Theory and Experimental Study of Corona Initial E-Field Strength of HVDC Large Fittings

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Abstract. The electrode were used to imitate the valve tower shield plate, grading ring, grading ball and grading shield for UHVDC valve hall. Uneven electric field of the irregular conductor can not be calculated theoretically or measured accurately. The variation of typical electrode corona inception electric field strength is analyzed and threshold value of the corona inception electric field of the valve hall fittings is acquired. With the adequate modification, limited electric field magnitude for the valve hall is proposed. With the gray system MGM (1, M) model fitting and predicting technology, the E-field strength single-point high-precision measurement and the the wide-area time interval corona initial E-field fitting and predicting operation can be realized. The experimental results show that the maximum error is 3.25% within the measured concentration range, which increases with applied voltage. The maximum RSD% is less than 2.7%, showing the good stability. This system can provide the novel method for the study of corona detection of large fittings in UHVDC valve hall.

1. Introduction
The corona discharge brings many hazards, so it is necessary to find out influencing factors and prediction methods of corona discharge[1-4]. The shape and structure of different hardware in the valve hall are quite different. The curvature radius of the valve tower shield plate and some composite insulator grading rings are mostly mm, and the curvature radius of the grading shield ball is mostly m, that is to say, the corona field strength of different structures and shapes of the valve hall hardware may vary greatly[5-7]. For this reason, the DC corona tests of the spherical and annular electrodes with different curvature radii are designed. The shielding plate and the grading ring of valve tower with small curvature radii in the valve hall are simulated with small ball and small ring, and the grading ball with large curvature radii in the valve hall and the grading cover of bushing are simulated with large ball to study their corona characteristics and control field strength respectively.

There are non-smooth jumps between the adjacent data points in the time series of corona field strength, and there are coupling effects among various time series of corona field strength. Therefore, the accuracy of traditional display function fitting and prediction methods needs to be further improved. In theory, the method of fitting and predicting the time series of corona field strength by gray system with rich theoretical basis is given, which provides an effective theoretical tool for its research[8,9]. It is found in the actual test and the operation and maintenance of the large fittings in UHVDC valve hall can be used to directly judge the change trend, but the data acquisition process is time-consuming and labor-consuming. If the data that has been collected can be effectively fitted and predicted, then no time is needed to collect the subsequent data. If the data exceeds the control limit of the corona initial E-field strength, the early warning processing of power equipment maintenance can
be carried out, so as to find the potential electrical defects of high-voltage switch-gear. According to theoretical characteristics of gray system method, it can effectively avoid all kinds of influencing factors of outside and measurement, and improve the accuracy of fitting and prediction.

2. Prediction of corona field intensity on large electrode surface

Based on the mechanism of secondary electron avalanche emission, the relationship between the corona field intensity and the curvature radius of the electrode is discussed[10-14]. It is assumed that the surface field strength of the cylindrical electrode is \( E \). \( E_0/N_0 \) is the threshold of ionization, assume:

\[
E = E_0 \frac{c \delta}{r}
\]

(1)

According to the theory of ionization film, \( R \) is the radius of cylinder, \( C \) is proportional constant, guaranteed on cylinder surface \( E = E_0 \delta \), that is to say, the surface field strength makes the effect of ionization and adsorption equivalent, and under this condition, the field strength is in direct proportion to the air density. The process of electron collision and adsorption and the electric field distribution in the ionization region affect the corona initiation. The starting criterion of corona is:

\[
\exp \left[ \int_{r_i}^{r_c} \left( \alpha(r) - \eta(r) \right) dr \right] = Q
\]

(2)

In the above formula: \( \alpha \)、\( \eta \) - are electron collision coefficient and the adsorption coefficient respectively. \( r_i \)、\( r_c \) - are the ionization boundary and radial position respectively; \( Q \) is a constant.

