Optimization of Corona Ring Design Used in UHV Composite Insulator by PSO Algorithm

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Abstract. The three-dimensional model for the V and I type composite insulators used in AC 1000kV single-circuit tangent power transmission tower has been established, and conducted E-field calculation in FEM software, the results show that maximum electric field strength of corona ring used in V type insulator is about 13.9% and insulator surface 29.2% higher than that of I type, thus corona ring structure should be further optimized. So PSO algorithm has been implemented, meanwhile, submodeling technique was also used to solve such large calculation amount problem due to complexity of used model which can effectively reduce calculation amount without lose of accuracy. Then the method combining FEM and PSO algorithm has been applied to corona ring structure multi-parameter optimization used in V and I type insulators, finally, maximum E-field located in surface of ring and insulator shed can meet the electric control value, and no corona discharges can be observed when corona rings were used in actual project. The method proposed in the paper can solve structure optimization problem for large field domain and multi-media complex model, meanwhile, have reference value for researching field of insulation structure optimization with PSO algorithm.

1. Introduction
With the rapid development of China's economy, the demand for electric energy is increasing day by day, and the demand for line transmission capacity is increasing rapidly. In order to solve this problem, China vigorously builds UHV transmission lines[1]. Composite insulators are widely used in UHV transmission lines due to their high mechanical strength and good pollution resistance. However, composite insulators are composed of organic materials with poor aging resistance, which are prone to corona, deterioration and flash-over. These problems become more prominent in UHV transmission lines. At this time, it is necessary to install the appropriate grading ring to improve the electric field distribution of composite insulator string and meet its service conditions[2,3]. Therefore, the structure optimization of grading ring of composite insulator needs further research.

In the early literature, the traditional exhaustive method is generally used to optimize the structure of grading ring, but the method needs to constantly adjust the structural parameters of grading ring, and the manual operation is cumbersome. The follow-up research shows that the artificial intelligence algorithm can effectively solve the practical engineering problem of multi parameter optimization of grading ring structure: in reference[4], the optimal parameters of the grading ring of UHV composite insulator are obtained by introducing genetic algorithm with the maximum field strength of insulator as the objective function. In [5], neural network is used to fit the relationship between the structural parameters of grading ring and the optimization objective, and the optimal solution of the structural parameters of grading ring is obtained. In view of this, this paper continues to carry out research and
analysis from the following two aspects: ① further improve the three-dimensional finite element (FEM) calculation model of composite insulator in the finite element analysis. For the problem of increasing the amount of calculation caused by the complex structure of the model, the sub-modeling technology is used to effectively reduce the amount of calculation and achieve high accuracy. ② Considering that particle swarm optimization (PSO) is a popular and fast developing artificial intelligence algorithm, it has the advantages of strong search function, the good optimization effect and the strong convergence characteristics.

Taking the composite insulator of 1000kV AC single circuit transmission line on the same tower as the research object, this paper introduces in detail the implementation process of the combined FEM and PSO optimization algorithm under the calculation platform, and applies the method to the structure optimization of grading ring of composite insulator. The results show that this method can effectively realize the optimal configuration of grading ring, and has the characteristics of fast calculation speed and high degree of automation. The research results of this paper have been successfully applied to UHV engineering construction, and have a certain reference value for the research of particle swarm intelligence algorithm in the field of power system insulation structure optimization design.

2. Computing resources and initial simulation results

2.1. Computing resource
The basic principle is as follows: the problem of definite solution described by partial differential equation is transformed into the variational problem or the weighted residual equation, and then the variational problem is discretized into an extremum problem of the multivariate function by using the partition difference, or the weighted residual equation is expanded directly to form system of algebraic equations. Finally, the approximate solution of the problem is obtained by using an appropriate solver. When using the software to analyze the electric field, it only needs to establish the model, set the material properties, mesh generation, set the load, and finally solve and carry out the corresponding post-processing[6-8].

2.2. Computational model
In China's UHV AC test demonstration project, the composite insulator arrangement of single circuit transmission line on the same tower adopts “m” type, that is, single V-string is used in the middle phase of the tower, and double I-string is used in both sides of the tower[9]. In the calculation model, considering the distortion of electric field distribution of composite insulator string caused by tower, bundled conductor and fittings, the model does not have axial symmetry, so it needs to use three-dimensional full model for finite element analysis[10]. The type of tower is wine cup tower, and the height of cross arm to the ground is 45000 mm. The length of insulator string is 8970mm, the distance...
between double I series connection is 600mm, and the diameter of big umbrella is 210mm, the diameter of middle umbrella is 180mm, and the diameter of small umbrella is 150mm. The bundle conductor adopts eight bundle, the model is LGJ-500 / 35, and the bundle spacing of sub conductors is 400mm. Considering the interaction between the three phases, the 1/2 symmetrical model is adopted in the calculation, and the calculation domain is as shown in Figure 1. The model includes V-string and I-string composite insulators. The structural details of the model are shown in Figure 2. The simplified principles and assumptions in the modeling process are as follows: The ground wire which has little influence on the potential and electric field distribution of composite insulator along the string is ignored. In the simulation calculation, it is assumed that there is no water drop and pollution layer on the surface of composite insulator, fittings, conductor and grading ring; Zero potential is applied to the boundary of the whole computational domain to simulate the infinite boundary condition[11].

