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±800 kV特高压直流线路均压环优化研究

邓桃，李庆峰，张学军，宿志一，范建斌
(中国电力科学研究院，北京市 海淀区 100192)

The Optimization of Grading Ring Design for ±800 kV UHV DC Transmission Lines

DENG Tao, LI Qing-feng, ZHANG Xue-jun, SU Zhi-yi, FAN Jian-bin
(China Electric Power Research Institute, Haidian District, Beijing 100192, China)

ABSTRACT: The three-dimensional finite element method is used to calculate the electric field of insulator strings for ±800 kV UHV DC transmission lines. After the comparison of electric field distribution and voltage distribution with different ring diameter, tube diameter and shielding depth, the dimension and position of grading ring is recommended. The ball-gap method is used to measure the voltage distribution of insulator strings for ±800 kV UHV DC transmission lines. Test results are consistent with calculation results. Findings of this paper are important for the grading ring configuration of ±800 kV UHV DC transmission lines.

KEY WORDS: electric field; finite element method; grading ring; insulator strings; optimization; UHV transmission lines

摘要：采用三维有限元方法对±800 kV特高压直流输电线路绝缘子串进行电场计算，比较不同外径、不同管径、不同安装位置的均压环对绝缘子串的电压分布和电场分布特性的影响，给出均压环合理结构尺寸和安装位置。然后通过球隙法测量±800 kV特高压直流输电工程绝缘子串的电压分布，试验结果与有限元计算结果一致。该文的研究成果对指导±800 kV特高压直流输电工程均压环的优化配置具有重要意义。

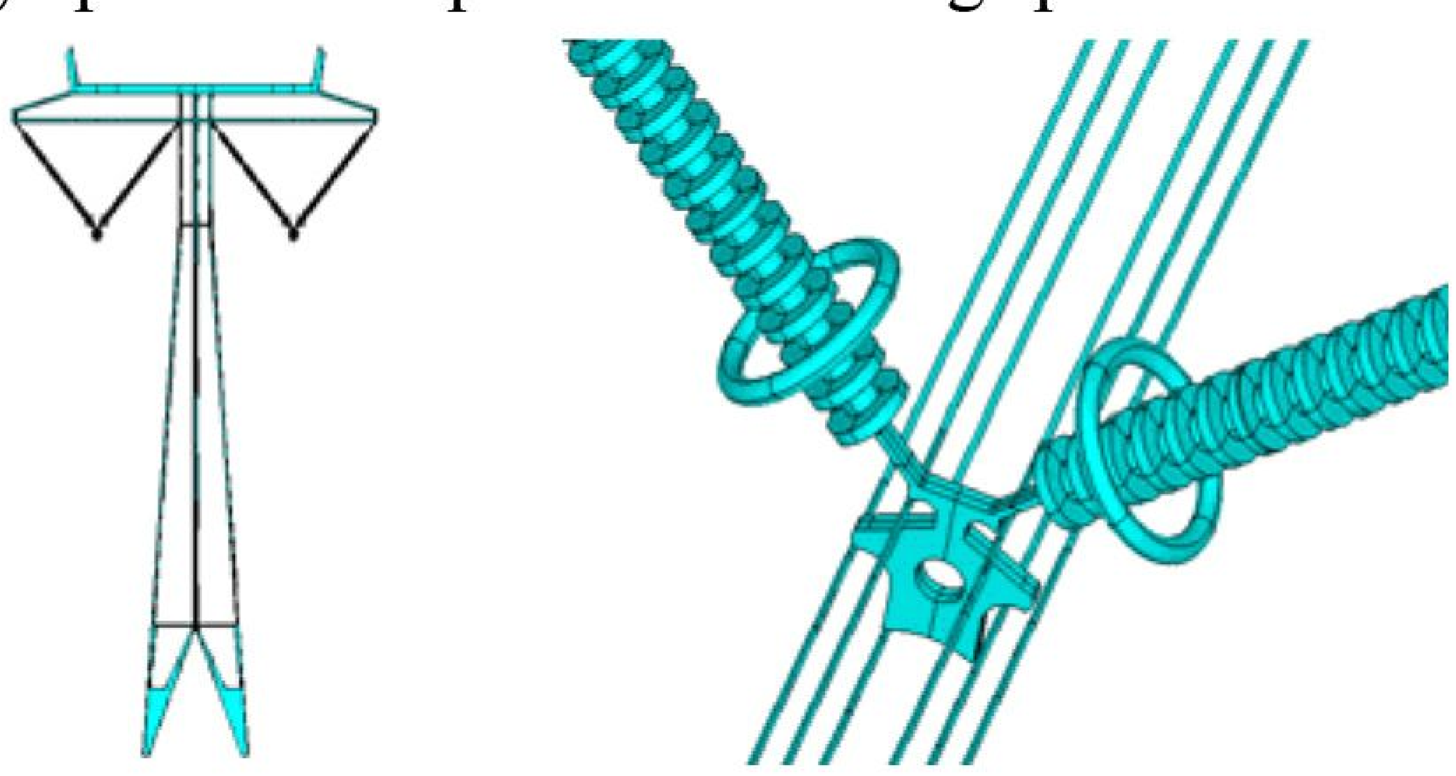
关键词：电场；有限元；均压环；绝缘子串；优化；特高压输电线路

0 INTRODUCTION

The electric field strength and voltage distribution of insulator string without grading ring under DC voltage are uneven [1-4]. The undertaken voltage of the conductor side insulators is much higher than other insulators. And the electric field strength on insulator feet-side near the conductor side is relatively high. These make the corona effect and deterioration of insulator strings often start from the conductor side insulators. Because of the higher tower and longer insulator strings on UHV DC transmission line, the voltage distribution of insulator strings is more uneven. Owing to the shielding role of grading ring, the electric field strength and voltage distribution on insulator trip can be effectively improved by the reasonable placement of grading rings. Because the electric field distortion problem has not been solved effectively, electric field distribution along insulator string surface still can't be measured accurately. Therefore, in engineering applications, the DC voltage distribution measurement of insulator strings is always used to improve both grading ring and shield ring configuration [5-8]. The voltage distribution of insulators under DC voltage has great dispersion because it is influenced not only by the structure and volume resistivity of different materials, but also by space charge and ion flow. Besides, the measurement has a higher cost and longer cycle compared with the calculation. Measurement results are influenced by the sensor, test environment, test conditions to certain extent. In recent years, with the development of computer science, the finite element method shows superiority in solving electromagnetic field problem. Without the environment and conditions limitation, the calculation method is more flexible than the test method. The size and location of grading ring can be changed randomly, so the optimization of grading ring design can be greatly simplified [9-14]. However, because the space charge and ion flow have great impact on voltage distribution of DC insulator strings and the two factors can't be easily considered in calculation method, there is certain deviation between calculation results and actual conditions. In this paper, the quantitative calculation superiority of the finite element method is taken to carry out the grading ring optimization design. Then the voltage distribution measurement is used as verification. The results introduced in this paper provide both a reference for engineering applications and an effective way of grading ring optimization.

