A Simplified Predictive Control Method of Power Frequency Electric Field on Roof near 500 kV Transmission Lines

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Abstract. In order to get a simplified predictive control method of power frequency electric field on roof near 500 kV transmission lines, a three-dimensional electric field simulation model including the lines, tower and house is established based on the finite element method. Based on the knowledge that obtained from existing studies, the spatial distance between the house and the transmission line is the main factor affecting the power frequency electric field intensity on the roof. Therefore, the spatial distance is determined as a variable, and the least squares method is used to fit the optimal electric field distribution function. A simplified prediction model of the power frequency electric field at fixed monitoring point on the roof near the transmission line is derived. The results show that the fitting function of the third-order polynomial can achieve better predicting effect. The specific mathematical expression of the prediction model is provided. A deductive process of the application of the proposed method is given. The proposed power frequency electric field predictive control method can provide reference for the planning, design and environmental impact assessment of transmission line projects.

1. Introduction

With the rapid increase of the demand of electric energy, the scale of UHV and EHV transmission lines is also growing, and their electromagnetic environmental impact is also getting more and more attention[1-3]. Especially with the gradual increase of the height and density of residential buildings near the line, the distortion of power frequency electric field on the roof of houses is particularly serious. At present, in the planning and design stage of the transmission line project, the ground electric field is usually estimated according to the typical design samples, and there is no convenient prediction method for the distorted electric field (such as the distorted electric field on the roof of the house near the line), which brings the risk of electromagnetic environment out of control. If the power frequency electric field intensity exceeds the limit requested in relevant standards when the line is turn into operation, the cost of reconstruction or adaptation will be very high and the work will be very passive. Therefore, it is necessary to predict and control the power frequency electric field level on the house roof near the line in the planning and design stage of the line project.

In this paper, the power frequency electric field simulation model of 500kV transmission lines and nearby houses is established. Based on the numerical simulation results of electric field distribution on the roof near the line, the least square method is used to fit polynomial functions for the prediction of electric field at fixed monitoring point on the roof. The optimal fitting function expression of electric
field varying with the influencing factors is derived, and the prediction model of power frequency electric field on the roof near transmission line is obtained. Then the proposed prediction model is validated by field measurements. A deductive process of the application of the proposed method is given.

2. Modelling of the transmission line and the house
The principle of simulation mode is the finite element method, which converts the differential equation model to be solved into the corresponding variational problem on the basis of the variational principle. By means of partition interpolation, the variational problem is discretized into the extreme problem of ordinary multivariable functions. Since the power frequency electric field near the corner tower is a quasi-static field, it can be treated by solving the electrostatic field. Thomson's theorem indicates that the electric field of the transmission line synthesized in space should have the minimum electrostatic energy. The regularity of the excited electrostatic field problem is expressed as by energy integral

\[ W_e = \iiint \left( \frac{1}{2} \varepsilon E^2 \right) dV = \iiint \left( \frac{\varepsilon}{2} |V \phi|^2 \right) dV = \iiint \frac{\varepsilon}{2} \left( \frac{\partial \phi}{\partial x} \right)^2 + \left( \frac{\partial \phi}{\partial y} \right)^2 + \left( \frac{\partial \phi}{\partial z} \right)^2 \right) dV = \min \]  

(1)

Practices of transmission line projects show that at the power frequency electric field on the roof near angle tower is often the most serious situation and easy to exceed the control limit. The control of electric field level on the roof is realized by controlling the field level at the monitoring point with the maximum field intensity to be lower than relevant standard limited values. Experiences show that the monitoring point with the maximum field intensity is at the monitoring point nearest to the corner of the roof closest to the transmission line. According to the current measurement standard in China, the monitoring point is at least 1.5 m away from the roof edge and 1.5 m above the roof plane. Therefore, our concern is focused on cases near angle towers. The monitoring point is fixed at the point 1.5 m away from the roof edge and 1.5 m above the roof plane, near the roof corner closest to the transmission line.

According to a practical case, the three-dimensional model of angle tower of 500 kV double circuit transmission line is established based on the finite element simulation method, as shown in Fig.1. The steering angle of the line is 40°, and the lowest conductor is 30 m above the ground. The electric field distribution on the roof at the monitoring point, varying with the steering angle, tower and conductor height, house height and distance, was calculated and reported in our previous work [5].