In AC and DC conditions, the corona initiation criteria are all applicable, and the corona initiation conditions of complex electrode structure can also be expressed by the formula. The ionization boundary usually refers to the position where the electron collision coefficient is equal to the adsorption coefficient. For the relationship between the structure of coaxial cylindrical electrode and the spatial field strength and the number of neutral gas molecules per unit volume:

\[
\frac{\alpha}{N} = B \left( \frac{E}{N} \right)^2 - \left( \frac{E_0}{N_0} \right)^2
\]

(3)

Where \( \alpha' = \alpha - \eta \), \( N \) is the molecular number of neutral gas in unit volume, \( E \) is electric field strength, \( E_0 / N_0 \) is the threshold value of \( E/N \) for the generation of positive ions. From the integration of the electrode surface to the point \( c \) from the electrode surface, it is obtained that:

\[
NBR \left( \frac{E_0}{N_0} \right)^2 \left( \frac{c}{r} - 1 \right)^2 = \ln Q
\]

(4)

Namely:

\[
\frac{c}{r} = 1 + \frac{(\ln Q)^{1/2}}{(E_0 / N_0)(\delta BN_0 r)^{1/2}}
\]

Substitute formula (1) to get the form of Peek formula:

\[
E_e = E_0 \delta [1 + \frac{(\ln Q)^{1/2}}{(E_0 / N_0)(\delta BN_0 r)^{1/2}}]
\]

(5)

When ionization integral \( Q=10^4 \), \( E_0=24.72 \text{kV/cm} \), \( E_0 / N_0=98.5 \times 10^{-17} \text{V/cm}^2 \), \( B=2.08 \times 10^{12} \text{V}^2/\text{cm}^2 \), \( N_0=2.51 \times 10^{19} \text{cm}^3 \), the peek formula is obtained:

\[
E_e = 25 \delta [1 + \frac{0.4}{\sqrt{\delta r}}]
\]

(6)

According to the fitting of altitude and relative air density, we can get:

\[
\delta = 1.0572 \delta_0 e^{-0.10799H}
\]

(7)

In the formula: \( H \), altitude, km; is the relative density of air when the altitude is \( h \); is the relative density of air when the altitude is 0km, so there are:
3. Modeling and optimization of non equidistant MGM (1, M)

In the actual social and economic system, there are many variables, each variable is related to each other, and MGM (1, m) model can describe the relationship between the variables, and optimize the background value from the construction error of the traditional non equidistant MGM (1, m) model, so as to establish the non equidistant MGM (1, m) model of background value optimization. Let original data matrix be:

\[
X^{(0)} = \begin{bmatrix}
X_1^{(0)} & X_2^{(0)} & \cdots & X_m^{(0)}
\end{bmatrix}
\]

(9)

Where, \(X_j^{(0)}\) is a non equidistant sequence, which represents observation value sequence of the \(j^{th}\) variable at \(k_1, k_2, \ldots, k_n\) time, namely:

\[
X_j^{(0)} = \{x_j^{(0)}(k_1), x_j^{(0)}(k_2), \ldots, x_j^{(0)}(k_n)\} (j=1,2,\ldots,m).
\]

The new data matrix is obtained by first-order accumulation of the sequence \(X_j^{(0)}\), \(X_j^{(1)}\), \(X_j^{(2)}\), respectively. It is called the first-order accumulation generation matrix of the original data matrix \(X^{(0)}\). It is recorded as follows:

\[
X^{(1)} = \begin{bmatrix}
X_1^{(1)} & X_2^{(1)} & \cdots & X_m^{(1)}
\end{bmatrix}
\]

(10)