1 CALCULATION MODEL

According to the basic data of ±800 kV Xiangjiaba-Shanghai UHV DC project, including size of tower, conductor, and fitting, the three-dimensional finite element models for different types of insulator, string and tower are set up to calculate its voltage distribution and electric field distribution. In order to expound the optimization method of grading ring design, a single V type porcelain insulator suspension string of 2×300 kN is taken as an example to describe the optimization process from ring diameter, tube diameter and mounting position three aspects. The insulator unit spacing is 195 mm and the disc diameter is 400 mm. Some factors are considered in the calculation such as single grading ring, 6×ACSR-720/50 conductors and 81 m cross arm height towers. The applied voltage for the system is the maximum operating voltage (816 kV). Fig. 1 shows the established finite element models. According to calculation experience, the sheds profile and deep under-rib sheds of the porcelain insulator have little impact on the whole electric field distribution, so they are not considered to save the memory space and improve the solving speed.



(a) Frontal diagram of calculation model　　(b) Grading ring model

图 1　计算模型

Fig. 1　Calculation model

2 THE ELECTRIC FIELD COMPARISON OF STRINGS WITH OR WITHOUT GRADING RING

The voltage distribution with unit of kV and electric field distribution with unit of kV/mm of porcelain insulator suspension strings without grading ring are shown in Fig. 2 and Fig. 3 respectively. The voltage distribution on each unit is shown in Fig. 4.

