Research on Digital Twin Virtual Model of UHV Core Power Equipment

Shiling Zhang

1State Grid Chongqing Electric Power Company Chongqing Electric Power Research Institute, Chongqing, 401123
zhangshiling@cq.sgcc.com.cn

Abstract. In this paper, voltage equalization, corona prevention and noise reduction are studied by using finite element calculation method and multi-objective optimization algorithm for UHV substation, series compensation circuit, transmission line, DC valve hall and outdoor field. The calculation model of multi parameter and multi-objective optimization design is established, the optimal configuration parameters of voltage equalizing structure are obtained, the electric field distribution uniformity and structure rationalization are realized, the corona discharge is effectively restrained, the key technology of voltage equalizing and anti corona is solved, the cost is reduced, the efficiency is improved, and a simulation calculation and optimization design platform with independent intellectual property rights is formed. The research results have been successfully applied to UHV projects in China.

1. Introduction
The distribution of energy resources and productivity in China is very unbalanced. 76% of the retained reserves of coal resources are distributed in the north; 80% of hydropower resources are distributed in the western region[1,2]. Land wind energy is mainly concentrated in the northern region, while more than two-thirds of the energy demand is concentrated in the central and eastern regions, which objectively determines that China must take the road of long-distance and large-scale power transmission and the road of optimal allocation of energy resources throughout the country. UHV has the characteristics of long distance, large capacity, low loss and saving corridor resources. It represents the highest level of today's transmission technology, which is conducive to the optimal allocation of energy resources in a wider range and promote the coordinated development of power grid [1]. With the continuous improvement of voltage level and the continuous expansion of power grid construction scale, the electromagnetic environment problems caused by UHV transmission are becoming increasingly prominent[3,4]. There are many kinds of UHV lines and substation equipment, complex towers and frames, and various connection modes. The interaction between high-voltage conductors, jumpers, fittings and interphase, upper and lower frame towers makes the electric field distortion serious, and corona and noise become the main factors affecting the environment. Therefore, it is very important to carry out the research on the characteristics of UHV corona, uniform the electric field distribution of insulators, configure reasonable voltage equalizing parameters and inhibit the corona discharge on the surface of fittings, so as to reduce noise pollution, reduce energy loss and improve the safe operation reliability of UHV substation and transmission line[5,6].

The traditional design concept of UHV core power equipment is to carry out electrical, thermal and mechanical physical structure design according to the fixed performance parameters of power equipment operation environment, including internal insulation structure design of UHV converter.
transformer, insulator string structure design of overhead transmission line, structure design of UHV series compensation device, UHV converter/wall bushing structure design Structural design of basin insulator for UHV GIS/GIL, structural design of valve tower of UHV converter valve hall, etc. In fact, the external environmental factors, voltage and current loads of various UHV power equipment in the actual operating environment are real-time changing processes[7]. The above UHV core power equipment are physical entity structures. If they can be mapped into digital twin model, the numerical results of electrical, thermal and mechanical fields of power equipment can be simulated in real time and visualized online. The multi-dimensional physical quantities such as temperature, pressure, stress, voltage, current and electric field at the key position of the physical entity model of power equipment are monitored in real time through the on-line sensing technology, compared with the real-time physical simulation results, and the digital twin model simulation results are modified by the iterative algorithm to realize the convergence and unity of the two. Further, combined with the historical physical field data time series of UHV power equipment and the simulation results of digital twin model, the sequence data are predicted and analyzed to evaluate the operation state and life value of UHV core power equipment[8].

This paper focuses on the construction process of digital twin entity model of typical power equipment such as UHV substation, typical tower structure of UHV transmission line, UHV series compensation circuit, converter valve tower of UHV DC valve hall, outdoor field of UHV DC valve hall, and realizes the large field visualization of refined model based on the electric field and voltage distribution.

2. Application of optimization technology in UHV Substation

UHV substation is mainly composed of main transformer circuit, GIS circuit, high impedance circuit and frame tower. There are many equipment, complex structure and great difficulty in simulation calculation[9]. Aiming at the UHV test demonstration project, this paper establishes the three-dimensional finite element simulation calculation model of Changzhi, Jingmen Substation and Nanyang switching station, including various substation equipment, bus, fittings, connecting lines and frame towers, calculates and analyzes the potential and electric field distribution of substation equipment, bus, fittings and connecting lines, and obtains the electric field distribution law of different equipment. The structure of the voltage equalizing device is optimized, and the optimal configuration parameters are proposed, which provides an important basis for the design of UHV substation and switchyard.