Where \(X_j^{(1)}\) is the first-order accumulation generating sequence of original sequence, i.e. \(X_j^{(0)} = \{x_j^{(0)}(k_1), x_j^{(0)}(k_2), \ldots, x_j^{(0)}(k_n)\}\), where \((j=1,2,\ldots,m; i=1,2,\ldots,n)\). The first order whitening differential equations of MGM (1, m) model with unequal spacing are as follows:

\[
\frac{dx_1^{(i)}}{dt} = a_{11}x_1^{(i)} + a_{12}x_2^{(i)} + \cdots + a_{1m}x_m^{(i)} + b_1
\]

\[
\frac{dx_2^{(i)}}{dt} = a_{21}x_1^{(i)} + a_{22}x_2^{(i)} + \cdots + a_{2m}x_m^{(i)} + b_2
\]

\[
\vdots
\]

\[
\frac{dx_m^{(i)}}{dt} = a_{m1}x_1^{(i)} + a_{m2}x_2^{(i)} + \cdots + a_{mm}x_m^{(i)} + b_m
\]

(11)

\[
A = \begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1m} \\
a_{21} & a_{22} & \cdots & a_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
a_{m1} & a_{m2} & \cdots & a_{mm}
\end{bmatrix}, \quad B = \begin{bmatrix} b_1 \\
b_2 \\
\vdots \\
b_m \end{bmatrix}
\]

The above formula can be recorded as:
\[
\frac{dX^{(1)}(t)}{dt} = AX^{(1)}(t) + B
\]

\[
X^{(1)}(t) = \{x^{(1)}_1(t), x^{(1)}_2(t), \ldots, x^{(1)}_m(t)\}^T.
\]

4. Corona test and analysis of large size ball electrode

The corona test of large-scale ball electrode is carried out in the high-voltage hall[15]. The DC voltage of the test is generated by the DC high-voltage generator with the rated maximum output voltage of 1800kV in the hall. Limited by the coupling capacitor and voltage divider of the test circuit, the actual output voltage is not more than 1000kV. The electrode used in the experiment is the smooth aluminum alloy ball, and the manufacturing process of the ball is better. The sphere diameter is 500mm, 600mm, 700mm, 800mm, 900mm and 1000mm respectively, and it is connected with the tube bus with the diameter of 300mm by the way of terminal ball encapsulation[16]. As shown in Figure 1, the electrode is arranged in the form of ball plate electrode, which is the aluminum alloy smooth ball for test, and the plate electrode is the grounding iron sheet laid on the ground.

![Fig.1 Large ball electrodes corona test](image)

The test procedure is similar to the small ball corona test. The positive and the negative corona tests are carried out independently for each ball electrode with the different diameters, and the corresponding test phenomena and data are recorded. Test and record the same sample for many times, and take the average value as the corona voltage of the electrode. During the test, the environmental parameters are: altitude 95m, air pressure 100.1kpa, temperature 17.4℃, relative humidity 49.3%. In the positive corona test, the corona starting voltage of 500mm diameter ball electrode is 650kV; the corona starting voltage of 600mm diameter ball electrode is 735kV; the corona starting voltage of 700mm diameter ball electrode is 830kV; the corona starting voltage of the 800mm diameter ball electrode is 910kV. No corona discharge was observed at the 900mm and 1000mm ball electrodes. In the negative corona test, the corona starting voltage of 500mm diameter ball electrode is 570kV; the corona starting voltage of 600mm diameter ball electrode is 650kV; the corona starting voltage of 700mm diameter ball electrode is 735kV; the corona starting voltage of 800mm diameter ball electrode is 790kV; the corona starting voltage of 900mm diameter ball electrode is 850kV; the corona starting voltage of 1000mm diameter ball electrode is 880kV. Take 600mm ball electrode as an example, the UV image of positive and negative corona is shown in Figure 2.

![Fig.2](image)

(a) Corona ultraviolet image 600mm smooth ball of positive polarity (b) Corona ultraviolet image 600mm smooth ball of negative polarity
5. Comparison of the fitting and prediction of the corona field strength of the ball electrode

In the form of the Peek formula, in the sphere electrode diameter range of 33-1000mm, the least square nonlinear regression fitting method is used to obtain the fitting formula of corona field strength of negative electrode. When the electrode diameter changes in the range of 0-1000mm, the relationship between the electrode diameter and the initial electric field strength of corona is shown in the Fig.3.

