The Electrical and mechanical simulation and computer-aided geometric optimization of high voltage post-insulator based on RBF neural network and finite element method

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Abstract. The High-voltage post insulators are widely used in power systems. The electrical and mechanical properties of post insulators are closely related to the operation stability of power system. Based on the three-dimensional finite element method (FEM), the mechanical and electrical properties of post insulator are modeled and analyzed. The results show that the maximum electric field strength of the insulator is located on the surface of the voltage-equalizing ring near the high voltage side, and the first principal stress maximum value of 150MPa is mainly concentrated on flange supporting side. The PSO-RBF hybrid algorithm is proposed to optimize nonlinear inversion structural parameters of the post insulator. The results show that the PSO-RBF neural network has good effect on the nonlinear fitting mapping of the original finite element calculation data, and the algorithm has good convergence. The mechanical and electrical properties of the post insulators and the configuration of the post insulator-related voltage sharing ring and shielding ring are obtained, which can provide the theoretical basis for the insulation structure design and fittings configuration of UHV and below post composite insulators.

1. Introduction
The basic function of high voltage post insulators is to mechanically fix the conductors with different voltage in electrical equipment. Pipe buses and live bodies of various electrical equipment in the substations of various voltage levels need the mechanical support of pillar insulators to insulate them from grounding objects to ensure safe and reliable transmission of electric energy. Pillar insulators are widely used in the power transmission systems [1-3]. Taking 750kV post insulator as the example, the field ultraviolet imager observation is carried out. It can be seen that the post insulator has both the function of pipe support and electrical insulation. With the development of high-voltage and large-capacity energy system in China, when the voltage and current of power system increase, the requirements for the electrical and mechanical properties of the post insulator are raised accordingly [4, 5]. The spatial flash-over voltage of post insulators can be improved by increasing their height, but the mechanical performance decreases with increasing their height. Most of the post insulators are exposed to the atmosphere, and various atmospheric environments have significant impact on their working status. With the development of 1000kV AC transmission technology in China, the technical difficulties of insulation design for post insulators become obvious. In order to overcome technical difficulties, the two-dimensional axisymmetric finite element model (FEM) of high-voltage pillar insulators is established by using finite element simulation technology in domestic and foreign
literatures. The electric field distribution of pillar insulators is simulated and calculated, and the electric field distortion of ceramic sleeves under ice and rain conditions is also simulated in detail [6]. On the other hand, the research shows that the power frequency, lightning and switching impulse flash-over voltage of high voltage grade post insulators can be effectively improved by installing appropriate size equalizing ring at the high voltage end. Based on this, the sub-domain finite element analysis technique is proposed, which can build a three-dimensional full model of post insulator, and focus on three-dimensional electric field distribution in the areas of concern (such as the equalizing ring area at the end of the post insulator and the area along the porcelain). The sample database of electric field distribution is established by using FEM calculation technique. The paper can provide theoretical basis for insulation structure design and metal fittings configuration of UHV and below post insulators.

2. Calculation model of high voltage rod post insulator

The calculation model is based on post insulator drawings and related parameters, according to actual size, combined with the conditions of earth, voltage equalizing ring and so on. Because mechanical and electrical characteristics analysis are different, the full model of the two kinds of characteristics analysis is established separately [7-9]. The structure size and calculation model of the model are shown in Figure 1.

![Figure 1. External contour of the post insulator.](image)

The rod post insulator: 300mm aluminum tubular bus-bar, tube center from the ground 16750mm. Two side pressure rings are arranged on the side of the supporting insulator bus-bar side, and the pressure rings are arranged in the side configuration of the supporting insulators. The support height of the rod post insulator is 4623mm.

![Figure 2. 3D calculation model of post insulator.](image)

Considering that the elastic modulus of the outer ceramic sheath umbrella group is much smaller than that of the insulator mandrel and flange, the mechanical analysis of the pillar insulator is carried
out to simplify the modeling of the silicone rubber umbrella. The electrical and mechanical three-dimensional simulation models are shown in Figure 2, respectively. The three-dimensional electrical simulation model needs to consider the influence of voltage equalizer and tubular bus-bar on the electric field distribution of the post insulator. The mechanical model can consider the end of the insulator as concentrated load, and only consider the stress of main part of the post insulator. The field application of ultraviolet images to the post insulator shows that the visible corona discharge is easy to occur in the end voltage equalizing device of post insulator. Observation results are shown in Figure 3.

![Figure 3. Corona discharge of post insulator.](image)

(a) Grading ring discharge.  (b) Hardware discharge.