Through the electric field calculation and structural optimization of the equipment, bus, wiring and fittings of the main transformer circuit, GIS circuit and high impedance circuit of Changzhi and Jingmen substations and Nanyang switchyard of the UHV AC test demonstration project, the main transformer circuit, HGIS circuit and high impedance circuit of Changzhi and Jingmen substations, the equipment, bus, wiring, fittings of GIS circuit and high impedance circuit of Nanyang switchyard The surface field strength of terminal ball and voltage equalizing shielding ring is less than 15kV/cm under peak voltage.

Figure.1 Establishment of digital twin model of UHV test demonstration project
The surface field strength of voltage equalizing shield ring of frame tower insulator is less than 20kV/cm under peak voltage. The field strength at 1.5m from the ground can be controlled within 10kV/m except that the field strength in individual areas of HGIS is 13kV/m. The corona noise at 1000kV side is lower than that at 500kV side.

3. Application of optimization technology in UHV transmission line

UHV transmission line involves tangent tower, tension tower, large span tower, porcelain insulator, composite insulator and rigid jumper. Due to the influence of stray capacitance of tower and high-voltage conductor, the distribution voltage of porcelain insulator and electric field of composite insulator are very uneven, and the electric field on the surface of voltage equalizing ring, shielding ring, jumper and fittings is relatively concentrated[10]. Therefore, exploring the voltage equalizing method of UHV transmission line insulators, optimizing voltage equalizing parameters, homogenizing the electric field distribution of insulators and improving the external insulation characteristics of insulators are very important for the safe and reliable operation of UHV transmission lines.

Aiming at the UHV AC test demonstration project and the UHV AC projects from Huainan to Shanghai and Ximeng to Nanjing, this paper calculates and analyzes the potential and electric field distribution of porcelain and composite insulators of linear tower and tension tower, and optimizes typical tower types, various string shapes. According to the voltage equalizing structure of insulators of different materials, the distribution law of potential and electric field of insulators is obtained, and the reasonable configuration parameters are put forward, which provides an important basis for the design of UHV transmission line.

Figure 2 Digital twin model of tangent tower and tension tower in UHV test demonstration project

Through three-dimensional finite element calculation and multi-objective optimization of large field and complex structure of UHV transmission line, it is found that the potential and electric field distribution of UHV AC line insulator string are very uneven, and the voltage or field strength on the conductor side of insulator string is 5~8 times higher than that in the middle of insulator string; The structure, shape and installation position of voltage equalizing device are the main factors affecting the distribution of insulator voltage and electric field, and the distribution of electric field on the surface of voltage equalizing shielding ring and fittings[11]. The jumper arrangement has a great influence on the potential and electric field distribution of tension insulator string. Therefore, the conductor side can be equipped with single ring, double ring, combined ring or combined ring according to the installation mode of insulator, optimize the position, pipe diameter and ring diameter of voltage equalizing shielding
ring, pay attention to the impact of tension winding and jumping on the distributed voltage of insulator at high-voltage conductor side, so that the maximum voltage on single porcelain insulator is lower than 30kV. The maximum field strength of composite insulator is below 0.4kV/cm. Except for individual tower shape, the field strength on the surface of grading ring, shielding ring, jumper and fittings is less than the control field strength of 20kV/cm.

4. Application of optimization technology in UHV series compensation circuit
Calculation of electric field distribution and voltage equalizing characteristics of electrical circuit equipment and connecting fittings of series compensation device in UHV AC power station, including potential and electric field distribution of series compensation platform, lightning arrester, circuit breaker, disconnector, post insulator and connecting fittings, as well as calculation and analysis of electric field distribution of series compensation circuit at 1.5m to the ground.

