Optimization Research of Grading Ring for 330 kV Power Transmission Line

CAO Jin91,ZHANG Qin, XIE Lian91,GU Li-li, QUAN Shan-shan, PENG Zong—ren2(1). China Electric Power Research Institute, Wuhan 430074,Hubei,China;2. State Key Laboratory of Electrical insulation and Power Equipment(Xi'an Jiaotong University),Xi'an 7 10049,Shaanxi,China)

ABSTRACT: The simulation and electric-field strength calculation of 4 kinds of different pipe diameter and 2 kinds of different curvature radius for grading rings of 330kV transmission line by finite element method were discussed and experimental research work of visual corona was performed at Ultra-high Voltage Testing Field and Environmental Climate Laboratory. The electric-field distribution, test results of optimized grading ring and inception voltage characteristic curves at different altitudes were given for different types of grading rings. It is indicated that it is feasible to reduce electric-field strength to enhance inception and extinction voltage by optimizing pipe diameter and curvature radius of grading rings. Correction errors by the recommended formula discussed at the end of the paper are lower than that of GB311.1-1997 and IEC60071-2:1996, and can be used as reference for the type selection and optimization design for grading rings of high altitude transmission line.

KEY WORDS: high altitude; grading ring; corona discharge; finite element method; electric-field distribution; altitude correction

Along with transmission line voltage level increase, the problem of power line influence on surrounding electromagnetic environment rises, hazards like corona noise, radio interference, electrostatic effect caused by corona discharge have gradually raised concern[1]. Corresponding research result shows that 330kV AC transmission line grading ring has the problem of severe corona discharge and has become one of the main component of electromagnetic pollution. In consideration of altitude correction, grading ring audible discharge corona noise and radio interference will increase greatly, corona discharge character makes it difficult to meet requirement of high altitude operation[2].

Composition of grading ring corona discharge influencing factor is complex, sections with high field strength are mainly at the ring curve where electric field is unevenly distributed, this is mainly caused by vulnerability of small radius of electrode curvature to partial corona discharge; in the mean time, grading ring discharge can be easily influenced by operation environment including atmospheric pressure, temperature and humidity. The three atmospheric parameters combined effect can be equivalent to discharge voltage descends while altitude rises[3]. China Electric Power Research Institute conducted simulation modeling research on ± 800 UHV DC transmission line single V-type composite insulator dangling string, introducing optimal configuration scheme for composite insulator grading ring[4]; State Grid Electric Power Research Institute conducted research of insulator string voltage distribution as well as grading ring optimal configuration research on 750kV compact common-tower double-circuit transmission line, come up with fitting optimal design scheme combining optimized calculation and test procedure[5], provides reference for engineering design.

This article establishes grading ring stimulating calculation model applying finite element method, calculates and analyses electric field distribution on grading ring surface in consideration of surrounding

wire, tower and equipment influence; meanwhile conduct research on corona character of multiply structured grading rings on the CEPRI UHV outdoor test field and in UHV AC test base climate laboratory, measure corona characteristic parameter with Ultraviolet Imager, draw grading ring initial corona voltage characteristic curve, bring forward altitude calibration method satisfying requirement of engineering, provides reference for grading ring design and optimization for high altitude areas.

1. Grading ring finite element modeling and analyze

1.1 Tension grading ring modeling

Modeling applies 330kV AC transmission line tension string with finite element method, tension grading ring model as shown on figure 1. Practical height of model tower is 15.5 m, length of tension insulator string is 255 mm, conductor applies 2×LGJ-300/40 steel reinforced aluminum cable, with diameter of 23.9 mm, intrabundle spacing is 400mm, grading ring pipe diameter is 32 mm.

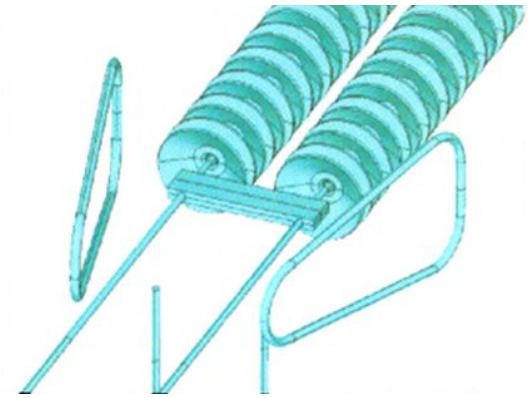

Figure 1 Calculation model of grading ring

As drawn from model shown on figure 1, single phase voltage added equals peak value of maximum system operating phase voltage during calculation. Result of stimulating calculation shows that pipe diameter is 32 mm, grading ring surface maximum field strength is 27.8 kV/cm (see figure 2), approaching standard air critical field strength. In order to fulfill requirement for application in high altitude region, measures should be taken to improve electric field distribution, lower partial high field strength, raise overall dielectric strength of the insulating structure, thus adjust electric field. This article optimizes grading ring via increasing pipe diameter and improving curvature radius.

