure intensity distribution of simulation results is shown in Figure 8. As can be seen from the figure, there is an obvious sound field concentration phenomenon on the surface of piezoelectric crystal. After calculation, the average sound pressure of the surface of the piezoelectric crystal was 5.56 Pa. Compared with the incident sound pressure of 1 Pa and the amplification factor of 27.8, the ultrasonic intensity is greatly improved. However, it can be clearly seen from the figure that the uneven distribution of sound pressure is apparent on the surface of the piezoelectric crystal. The reason is analyzed. This is mainly because the sound waves emitted from the inner surface of the screening can will converge to the focus. Therefore, the closer to the focus, the greater the sound pressure. To explore the directional characteristics of the ultrasonic screening can, the direction of the incident ultrasonic wave is changed, the incident intensity is kept constant, and the average sound pressure intensity of the piezoelectric crystal surface is calculated. The result is shown in Figure 2(b). It can be seen from the figure that as the incident angle increases, the ultrasonic detection intensity shows a significant downward trend. When the incident angle is greater than 10 degrees, the ultrasonic detection intensity drops sharply. It shows good directionality and shielding.

\[
\beta = \frac{\pi d_2^2}{\pi d_1^2}
\]  

(1)

In addition, theoretical analysis shows that the ultrasonic signal passed in different positions at the ultrasonic screening can entrance may appear traveling standing wave phenomenon on the surface of piezoelectric crystals due to the different time that the ultrasonic signal is transmitted to the piezoelectric crystal surface. For incident waves of different frequencies, the phase difference is different. Therefore, the detection intensity of incident wave at different frequencies is different. Combined with the frequency band of the conditioning circuit, the difference of the detection intensity of the piezoelectric crystal in the frequency range of 36 Hz ~ 44 Hz is calculated, as shown in
Figure 3. It can be seen from the figure that as the frequency increases, the detection intensity shows a downward trend. However, the variation can be ignored relative to the detection intensity. Therefore, it can be generally considered that the intensity of in-band ultrasonic detection is consistent.

![Graph of ultrasonic intensity vs. frequency](image)

Figure 3 The relationship between ultrasonic intensity and frequency

3. Design of sensor conditioning circuit

3.1. Selection of ultrasonic probe
Ultrasound probes have three main performance indicators: temperature, frequency and sensitivity. These three indicators are determined by the piezoelectric crystal in the ultrasonic sensor. The ambient temperature detected by ultrasonic testing of overhead insulated wires is equal to the outdoor room temperature. The temperature range is from 0 ~ 40 °C. The operating temperature of the selected ultrasound probe can cover this temperature range. When the ultrasonic wave propagates in the air medium, the attenuation degree is approximately proportional to the square of frequency. Therefore, when the ultrasonic wave generated by the partial discharge of the insulated overhead wire propagates to the ultrasonic sensor, the high-frequency component has almost completely attenuated. Studies have shown that the center frequency of the ultrasonic signal generated by partial discharge in air is 40 kHz [12]. Therefore, an ultrasonic probe with a piezoelectric crystal center frequency of 40 kHz should be selected. The sensitivity of an ultrasound probe depends on the electromechanical coupling coefficient of the piezoelectric crystal. The electromechanical coupling coefficient essentially depends on the properties of piezoelectric material itself. The definition of electromechanical coupling coefficient $K$ is:

$$K^2 = \frac{W_e}{W_m}$$  \hspace{1cm} (2)

In the formula, $W_m$——the mechanical energy absorbed by a piezoelectric crystal; $W_e$——electrical energy converted from mechanical energy.

In summary, high-sensitivity ultrasound probes are selected as much as possible while ensuring temperature range coverage and frequency requirements. Under the premise of satisfying all the above requirements, the SR40M ultrasonic probe has a peak sensitivity of $\geq-75$dB, which satisfies the requirements for ultrasonic testing of overhead insulated wires. The detailed technical parameters are shown in Table 2.

3.2. Conditioning circuit design
The conditioning circuit consists of preamplifier, band-pass filter, program-controlled gain amplifier and signal acquisition and control system. From these four aspects, conditioning circuit is designed. The basic schematic diagram of conditioning circuit is shown in Figure 4.