![Figure 3 Digital twin model of UHV series compensation circuit](image)

After electric field calculation, analysis and structural optimization of electrical circuit equipment and connecting fittings of 1000kV series compensation device, the surface field strength of lightning arrester, circuit breaker, disconnector, post insulator, connecting fittings and grading ring in series compensation system is less than 15kV/cm. There are many structural forms of connecting clamps and expansion clamps between equipment, and the maximum electric field intensity on the surface does not exceed 21kV/cm. The field strength in most areas of the series compensation circuit is below 10kV/m at 1.5m to the ground, and the field strength in some areas is relatively high, between 10kV/m and 15kV/m. The electric field distribution and corona characteristics of UHV series compensation circuit basically meet the control requirements.

5. Optimization technology in UHVDC valve hall, outdoor field and transmission line
The valve hall of UHV converter station has many equipment, various interfaces and complex electromagnetic field distribution. The valve tower, converter valve side bushing and grounding switch, current transformer, voltage divider, wall bushing, post insulator, suspension insulator, tube bus, lightning arrester and other equipment in the valve hall, as well as various voltage equalizing shielding and connecting drainage fittings, have different forms, many voltage levels, complex electrical and gas connections, some equipment bear AC and DC superimposed voltage, and the space in the valve hall is limited. It is necessary to reduce the air clear distance between equipment with different potentials as much as possible, which leads to complex electromagnetic field distribution in the valve hall and prone to electric field distribution distortion and corona discharge of equipment[12]. Therefore, it is necessary to quantify the electric field distribution in the valve hall through electromagnetic field simulation calculation, design the equipment voltage equalizing shield (ring) and connecting fittings, improve the electric field distribution on the surface of the equipment voltage equalizing shield (ring) and connecting fittings, suppress corona and reduce noise, so as to provide a basis for the design of the valve hall and the optimal layout of the voltage equalizing shield (ring) and connecting fittings of the converter main equipment.
Through the calculation of three-dimensional potential and electric field distribution and voltage equalizing characteristics of UHVDC valve hall, outdoor field and transmission line, it is found that the electric field distribution in the valve hall is uneven and there are differences in the electric field distribution among various equipment due to the influence of AC/DC mixed field, phase to phase, different potential and different equipment. The calculated surface field strength of converter valve layer is no more than 21kV/cm; The surface field strength of arrester grading ring (ball) shall not be greater than 10kV/cm; The surface field strength of OCT grading ring shall not be greater than 13kV/cm; The surface field strength of pressure equalizing ball (shielding cover) of converter bushing and through wall bushing shall not be greater than 11kV/cm; The surface field strength of the grading ball of fittings shall not be greater than 9kV/cm; The electric field distortion on the surface of the valve layer shield is serious, and the maximum field strength is 26.4kV/cm. The electric field distribution of ±800kV transmission line insulator and voltage equalizing shielding ring is within the control field strength range. Through calculation and analysis, the design ideas and control parameters of voltage equalizing and anti corona of ABB and Siemens UHV DC valve hall are basically understood, which lays a good foundation for the independent design of UHV DC valve hall in China.

6. Application of optimization technology in UHV corona test
One problem faced by UHV corona test is that it is difficult to achieve the same real test as the actual working condition. Therefore, we propose a test method to replace the real corona test - field strength equivalent method. In this method, the difference of electric field distribution between the test layout and the actual working condition is obtained through simulation calculation, and the correction coefficient of corona test voltage is obtained by using the field strength equivalent method, so as to
determine the reasonable corona test voltage. The field strength equivalent method has been applied in the corona test of State Grid Institute of electrical Sciences, which effectively solves the key technology of simulating the actual working conditions for corona test, reduces the cost, improves the efficiency, and provides a method and way for UHV corona test.

Figure 6: Simulation calculation of corona test arrangement and field strength equivalence of UHV insulator.

7. Digital twin model processing algorithm for UHV power equipment

Based on the digital twin three-dimensional model established by typical UHV power equipment, the above equipment models have realized fine and large field modeling and analysis. Through the above physical entities and digital virtual models, the static and dynamic solutions can be carried out for the multi physical fields of electricity, heat, force and machine of typical power equipment, so as to realize the visualization of real-time operation state characteristics of power equipment. Through the external sensing and monitoring technology, the adaptive sensing of various physical quantities at the key positions of typical power equipment is realized, the characteristic data curve of the actual time series is obtained, and the simulation results of the digital twin model are corrected in real time. The image database is established through multi-spectral methods such as infrared and ultraviolet testing to provide three-dimensional holographic image data comparison for the digital twin model. The processing algorithm flow is shown in Fig. 7.