On the other hand, in the range of 500-1000mm, the curve between the electrode diameter and the initial electric field intensity of corona is shown in Figure 4. Firstly, peek formula is used for fitting, and the classical expression of Peek formula is $E_i = A \times (1 + \frac{B}{\sqrt{d}})$. The fitting parameters are $A=1353$, $B=9.916$. Now we will use peek formula to fit the small size and large size joint, and the fitting results are shown in the following Figure.
The above figure shows that peek formula still has a good fitting effect in the full-scale range, but it has a poor fitting effect for the corona initial field strength of small-scale fittings, which to some extent shows that the mechanism of small-scale and large-scale corona initiation is different. Under the condition of altitude correction, it is only necessary to introduce altitude correction term on the basis of PEEK formula. In fact, the introduction of altitude correction term can effectively consider the influence of altitude condition on the initial field strength of corona, so peek formula is:

\[ E_c = A \cdot e^{-Bh} \left[ 1 + \frac{C}{\sqrt{e^{-Bh} \cdot r}} \right] \]

Among them, three parameters \( a, B, \) and \( C \) need to be determined. The corona starting parameters of the large size fittings in electric valve hall are selected as the original non equidistant series to establish the grey equidistant Verhulst model of the time response optimization. And the known data series are recorded as \( X(1) \). The first 10 data are taken to establish the grey non equidistant Verhulst model[17], and the last 4 data are used for prediction and comparison.
Taking the corona starting voltage of large-size fittings in valve hall as the sequence \( X_1^{(0)} \), the corona starting electric field strength of fittings as the sequence \( X_2^{(0)} \), and the corona starting physical structure size of fittings as sequence \( X_3^{(0)} \), the non-equidistant MGM (1,3) model is established, and a single variable non-equidistant GM (1,1) model is established for the above sequences respectively. There is a certain relationship between the three corona starting parameters of the large-size fittings in the valve hall. A non-equidistant MGM (1,3) model is established for the three variables. The whitening differential equations are as follows:

\[
\begin{align*}
\frac{dx_1^{(1)}}{dt} &= 14.9983x_1^{(1)} - 428.757x_2^{(1)} - 1.8151x_3^{(1)} + 115.6621 \\
\frac{dx_2^{(1)}}{dt} &= 0.6646x_1^{(1)} - 19.6994x_2^{(1)} - 0.0523x_3^{(1)} + 3.4444 \\
\frac{dx_3^{(1)}}{dt} &= 8.6736x_1^{(1)} - 289.62x_2^{(1)} + 0.2187x_3^{(1)} + 104.8282
\end{align*}
\]

The first order differential equations of the unequal interval GM (1,1) model of \( X_1^{(0)}, X_2^{(0)}, X_3^{(0)} \) are as follows:

\[
\begin{align*}
\frac{dx_1^{(1)}}{dt} &= -0.5227x_1^{(1)} + 133.5707 \\
\frac{dx_2^{(1)}}{dt} &= -0.4970x_2^{(1)} + 4.1138 \\
\frac{dx_3^{(1)}}{dt} &= -0.2722x_3^{(1)} + 108.9011
\end{align*}
\]

The simulated predicted values and relative errors of the three sequences of unequal interval MGM (1,3) model and unequal interval GM (1,1) model are shown in the table below. Through the prediction of corona field intensity on the surface of large-scale electrode and the modeling and optimization analysis of unequal spacing MGM (1, m), it is found that although the altitude correction formula and the grey prediction model are based on their respective theoretical systems in principle, they are similar in terms of formula structure, data fitting and prediction effect.