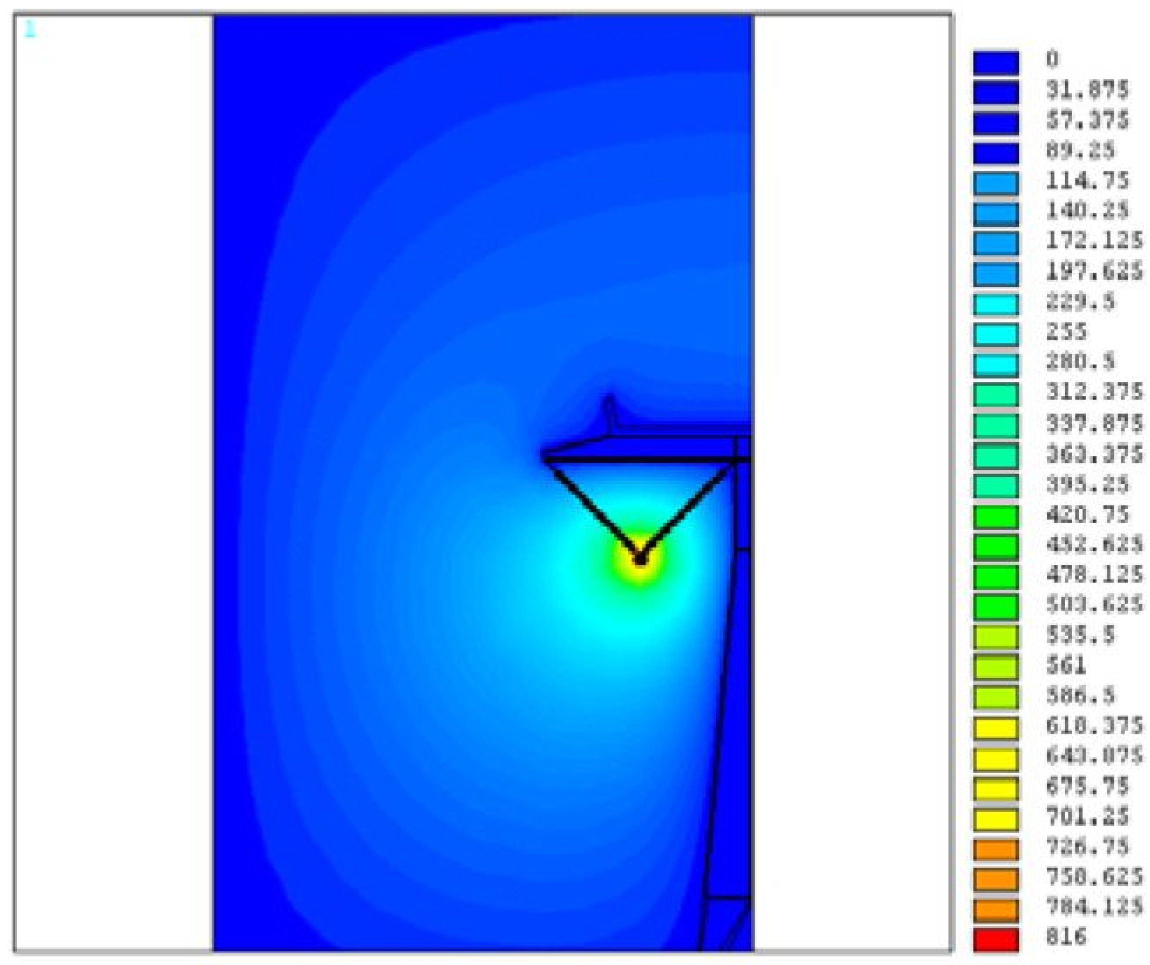


图 2　无均压环时电位分布

Fig. 2　Potential distribution without grading ring

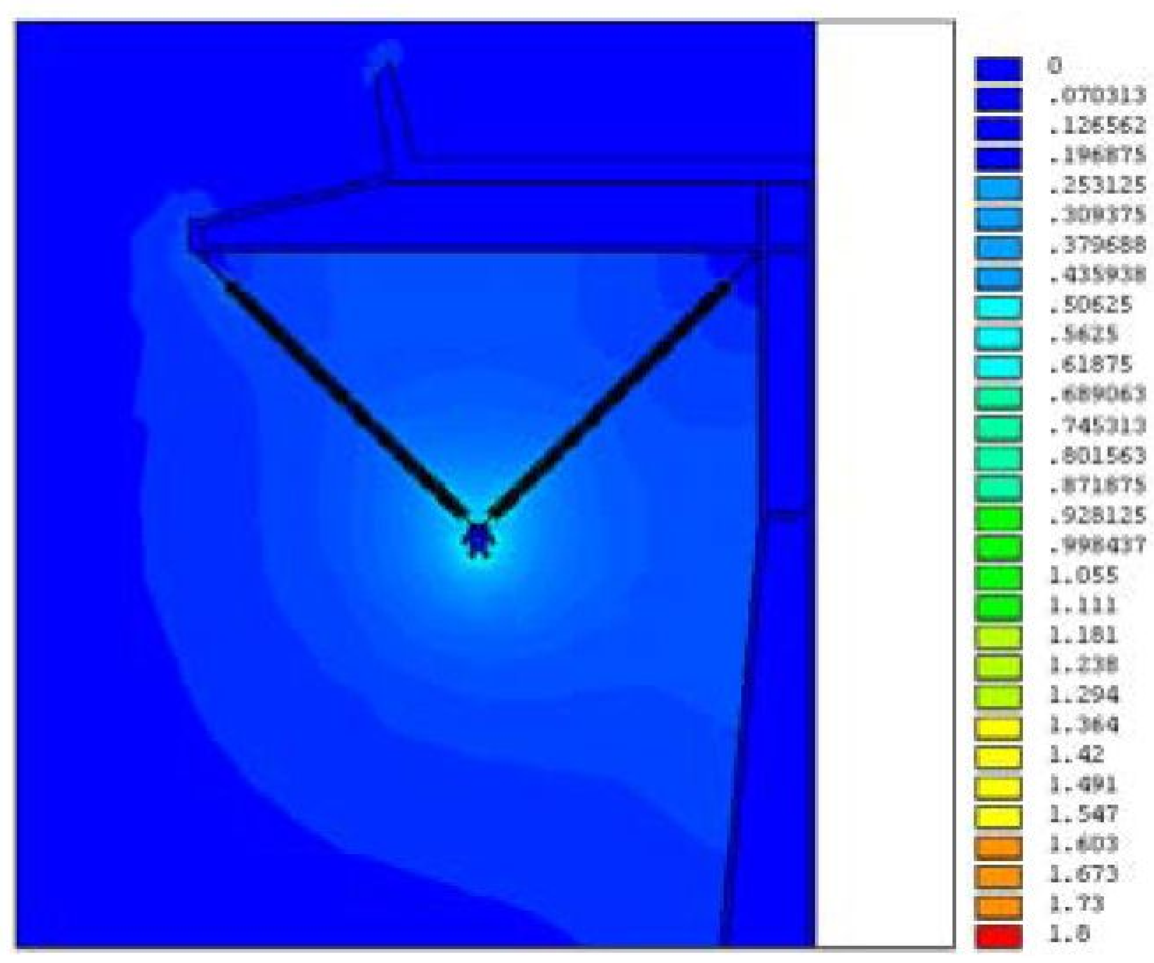


图 3　无均压环时电场分布

Fig. 3　Electric field distribution without grading ring

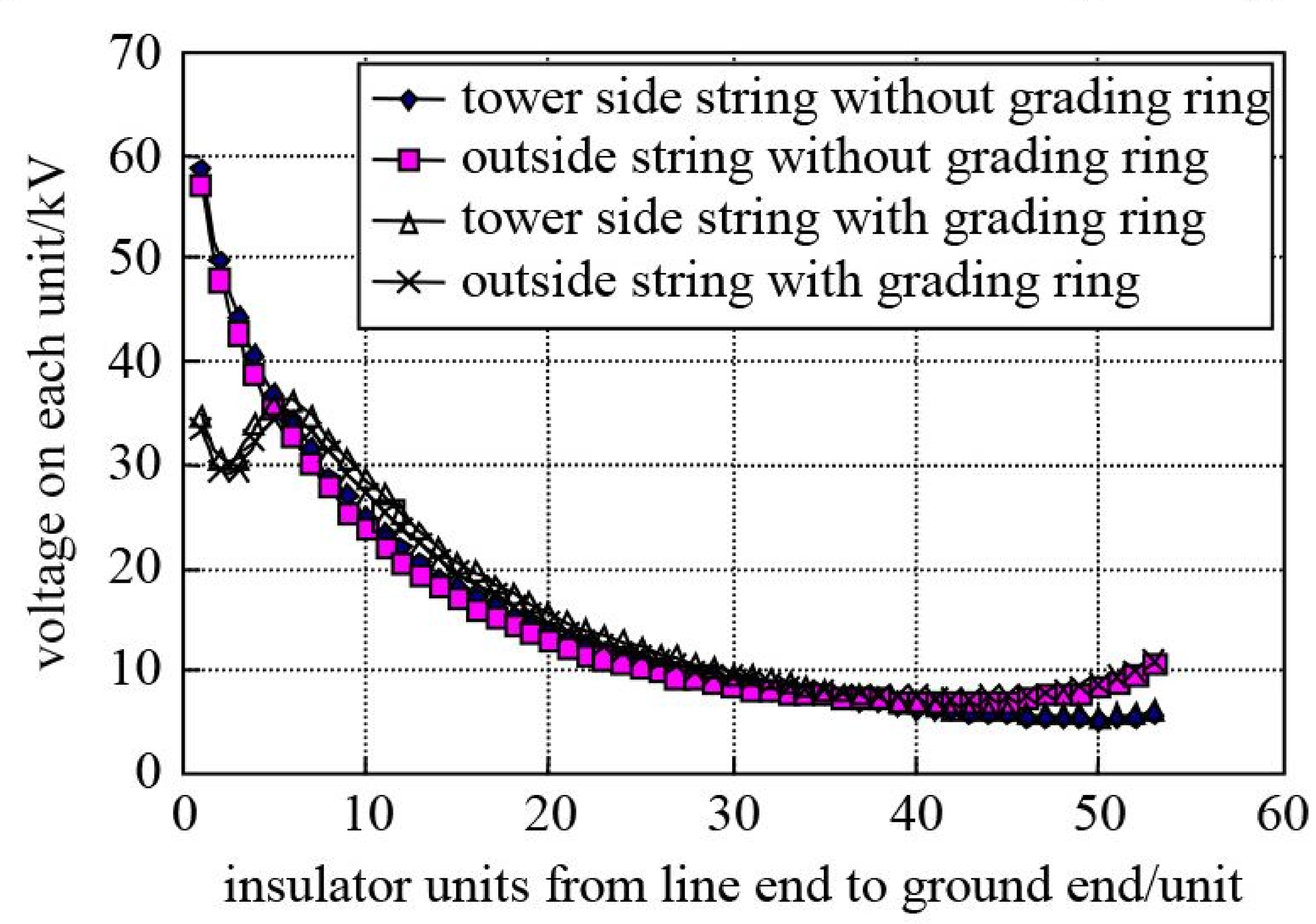


图 4　有无均压环时每片绝缘子分担电压对比

Fig. 4　Voltage distribution on each unit with or without grading rings

It is shown in Fig. 4 that the voltage distribution and electric field distribution of insulator strings without grading rings are very uneven. The voltage on conductor end insulators is higher than that on central insulators. But the voltage on ground end insulators increases gradually. Because of the shielding effect of tower, voltage on ground end insulators of the inside string is a little lower than that of the outside string. After the grading ring is installed, the voltages on line end insulators are obviously reduced by 39.5%. So, the grading ring can effectively improve the effect of voltage uniform distribution.

3 THE OPTIMIZATION OF GRADING RING

3.1 The Mounting Position Optimization

The voltage distribution on insulators varied greatly with different mounting position of the grading rings. Taking the strings away from tower as an example, with the mounting position away from the conductors or increasing the shielding depth, the maximum voltage on each insulator is reduced. That means the voltage distribution can be improved by increasing the shielding depth which is shown in Fig. 5. But the deeper the shielding depth, the longer the carriage of the grading ring would be, which is not good for the stability and mechanical strength of the grading ring. It should be noted that the dry arcing distance between the conductor end and the ground end is shortened as the grading ring is moved above the end fitting, and this reduction will reduce the impulse and power frequency of the insulator flashover voltages. So it is suggested that the grading ring be mounted between the third and forth insulators near the conductor side. If there are mounting difficulties, it can also be mounted between the second and third insulators.