1.2 Enlarge grading ring pipe diameter

Conduct modeling calculation with 3 different pipe diameters including 42 mm, 45 mm, 50 mm. It can be concluded through stimulating calculation that maximum surface field strength corresponding the 3 pipe diameter are 24.1 kV/cm, 23.1 kV/cm, 21.7 kV/cm, lowered 13.3%~21.9% compared to 32 mm diameter grading ring (see table 1).

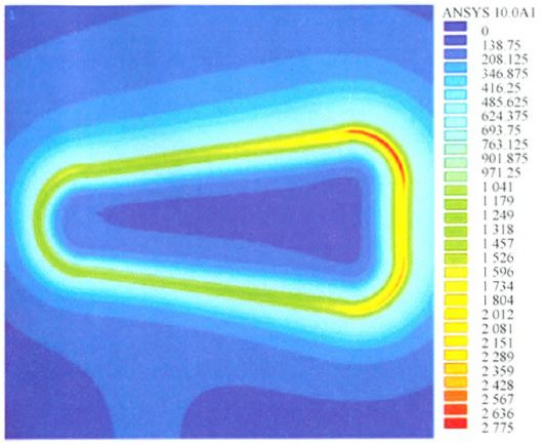

Figure 2 Surface electric field distribution of grading ring
(pipe diameter: 32 mm)

Table 1 Electric field strength with different external diameter of grading ring

Grading ring pipe diameter/mm	Surface field strength/(kV • cm^{-1})	Degree of reduction/%
32	27.8	
42	24.1	13.3
45	23.1	16.9
50	21.7	21.9

1.3 Enlarge grading ring curvature radius

Grading ring surface electric field is in direct proportion to electric density. Corona is easily generated due to small curvature radius at camber curve and no conductor shield at large camber curve, large surface charge density, dense power line and high electric field strength. By enlarging grading ring large camber curve radius, surface field strength is efficiently lowered. Enlarge grading ring with 42mm pipe diameter large camber curve inner curve radius from 12 mm to 220 mm via stimulation modeling, see

figure 3 for model. Maximum surface field strength of optimized grading ring is 21.6 kV/cm, see figure 4, approaching maximum surface field strength of 50 mm diameter grading ring.

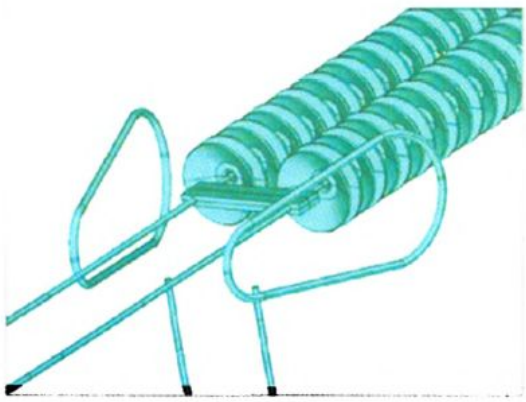

Figure 3 Optimized model of grading ring

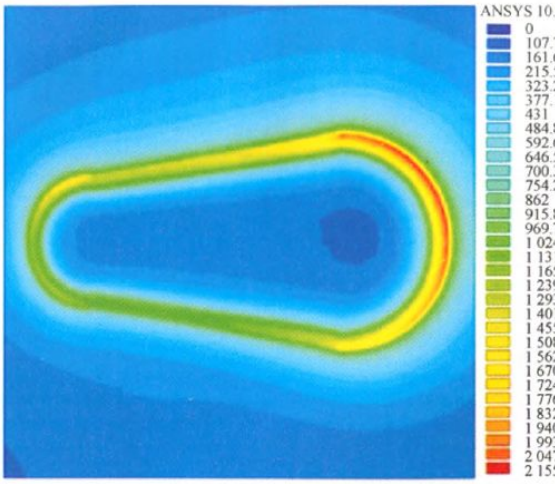

Figure 4 Surface electric-field distribution of grading ring

(pipe diameter: 42 mm)

In comprehensive consideration of tension grading ring optimization, enlarging pipe diameter is applicable yet with direct influence on cost rise. Enlarge grading ring curvature radius via optimization design helps to lower surface field strength thus satisfy requirement for grading ring performance, meanwhile reduce cost for processing.