In the simulation of electric field of pillar insulator, the fine modeling and analysis are needed for end voltage equalizing device to obtain the distribution law of electric field on the surface of voltage equalizing insulator. The electric field distribution of insulator body is controlled by adjusting the size and position of voltage equalizing insulator. The model of the voltage equalizing device is shown in Figure 4. Adding voltage equalizing rings to bus-bar end and the grounding support end of the post insulator can effectively shield the high field intensity area nearby and improve the flash-over voltage value of the post insulator body.

3. **Electrical and mechanical performance simulation of rod post insulators**

3.1. *Simulation results of electrical performance of post insulator*

In the electric field simulation calculation, high potential is applied to the tubular bus-bar and equalizing ring of the post insulator, zero potential is applied to the end of the grounding support, and the high voltage is applied to the intermediate bar type ceramic metal connection structure, which is treated by coupling metal potential. The overall potential and electric field distribution of the rod post insulator are shown in Figure 5.
Figure 5. Voltage distribution of post insulator.

Figure 5 shows that the overall potential of the post insulator transits evenly from the high-voltage bus to the grounding bracket, and the high field strength area mainly concentrates near the tubular bus and the high-voltage side equalizing ring. On the other hand, it can be seen from Figure 1 that the net distance of the insulating space of the prop insulator body is 11777.5mm, while the dry flash-over voltage of the rod-type insulator is close to breakdown voltage of the air gap between the electrodes. The relationship between the dry flash-over voltage and the dry flash-over distance can be estimated by relationship between the rod-plate air gap of the extremely in-homogeneous electric field:

\[ U_f = 5.6r_0 f \]

(1)

\( U_f = 3252kV \) is calculated by substitution of the above formula, which is higher than the peak value of phase voltage of UHV pillar insulator. The distribution of electric field of the voltage equalizing ring and the ceramic bushing on the bus side of the pillar insulator is listed in Figure 6.

Figure 6. E-field distribution of key points.

It shows that the maximum electric field strength on the surface of the voltage equalizing ring is 1136V/mm, which is lower than the air breakdown field strength of 3000V/mm. The alloy has the surface field strength control standard. The distribution of potential and electric field near the tube
bush of the pillar insulator is slightly distorted. The field strength at the end of umbrella group is 584V/mm, which exceeds the control standard of 500V/mm, which is not conducive to the long-term operation of the insulator. Therefore, the grading ring of insulator side should be further optimized to improve the electric field distribution of the porcelain bushing body.

At the same time, the typical axial voltage and electric field distribution curves of the prop insulator body are listed in Figure 7. The variation trend of the curve is representative for the prop insulator. The electric field distribution curve shows high trend at both ends and low in the middle. Because the interception path passes through the large, medium and small umbrella groups of porcelain bushes, it shows jump change law. The bonding structure of intermediate rod type ceramic metal is metal, and its internal electric field intensity is zero. Therefore, four zero-value regions appear in the electric field distribution curve, and potential distribution curve presents uniform transition from the highest potential to zero potential. The calculation results show that the pillar insulator can effectively uniform the voltage distribution.

![E-field distribution](image1)

![Voltage distribution](image2)

**Figure 7.** Electric and voltage distribution curves.

### 3.2. Simulation results of mechanical performance of post insulators

The mechanical properties of post insulator is simulated and calculated. The results of three cases, tension, bending and torsion, are shown in Figure 8.
Figure 8 shows that the tensile stress of rod-type post insulators under 40kN tensile load is concentrated at the joint of flange and mandrel, the stress is 120MPa, which is less than tensile fracture stress of mandrel and steel, but attention should be paid to strengthen the strength of the joint. When the bending stress of 12.5kV is applied, maximum value of the first principal stress is mainly concentrated in flange. The maximum equivalent stress is 45MPa when the torque of 10kN*m is applied, and the maximum shear force is 30MPa on flange. The maximum first principal stress is also concentrated on the flange support, and its value is 50MPa, which does not exceed the fracture stress.