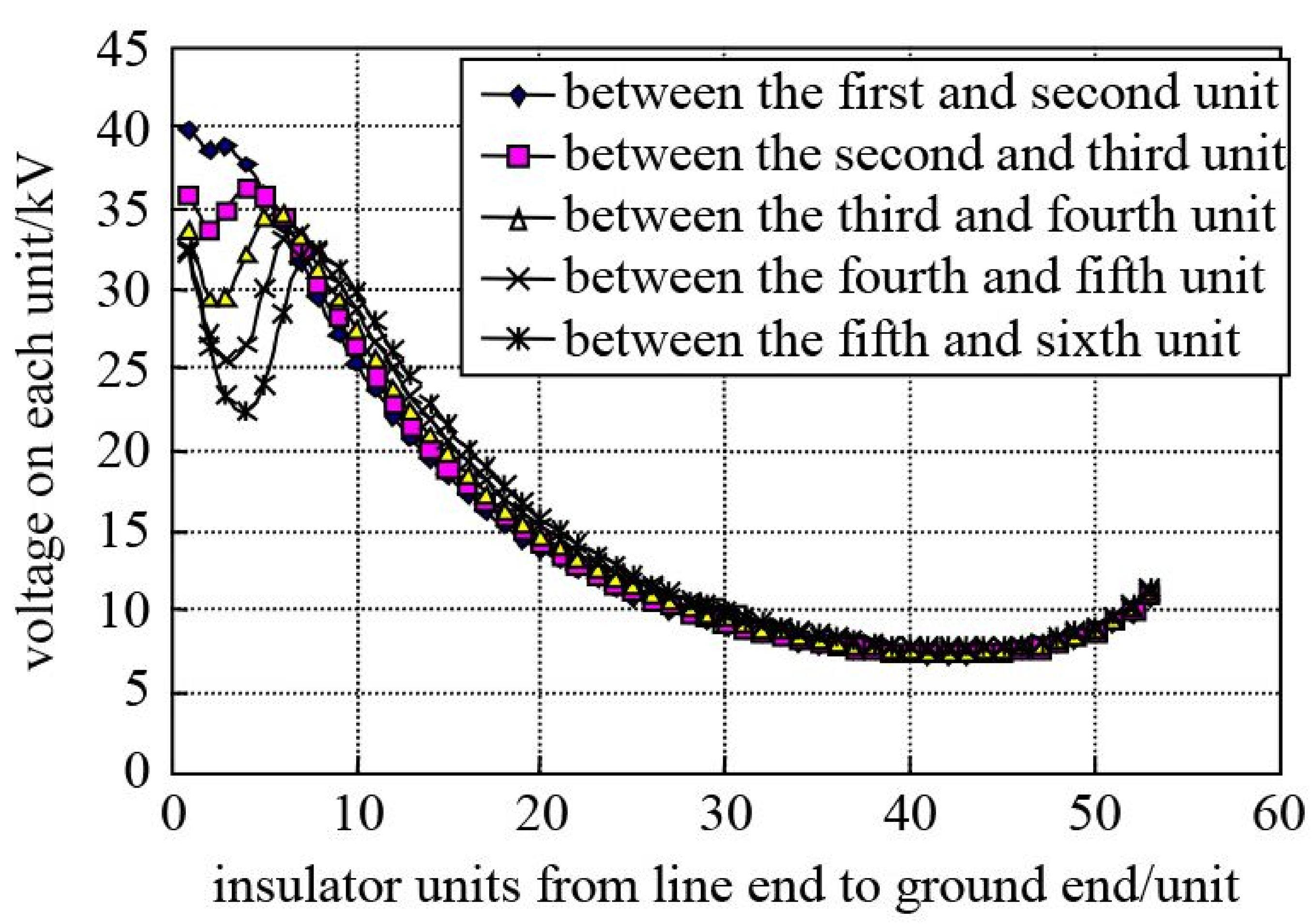
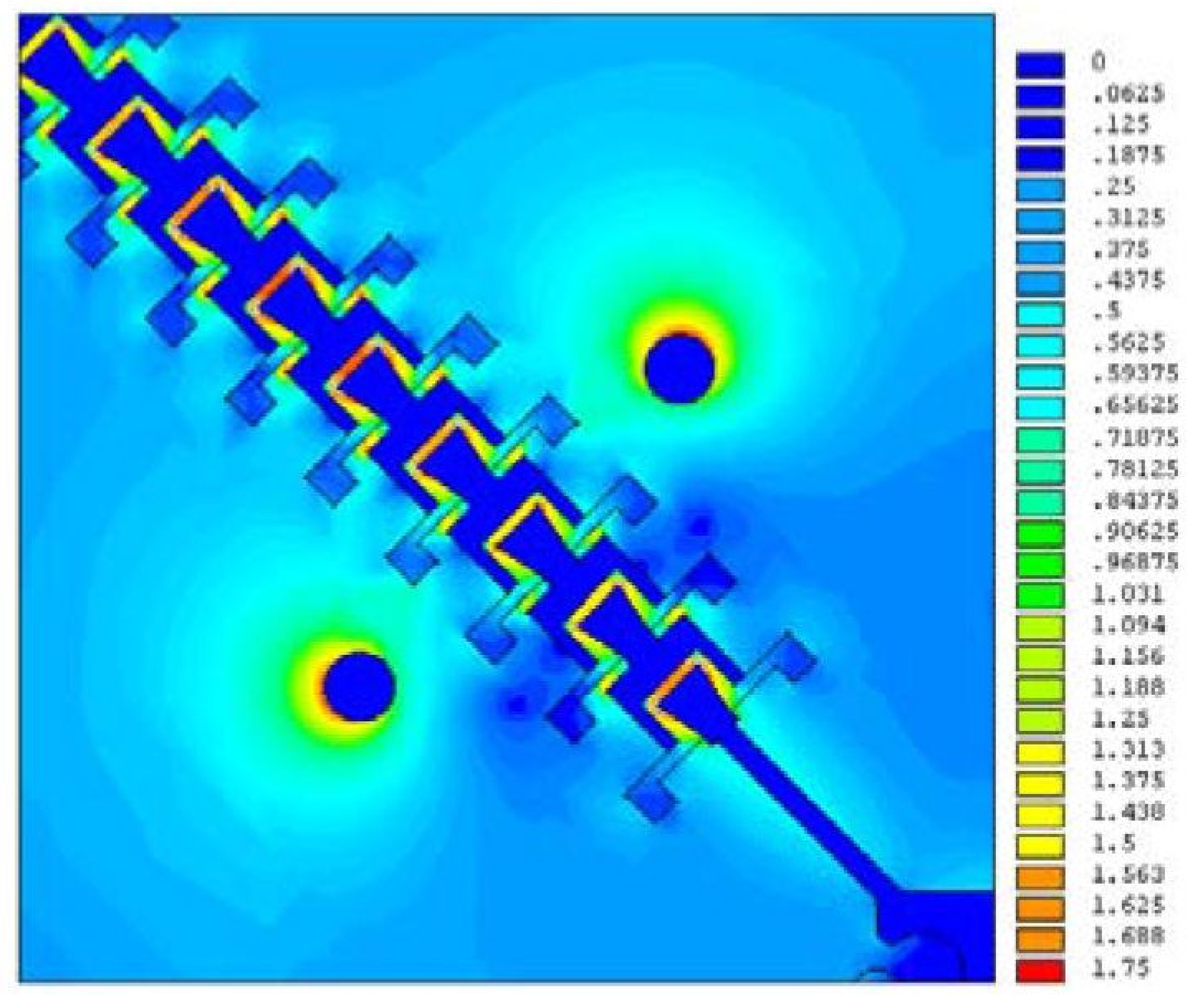