When the ultrasonic wave generated by the partial discharge of the overhead insulated wire is transmitted to the ultrasonic probe, the intensity is greatly attenuated. When the detection distance is very long, the voltage level detected by the ultrasonic probe is even as small as μV. Therefore, the
The voltage signal is preamplified. The selection of preoperational amplifiers should follow the following principles: high input impedance, high magnification, low input noise, low misalignment voltage, low misalignment and low bias current, and low temperature drift. Combining the above factors, the low-noise full-difference operational amplifier LT6600 is selected. The LT66004 has a high input impedance. The high common mode rejection ratio is 111 dB. The low input noise is 1.8 nV/√Hz. The low offset voltage is 5 μV. The low offset current is 10 nA. The low bias current is ±10 nA. The low temperature drift is 0.2 μV/°C. The gain bandwidth product is 12 MHz. The magnification of the preamplifier is set to 100 times. The preamplifier circuit is shown in part A of Figure 4.

Using the Multism circuit simulation software, the parameters of the simulation circuit shown in Figure 4 are established. The amplitude-frequency characteristics of the conditioning circuit are shown in Figure 5(a). It can be seen from the figure that the center frequency of the conditioning circuit is 40 kHz, and the -3dB bandwidth is 38 kHz~42 kHz. The amplitude of the input signal is changed. The magnification of the programmable gain amplifier is measured. The results are shown in figure 5(b). It can be seen from the figure that when the amplitude of the input signal is less than 1 mV, as the amplitude of the signal is weakened, the amplification factor of the conditioning circuit is gradually increased to ensure the detection sensitivity of the small signal.

4. Laboratory test and field application

4.1. Laboratory test

The performance of the super-sensor is mainly evaluated from two aspects: sensitivity and directionality. Due to the instability of the ultrasonic source in the field test, the test results at different times are not comparable. Therefore, the experimental platform is built in the laboratory. The
The experimental platform is mainly composed of two parts: a constant pulse ultrasonic source and an ultrasonic sensor, as shown in Figure 6.

The constant ultrasonic source emits a single pulse ultrasonic signal with a center frequency of 40 kHz and a constant ultrasonic intensity, and suspends the ultrasonic source 8 m above the ground. The ultrasonic sensor is placed on the ground. On the ultrasonic sensor, an infrared range finder and a gyroscope are installed. The infrared range finder is used to measure the linear distance between the ultrasonic sensor and the ultrasonic source. The gyro is used to detect the deviation of the ultrasonic sensor from the ultrasonic source. The specific implementation method is to calibrate the orientation of the ultrasonic source by an infrared range finder, and record the orientation at this time by the gyroscope. When the orientation of the ultrasonic sensor changes, the angular deviation of the sensor from the direction of the ultrasonic source can be read by the gyroscope.

The emission intensity of the ultrasound source remains unchanged. The infrared range finder is used to make the ultrasonic sensor face the ultrasonic source. The distance between them and the orientation of the sensor are changed. The measurement results are shown in Figure 7. As can be seen from Figure 7(a), as the detection distance increases, the ultrasonic intensity attenuates sharply. As the angular deviation increases, the intensity of the ultrasonic detection drops sharply. Figure 7 (a) and Figure 7 (b) are compared. It can be found that ultrasonic screening can significantly improve the intensity and directionality of ultrasonic testing, thereby improving the anti-jamming capability of the sensor. Under the condition of ultrasonic screening can, the voltage waveforms of the input and output of the conditioning circuit under 50m distance are detected. The results are shown in Figure 8. As can be seen from the figure, the ultrasonic signal at the input end has been submerged in the noise. However, after filtering and amplifying by the conditioning circuit, the ultrasonic signal can be accurately detected.
4.2. Field application
The designed ultrasonic sensor was used to inspect the 10kV overhead insulated wire of the distribution network for 10km. The ultrasonic sensor is facing the overhead insulated line. When the ultrasonic sensor gives an alarm (the threshold can be set artificially), the position of the ultrasonic sensor remains unchanged. The orientation of the ultrasonic screening can is changed to find the strongest ultrasonic signal. Combined with infrared rangefinder, the location of ultrasonic source is determined.

During the line inspection, it was found that the ultrasonic intensity was the strongest when the sensor was facing the red circle mark of Figure 9(a). Therefore, a close-up photograph of Figure 9(a) is performed using a visualized camera. The result is shown in Figure 9(b). It can be seen from the figure that in the red circle mark, the A-phase arrester of the overhead insulated wire is too close to the wire (the wire skin is also damaged), so that the insulation spacing is insufficient, resulting in partial discharge, and then ultrasonic signals appear. To verify the effectiveness of the sensor under remote testing, the ultrasonic sensor is directed at the discharge. The distance between the sensor and the source of the fault is gradually increased. An infrared ranging aid is used to measure the position of the sensor and the discharge source. When the distance between the sensor and the power supply is 50m away, the ultrasonic intensity is significantly reduced, but the sensor can still detect the obvious ultrasonic signal.

