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Optimization of Grading Ring of 624 kV Zinc Oxide Surge Arrester using Finite Element Technique

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Zinc oxide (ZnO) surge arresters are being used extensively in high voltage power systems for providing protection to the transmission lines and the associated substation equipment from over voltages caused due to lightning and switching surges. It has been observed in practice that the voltage distribution in a tall multi-section arrester under normal operating conditions is quite non-uniform. As a result, the ZnO blocks at the top section share higher voltage and hence higher thermal stresses than the ZnO blocks at the bottom section. This leads to accelerated thermal aging of the blocks at the top if proper measures are not taken to make the voltage distribution uniform along the entire length of the arrester. Generally, provision of grading rings is a common method for achieving uniform voltage distribution through out the length of arrester. In this paper, the results of the optimization of the grading ring dimensions for a 765 kV system arrester with a rated voltage of 624 kV using Finite Element based 2D Elecnet software are presented.

Keywords: *Grading ring, Zinc oxide surge arresters, Voltage distribution of arrester, Electric field distribution.*

1.0 INTRODUCTION[2–5]

An uninterrupted and reliable power supply can be guaranteed to the end consumer by paying a special attention towards protection of transmission lines and substation equipment from over voltages caused due to lightning and switching surges. This can be achieved by installing efficient and most reliable protection devices like surge arresters that are designed with protective characteristics yielding sufficient protective margins between the protection level of the surge arrester and the basic insulation level of the equipment to be protected. The arresters installed today are almost all non-linear zinc oxide (ZnO) arresters without gaps. The performance of a ZnO surge arrester is defined by its protective levels, temporary over voltage and energy discharge capabilities and the long-term stability of the ZnO material. The temporary over voltage and energy handling capabilities mainly depend upon the temperature of the ZnO blocks during normal operation. This temperature depends on the power losses and increases rapidly even with a small rise in voltage stress. The temperature during normal operating conditions can be minimized by properly designing the blocks to have inherently low power losses. In addition to this, a linear voltage distribution along the axial length of the arrester is also another important parameter to minimize the temperature of the blocks. It has been observed in practice that the voltage distribution in the arrester is quite non-uniform. As a result, ZnO blocks at the top are subjected to higher voltage than the remaining discs. This leads to a faster thermal aging of the

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ZnO blocks at the top. It is reported that arresters (upto a deviation of 12–15% work satisfactorily without any problem for more than 15 years [1]. However, it is advisable to make efforts and design the grading ring such that the deviation is as less as possible. Thus, the voltage and electric field distribution in an arrester are very important for its long-term performance. Under steady-state conditions, the total leakage current is composed of a large capacitive component and a small resistive part. Hence, the voltage distribution under normal power frequency voltage is mainly governed by capacitance and the resistances of the nonlinear resistors, the stray capacitance from the nonlinear resistor columns and the metal flanges to earthed and live parts. The stray capacitances result in uneven voltage distribution along the resistor column with the maximum voltage stressed typically appearing across the upper part of the arrester. If the voltage distribution is not controlled, the blocks which are stresses more will get heated up fast leading to a faster thermal aging of these highly stressed blocks.

The stray capacitances are strongly dependent on the height of these non-linear blocks. Short arresters up to about 1 m in height usually have a sufficiently linear voltage distribution, as the self-capacitance of the ZnO blocks is relatively high. For taller arresters, the effect of stray capacitances dominates the stray capacitances and contributes to the nonlinear voltage distribution along the length of the arrester. In the absence of proper measures to prevent this uneven voltage distribution on a tall arrester, the local voltage stress at the top will reach the knee-point of the voltage–current characteristic of the ZnO material. This leads to a localized increase in the power losses, with high temperatures in the block column as consequence.

The use of grading rings has become a very common measure employed for reducing the nonlinear voltage distribution along the axial length of the arrester. By means of properly designed grading rings, efforts are made to make the voltage distribution as uniform as possible.