![Fig.2 Calculation model for composite insulators](image)

It can be seen from Figure 2 that the V-string and I-string of composite insulator are equipped with grading ring structure, in which the circular grading ring is used for single V-string and the runway type is used for double I-string. In the mesh generation, insulator, grading ring and tower are divided freely by 3-D ten node tetrahedral element, and bundled conductor is divided by 3-D twenty node hexahedral element. Finally, 5146768 elements and 7620700 nodes are generated. During the loading process, according to the sinusoidal waveform of three-phase AC voltage, the peak value of operating phase voltage $U_p$ is applied to the high potential fittings of middle phase V-string, and $-U_p/2$ is applied to the I-string on both sides respectively. At this moment, the potential and electric field distortion of V-string insulator is most serious. Similarly, most severe electric field and potential distribution of I-string insulator can be obtained by applying up on I-string and $-U_p/2$ on the other two phases:

$$U_p = 1100\text{kV} \times \frac{\sqrt{2}}{\sqrt{3}} \approx 898146\text{V} \quad (1)$$

2.3. Calculation results and analysis

The conjugate gradient PCG solver is used to solve the electrostatic field. The solver can achieve a high speed for solving large-scale problems (the degree of freedom is more than 50000~1000000), but it has a high demand for the hardware memory, and the solution accuracy is set to $10^{-8}$. The calculation results are shown in Figure 3 when the grading ring is configured or not. It can be found from the figure that without the grading ring (Fig.3 (b)), there are local high field strength areas on the surface of split conductor and fittings, and the maximum field strength values for V string and I string are about 2500V/mm and 1930V/mm. The maximum field strength of composite insulator surface appears at the junction of silicone rubber, metal and air. In the case of grading ring (Fig. 3 (a)), due to the shielding effect of the grading ring, the local high field strength is effectively prevented. The maximum field strength is transferred to the surface of grading ring, which are 2120V/mm (V string)
and 1825V/mm(I string), respectively. The maximum field strength position of insulator sheath is moved to the upper end of grading ring, and the electric field distribution along the axial direction of insulator string is shown in Fig. 4.

![E-field distribution](image1)

It can be seen from the figure that the maximum field strength at the high-voltage end of series V (at A) is about 500V/mm, which is higher than that at the high-voltage end of series I (at C), but the maximum field strength at the low-voltage end of series I (at D) is more serious “tail warping” than that at the low-voltage end of series V (at B). In order to prevent corona on the surface of fittings and electrical aging of insulator sheath, and leave a certain margin, the field strength control value on the surface of fittings and insulator sheath are taken as 2100V/mm and 450V/mm. It can be seen that the initial design can not meet the control requirements, and the structure of insulator grading ring needs to be further optimized.

![E-field distribution along insulator strings](image2)
3. Implementation of joint optimization algorithm of FEM and PSO
Implementation of submodeling FEM technology in the above simulation calculation, more accurate calculation results can be obtained because the calculation model is real and complex and the grid is dense, but it takes about 1h to complete the solution of finite element sparse matrix and the calculation and storage of the element results. It is unrealistic to use the usual FEM process for this large-scale electric field calculation problem. This paper considers using submodeling technology to solve it, and the method is programmable and modular, convenient for the repeated automatic call, and provides conditions for the implementation of PSO optimization algorithm. The specific process is as follows:

1) The V-string and I-string composite insulators, grading ring and adjacent air region in the overall model are selected as the calculation sub models, as shown in Figure 5. The number of all geometric entities is compressed by the numcmp and all commands, so that all entity numbers of sub model are continuous.

Fig.5 Submodels for V and I type insulator strings

Fig.6 Calculation results of submodels
2) After all the node numbers on the model surface are automatically obtained, the potential values of each node can be extracted because the potential values of each node have been calculated in the initial calculation of the whole model. The key to interpolation is to ensure that the potential and electric field between nodes on the boundary surface are continuous without distortion in local region. This paper has made the interpolation process automatic by programming. Next, only internal loads are required on the sub model. For the specific problems in this paper, the peak voltage of operating phase up shall be applied to the fittings and split conductors at the high voltage end of V-string and I-string insulator, and the fittings at the low-voltage end of insulator string shall be applied with zero potential. The results after boundary interpolation and internal load are completed are shown in Figure 6 (a).