图5 安装位置改变时每片绝缘子分担电压

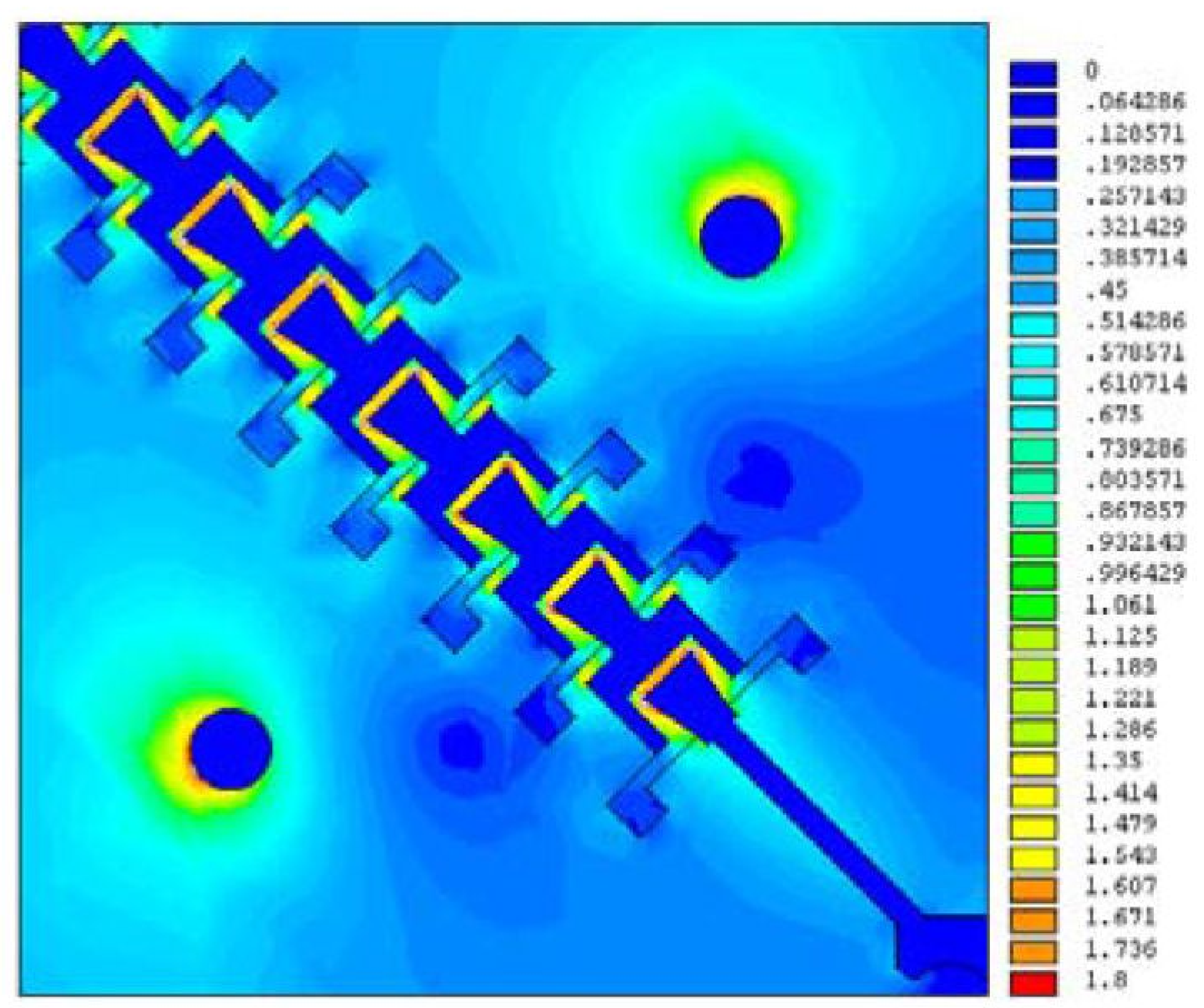
Fig. 5 Voltage distribution on each unit with variable mounting position

3.2 The Ring Diameter Optimization

The ring diameter affects the shielding effect a lot. The larger the ring diameter, the wider the shielding range is, as shown in Fig. 6. However, according to Fig. 7, the voltage distribution of insulator is not improved obviously. And the larger the ring diameter, the heavier the weight of grading ring is. That is not conducive to transport and install. So the grading ring with 1 000 mm diameter is recommended.



(a) ring diameter is 900 mm



(b) ring diameter is 1 200 mm

图6 外径为900 mm和1 200 mm时导线侧电场分布

Fig. 6 Electric field distribution at line end with ring diameter of 900 mm and 1 200 mm

