Study on Measurement Error of Power Frequency Electric Field Intensity Caused by Change of Air Dielectric Constant with Humidity

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Abstract: People are paying more and more attention to the influence of power frequency electric field on their living environment, so the measured value of power frequency electric field under AC transmission line becomes an important reference for judging whether the surrounding environment is polluted or not. In actual measurement, it is found that the measured value of electric field intensity in high humidity areas is often relatively large. This paper will investigate the influence of the change of air dielectric constant on electric field measurement. Through experiments and simulations, it is found that air dielectric constant increases with the increase of humidity, which increases rapidly before the ambient humidity reaches 75%, and increases slowly after the ambient humidity exceeds 75%. However, it was found by simulation that the change of air dielectric constant has no obvious influence on the surrounding electric field intensity. Therefore, the change of air dielectric constant is not the main factor leading to relatively large measured value of field intensity in high humidity areas.

1. Introduction
With the rapid development of national economy, the scale of power grid increases with the increase of social demand for electricity. Living line corridors have also become a common sight everywhere. Electromagnetic radiation under high-voltage transmission lines has attracted attention from all walks of life, and electric field intensity, as an important index of magnetic field measurement, is widely used in electromagnetic environment monitoring. Therefore, it is of great significance to study the measurement of the power frequency electric field under high-voltage lines for environmental protection.

As early as 1990s, the State Environmental Protection Administration promulgated the Technical Regulations on Environmental Impact Assessment of Electromagnetic Radiation Produced by 500 kV Ultrahigh Voltage Transmission and Transfer Power Engineering (HJ/T24-1998) [1]. The standard combines the whole actual situation of China with the latest research results of developed countries at that time. The proposing of the standard has important guiding significance for evaluating the impact of power transmission and transformation engineering on electromagnetic radiation environment. However, the standard give no consideration to the influence of topography, climate, especially humidity on the measurement of power frequency electric field intensity [2-3]. A large number of practices have proved that the measured value of power frequency electric field increases with the increase of measurement ambient humidity, especially in areas with high ambient humidity, such as
Sichuan Basin and Shanghai. Therefore, it is of great significance to carry out subject research on the influence of humidity on electromagnetic environment around high-voltage overhead transmission lines.

At present, scholars’ researches mainly focus on the influence of insulation support of measuring instrument on the measurement of electric field intensity. Zhang Guangzhou’s team proved that humidity does not change the distribution of electric field; it is the insulation support that changes the distortion degree of electric field. However, humidity will cause the material characteristics of the insulation support to change, thus indirectly changing the electric field distribution [4]. Taking a wooden support as an example, the measurement results of the field intensity measuring instrument above it increase exponentially with the increase of the humidity around the transmission line. For supports made of hydrophobic materials such as epoxy resin and polytetrafluoroethylene, the measurement results of the field intensity meters above them will have a larger error rate when the environmental relative humidity is greater than 60% [5]. To sum up, the domestic research mainly focuses on the influence of the material characteristics of the insulation support for measuring instrument on the measurement of electric field intensity, but there is still no final conclusion reached on whether the air capacitance has an influence on the measurement of electric field.

In order to describe the influence of ambient humidity on the measurement of electric field intensity, this paper takes the air capacitance around the measuring instrument as the research index and carries out quantitative analysis. The experimental environment for measuring air capacitance under different humidity is established. A 3D model of transmission line and measuring instrument is established to simulate the actual environment in measurement, and the air capacitance measured in the experiment under different humidity is brought into the model parameters. The finite element simulation software is used to solve the actual electric field intensity of the measuring instrument under the power frequency electric field, and the variation rule of the electric field intensity around the measuring instrument under different humidity is simulated. Taking the influence of water molecule content in different humidity on air capacitance as a bridge, the influence of ambient humidity on electric field measurement is explored. The results of surrounding electric field are calculated through COMSOL simulation, and the calculated results are compared with the actual situation and analyzed. [5]

2. Test Methods

2.1. Working principle of electric field measuring instrument

At this stage, the measuring instrument of power frequency electric field used in actual environmental assessment and monitoring at home and abroad is mainly suspension field intensity meter. This measuring instrument measures the induced charge and power frequency induced current between two parts of an isolated conductor. Field intensity meter is usually composed of probe, optical fiber, test circuit, display unit and so on, which is used to measure space electric field. In practice, the sampling resistance of field intensity meter and the voltage of the two parts form a closed circuit, and induced current is obtained from the circuit. The induced current can be obtained by measuring the voltage of the sampling resistance. Finally, the power frequency electric field value is measured by using the corresponding relationship between field intensity and current. A suspension field intensity meter used commonly is shown in Figure 1. As shown in Figure 1A, the effective value of the induced charge on the hemisphere of the spherical probe is Q, and Formula (1) is satisfied.

$$Q = 3\pi\varepsilon_0 r^2 E$$  \hspace{1cm} (1)

Where, E is the effective value of the uniform electric field intensity, and r is the radius of the spherical probe.