In this paper, the results of the study on optimization of grading ring for a 624 kV rated voltage arrester for use in a 765 kV system are presented. The study comprised of the determination of the dimensions and the position of the grading ring based on the computed voltage and electric field distribution along the axial length of the arrester. The electric field and the voltage distributions are computed using the commercially available "Elecnet" field computation software based on Finite Element Method.

2.0 SURGE ARRESTER AND ITS MODELING

The arrester considered for the study is having six sections in series with a total height of about 6 m. The arrester housing is made of silicon rubber material and has one grading ring at the end of top section and one corona ring on top of high voltage point. The arrester is having a Maximum Continuous Operating Voltage (MCOV) of 490 kV. The Auto CAD drawing of the arrester supplied by the customer is shown in Figure 1.

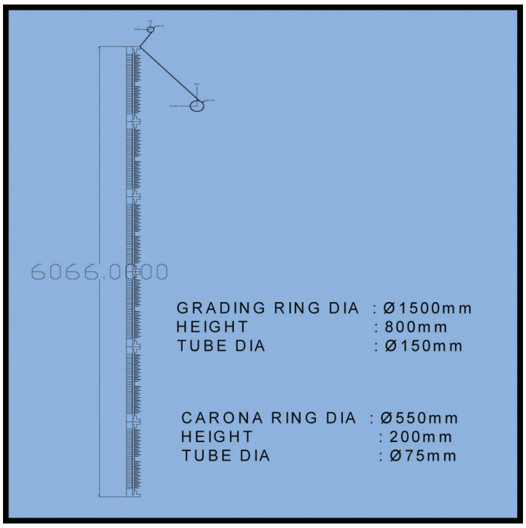


FIG. 1 AUTO CAD DRAWING OF 624 kV LIGHTNING ARRESTER CONSIDERED FOR THE STUDY

The study of the electrostatic field distribution was conducted with the finite element method. The basic data that was used in the modeling were arrester dimensions, including size and location of ZnO blocks, metal spacers inside the polymer housing, polymer housing geometry and geometry of metal flanges between the arrester sections, dimensions of grading rings and electrical permittivity of the materials of all the major components of the arrester. The permittivity of polymer, fiber and ZnO material is taken as 4, 7 and 800 in this study. The potential of the top electrode, corona ring and grading rings was set to 490 kV. The top four sections have 35 ZnO blocks and the bottom two sections are having 34 ZnO blocks, making the average voltage across the top four sections to be 82.45 kV and the bottom two sections as 80.096 kV. These are the voltages that shall appear across each of the arrester sections under ideal conditions of uniform voltage distribution along the length of the complete arrester. This is the ideal voltage across each of the sections which is very difficult to achieve in reality, and the actual value will be different from the ideal value depending upon the design. In order to find out the deviation in the actual voltage distribution along the arrester length from this ideal distribution, the arrester was modeled in free space with a potential difference of 490 kV RMS (MCOV of the arrester) applied between the top conductor and ground. The potential of the bottom metal part and the pedestal was set to zero. The outer radial boundary of the model was set to ground potential. Since the surge arrester is having axial symmetry, it was modeled as an axi symmetric 2D problem.

3.0 ANALYSIS

For the purpose of the computation of voltage distribution, an electrostatic (Capacitive) simulation of the surge arrester is considered in this study. Further, the optimization study was carried out in different steps which are given below:

1. Determination of voltage distribution assuming a pedestal height of 3.5 m for the given grading ring diameter, the tube diameter with the given position of the grading ring and compare this distribution with the voltage distribution obtained without the grading ring.
2. Computation of the voltage distribution for various positions of the grading ring varying the grading ring diameter for a fixed tube diameter and pedestal height and computing the voltage distribution.
3. Determination of the effect of tube diameter on the voltage distribution for a fixed pedestal height and for the optimized ring diameter obtained from step 3 and optimized ring position decided at step 2.
4. Finally, the determination of the effect of pedestal height on the voltage distribution for the optimized parameters selected from the above four steps.

