

# Method for measuring the electric field strength under UHV/EHV AC/DC parallel transmission lines

YANG Zhaoguang, WEN Dingjun, Gao Lichao, Bao Yanyan, Chen Bodong

(State Grid Gansu Electric Power Research Institute, Lanzhou 730050, China)

**Abstract.** In the measurement of hybrid electric field strength such as electric field under UHV/EHV AC/DC parallel transmission lines, simultaneous measurement of direct current component and ac electric field components is a key problem to be solved. In this paper, an improved method for AC/DC hybrid field strength measuring device (rotary voltmeter) is proposed, and a type of Bernoulli curve stator is designed. After using the new structure, when the rotor is rotating, the stator area exposed to the electric field changes sinusoidally. The mathematical expression of the change of the area is derived from the principle of mathematics, based on this, the spectral characteristics of the output of the measuring equipment under the AC and DC hybrid electric fields are studied. In addition, the corresponding relationship between the AC/DC electric field and the spectrum of the result of the measurement is established. This paper presents a method of measuring the ground electric field of AC/DC parallel transmission lines considering both AC/DC components. A calibration experiment is carried out in DC electric field, which verifies the accuracy and effectiveness of the method.

## 1. Introduction

In recent years, China's land resources have become increasingly tense, with the construction of a large number of UHV transmission lines, it is costly to build new transmission corridors in developed areas. This would require the power industry to increase the utilization of existing transmission corridors to achieve compact transmission. At present, the construction of UHVDC transmission lines and AC transmission lines using the same corridor has appeared, in the design of EHV/UHV transmission lines, the ground electric field intensity is an important principle, therefore, the accurate measurement of the hybrid electric field at the ground of the parallel transmission corridor will play an important guiding role in the design of AC / DC parallel transmission lines.

The most direct and reliable method to study the distribution of hybrid electric field around the AC/DC parallel lines is experimental measurement, however, the existing device for measuring the hybrid electric field, which has a fanshaped stator, cannot accurately measure the hybrid electric field strength.[1-8]

In this paper, based on the deep study of the mechanism of the measurement of ground electric field of DC transmission line, the DC component and AC component of the hybrid field can be obtained by the method of spectrum analysis which provides a valid means for the measurement of AC / DC hybrid electric field strength.

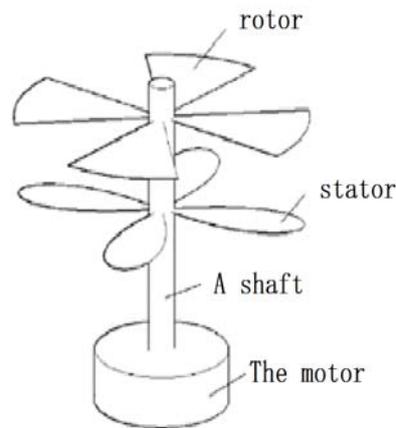
## 2. Hybrid electric field strength measurement method

In order to solve the problem that the hybrid electric field strength cannot be measured accurately, an improved method of hybrid electric measuring device is proposed in this paper. The fanshaped stator is no longer used, and it is replaced by a new stator with the structure of Bernoulli curve. Using the



improved method can accurately measure the DC electric field strength and AC electric field strength. Specific technical solutions are as follows.

The probe of the AC/DC hybrid electric field measuring device consists of 2 discs with a plurality of fan-shaped holes at fixed angles, the two discs are spaced at a fixed distance and are mutually insulated. The upper disc rotates with the shaft and is directly grounded, it is called the rotor. The bottom disc is stationary and is grounded through a resistance, called the stator. Figure 1 shows the schematic diagram of the structure of the rotary voltmeter, when the rotor is rotating, the AC / DC electric field passes through the fanshaped holes in the rotating disc, it is sometimes acting on the stator, and sometimes shielded. There is a alternating current signal between the stator and the ground, and the strength of the AC / DC electric field can be obtained by measuring the magnitude of the alternating current.



**Figure 1.** Schematic diagram of the overall structure of the rotating voltmeter.

Suppose there are  $n$  fan holes on each disc, and each fan hole area is  $A_0$ . The angular velocity of the rotor is  $\omega$ . When the rotor rotates, total area of stator exposed to DC electric field is  $A(t)$ , the expression of  $A(t)$  is

$$A(t) = \frac{1}{2} n A_0 (1 - \cos n \omega t) \quad (1)$$

The proof is as follows:

The polar coordinate equation of the Bernoulli hyperbola is:

$$r^2 = 2a^2 \cos 2\theta \quad (2)$$

As for

$$r^2 = 2a^2 \cos n\theta \quad (3)$$

It is called the polar coordinate equation of Bernoulli  $n$  curve.