2. Research for grading ring corona test

2.1 Test conditions and object of research

Test power supply of ultra high voltage outdoors test field applies power-frequency test transformer with 2250kV nominal voltage and 9000kV·A nominal capacitance. Tank diameter of ultra high voltage climate laboratory is 22m, 32m in height, capable of pressure decline from atmospheric pressure to 50kPa to simulate different altitude, test power supply applies power-frequency test transformer with nominal voltage of 1500kV and nominal capacitance of 6000kV·A. Double split hard aluminum conductor for test stimulation is 8m in length, 400mm split interval, grading ring is installed at one end of the aluminum conductor and shielding ring(outer diameter:1 m) installed at the other end, height above ground of the test object is 4m. This article selects two grading rings of 32mm pipe diameter and 42mm pipe diameter for study of corona inception voltage test, during which to compare influence of curvature radius towards electric field on grading surface, 42mm diameter grading ring is selected for test study with curvature radius of 120mm and 220mm. Meanwhile, to study influence of altitude towards grading ring corona inception voltage, this article conducts grading ring corona test under different simulated altitude in the climate laboratory of UHV AC test base.

2.2 Observation equipment and test method

UV corona detector which is applicable to day-time corona discharge detection is currently the main measurement apparatus for corona test study[6-7]. This article applies UV imager developed by the Israel company OFIL to observe and record the entire process of grading ring corona discharge, as shown on figure 5, UV imager is placed 13m away from the grading ring. The prepared tension string is suspended with insulating sling on both ends beneath the simulated cross arm, suspend the whole set with a crane underneath wall bushing of the climate laboratory. Gradually increase the applied voltage until corona is observed through UV imager, preserve for 5 minutes and record the indicated voltage as corona inception voltage of the grading ring, then gradually lower applied voltage until corona vanishes, record the indicated voltage as corona extinction voltage, preserve for 5 minutes, repeat the stated process 3 times, take average value as corona inception voltage and corona extinction voltage of the grading ring[8].

Figure 5 Ultraviolet imager

3. Test result and analysis

3.1 Grading ring optimization test

Grading ring optimization test is practiced in outdoor test field, visible corona discharge test is conducted correspondingly towards grading ring before and after optimization. Grading ring pipe diameter before optimization is 32mm, curvature diameter at major arc side is 120mm. There are two structures after optimization: enlarge pipe diameter to 42mm, same curvature radius; enlarge pipe diameter to 42mm and extend curvature radius to 220mm. Test result for visible corona test of the three types of grading rings as shown on figure 2.

Table 2 Corona test results of grading rings with different types

Grading ring structure	Corona inception voltage/kV	Corona extinction voltage/kV
Pipe diameter 32mm	245	228
Pipe diameter 42mm (curvature radius 120mm)	296	289
Pipe diameter 42mm (curvature radius 220mm)	307	297

As drawn from data in table 2, grading ring corona inception voltage and corona extinction voltage of grading ring increased by 20.8% and 26.8% respectively after optimization of pipe diameter; grading ring corona inception voltage and corona extinction voltage of grading ring increased by 25.3% and 30.3% respectively after further optimization of curvature radius. Optimization through modifying grading ring pipe diameter and enlarge curvature radius is proved applicable by test result.

3.2 High altitude stimulation test

To extract the rule between characteristics of grading ring corona and altitude, this study simulates 19-4300 altitude by changing atmospheric pressure in climate laboratory to conduct test study of corona discharge study for grading rings with pipe diameter of 42mm, grading ring corona test result as shown on figure 6. U_i represents corona inception voltage of the test object (kV); H represents altitude (km).

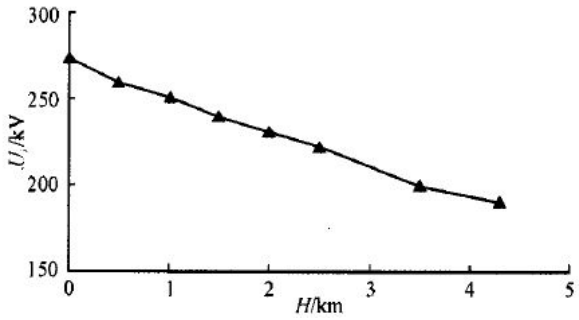

Figure 6 Corona inception voltages of grading ring at different simulated altitudes

According to test result showed above, corona inception voltage of grading ring drops as altitude rises. Corona inception voltage is 190kV at 4300m altitude, dropped by 30.4% compared to altitude at 19m. Thus, it is necessary to take into consideration of severe corona discharge[9-11] and corona inception voltage drop caused by altitude increase when grading ring is used in high altitude region.