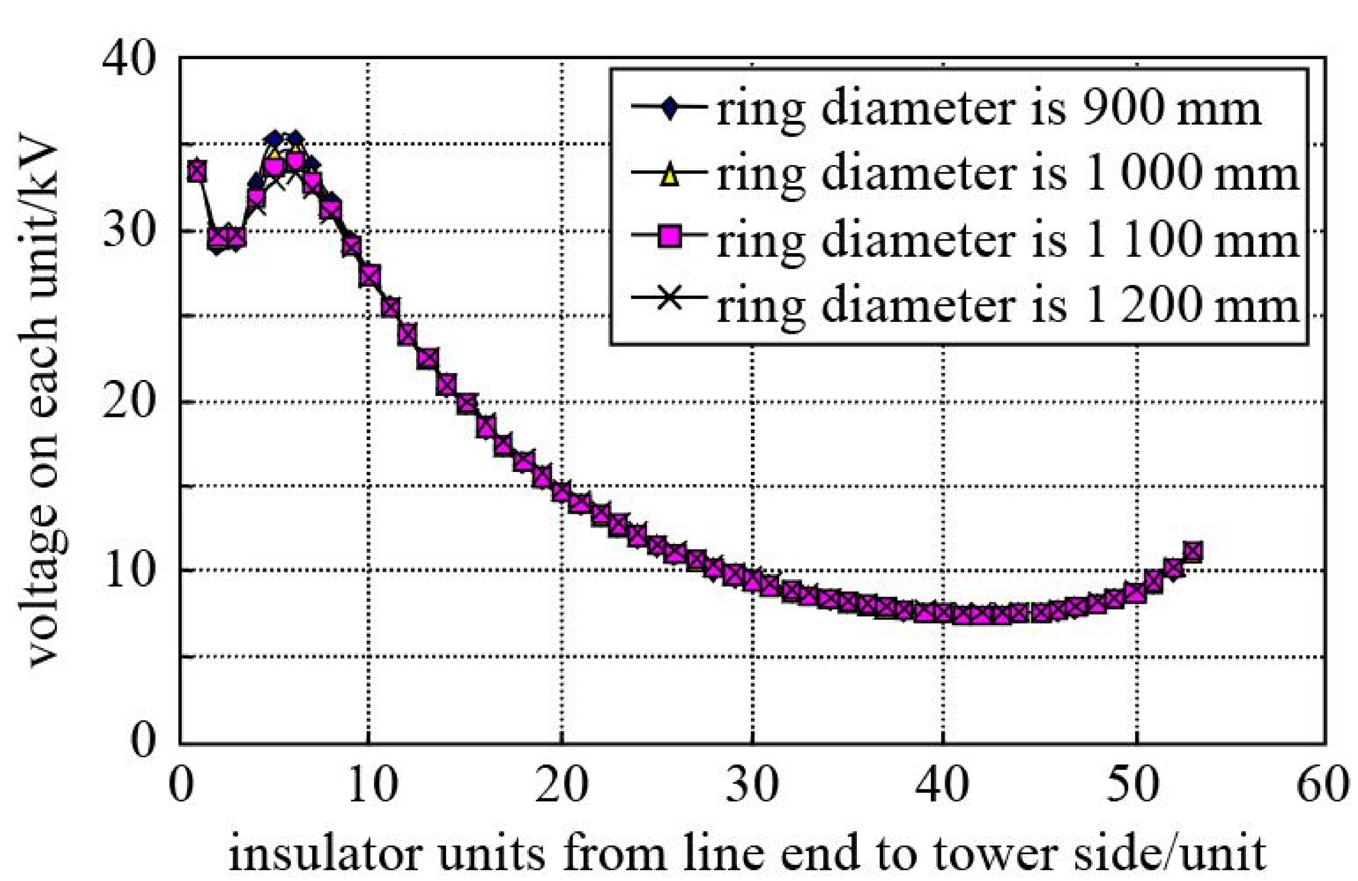


图7 外径改变时每片绝缘子分担电压

Fig. 7 Voltage distribution on each unit with variable ring diameter

3.3 Optimization of Tube Diameter

With the tube diameter increasing, the voltages on conductor end insulators are reduced gradually but slightly as shown in Fig. 8. Obviously, it is not very helpful for improving voltage distribution by increasing the tube diameter. But it is an important factor in controlling the field on the grading ring to avoid corona as shown in Fig. 9. With the tube diameter increased from 60 mm to 140 mm, the maximum electric field strength on grading ring surface decreased 35% from 2.7 kV/mm to 1.75 kV/mm. When the tube diameter increases to 100 mm, the reducing trend of the surface field strength slows down. The electric field strength is less than 2 kV/mm which is the initial discharge electric field strength of air. Considering the anti-corona effect of itself, 100~120 mm tube diameter is recommended.