5. Conclusion
Based on the analysis of the problem of long-distance ultrasonic testing of insulated overhead lines in distribution network, an ultrasonic sensor with high sensitivity and directionality was designed. The development of the ultrasonic sensor is mainly divided into two parts: the development of the super god screening can and the design of the conditioning circuit. Through theoretical analysis and COMSOL finite element simulation software, an ultrasonic screening can with good convergence
performance and strong directionality is designed. The conditioning circuit mainly includes pre-differential operational amplifier, programmable gain operational amplifier, narrow bandpass filter, and acquisition control system. The detection sensitivity of the ultrasonic sensor is ensured under long distance conditions. In field applications, the sensor can be used with infrared rangefinders, ultra-high frequency coils and cameras to improve the efficiency of detection and positioning of overhead discharges. Laboratory tests and field application results show that the sensor can be effectively used to detect insulation defects in insulated overhead lines.

Acknowledgments

This research was partially supported by Science and technology project of State Grid Corporation of China grant: 521104180025.

References

[1] Zhao Chenxu, Sun Minghao and Hanyu, "Distribution networks distribution network condition based maintenance application present situation and development," 2014 China International Conference on Electricity Distribution (CICED), Shenzhen, 2014, pp. 396-398.

[2] Z. Wang et al., "A Full-Scale Experimental Validation of Electromagnetic Time Reversal Applied to Locate Disturbances in Overhead Power Distribution Lines," in IEEE Transactions on Electromagnetic Compatibility, vol. 60, no. 5, pp. 1562-1570, Oct. 2018.

[3] Pihler J and Ticar I 2005 Design of systems of covered overhead conductors by means of electric field calculation IEEE Trans. Power Del. 20 807–14.

[4] V. Zimackis and S. Vitolina, "Simulation of direct lightning strike in medium voltage covered conductor overhead line with arc protection device," 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, 2017, pp. 1-4.

[5] M. Borecki, J. Starzyński and Z. Krawczyk, "The comparative analysis of selected overvoltage protection measures for medium voltage overhead lines with covered conductors," 2017 Progress in Applied Electrical Engineering (PAEE), Koscielisko, 2017, pp. 1-4.

[6] W. He, H. Sun, H. Li, D. Liang, Z. Sun and B. Liu, "A Novel Time Alignment Technique for Online PD Location in Covered Conductors," in IEEE Transactions on Power Delivery, 31(6), 2016: 2559-2561.

[7] C. Chou and C. Chen, "Measurement and analysis of partial discharge of high and medium voltage power equipment," 2018 7th International Symposium on Next Generation Electronics (ISNE), Taipei, 2018, pp. 1-4.

[8] V. Basharan, W. I. Maria Siluvairaj and M. Ramasamy Velayutham, "Recognition of multiple partial discharge patterns by multi-class support vector machine using fractal image processing technique," in IET Science, Measurement & Technology, vol. 12, no. 8, pp. 1031-1038, 11 2018.

[9] M. Isa, G. M. Hashmi and M. Lehtonen, "Comparative study of on-line three phase PD monitoring systems for overhead covered conductor distribution lines," 2009 44th International Universities Power Engineering Conference (UPEC), Glasgow, 2009, pp. 1-5.

[10] S. Misák, J. Fulnećek, T. Vantuch, T. Burianek and T. Jezowiec, "A complex classification approach of partial discharges from covered conductors in real environment," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 24, no. 2, pp. 1097-1104, April 2017.

[11] Q. Xie, T. Li, J. Tao, X. Liu, D. Liu and Y. Xu, "Comparison of the acoustic performance and positioning accuracy of three kinds of planar partial discharge ultrasonic array sensors," in IET Radar, Sonar & Navigation, vol. 10, no. 1, pp. 166-173, 1 2016.

[12] Q. Xie, T. Li, J. Tao, X. Liu, D. Liu and Y. Xu, "Comparison of the acoustic performance and positioning accuracy of three kinds of planar partial discharge ultrasonic array sensors," in IET Radar, Sonar & Navigation, vol. 10, no. 1, pp. 166-173, 1 2016.