6. Conclusion
DC hardware corona has obvious polarity effect, that is, the negative corona is relatively mild, the number of photons is small, the noise is small, it is easy to corona, it is difficult to breakdown, the positive polarity is just the opposite. When the radius of curvature of the fittings increases in a small range, the corona voltage increases approximately linearly, but in a larger radius, the corona voltage
increases with saturation. With the grey system MGM (1, M) model fitting and predicting technology, the gas volume fraction single-point high-precision measurement and the wide-area time interval gas concentration fitting and predicting operation can be realized. The experimental results show that the maximum error is 3.25% within the measured concentration range, which increases with the radius of curvature of the fittings. The maximum RSD% is less than 2.7%, showing good stability.

References

[1] Qiao Xueguang, Wang Jia, Jia Zhen’an, et al. Experiment research for optical fiber methane gas sensor[J]. Journal of Optoelectronics Laser, 2009, 20(7): 851-854(in Chinese).

[2] Liu Guohua, Zhang Yujun, Zhang Kai, et al. Research on online correction algorithm with neural network multi-environment factors for CO detection of motor vehicle exhaust[J]. Infrared Millim Waves, 2018, 37(6): 704-710(in Chinese).

[3] Chen Chen, Zhang Yujun, He Ying, et al. Performance simulation analysis of NDIR sensor for vehicle exhaust[J]. Infrared Technology, 2017, 39(6): 567-573(in Chinese).

[4] Chen Miao, Huang Zhengwei, Wang Yi. Development of multicomponent measurement by single light source and optical path based on an infrared gas analyzer of NDIR principle[J]. Analytical Instrumentation, 2017(3): 20-25(in Chinese).

[5] Ji Shengchang, Zhong Lipeng, Liu Kai, et al. Research and development of SF6 decomposition components analysis under discharge and its application[J]. Proceedings of the CSEE, 2015, 35(9): 2318-2332(in Chinese).

[6] Peek FW. The Law of Corona and the Dielectric Strength of Air[J]. Transactions of the American Institute of Engineers, 1911, XXX(3): 1889-1965

[7] Khaled M. Computation of breakdown phenomena in non-uniform air gaps[D]. Zurich, Switzerland: Switzerland Federal Institute of Technology. 1975.

[8] QIU Yuchang, SHI Wei, ZHANG Wenyuan. High voltage engineering[M]. Xi’an: Xi’an Jiaotong University Press, 1995: 11-14

[9] Hu Qin, Shu Lichu, Jiang Xingliang, et al. Conductor’s ac corona onset voltage prediction under different atmospheric parameters and conductor surface conditions[J]. High Voltage Engineering, 2010, 36(7): 1669-1674.

[10] Cao Jing, Zhang qin, Yang Yinjian, Corona discharge characteristic for fittings of high altitude ac transmission line[J]. High Voltage Engineering, 2011, 37(12): 2924-2928.

[11] ZHANG Renyu, CHEN Changyu, WANG Zhangchang. High-voltage testing technology[M]. Beijing, China: Tsinghua University Press, 2003: 71-82

[12] MA Bin, ZHOU Wenjun, WANG Tao, et al. Corona Discharge of the Severe Non-uniform Electric Field Based on the UV-light Imaging Technology[J]. High Voltage Engineering, 2006, 32(7): 13-16.

[13] YAN Zhang, ZHU De-heng. Technology of high voltage insulation[M]. Beijing, China: Electric Power Industry Press, 2002: 64-69

[14] Peek FW. The Law of Corona and the Dielectric Strength of Air[J]. Transactions of the American Institute of Engineers, 1911, XXX(3): 1889-1965

[15] Khaled M. Computation of breakdown phenomena in non-uniform air gaps[D]. Zurich, Switzerland: Switzerland Federal Institute of Technology. 1975.

[16] QIU Yuchang, SHI Wei, ZHANG Wenyuan. High voltage engineering[M]. Xi’an: Xi’an Jiaotong University Press, 1995: 11-14

[17] Hu Qin, Shu Lichu, Jiang Xingliang, et al. Conductor’s ac corona onset voltage prediction under different atmospheric parameters and conductor surface conditions[J]. High Voltage Engineering, 2010, 36(7): 1669-1674.