4. Structure optimization of voltage equalizing device for post insulator
The PSO-RBF neural network is used to train the learning finite element method to simulate the electric field intensity of the key position of the post insulator. The parameters of PSO algorithm are set to the learning factor $C_1=1.6$, the initial and the termination values of the inertia weight $W_{\text{max}}=0.9$ and $W_{\text{min}}=0.4$, and the maximum number of iterations is set to 1800, and the combined PSO-RBF algorithm iterates. The convergence process is shown in Figure 9.
The radial basis function network is designed by using the Newrb function in MATLAB. The format of M language call is net = Newrb (p, t, spread). \( P \) is the input vector of the support insulator voltage equalizing device, \( t \) is the output vector of the electric field strength at the key position of the support insulator, and the spreads is the dispersion constant of the radial base. Its set value is 1, and the output is the radial basis network. Weights and threshold satisfy the relationship between input and expected value. Figure 9 shows that the PSO-RBF neural network compiled in M language under the operating environment of MATLAB has the good convergence in the process of three iterations, which shows that the joint algorithm is suitable for the non-linear mapping scenario of the insulator voltage balancing device structure optimization. For non-linear inversion method of the optimal structural parameters of the RBF neural network, the electric field intensity at the key position of the post insulator is taken as the input vector \( p \), the structural parameters of the post insulator equalizing device as the output vector \( t \), and the structure of RBF neural network is \( 4 \times 6 \times 3 \). The electric field intensity at the key point is input into PSO-RBF network, and the output is reverse optimization design structural parameter of insulator voltage equalizing device. Taking diameter \( d/\text{mm} \), depth \( H/\text{mm} \) and maximum electric field intensity \( E \) as examples, the non-linear mapping effect of PSO-RBF neural network is illustrated as shown in Figure 10. It shows that the PSO-RBF neural network has good effect on the non-linear fitting mapping of the original finite element method calculation data points, and has a good extension on basis of the original data points. The objective vector \([920,700,550,440] \) composed of large equalizing ring, small equalizing ring, flange structure and maximum electric field strength on the surface of ceramic sheath are input into the RBF neural network for non-linear inversion calculation, and the output vector of structural parameters of equalizing ring is \([D=1420, d=145, H=255] \).

**Figure 9.** Convergence curves of PSO-RBF algorithm.

**Figure 10.** Nonlinear fitting of PSO-RBF neural network.
5. Conclusions
1) The results show that the maximum electric field strength on the surface of the equalizing ring is 1136 V/mm, which is lower than the air breakdown field strength of 3000 V/mm. The distribution of potential and electric field near the tube bush of the pillar insulator is slightly distorted. The field strength at the end of umbrella group is 584 V/mm, which exceeds the control standard of 500 V/mm, which is not conducive to long-term operation of the insulator.

2) When applying 10kN*m torque, maximum equivalent stress is 45 MPa, and the maximum shear force is 30 MPa on the flange. The maximum first principal stress is also concentrated at the flange support sheet, and its value is 50 MPa, which does not exceed the fracture stress.

3) PSO-RBF neural network has a good effect on the non-linear fitting mapping of the original finite element calculation data points, and has good extension on the basis of the original data points, and the algorithm has a good convergence. The output vectors of the non-linear inversion calculation are $[D=1420, d=145, H=255]$ mm, and the target vectors of the maximum electric field intensity on the surface of the large, small, flange and ceramic sheaths are $[920, 700, 550, 440]$ V/mm, which meet the requirements of the control parameters.

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References
[1] Liang Xuming, Zhang Ping and Chang Yong 2012 Recent advances in high-voltage direct-current power transmission and its developing potential Power System Technology 36(4) 1-9
[2] Huang Daochun, Xie Xiongjie, Huang Zhengfang, et al. 2013 Grading ring parameter design and corona characteristic test arrangement of 1 000 kV AC compact transmission line High Voltage Engineering 39(12) 2933-2942
[3] Toshiaki rokunohe, Tatsuro kato, Makoto hirose and Testu ishiguro 2010 Development of insulation technology in compact SF6 gas-filled bushings: development of compact 800kV SF6 gas-filled bushings Electrical Engineering in Japan 171(1) 19-27
[4] Nie Dexin, Zhang Hailong, Chen Zhong, Shen Xing 2013 Optimization Design of Grading Ring and Electrical Field Analysis of 800kV UHVDC Wall Bushing IEEE Transaction on Dielectrics and Electrical Insulation 20(4) 1361-1368
[5] Chen Maosheng 2018 Research on mechanical property and critical crack size of porcelain post insulator under low temperature environment Insulators and Surge Arresters (04) 217-222
[6] Zhang Boyu, Zhang Cuixia, He Ziming, et al. 2018 Research and development of UHV arresters with high seismic resistance used as post insulator Insulators and Surge Arresters (04) 1-7
[7] Zhang Weichun, Pan Fengming, Zhang Xingen, et al. 2013 Power loss analysis for structural parts in transformer based on finite element method High Voltage Apparatus 49(11) 55-61
[8] Nathan D Jacob, William M McDermid and Behzad Kordi 2012 On-line Monitoring of Partial Discharges in a HVDC Station Environment IEEE Transaction on Magnetics 19(3) 925-935
[9] Li Zhe, Yang Fan and Deng Yinghai 2016 Static mechanical properties study and optimization of porcelain post insulator for GW4-220 kV disconnecter Insulators and Surge Arresters 01 1-6