The induced current can be derived from the charge differentiation of the electronic circuit

$$I = \frac{dQ}{dt} = 3\pi\varepsilon_0 \omega r^2 E$$  \hspace{1cm} (2)

Where, $\omega$ is the angular frequency and f is the frequency.

If the field intensity meter has a parallel probe, then Formula (3) can be used:
\[ I = K \omega E \] (3)

Where, \( K \) is a constant, which is related to the geometry of the parallel probe and determined by calibration coefficient. In a low humidity environment, field intensity meter itself has a certain calibration function of indication error. When the ambient humidity is high, the accumulated water molecules in the air increase, the conductance of the whole equipment to the ground increases, making the impedance between the probe and the ground and the line decrease. The exterior of the probe is sealed, and only the capacitance exists in the sensing electrode inside the probe. The proportion of the capacitance in the whole capacitance of the system increases, which makes the reading of measurement become larger. Under the condition of high humidity, leakage current may appear in field intensity meter. A condensation layer may be formed between the two sensing electrodes of field intensity meter. And the appearance of the condensation layer will lead to a local short circuit in the measurement circuit, which will make the measured value of the induced current relatively larger, thus making the measured value of electric field intensity relatively larger. In a low humidity environment, field intensity meter itself has a certain calibration function of indication error. The calibration conditions to be satisfied are: ambient temperature 15-30°C, relative humidity 45%-75%, and no external electromagnetic field interference. After calibration, the indication error is not more than ±1.5dB, and the change of the measured value of electric field intensity caused by the change of frequency between 30Hz and 2000Hz is less than or equal to ±3dB. In the actual measurement, it is also found that when the humidity is more than 75%, the measurement error of field intensity meter increases obviously. Therefore, the cause of this phenomenon is worthy of quantitative analysis.

![Figure 1 Common Field Intensity Meter Probe](image)

2.2. Test platform

In order to simulate the change of air capacitance caused by the change of water molecule content in the air, the two 40*40cm tin metal plates used for measuring air capacitance were pretreated in a constant temperature humidity chamber. Set the temperature of the constant temperature humidity chamber at 30°C, and record the capacitance between the parallel plates during the experiment when the ambient humidity increases from 68% to 90%. The experimental setup is shown in Figure 3. Place the positive and negative electrodes of the capacitance tester beside the upper and lower plates respectively, and conduct zero calibration for the instrument before connecting the plates to avoid the influence of conductor capacitance on the measurement of air capacitance. Start recording the air capacitance values after completing zero calibration. Take 30s as a sampling cycle to complete sampling. Sample the air capacitance values from ambient humidity 90% to ambient humidity 68%, with 40 sampling points in each group. Five measurements were completed in this paper, and the average value of the five measurement results was taken as the sampling value of the result. The distance between two plates was 0.5cm. Use the parallel plate capacitance formula
\[ C = \frac{\varepsilon S}{4\pi kd} \]

Where, \( S \) is the area of the parallel plate capacitor, \( k \) is the electrostatic constant, \( d \) is the distance between the two plates, and \( \varepsilon \) is the dielectric constant. Deduce the value of \( \varepsilon \) changing with the temperature, and substitute the \( \varepsilon \) value into the simulation model to get the relationship of electric field intensity.

3. Test Results and Simulation

3.1 Rule of Variation of capacitance with humidity

In the experiment, put the two parallel tin metal plates with an area of 40cm*40cm in a constant temperature humidity chamber. Before the experiment, set the temperature and humidity in the
chamber to 30℃ and 65%, respectively. At the same time, turn on the capacitance measuring instrument and conduct zero calibration for it. Start the experiment when the temperature in the chamber gets stabilized at 30℃ and the humidity is 65%. During the experiment, set the humidity to 90% without changing the temperature, and record the change of capacitance during humidity climbing. After finishing five complete experiments, average the experimental data. The relationship between dielectric constant and humidity is shown in Figure 3. From Figure 3, it can be seen that when the ambient humidity was lower than 75%, the capacitance was more affected by the change of ambient humidity, and when the ambient humidity was higher than 75%, an inflection point of the rise of the curve would appear, and the capacitance would be less affected by the change of ambient humidity. However, with the increase of humidity, the capacitance would not change much. Before the humidity increased to 75%, the capacitance growth rate was 17.7%. When the humidity was between 75% and 90%, the capacitance growth rate was 0.67%.