3. Prediction Model of Electric Field on the Roof
From our previous studies reported in reference [5], it is known that the space distance between the houses and the lines is the main factor determining the field intensity at the measuring points on the roof. However, most of the current studies are qualitative analysis. In order to control the electric field predictively, quantitative analysis is needed to summary the law of its variation with distances. Adopting the least square method to fit polynomial function, by calculating and comparing the correlation coefficient and residual of fitting function, the optimal fitting function expression could

Fig.1 Three-dimensional simulation model
be derived, and the predictive control model of the roof electric field near the transmission lines could be obtained.

The Cartesian coordinate system is established to fit the relationship between the electric field at the monitoring point on the roof and the space distance between the house and the line with mathematical functions. The x-axis is the horizontal distance between the house edge and the closest line conductor. The y-axis is the vertical distance from the roof plan to the lowest line conductor. And the z-axis is the electric field intensity at the monitoring point on the roof. First, the simplest plane function is used to fit the electric field change at the monitoring point on the roof of the house near the line. The expression of the plane fitting function is as following:

\[ z = z_0 + ax + by \]  

(2)

Electric field fitting figure of plane function on the rooftop is obtained by several iterations as shown in Fig. 2, in which the dots representing the numerical calculated electric field intensity at the monitoring point under different house distance conditions.

The correlation coefficient COD (R\(^2\)) and Residual Sum of Squares (RSS) are two important indexes to evaluate the accuracy and validity of mathematical function fitting. The closer the COD (R\(^2\)) is to 1 and the closer the RSS is to 0, which shows that the fitting function is closer to the actual electric field distribution. When the plane function is used, COD (R\(^2\)) is 0.92363 and RSS is 19.41131. The deviation is still large. It can also be seen from Fig.2 that the fitting plane cannot effectively cover the distribution points of the roof field intensity, especially in the boundary position.

Then, the parabolic function is used to fit the electric field distribution on the roof of the house near the line, and the expression of the parabolic fitting function is as following:

\[ z = z_0 + ax + by + cx^2 + dy^2 \]  

(3)

After several iterations, the parabolic function fitting figure of the electric field distribution on the roof is obtained as shown in Figure 3. The COD (R\(^2\)) of the parabolic fitting function is calculated to be 0.92630, and RSS is 18.18787. As a special case of second-order polynomial, parabolic function has similar fitting effect with plane function, which cannot effectively fit the electric field on the roof.

Furthermore, the second-order polynomial function is used to fit the electric field distribution on the roof of the house near the line. The expression of the second-order polynomial fitting function is as following

\[ z = z_0 + ax + by + cx^2 + dy^2 + fxy \]  

(4)

After several iterations, the second-order polynomial function fitting figure of the electric field distribution on the roof is obtained as shown in Figure 4. The COD (R\(^2\)) of the second-order polynomial fitting function is calculated to be 0.99387, and RSS is 1.49055. It can be seen that COD
(R²) has been significantly improved, RSS has decreased by about 90%, and the fitting surface covers most of the field intensity distribution points, but there are some deviations at the extreme points.

In order to explore the fitting effect of higher order polynomial, the third order polynomial function is used to fit the electric field distribution on the roof near the line. The expression of the third order polynomial fitting function is as following

\[ z = z_0 + ax + by + cxy + dx^2 + ey^2 + fxy + gxy^2 + hx^3 + iy^3 \]  

(5)

After several iterations, the third-order polynomial function fitting figure of the roof electric field distribution is obtained as shown in Fig.5. The COD (R²) of the third-order polynomial fitting function is calculated to be 0.99942, and RSS is 0.13325. It can be seen that COD (R²) is very close to 1 and RSS is close to 0. The fitting surface almost completely covers all the field intensity distribution points.

\[ E = 21845 - 1666.29d - 476.52h_r + 88.35dh_r + 22.54d^2 - 25.58h_r^2 - 1.65d^2h_r - 0.49dh_r^2 + 0.24d^2 + 0.58h_r^3 \]  

(6)

In the equation (6), \(d\) represents the horizontal distance between the external wall of the house and the nearest line, and \(h_r\) represents the vertical distance between the house roof and the lowest line.

According to reference[6], the horizontal distance between the house and the line is at least 5m. According to the theoretical analysis and engineering experience, the power frequency electric field on the roof can meet the standard when the distance between the house and the line is more than 25m. Therefore, the consideration range for determining the horizontal distance \(d\) between the house and the line is 5-25 m.