Figure 7: Twin data processing based on GA and BP neural network.
Taking the UHV converter valve hall as an example, the infrared thermal imager analysis results of through wall casing, converter valve casing, converter valve tower and tube parent metal fittings are listed in Figure 8. Through three-dimensional modeling technology and finite element division technology, UHV power equipment can be divided into fine units, taking UHV transmission tower as an example, as shown in Figure 10.

![Figure 8 Observation results of infrared thermal imager for power equipment](image)

The potential value of each micro unit of transmission tower realizes three-dimensional visualization, and the results can be mapped to the specific location of the equipment.

![Figure 9 Observation results of power equipment ultraviolet imager](image)

![Figure 10 Potential distribution of UHV transmission tower](image)
8. Conclusion
The application of simulation optimization technology in UHV substation, series compensation circuit, transmission line, DC valve hall and outdoor field construction plays a good role in uniform electric field distribution, restraining corona discharge, reducing noise pollution, reducing energy loss, improving the safe operation reliability of UHV substation and transmission line, and provides methods and ways for UHV corona prevention and noise reduction. It is expected to be more widely used in UHV Engineering Construction and other fields in the future.

References
[1] Valentina Cecchi, Aaron St. Leger, Karen Miu, Chika O. Nwankpa. Incorporating temperature variations into transmission-line models[J]. IEEE Transactions on Power Delivery, 2011, 26(4): 2189-2196.
[2] Liu Yadong, Chen Si, Cong Zihan, et al. Key Technology and Application Prospect of Digital Twin in Power Equipment Industry[J]. High Voltage Engineering, 2021, 47(05): 1539-1554.
[3] Mohammad R. Hesamzadeh, Nasser Hosseinzadeh, Peter Wolfs. An advanced optimal approach for high voltage AC bushing design[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2008, 15(2): 461-466.
[4] Xie Hengkun, Ma XinShan, Kao KC. Computation of electric fields and study of optimal corona suppression for bushing-type insulators[J]. IEEE Transactions on Electrical Insulation, 1986, EI-21(1): 41-51.
[5] Qi Bo, Zhang Peng, Zhang Shuqi, et al. Application Status and Development Prospects of Digital Twin Technology in Condition Assessment of Power Transmission and Transformation Equipment [J]. High Voltage Engineering, 2021, 47(05): 1522-1538.
[6] ZHANG Shiling, PENG Zongren. Design of SF6 gas bushing external insulation structure on high voltage converter transformer valve side[J]. High Voltage Apparatus, 2019, 55(4): 117-124.
[7] Dexin Nie, Hailong Zhang, Zhong Chen, Xing Shen. Optimization Design of Grading Ring and Electrical Field Analysis of 800kV UHVDC Wall Bushing[J]. IEEE Transaction on Dielectrics and Electrical Insulation, 2013, 20(4): 1361-1368.
[8] ZHANG Shiling, PENG Zongren. Design and analysis of insulation structure of ±800 kV valve side converter transformer bushing[J]. High Voltage Engineering, 2019, 45(07): 2257-2266.
[9] Zhang Liangxian, Chen Mosheng, Peng Zongren et al. Eddy current loss calculation and shield analysis of UHV converter transformer[J]. TRANSFORMER, 2013, 50(3): 15-21.
[10] Shibao Zhang. Evaluation of thermal transient and overload capability of high-voltage bushings with ATP[J]. IEEE Transactions on Power Delivery, 2009, 24(3): 1295-1301.
[11] WANG Jialong, PENG Zongren, LIU Peng, et al. Analysis of electric field on the surface of grading and shielding fittings inside ±1100 kV ultra-high voltage converter valve hall[J]. High Voltage Engineering, 2015, 41(11): 3728-3736.
[12] ZHANG Shiling, PENG Zongren. Nonlinear E-field simulation of converter transformer outlet and its structure optimization[J]. High Voltage Engineering, 2018, 44(6): 2048-2059.