Figure 4 Relationship between Capacitance and Ambient Humidity

3.2 Influence of humidity on dielectric constant

According to Formula (4) and the relationship between dielectric constant ε and capacitance, the variation rule of dielectric constant when the humidity is between 68% and 90% can be calculated. As shown in Figure 4, the change curves of dielectric constant and capacitance are similar, and the inflection point of data is at 75% humidity. When the ambient humidity was less than 75%, the dielectric constant varied relatively more with the humidity. When the ambient humidity rose from 68% to 75%, the growth rate of dielectric constant was 20.7%, and when the ambient humidity changed from 75% to 90%, the dielectric constant changed relatively slowly, and its growth rate was 1.17%.

Figure 5 Relationship Between Dielectric Constant and Ambient Humidity
3.3 Simulation of electric field intensity

In order to restore the scene of electric field intensity measurement to the maximum extent, this paper used COMSOL software to build a 3D model of transmission line and measuring instrument, and calculated the electric field distribution nephogram under the transmission line with different air dielectric constants. Structurally, the upper cylinder in the model was the transmission line, and the field intensity meter supported by an insulation support made of ABS resin was placed under the transmission line. The lowest small cylinder was the ground. The whole model was wrapped by an infinite element domain. As shown in Figure 6.

![Figure 6 COMSOL Structure Model](image)

In this paper, the electric field intensity measurements at humidity of 70%, 80% and 90% were selected, and the electric field distribution nephogram had no obvious change. According to the data table, when the humidity rose from 68% to 90%, the electric field intensity had no change, which is within the measurement error range of the field intensity meter. Therefore, the change of air dielectric constant has no obvious influence on electric field measurement.

![Figure 7 Electric Field Distribution Nephogram](image)

4. Discussion and Analysis of Results

4.1. The distribution of power frequency electric field has no relation to humidity

When studying the distribution of the power frequency electric field under a transmission line, the line and the earth, as a whole, can be regarded as a capacitor approximately. When a line is erected parallel to the ground, the capacitance value is only related to the height of the line from the ground, the length of the line in the research area and the space medium between them. Under windless and stable conditions, the line–earth capacitance can be defined as:

$$C = \frac{Q}{U}$$

(5)
Where, $Q$ is the amount of charge from the surface of the conductor; $U$ represents the line voltage. When the humidity of the air between the line and the earth increases, the medium between the line and the earth will change from dry air to humid air with a dielectric constant of $\varepsilon_r$. The variation of its capacitance $C$ is:

$$C = \varepsilon_r C_0$$  \hspace{1cm} (6)

In the above formula, $\varepsilon_r$ is the relative dielectric constant of space medium, $C_0$ is the absolute vacuum capacitance.

It can be known from the definition formula of electric field intensity, the field intensity $E(x,y,z)$, generated by the charged charge on the line, at a certain point $M(x,y,z)$ in space is

$$E(x,y,z) = \frac{Q}{2\pi \varepsilon_0} d(x,y,z)$$  \hspace{1cm} (7)

Where, $Q$ is the amount of charge on the wire surface; $d(x,y,z)$ is the distance function from the point charge to Point $M$. By integrating the above three formulas, we can get:

$$E(x,y,z) = \frac{C_0 \varepsilon_r U}{2\pi \varepsilon_0 \varepsilon_r} d(x,y,z) = \frac{C_0 U}{2\pi \varepsilon_0} d(x,y,z)$$  \hspace{1cm} (8)

It can be known from Formula (8) that the space electric field, generated by a finite length transmission line, at a certain point in the space is only related to the spatial position of the point, and has no relation to the spatial medium itself.

Theoretically, the electric field intensity under the power frequency AC transmission line has no direct relationship with humidity. The increase of air dielectric constant with the humidity has no obvious influence on the measurement of electric field, so the interference of air dielectric constant as the main factor on the measurement of field intensity can be eliminated.