According to reference[6], the minimum vertical distance between the house and the line is 9m. Based on the survey and engineering experience of the height range of the line and the general height of the house, the vertical distance between the line and the roof is usually not higher than 25m. Even if the vertical distance between the line and the roof can reach more than 25m, the power frequency electric field on the roof also meets the standard. The consideration range for determining the vertical distance \(h_r\) between the house and the line is 9-25m.
4. Verification of the Prediction Model

The prediction model of roof electric field level based on the third-order polynomial fitted by least square method is calculated by numerical simulation. The validity of the prediction model needs to be verified by field measurement.

According to the investigation of a 500kV transmission line project, the electric field intensity on the roof of the houses near the angle tower is measured. The electric fields on the roofs of houses near the line were measured. The values of \((d, h_r)\) are substituted into the mathematical expression \((6)\) of the prediction model to calculate the predicted electric field intensity \(E\) at monitoring points on the roofs, while the measured field value is expressed by \(E'\). The predicted value of the roof electric field and the measured field value are obtained, as shown in Table 1.

| No. | Parameters \((d, h_r)\)/(m,m) | Predicted data\((E)\)/kV.m\(^{-1}\) | Measured data\((E')\)/kV.m\(^{-1}\) | Error |
|-----|-----------------------------|----------------------------------|----------------------------------|-------|
| 1   | 16, 21                      | 3.39                             | 3.28                             | -3.4% |
| 2   | 18, 15                      | 3.48                             | 3.56                             | 2.2%  |
| 3   | 20, 18                      | 2.75                             | 2.88                             | 4.5%  |
| 4   | 22, 18                      | 2.32                             | 2.25                             | -3.1% |
| 5   | 24, 16                      | 2.11                             | 2.05                             | -2.9% |
| 6   | 28, 18                      | 1.51                             | 1.65                             | 8.5%  |

According to the actual investigation, the houses near the 500kV transmission line are all self-built by villagers. So the houses have high randomness in location and height, which makes it very difficult to predict the power frequency electric field induced from the transmission line. It can also be seen from the house parameters in Table 1 that the relative position of the house and the line is highly uncertain. The error between \(E\) and \(E'\) is no more than 10%. Moreover, the most deviated house is in the remote location, and the prediction deviation of roof field strength in more concentrated locations can be less than 5%. Therefore, the power-frequency electric field prediction model established in this paper on the roof of houses near the 500kV transmission line can well predict the field intensity at the measured location of the area on the roof. It provides reference for the planning, design and environmental impact assessment of transmission line projects.

5. Application of the Proposed Predictive Control Model

The above proposed predictive control model can be conveniently applied for the control of roof electric field level.

Step A: Determine the horizontal distance \(d\) between the external wall of the house and the transmission line according to the relative position between the house and nearest conductor of the double circuit 500kV transmission line;

Step B: Determine the vertical distance \(h_r\) between the lowest conductor and the roof plan;

Step C: According to the estimation formula, predict the electric field strength \(E\) that may appear at the most critical monitoring point on the roof;

Step D: Compare \(E\) with the exposure limit specified in the public power frequency electric field exposure limit standard. If \(E\) is less than the exposure limit, the predicted power frequency electric field level on the roof has been controlled within the exposure limit specified in the standard. If \(E\) is greater than or equal to the exposure limit, which means that the predicted roof power frequency electric field level exceeds the standard, increase \(h_r\) or \(d\) according to the project allowable conditions. After that, predict the power frequency electric field intensity that may appear at the roof monitoring point again according to the estimation formula until \(E\) is less than the exposure limit. Then the power frequency electric field level on the roof is controlled within the exposure limit specified in the standard. The process of applying this method is shown in Fig. 6.
6. Conclusion

Based on the analysis of the numerical simulation results of the power frequency electric field on roofs of houses near 500 kV double-circuit transmission lines, a predictive control model of the electric field level at the critical monitoring point on the roof is established. The third-order polynomial function is fitted by least squares method, which can better reflect the variation rule of roof electric field with the space distance between the house and the line, without increasing the polynomial order. The effectiveness of the proposed predictive model is validated. A deductive process for the application of the predictive control method is also provided. This simplified power frequency electric field level control method can avoid the complicated numerical simulation process and be applied in the planning, design and environmental impact assessment stage of the transmission line project conveniently.

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