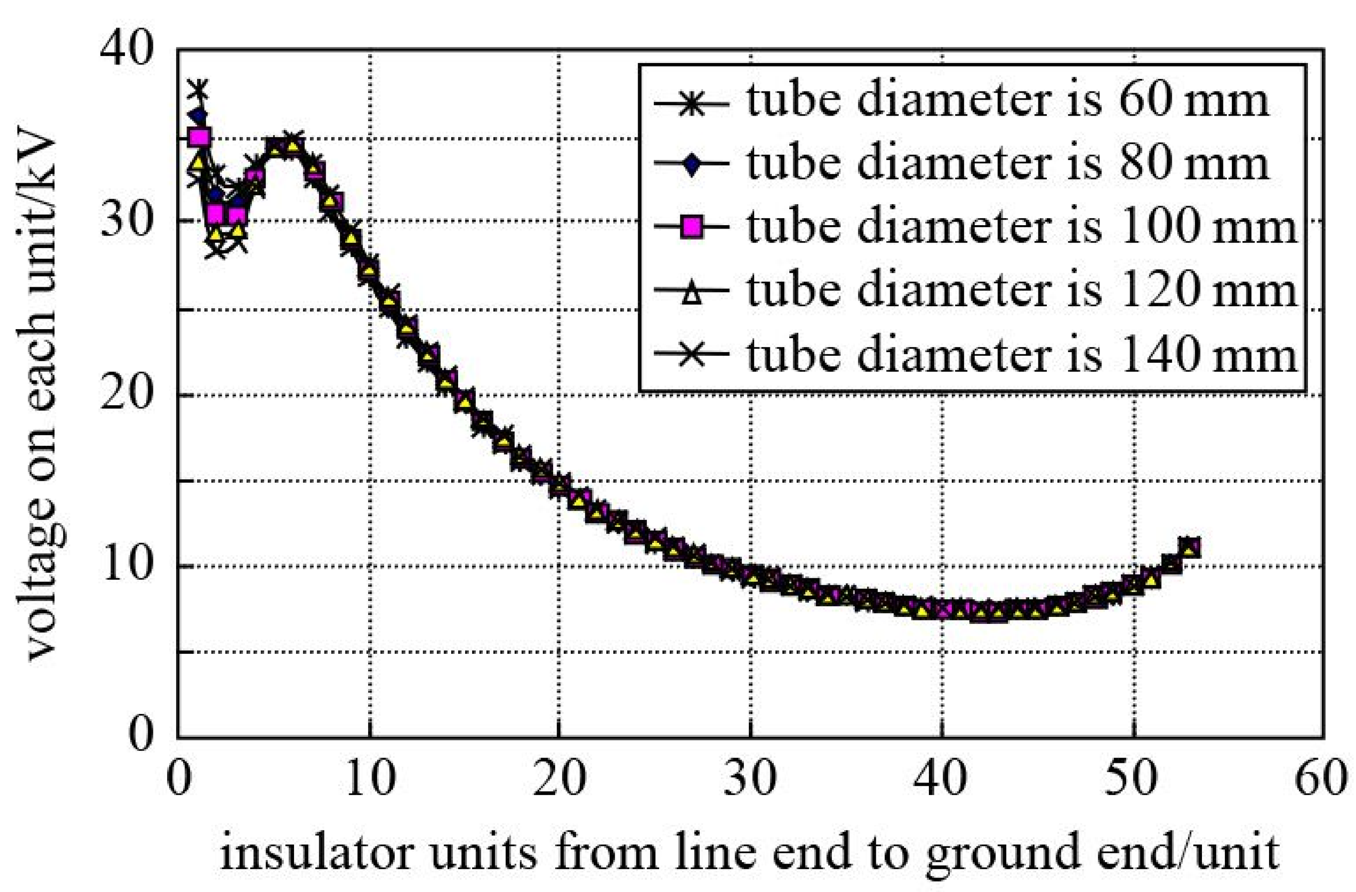


图 8　均压环管径改变时每片绝缘子分担电压

Fig. 8　Voltage distribution on each unit with variable tube diameter

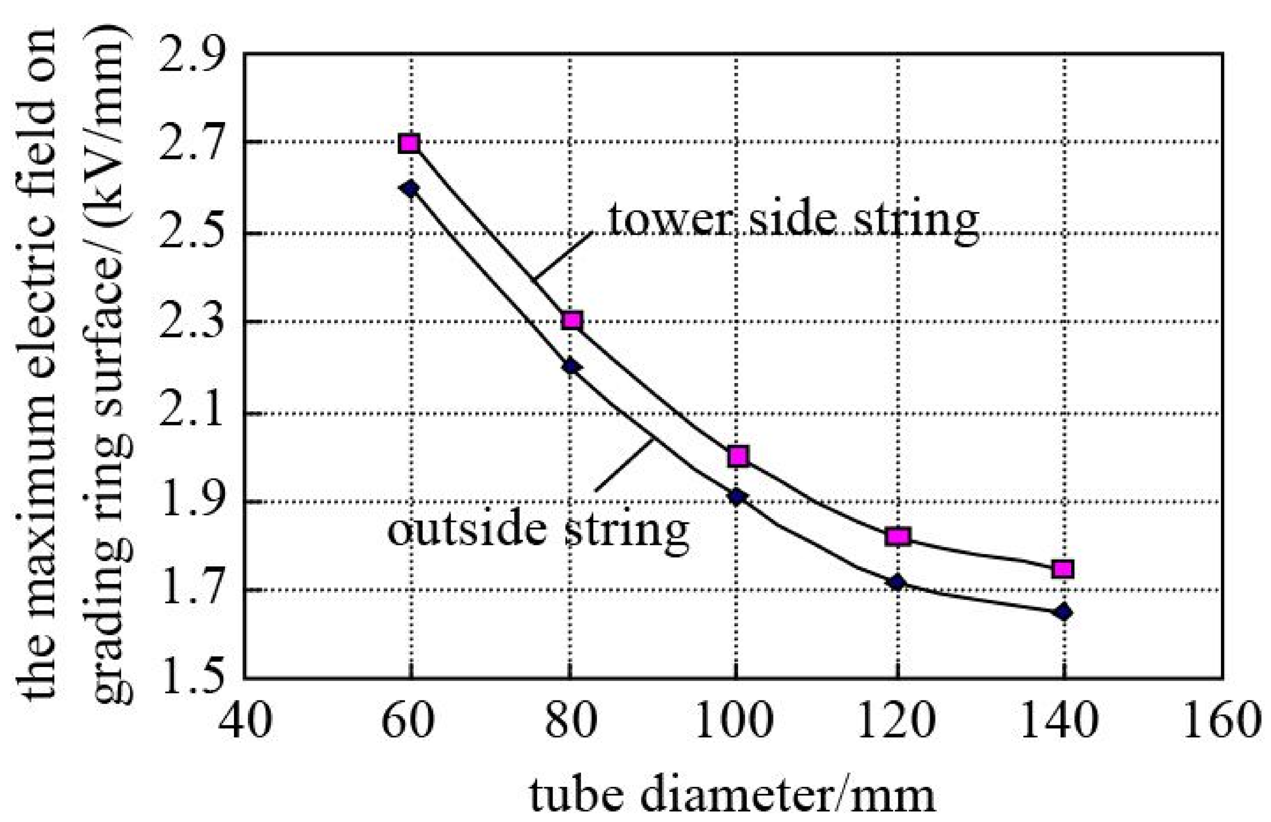


图 9　管径改变时均压环表面场强对比

Fig. 9　Electric field strength contrast with variable tube diameter

4 THE VOLTAGE DISTRIBUTION MEASUREMENT OF INSULATOR STRINGS AS VERIFICATION TEST

There are several DC system voltage distribution measurement methods including ball-gap method, parallel high-resistance resistor divider method, changing parallel resistance calculation method, electrostatic voltage meter type laser emission method, etc. Because the existing parallel resistance changed the equivalent resistance of the insulator and the surrounding electric field, the measurement results and the actual voltage distribution are not equivalent by the parallel high-resistance resistor divider method and changing parallel resistance calculation method. The input resistance can be considered to be infinite with the electrostatic voltage meter type laser reflection method and the common ball-gap discharge method. But the laser reflection method requires special equipment, while the ball-gap method is more simple and reliable. The principle of the ball-gap is to parallel a known distance of the ball diameter and ball clearance gap at both ends on the measurement of insulators. First, increase the system voltage uniformly until the ball-gap flashover, and record the voltage at this moment. Then search the ball-gap discharge voltage table to get the voltage on this insulator. The rest may be deduced by analogy and the voltage on each insulator can be measured. Because the voltage on insulator strings is affected significantly by space charge surrounding the sample, the measurement unit should not generate corona. Taking into account the measurement voltage range, two ball-gaps with 55 mm and 20 mm diameter are chosen. In order to avoid the leakage current induced by the ball-gap support to change the voltage distribution of insulator strings, the ball-gap is fixed on the caps of two adjacent insulators by clubs and fixture. The lead shape of conductor is specially designed to minimize the distortion of the electric field as shown in Fig. 10 and Fig. 11. Because it is difficult to consider the space charge and ion flow effect in numerical