3) After the boundary interpolation and internal load are applied, the sub model can be solved. The potential electric field distribution is shown in Figure 6 (b) and (c). In fact, the influence of the area outside the sub model on the distribution of potential electric field of insulator string can be equivalent to applying the boundary conditions to the sub-model. If the boundary conditions are interpolated correctly, the results of the sub-model and the whole model can be consistent. The distribution curves of insulator string electric field obtained by the two algorithms in Figure 7 are almost coincident, which shows the correctness of the calculation of the sub model.

![Fig.7 The comparison of E-field along insulator between two calculation approaches](image)

It can be seen that the number of sub model nodes accounts for 3.93% of the whole model. Under the hardware conditions in this paper, the calculation time is about 3.89% of the whole model, and the amount of calculation is greatly reduced. A lot of repeated calculation is needed in the optimization design. If the full model is used, a lot of calculation time will be consumed. If only the local area near the grading ring is changed, the overall potential and electric field distribution of the full model will not be affected. Therefore, sub-modeling FEM technology is feasible, which is the basis of subsequent repeated calculation.

The Particle Swarm Optimization (PSO) was proposed by Kennedy and eberhar of the United States in 1995 according to the foraging behavior of birds. PSO is to find the optimal solution through the cooperation between individuals, and its outstanding advantage is that the concept is simple and easy to implement. In PSO, the potential solution of each optimization problem is a particle in the search space, and the collective composed of all particles is called swarm. All particles have a fitness value determined by the optimized objective function, and the fitness value is determined by the position vector of the particle (equivalent to a feasible solution in the optimization problem, \( N \) is the number of optimization variables). Each particle also has a velocity vector that determines their direction and velocity. Particle swarm optimization searches in solution space by following the current...
optimal particle. PSO is initialized as the group of random particles, and then the optimal solution is found through iteration. The specific mathematical description of the process is as follows:

\[
v_d^i(k+1) = v_d^i(k) + c_1 r_1^i (p_d^i - x_d^i(k)) + c_2 r_2^i (g_d^i - x_d^i(k))
\]

\[
v_d^i(k+1) = \frac{v_d^i(k+1)}{|v_d^i(k+1)|} \max(1) \cdot v_d^\max
\]

\[
x_d^i(k+1) = x_d^i(k) + v_d^i(k+1)
\]

\[
f(x) = \sum_{i=1}^{3} x_i^2
\]

In the test, PSO is repeatedly used to search the minimum value of equation (3) for three times. The convergence curve is shown in Figure 8. Each time, it effectively converges to the minimum zero value, and the convergence curve does not coincide, which verifies the essence of the PSO random algorithm and the correctness of its implementation.

4. Implementation of mathematical model for structural optimization of pressure equalizing ring

For the problem studied in this paper, it is necessary to establish the mathematical model of pressure equalizing ring structure optimization. The objective of the grading ring structure optimization is to improve the electric field distribution along the composite insulator and meet the control requirements of 2100V/mm on the grading ring surface and 450V/mm on the insulator umbrella group surface. From the perspective of practical engineering application, the surface field strength of grading ring and insulator umbrella group is controlled to be equal to the above value, which can not only avoid corona erosion, but also reduce the size of grading ring and facilitate installation.
From the initial calculation results, it can be seen that the field strength distribution at the high voltage end of V-string and I-string insulators needs to be further optimized. The structural parameters of the grading ring include three parameters: lifting height $H$, pipe diameter $R$ and center distance $D$, and two grading rings at the high-pressure end of string I and string V need to be optimized. Therefore, there are 6 optimization parameters, as shown in Figure 9. Then the objective function $f$ of the pressure equalizing ring optimization can be expressed by formula (4). The objective function is the algebraic transformation of the above sphere function. When the each maximum field strength is equal to the control value, the objective function obtains the minimum zero value.

$$\min f = \sqrt{\sum_{i=1}^{2} \left( \frac{E_{i \text{max}} - 2100}{2100} \right)^2 + \sum_{i=1}^{2} \left( \frac{E_{i \text{max},S} - 450}{450} \right)^2}$$  \hspace{1cm} (4)