4.2. Relationship between relative air humidity and dielectric constant

The water vapor content in air is usually measured by relative air humidity $RH$. The definition formula of air relative humidity $RH$ is shown in Formula (9)

$$RH = \left(\frac{P_{H,O}}{P_{H,O}^*}\right)_{PT}$$  \hspace{1cm} (9)

Where, $P_{H,O}$ is the actual water vapor pressure of air, $P_{H,O}^*$ is the water vapor pressure in saturated air at the same temperature and pressure. Saturation vapor pressure has a certain functional relationship with temperature, so at a certain environmental temperature, saturation vapor pressure is a quantitative constant. [6]

The relative dielectric constant of air is a function of air component bias, and its functional relationship is

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N_A}{RT} \frac{1}{3\varepsilon_r} \Sigma P\alpha_i$$  \hspace{1cm} (10)

Where, $\alpha_i$ is the polarization intensity of various substances in the air. If listing the water vapor pressure separately, Formula (10) can be expressed as

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N_A}{RT \varepsilon_0} \left(P_{H,O} \alpha_{H,O} + \Sigma P_j \alpha_j\right)$$  \hspace{1cm} (11)

According to Formula (11), the corresponding relationship between water vapor pressure $P_{H,O}$ and $\varepsilon_r$ at any environmental pressure and temperature can be solved. In practice, the relative air dielectric constant can be obtained by measuring the water vapor pressure, which follows the formula:

$$\frac{dP_{H,O}}{d\varepsilon_r} = \frac{9RT\varepsilon_0}{N_A \alpha_{H,O}(\varepsilon_r + 2)^2}$$  \hspace{1cm} (12)

When $\varepsilon_r$ shows a small change trend, Formula (12) can be approximately transformed as:
By substituting Formula (12) into Formula (9), the relationship between the change of relative air humidity and the change of relative air dielectric constant under different atmospheric pressures and temperatures can be obtained:

$$\Delta P_{H,O} = \frac{9RT\varepsilon_0}{N_A\alpha_{H,O}(\varepsilon_r + 2)^2} \Delta \varepsilon_r$$

(13)

Since dielectric constant $$\varepsilon = \varepsilon_0\varepsilon_r$$ after substituting it into Formula (14), we can get

$$\Delta RH = \frac{9RT\varepsilon_0}{P_{H,O}N_A\alpha_{H,O}(\varepsilon_r + 2)^2} \Delta \varepsilon_r$$

(14)

Let $$\beta = \frac{9RT}{P_{H,O}N_A\alpha_{H,O}(\varepsilon_r + 2)^2}$$, then Formula (15) can be expressed as

$$\Delta RH = \beta \Delta \varepsilon$$

(15)

(16)

5. Conclusions

1) Air dielectric constant was measured under different humidity by experiments. Through theory and experiment, it was found that air dielectric constant increases with the increase of humidity. The dielectric constant increases obviously before the ambient humidity is 75%, and the inflection point appears when the ambient humidity is 75%, and the increasing trend tends to be flat.

2) Ambient humidity itself has no direct influence on the electric field intensity under power frequency AC transmission lines. Ambient humidity can change air dielectric constant, but the change of air dielectric constant has no actual influence on electric field measurement. When air dielectric constant increases from 0.045(F/m) to 0.055(F/m), the change rate of electric field intensity is only 0.001%. The change of air dielectric constant is not the main factor that causes the actual measured value to be relatively larger.

References

[1] HJ/T 24-1998, Technical regulations on environmental impact assessment of electromagnetic radiation produced by 500 kV ultrahigh voltage transmission and transfer power engineering [S].

[2] Yang Xu, Xiaqing Zhang, Dasheng Yang. Power frequency electromagnetic environment of high voltage transmission line [J]. Journal of Electric Power, 2007, 22 (1): 9-14.

[3] Baba Y, Ishii M. Numerical electromagnetic field analysis on measuring methods of tower surge impedance[J]. IEEE Transactions on Power Delivery, 1999, 14(2): 630-635.

[4] Ishii M, Baba Y. Numerical electromagnetic field analysis of tower surge response[J]. IEEE Transactions on Power Delivery, 1997, 12(1): 483-488.

[5] GB/T 12720-1991 Measurement of power-frequency electric fields [S], 1991

[6] Zhenhui Wang, Xingyou Huang, Shuqing Ma. Atmospheric sounding [M]. Beijing, China: China Meteorological Press, 2011.3:92-93.