Research on Overvoltage Monitoring Technology for Transmission Lines

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Abstract: Overvoltage is one of the important factors that cause line tripping and equipment damage. Accurate monitoring of transmission line overvoltage is of great significance for safe operation of power grid. In this paper, a transmission line overvoltage sensor based on the principle of coupled capacitance partial voltage is designed. The high voltage arm capacitance of the sensor is the stray capacitance between the sensor metal sheet and the earth, and the low pressure arm capacitance is the coupling capacitance between the sensor metal sheet and the wire. At first, the structure characteristics and sensor principle of the sensor are described, and the parameters of the sensor are calculated. The results show that the sensor has high detection accuracy and can realize overvoltage monitoring of transmission lines.

1 Introduction
Experience at home and abroad shows that transmission lines are frequently exposed to overvoltage hazards during actual operation, which can easily lead to equipment damage or even serious accidents[1-3]. Although overvoltage suppression and preventive measures have been taken during operation, faults caused by overvoltage still occur from time to time[4]. The main reason for this phenomenon is the lack of efficient and reliable monitoring technology, which cannot accurately know the magnitude of overvoltage and the characteristics of the waveform, so that the design of insulation coordination is lack of basis, and the safe operation of the equipment cannot be reliably guaranteed[5-8]. The accurate acquisition of overvoltage characteristics in the actual operation of transmission lines can provide data support for the accident analysis and the optimization of insulation coordination, and help to reduce the occurrence of overvoltage accidents. Therefore, an efficient and reliable monitoring technique is urgently needed[9-10].

Paper[11] uses a shunt capacitor voltage divider to obtain the overvoltage signal on the generatrix. This method has high measurement precision and excellent frequency response of the sensor. However, the divider needs to run in parallel for a long time and is only suitable for 35kV and below voltage level system. Paper [12] introduces the use of electromagnetic voltage transformer to extract overvoltage signals, which is easy to saturate, and it is easy to produce serious distortion and saturation in high frequency response, as a result, it is difficult to accurately monitor the high frequency overvoltage signal. Paper [13-14] introduced a fiber-optic voltage sensor based on photoelectric effect. The sensor is light weight, high precision, and wide frequency band. However, this sensor has poor long-term operation stability and is difficult to be widely used.

Based on the principle of coupling capacitance and partial pressure, a new type of voltage sensor is
designed in this paper. The high voltage arm capacitance of the sensor is the stray capacitance between the sensor metal plate and the earth, and the low pressure arm capacitance is the coupling capacitance between the sensor metal sheet and the wire. The principle of the sensor is analyzed, the reasonable parameters are calculated, and then the lightning impulse characteristic is tested. The result shows that the voltage sensor can monitor the overvoltage of the transmission line.

2 Principle of voltage sensor
Figure 1 is a schematic diagram of the overvoltage monitoring principle described in this paper. The sensor and monitoring terminal are installed on the conductor of the measured transmission line. The coupling capacitance \( C_1 \) between the sensor metal sheet and the high voltage conductor is the low voltage arm capacitance, and the \( C_2 \) of the sensor metal plate to the earth coupling capacitance is the high-voltage arm capacitance. In Figure 1, 4 is a metal shielding shell with good conductivity. It has been specially treated with corona prevention and has good waterproof and dust-proof functions. The monitoring terminal is installed inside the metal shielded shell. The monitoring terminal collects data and sends it to the central station through wireless 3G/4G, and then the central station processes the collected data and outputs the final result.

3 Sensor parameter calculation
The value of the coupling capacitor is related to the shape, size, spatial arrangement of the electrodes and the medium distributed between the electrodes. In engineering applications, numerical calculation method is often used to determine the capacitance value, such as surface charge method, finite element method, and analog charge method and so on.

The sensor metal sheet used in this paper is an arc-shaped strip with a width of \( a \), a radius of arc \( R \), and an arc angle of \( \alpha \). The conductor radius is \( r \). The metal plate is coaxial with the conductor, and the metal piece is regarded as part of the cylindrical surface of the coaxial cylindrical capacitor. It can be concluded that

\[
C_1 = \frac{a}{2\pi} \times C
\]  

(1)

\( C \) is the capacitance per unit length of the coaxial cylindrical capacitor, which is

\[
C = \frac{2\pi\varepsilon_0}{\ln R_2 - \ln R_1}
\]  

(2)

Where \( R_2 \) and \( R_1 \) are the outer conductor and inner conductor radius respectively. Further expressions can be derived through formula (1) and (2):

\[
C_1 = \frac{aa\varepsilon_0}{\ln R - \ln r}
\]  

(3)

When \( a \) takes 1cm, \( a=\pi/3 \), \( R \) and \( r \) take 5cm and 1cm respectively, \( C_1=0.093\text{pF} \) is obtained.
through formula (3).

Because of the irregular shape of the capacitance plate and the earth, it is difficult to obtain the exact value of \( C_2 \). According to the calculation results of paper[11], the estimated \( C_2 \) range is about 1pF~3pF.

In order to measure the overvoltage about 500kV, it is necessary to increase the capacitance of the low voltage arm. After many times of estimation and testing, finally, a 0.1\( \mu \)F capacitor \( C_M \) is connected at both ends of the \( C_1 \).

From the equivalent circuit of the sensor, the sensor is a pure capacitance sensor, which is not good at high frequency response, and high frequency oscillation is easy to occur when measuring high frequency voltage signal.