4. Altitude calibration of grading ring corona inception voltage

Air is thinner and atmospheric pressure is lower at high altitude, average mean-free path of free electron in the air gets longer, corona discharge can be easily generated near large curvature electrode, the design of grading rings for high altitude transmission line needs to consider altitude influence, so that corona characteristics can meet requirement of corona prevention performance of transmission line at high altitude[12-14]. Current altitude calibration method on basis of national and international standard can be

divided in two:

Calibration coefficient in GB311.1-1997[15]

$$K=1/(1.1-0.1H)$$

In this formula, H represents altitude (km). This method applicable for voltage calibration of external insulation and dry-type transformer insulation test within range of altitude between 1000m and 4000m, take 1000m altitude as starting point for calibration, calibration coefficient remains 1 for regions below 1000m.

Altitude calibration coefficient in IEC 60071-2:1996[16]

$$K=e^{m(H/8.15)}$$

In this formula, m represents calibration coefficient relating to voltage type and interstitial structure, m=1 for short power frequency test of air clearance and clean insulator.

The existing calibration method is mainly based on test data from finite test point at low altitude level. This study applies calibration method combining multiple altitude level and comprehensive test data, closer to actual operating condition. Set grading ring inception voltage at simulate 19m altitude as reference value, comparative value of corona inception voltage at different simulate altitude can be tested and altitude calibration coefficient can be calculated, as shown on table 3.

Table 3 Calibration coefficient at different altitude

Altitude/km	Relative value of corona inception voltage/%	Calibration coefficient
0.019	100.0	1.00
0.5	94.9	1.05
1.0	91.9	1.09
1.5	87.9	1.14
2.0	84.6	1.18
2.5	81.3	1.23
3.5	73.3	1.37
4.3	69.6	1.44

Obtain calibration coefficient fitting data in table 3

$$K=1.001e^{0.085H}$$

Apply the three calibration methods mentioned to corona inception voltage of grading ring at simulate altitude, compare and analyze calibration result and test result simulating altitude at 19m, obtain calibration error as shown on table 4.

Table 4 Correction error with different methods

Altitude/km	Calibration error/%		
	GB311.1	IEC60071-2	Recommended method
0.5	-5.13	0.87	-0.91
1.0	-8.06	3.94	0.20
1.5	-7.46	5.68	-0.03
2.0	-5.98	8.15	0.40
2.5	-4.33	10.51	0.67
3.5	--2.32	12.56	-1.26
4.3	3.88	17.96	0.41

As drawn from table 4, calibration error under GB311.1 below 3500m are all minus deviation, maximum deviation is -8.16%, calibration error under IEC60071-2 are all plus deviation, error increases as altitude rises, reaching 17.96% at 4300m. Absolute value of error can be controlled within 2% applying calibration method based on matching of test data. Design of grading ring for transmission line at high altitude level may refer to method recommended in this article, select dimension of the equipment rationally based on different altitude to meet requirement of corona prevention performance.

5. Conclusion

1) Apply finite element method to electric field simulation calculation, establish electric field simulation model and conclude rules for electric field distribution on grading ring surface. When pipe diameter of the grading ring reaches 42mm, maximum field strength on surface of the ring body will lower to 24.1kV/cm, and can be lowered to 21.6kV/cm after curvature radius is enlarged to 220mm.
2) Test result of corona test with grading rings of different structures show that corona inception and distinction voltage of grading ring can be increased by 20.8% and 26.8% correspondingly after optimization of pipe diameter, corona inception and distinction voltage of grading ring can be increased by 25.3% and 30.3% correspondingly after optimization of curvature

radius.

3) Under the influence of altitude, corona inception voltage will decrease with stronger discharge along with the rise of altitude. Altitude calibration formula applicable for grading ring corona inception voltage can be obtained based on fitting of test data, absolute value of calibration error can be limited within 2% which provides reference for design of grading rings used on high altitude transmission line.

4) Test result of corona discharge test is under influence of comprehensive factors including test layout, surface status of the test object as well as test condition, with complicated principles of discharge.

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