Because  $r^2 \geq 0$ , which means  $\cos n\theta \geq 0$ , the range of  $\theta$  is  $[-\frac{\pi}{2n}, \frac{\pi}{2n}]$ . That is to say, the

angle of each fan blade is  $\varphi = \frac{\pi}{n}$ . So for the the polar coordinate equation of Bernoulli  $n$  curve, there are  $n$  fan blades.

As shown in figure 2, when the rotor rotates, the expression of the area of each fan blade exposed to the electric field is:

$$A(t) = \int_{\frac{\pi}{2n}}^{\frac{\pi}{2n}+wt} 2a^2 \cos n\theta d\theta = \frac{2}{n} a^2 \sin n\theta \Big|_{\frac{\pi}{2n}}^{\frac{\pi}{2n}+wt} = \frac{2}{n} a^2 \left[ \sin\left(-\frac{\pi}{2n} + wt\right) - \sin\left(-\frac{\pi}{2}\right) \right] \quad (4)$$

$$= \frac{2}{n} a^2 [-\cos nwt + 1] = \frac{2}{n} a^2 (1 - \cos nwt)$$

The area of each fan blade is

$$A_0 = \int_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} 2a^2 \cos n\theta d\theta = \frac{2}{n} a^2 \sin n\theta \Big|_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} = \frac{4}{n} a^2 \quad (5)$$

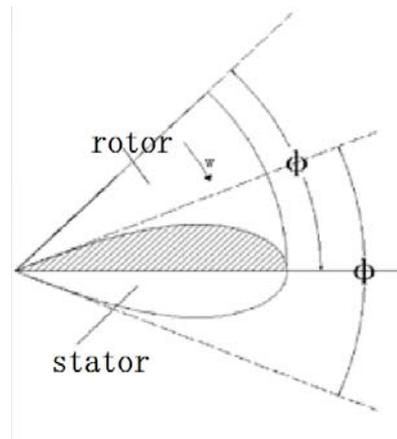
So  $a^2 = \frac{nA_0}{4}$ , replace it into the formula (4):

$$A(t) = \frac{1}{2} A_0 (1 - \cos nwt) \quad (6)$$

As for  $n$  fan blades:

$$A(t) = \frac{1}{2} nA_0 (1 - \cos nwt) \quad (7)$$

Q.E.D.



**Figure 2.** Rotation voltmeter process working principle diagram

If the electric field strength of the DC electric field is  $E$  and the dielectric coefficient of the air is  $\epsilon_0$ , the expression of the inductive charge  $Q(t)$  on the stator is:

$$Q(t) = \epsilon_0 EA(t) \quad (8)$$

Thus, the expression of the inductive charge in DC electric field is:

$$i_e(t) = \frac{dQ(t)}{dt} = \frac{1}{2} \epsilon_0 En^2 A_0 \omega \sin n\omega t \quad (9)$$

The strength of hybrid electric field  $E$  can be known by measuring  $i_e(t)$ .

It should also be noted that the ionic current that moves along the wire, also enters the stator through the fanshaped hole on the disc. If the density of the ionic current is  $j$ , the expression of ionic current entering the bottom disc is:

$$i_j(t) = j \cdot A(t) = \frac{1}{2} nA_0 \cdot j(1 - \cos n\omega t) \quad (10)$$

As seen from above, the current  $i(t)$  is composed of two components: the ionic current  $i_j(t)$  and the inductive current  $i_e(t)$ , the angle of deviation between  $i_e(t)$  and  $i_j(t)$  is 90 degrees. Arguably, if  $i_e(t)$  and  $i_j(t)$  can be accurately distinguished and measured, the device can be used to measure both the electric field strength  $E$  and the ionic current density  $j$ . But because the value of  $A(t)$  is small, so the value of  $i_j(t)$  is very small, and the value of  $j$  can not be obtained accurately. Because  $i_j(t) \ll i_e(t)$ , the value of  $i_j(t)$  has little effect on the value of  $i_e(t)$ , that is  $i(t) \approx i_e(t)$ . Therefore, the electric field strength  $E$  can be determined.