In order to improve the high-frequency response characteristics, a series damping resistor is in series to the capacitor to eliminate the high-frequency oscillation. The series resistance value is determined as follows:

\[
R_s = (0.25 \sim 1.5) \sqrt{\frac{L}{C_0}}
\]

\( L \) is the high voltage wire inductance, its value may take 0.94\( \mu \)H. \( C_0 \) is approximately equal to the high voltage arm capacitance \( C_2 \), which is approximately equal to 1 pF, and \( R_s = 242 \sim 1454\Omega \) is obtained at this time.

Wires, metal shields, and ground potentials of the collection circuit are equipotentially connected and the potential is 0. The actual earth can be considered as a high-potential conductor. The equivalent circuit of sensor is shown as Figure.2.

![Figure 2. Equivalent circuit of sensor](image)

Where \( U_1 \) is the high voltage conductor operating voltage. The actual partial pressure ratio is:

\[
k = \frac{U_1}{U_2} = \frac{2(C_M + C_2)}{C_2} \approx \frac{2C_M}{C_2}
\]

4 Experimental studies and analysis

4.1 Test layout

In order to obtain frequency response characteristics and measurement linearity of the sensor, the power frequency and lightning impulse withstand voltage tests were carried out on the sensor. The test layout is as shown in the following figure.
In Figure 3 above, the test wire is a steel tube with an outer diameter of 5.1 cm and a length of 5 m. Both ends of the test wire are suspended under the crane by insulation ropes. A 5 m * 5 m aluminum plate was placed directly below the test wire to simulate the ground. The sensor and monitoring terminal are fixed on the test conductor, and the terminal shell and the grounding circuit of the acquisition circuit are connected with the test wire. In the test, voltage is applied to the test wire by the experimental power supply, which can be measured by an oscilloscope after a standard voltage divider with a voltage division ratio of 1000, besides, voltage will be collected by the monitoring terminal and sent to the background center for analysis. The test power supply includes a rated voltage of 1000 kV, a capacity 1000 kVA power frequency test transformer, and an impulse voltage generator of rated voltage ±2400 kV.

4.2 Test results of frequency voltage
For the first measurement, apply 303.3 kV to the test wire, the voltage rms on the test wire measured by the sensor is 451.6 kV with a deviation of 49%. The main reason is the inaccurate estimation of the high-voltage arm capacitance $C_2$, which is smaller than the actual capacitance. Modify the ratio of the sensor according to the measured data, and the modified ratio is $k = \frac{200000}{451.6 \times 303.1} = 134233$. The power frequency voltage test is carried out after modifying the transducer's ratio. Compare the results of the sensor and the oscilloscope, as shown in Table 1 below:

| number | results of the oscilloscope /kV | results of the sensor/kV | deviation /% |
|--------|---------------------------------|------------------------|-------------|
| 1      | 151.11                          | 142.67                 | 5.52        |
| 2      | 247.73                          | 236.68                 | 4.46        |
| 3      | 339.52                          | 322.15                 | 4.97        |
| 4      | 466.14                          | 475.88                 | 2.12        |
| 5      | 551.32                          | 565.01                 | 2.54        |

It can be seen from the above table that the measured value of the power frequency voltage of the sensor is close to the standard value after the calibration, and the error is within 6%. In addition, the waveform uploaded by the monitoring terminal is basically the same as that of the oscillograph, indicating that the power frequency voltage response characteristic of the sensor is good.

4.3 Test results of lightning impulse voltage
The standard 1.2/50 μs lightning impulse voltage of different voltage is applied on the test wire, and the impulse voltage is collected synchronously by oscilloscope and sensor. The waveforms are shown as Figure 4 (a), (b).
The amplitude of the oscillograph waveform is 326kV, and the amplitude of the sensor is 319kV and the deviation is 2.15%. The wave head time and wave tail time of the sensor are 1.5μs and 46μs respectively, which are similar to the waveform of the oscillograph, which indicates that the high frequency response characteristic of the sensor is good and can be used to measure the overvoltage of the transmission line. A variety of different amplitudes of the lightning impulse overvoltage test is performed on the sensor. Amplitude of waveform measured by oscillograph and sensor are as shown in Figure 5.

When the amplitude of lightning overvoltage is less than 150kV, the maximum measurement error is 12.9%. When the amplitude exceeds 220kV, the average measurement error is less than 3%. It can be seen that for the measurement of higher amplitude overvoltage, the sensor has higher measurement accuracy, which can meet the measurement of 500kV transmission line overvoltage.

5 Actual application
Monitoring terminals are installed on the conductor of a 500kV transmission line, as shown in Figure 6 below.

Since the installation of the monitoring device, some overvoltage data have been collected. An example of the tripping fault caused by floater in this circuit is given. The voltage waveforms are shown in Figure 7 below.
an the operating voltage, in addition, the instrumentation, Zhang Zhaoyang, ... 100 300 400. Figure. 7 (a) is the power frequency voltage before fault occurrence with an amplitude of about 410kV, which is in line with the actual voltage of the 500kV line. Figure 7 (b) is the transient voltage at fault time, its amplitude is about 350kV, slightly lower than the operating voltage, in addition, the pulse width is wide, its frequency is far lower than the lightning overvoltage, which is in line with the typical non lightning fault characteristics.

6 Conclusion
1) The sensor has high measuring accuracy, it can not only measure the power frequency voltage, but also measure the lightning impulse voltage. Theoretically, it can be applied to overvoltage monitoring of all voltage grade transmission lines.
2) After the installation of monitoring terminals, a non-lightning fault voltage has been monitored, indicating that this technology can meet the actual operation requirements and has a good practical engineering application value.

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