The constraint condition of the optimization variable (the structural parameters of the grading ring) is equation (5):

$$H_{\text{min}} < H_i < H_{\text{max}}$$

$$R_{\text{min}} < R_i < R_{\text{max}}, i = 1, 2$$ \hspace{1cm} (5)

$$D_{\text{min}} < D_i < D_{\text{max}}$$

5. Engineering application of FEM and PSO joint optimization algorithm

The combination of FEM and PSO is used to optimize the structure of the ring. First, input the initial value of the structural parameters of the grading ring. The sub-modeling FEM technology is used to automatically complete the grading ring modeling, meshing, loading and electric field calculation. The maximum field strength at the concerned position is extracted by the post processor and substituted into the objective function for calculation, PSO algorithm revises the structural parameters of grading ring according to the calculation results for the next modeling.
Here, in order to reduce the amount of calculation and ensure that the PSO algorithm can effectively find the optimal solution, after many attempts, the number of particles \( N \) in the algorithm is set to 16, \( C_1 \) to 2 and \( C_2 \) to 2.6. In the optimization process, it is found that the calculation time of the whole optimization process is mainly spent in sub-modeling FEM module. According to the above analysis, under the hardware resources of this paper, operation time of the process is 146s, the PSO algorithm runs about 240 times, and the overall calculation time is 9.73h. If the full model calculation is adopted, it takes 250.1h. Therefore, the sub model calculation can effectively shorten the calculation time. After optimization, the objective function \( f \) is approximately zero. Figure 10 shows that after optimization, the maximum field strengths of V-string grading ring and umbrella group surface are 2109V/mm and 455V/mm, and the maximum field strengths of I-string grading ring and umbrella group surface are 2120V/mm and 447V/mm, meeting the requirements of control values. It is used for the construction of the UHV AC single circuit transmission line. After grid operation, no corona is observed with UV imager.

6. Conclusion

a) The three-dimensional finite element electric field solution of the composite insulated V-string and I-string of AC 1000kV single circuit transmission line on the same tower is carried out. The results show that the maximum field strength of V-string grading ring is 13.9% higher than that of I-string, and the maximum field strength of V-string insulator is 29.2% higher than that of I-string. The grading ring needs to be further optimized.

b) The basic optimization process is formed by combining FEM and PSO. The algorithm is used to optimize voltage sharing ring of UHV composite insulator, and the optimized structural parameters are obtained: the upper bearing height of I-string runway ring is 550mm, the center distance is 747mm, and the diameter is 88mm. The upper bearing height of V-string ring is 808mm, the center distance is 911mm, and the diameter is 124mm. No corona is found after optimizing operation of the equalizing ring hanging network.

References

[1] LIU Zhen-ya, Ultra-high voltage power grid[M], Beijing, China: China Economy Press, 2005.
[2] YAN Zhang, ZHU De-heng. High voltage insulation engineering[M], Beijing, China: China Electric Press, 2007.
[3] HUANG Ling, WEN Xi-shan, LAN Lei, YE Wan-qi. Optimization of grading rings for UHV composite insulator by the improved GA[J]. High Voltage Engineering, 2009, 35(2): 218-224.
[4] SIMA Wen-xia, YANG Qing, SUN Cai-xin et al. Optimization on corona ring design for EHV composite insulator using finite element and neural network method[J]. Proceedings of the CSEE, 2005,25(17): 115-120.
[5] XIE Tian-xi, MO Juan, PENG Zong-ren, LI Jing et al. Corona suppression of grading rings on suspension composite insulators on 500kV compact transmission line[J]. High Voltage Engineering, 2010,36(7): 1779-1784.
[6] HUANG Dao-chun, RUAN Jiang-jun, LIU Shou-bao. Potential distribution along UHV AC transmission line composite insulator and electric field distribution on the surface of grading ring[J]. High Voltage Engineering, 2010, 36(6): 1442-1447.

[7] Zhang Bo, Han She-jiao, He Jin-liang, et al. Numerical analysis of electric field distribution around composite insulator and head of transmission tower[J]. IEEE Transactions on Power Delivery, 2006, 21(2): 959-965.

[8] T.Doshi, R.S.Gorur, J.Hunt. Electric field computation of composite line insulators up to 1200kV AC[J]. IEEE Transaction on Dielectrics and Electrical Insulation, 2011, 18(3): 861-867.

[9] Andrew J.Phillips, John Kuffel, Anthony Baker, Jeffery Burnham et al. Electric field on AC composite transmission line insulators[J]. IEEE Transactions on Power Delivery, 2008, 23(2): 823-830.

[10] Imre Sebestyen. Electric-field calculation for HV insulation using domain-decomposition method[J]. IEEE Transactions on Magnetics, 2002, 38(2): 1213-1216.

[11] LIN Xin, CAI Qiang, XU Jian-yuan, LI Shuang. Large scale of electric field calculation of 1100kV disconnector based on domain decomposition method[J]. High Voltage Apparatus, 2011, 47(2): 1-6.