If the AC electric field and the DC electric field are superposed together, the area of disc exposed to the hybrid field remains to be

$$A(t) = \frac{1}{2} nA_0(1 - \cos(n\omega_1 t + \alpha)) \quad (11)$$

Suppose the DC electric field strength is  $E_1$ , the amplitude of AC electric field strength is  $E_2$  and the angular frequency of the rotor is  $\omega_2$ , the strength of AC / DC hybrid electric field is:

$$E = E_1 + E_2 \cos(\omega_2 t + \beta) \quad (12)$$

The expression of inductive charge on the stator is:

$$Q(t) = \frac{1}{2} \varepsilon_0 nA_0 \{E_1 + E_2 \cos(\omega_2 t + \beta) - E_1 \cos(n\omega_1 t + \alpha) - \frac{E_2}{2} \cos[(n\omega_1 + \omega_2)t + \alpha + \beta] - \frac{E_1}{2} \cos[(n\omega_1 - \omega_2)t + \alpha - \beta]\} \quad (13)$$

At this time the expression of inductive current of hybrid electric field is:

$$i_e(t) = \frac{dQ(t)}{dt} = \frac{1}{2} \varepsilon_0 nA_0 \{-\omega_2 E_2 \sin(\omega_2 t + \beta) + n\omega_1 E_1 \sin(n\omega_1 t + \alpha) + \frac{(n\omega_1 + \omega_2)E_2}{2} \sin[(n\omega_1 + \omega_2)t + \alpha + \beta] + \frac{(n\omega_1 - \omega_2)E_2}{2} \sin[(n\omega_1 - \omega_2)t + \alpha - \beta]\} \quad (14)$$

The expression of ionic current is still to be  $i_j(t) = \frac{1}{2} nA_0 \cdot j(1 - \cos n\omega_1 t)$  which could be ignored when compared to  $i_e(t)$ .

Therefore, the current measured by device is  $i_e(t)$ .

Suppose that the voltage of AC transmission line and voltage of DC transmission line is similar, so the peak of DC and AC electric fields near the ground is similar too. And the three values in the upper form are not very different, which can be measured separately without causing greater error.

### 3. Measurement application

#### 3.1. Example of measurement of hybrid electric field strength

As shown in Figure 1, the rotor and shell of the AC/DC hybrid electric field measuring device need to be grounded reliably, the stator is grounded through a large resistance. In the experiment, the AC / DC hybrid electric field measuring device is placed in the environment with AC / DC hybrid electric field, and the rotor is stably rotated when measuring. The specific steps are as follows:

- (1) Collect the signal of voltage on the resistance;
- (2) Calculate the current  $i_e(t)$  by the voltage signal and the value of resistance;
- (3) Analyze the time domain signal of the current by frequency spectrum, and the frequency spectrum of the current signal is obtained;

(4)The strength of the AC electric field  $E_1$  and the strength of the DC electric field  $E_2$  can be obtained by the characteristic frequency in the spectrum diagram.

The characteristic frequency  $f(A') = \omega_2 = 50\text{Hz}$  is the fundamental frequency component of alternating current, and the amplitude of corresponding current signal is:

$$i_e(A') = \frac{1}{2} \varepsilon_0 n A_0 n \omega_1 E_2 \quad (15)$$

The characteristic frequency  $f(B') = n\omega_1 = 288\text{Hz}$  (The stator and the rotor of this device consist of 18 pieces of fanshaped discs which means  $n=18$ , and the rotational frequency of the motor is 16Hz), the amplitude of the corresponding current signal is:

$$i_e(B') = \frac{1}{2} \varepsilon_0 n A_0 n \omega_1 E_1 \quad (16)$$

The characteristic frequency  $f(C') = (n\omega_1 + \omega_2) = 338\text{Hz}$ , the amplitude of the corresponding current signal is:

$$i_e(C') = \frac{1}{4} \varepsilon_0 n A_0 (n\omega_1 + \omega_2) E_2 \quad (17)$$

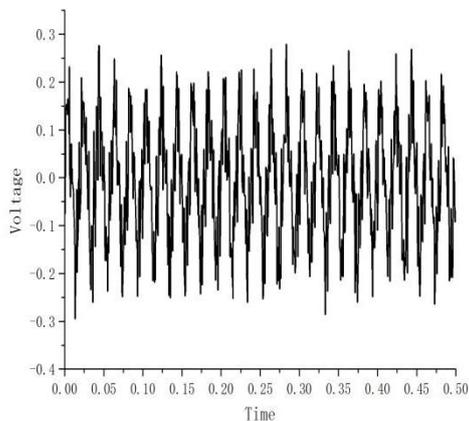
The characteristic frequency  $f(D') = (n\omega_1 - \omega_2) = 238\text{Hz}$ , the amplitude of the corresponding current signal is:

$$i_e(D') = \frac{1}{4} \varepsilon_0 n A_0 (n\omega_1 - \omega_2) E_2 \quad (18)$$