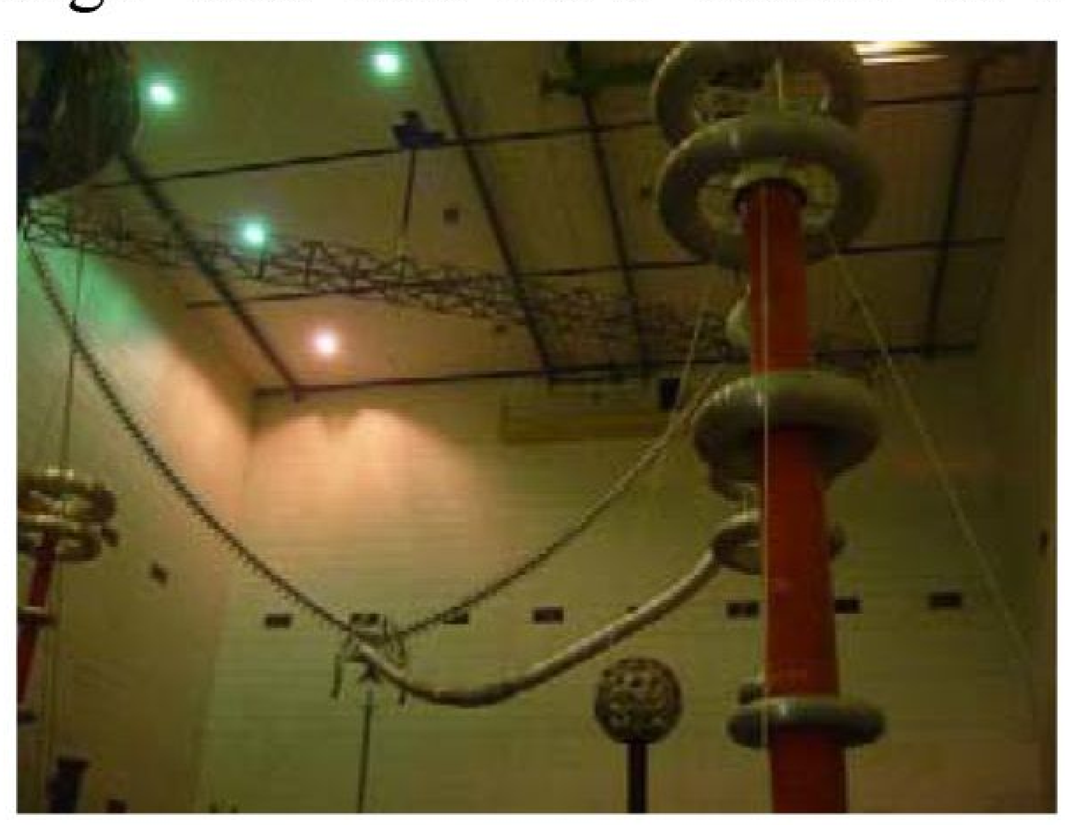


图 10　电压分布测量试验布置

Fig. 10　Test layout of voltage distribution measurement

calculation, there is some deviation between calculation results and measurement results as shown in Fig. 12.

图 11 试验用球隙

Fig. 11 Ball-gap used in experiment

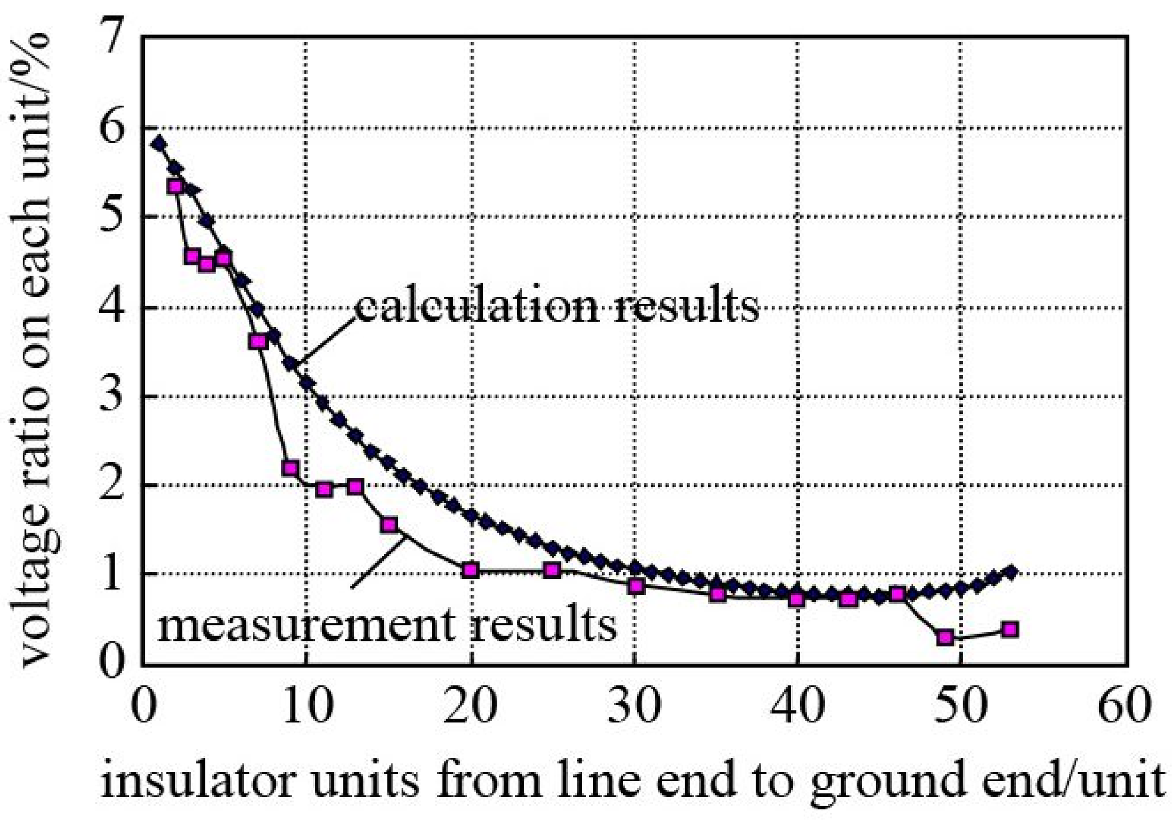


图 12 实测值与计算值对比

Fig. 12 Contrast of calculation results and measurement results

5 CONCLUSIONS

1）The three-dimensional finite element method is used to calculate the voltage distribution and electric field distribution of insulator strings of ±800 kV DC project. And the grading ring configuration of porcelain suspension strings for ±800 kV DC project is given.

2）The deeper the shielding depth, the better the effect of voltage uniform is in the range investigated in this paper. Considering the dry arcing distance and mechanical stability, it is recommended to mount the grading ring in the middle of the third and fourth insulator near the conductor side.

3）There is no obvious improvement on the voltage distribution by increasing the ring diameter. But the larger the ring diameter, the wider the shielding range is, which is beneficial to improve the electric field distribution on the conductor side. Synthetically, taking the electric field and the weight limitations itself into account, the 1 000 mm ring diameter is recommended.

4）The tube diameter mainly affects the electric field strength on itself but has little effect on the voltage distribution of the insulator strings. Considering the anti-corona effect, the 100~120 mm tube diameter is recommended.

5）The ball-gap method can be used to measure the voltage distribution of long insulator strings under DC voltage. Because it is difficult to consider the space charge and ion flow effect in numerical calculation, there is some deviation between calculation results and measurement results. But the trend is the same. And because voltage distribution measurement at DC system is greatly influenced by test conditions, there exists certain dispersion. The voltage distribution and electric field distribution measurement of insulators under DC voltage require further study.

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作者简介：

邓桃(1982—)，女，硕士，工程师，从事高电压试验技术及变电设备外绝缘研究，Dengtao@epri.ac.cn；

李庆峰(1977—)，男，高级工程师，从事高电压试验技术绝缘子检测和外绝缘方面研究工作；

张学军(1979—)，男，工程师，从事高电压试验技术研究工作；

宿志一(1946—)，男，教授级高级工程师，从事输变电外绝缘及高电压试验技术研究；

范建斌(1967—)，男，教授级高级工程师，从事高电压技术和输变电设备外绝缘及运行特性方面的研究。