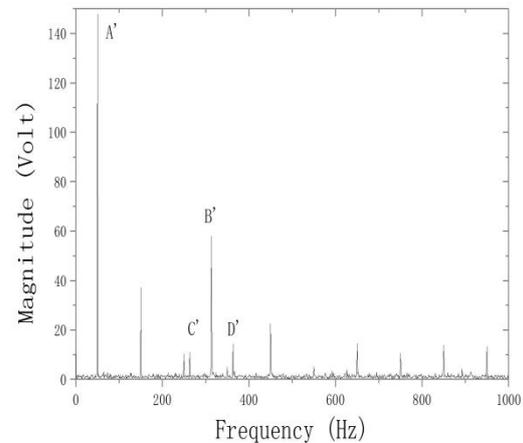
In the formula,  $\varepsilon_0$ ,  $n$ ,  $A_0$ ,  $\omega_1$ ,  $\omega_2$  are already known, so that DC electric field  $E_1$  and the AC electric field  $E_2$  can be obtained.



**Figure 3.** The picture of practical application of the rotary voltmeter



**Figure 4.** Time domain waveform of mixed electric field intensity.



**Figure 5.** Mixed field intensity spectrum

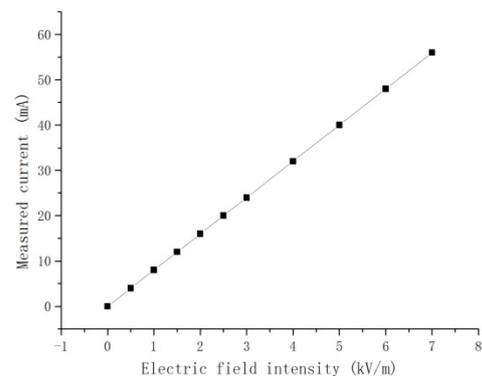
The strength of hybrid electric field under DC conductor is measured by the rotary voltmeter. The time-domain waveform is obtained as shown in figure. 4, and the corresponding spectrum is shown in figure 5. Several distinct spikes can be seen in the spectrum, their frequencies are  $f(A')=50\text{ Hz}$ ,  $f(B')=313\text{ Hz}$ ,  $f(C')=263\text{ Hz}$  and  $f(D')=363\text{ Hz}$ . The 4 peaks correspond to the characteristic frequencies described above,  $f(A')$  is the AC fundamental frequency,  $f(B')$  is the characteristic frequency of the rotating voltmeter,  $f(C')$ ,  $f(D')$  is the frequency difference of  $f(A')$  and  $f(B')$ . The characteristic frequency of the rotating voltmeter is 313Hz, which is slightly different from 288Hz, this may be due to the decrease of the voltage of the battery of the rotating voltmeter.

### 3.2. The calibration test of rotary voltmeter in the DC field

The rotary voltmeter is calibrated under a direct current field. The calibration experiment was carried out by a device which consists of several parallel placed aluminum plates, different electric field strength can be produced when different voltage is applied on the aluminum plates. The rotary voltmeter can be calibrated via the relationship between the fixed electric field strength and the current measured. The device used to calibrate the rotary voltmeter in the experiment is shown in figure. 6. The relationship between the fixed electric field strength and the current measured is shown in figure 7.



**Figure 6.** Device for calibrating experiment



**Figure 7.** Final calibration data

#### 4. Conclusion

(1) The frequency of the output signal of the existing ground electric field measuring device of the direct current transmission line is closely related to the frequency of the measured hybrid electric field.

(2) DC components and AC components of the hybrid electric field can be obtained simultaneously by the spectrum analysis of the output signal of the rotating voltmeter.

(3) The measurement and analysis in the DC electric field show that the proposed method is effective for measuring the DC components and AC components of the ground electric field in the AC / DC hybrid electric field. The method provides a reliable and convenient means for the study of the effect of ground electric field under the AC / DC parallel transmission line.

#### References

- [1] LIU Z Y 2005 *Ultra —high voltage grid* (Beijing: China Economic Publisheng House) p 260
- [2] LIU Z Y 2009 *UHVDC transmission line* (Beijing: China Electric Power Press) p 375
- [3] LIU Z Y 2009 *Electromagnetic environment of UHVDC project* (Beijing: China Electric Power Press) p 158
- [4] Kirkpatrick P and Iwao M 1932 *J. Rev. Scient. Inst.* **3** 1-8
- [5] W.Gohike and O .Newbert 1942 *J. Z. Techn. Phys.* **23** 70-76
- [6] Kasemir H W 1972 *J. Meteorologische Rundschau* **25** 33-38
- [7] ZHANG J G, MA S X and ZHANG G Z 2009 *J. High Voltage Engineering* **35** 3027-30
- [8] ZHOU H and ZHANG S Y 1992 *J. High Voltage Engineering* **64** 19-23