4.0 RESULTS OF THE STUDY

4.1 Voltage Distribution without and with Original Grading Ring

As mentioned above, in the first stage, the electric field and voltage distribution are computed using the given dimensions of the grading ring as the first approximation and the values are compared with the values obtained without grading ring. The values are shown in Table 1. The stresses

TABLE 1

VOLTAGE DISTRIBUTION WITHOUT GRADING RING AND WITH THE ORIGINAL GRADING RING WITH DIAMETER=1500 mm, POSITION=5366 mm FROM TOP AND TUBE DIAMETER=150 mm

Unit	Voltage with grading ring		Voltage without grading ring	
	kV	**% Devn. from uniform voltage drop**	**kV**	**% Devn. from uniform voltage drop**
1	84.56	2.56	120.85	46.57
2	82.67	0.26	89.58	8.65
3	75.51	–8.42	72.49	–12.08
4	73.32	–11.08	–25.24	–130.61
5	79.3	–0.99	156.64	95.58
6	94.64	18.16	75.68	–5.51

computed without grading ring are vary from 5.5 % to 130 % showing the greater extent of nonuniformity in the voltage distribution. The results also indicate that the bottom units are stressed more than the top units with the given grading ring dimensions and position. Although the grading ring redistributed the voltage sharing among the sections, the distribution is still not uniform.

4.2 Effect of Grading Ring Position on Voltage Distribution

From the computed voltage distribution corresponding to different positions of the grading ring, the percentage deviation of the voltage drop across each section with respect to average voltage drop is shown in Table 2. The results indicate that the percentage deviation across top section increases while the drop across the bottom unit reduces. Thus, there is an optimum position where the top unit voltage drop deviation is within 12 %. This position corresponds to 5666 mm height above ground level. However, at this position the percentage deviation of voltage drop across bottom unit is more than 12 %.

4.3 Effect of Grading Ring Diameter on Voltage Distribution

The percentage deviation of the voltage drop across each section is evaluated from the computed voltage drops across sections and the same are listed in Table 3. The values indicate

TABLE 2

VARIATION OF VOLTAGE DISTRIBUTION WITH GRADING RING POSITION GRADING RING TUBE DIAMETER=150 mm RING DIAMETER=1500 mm PEDESTAL HEIGHT=3.5 m

Unit	% voltage deviation across each section with respect to average voltage drop — Height of the center of the grading ring above ground in mm					
	5366	5466	5566	5666	5766	5866
1	3.15	5.88	8.62	11.40	14.75	16.56
2	1.00	1.27	1.60	1.64	0.96	1.87
3	–7.55	–8.21	–8.6	-9.27	–9.68	–10.1
4	–10.1	–10.7	–11.6	–12.20	13.13	–13.40
5	–2.55	–3.40	–4.24	–4.96	–5.63	–6.46
6	16.4	15.52	14.47	13.65	12.74	11.67

TABLE 3

EFFECT OF GRADING RING DIAMETER ON VOLTAGE DISTRIBUTION, GRADING RING TUBE DIAMETER=150 mm RING POSITION=5466 mm AND PEDESTAL HEIGHT=3.5 m

Unit	% voltage deviation across each section with respect to average voltage drop — Diameter of the grading ring in mm					
	1200	1300	1400	1500	1600	1700
1	10.2	8.66	7.19	5.88	4.57	2.79
2	4.81	3.73	2.48	1.27	0.43	2.04
3	–7.63	–7.72	–7.97	–8.21	–8.29	–7.85
4	–12.1	–11.67	–11.22	–10.7	–10.36	–12.2
5	–6.21	–5.33	–4.29	–3.40	–2.69	–0.22
6	11.08	12.53	14.09	15.52	16.73	20.1

that the increasing diameter has an effect of reducing the voltage drop across the top unit and increasing the drop across the bottom unit. Thus, the diameter of 1200 mm and 1300 mm has redistributed the voltage drop across the various sections in such a way that the maximum deviation of this voltage drop from the average value is 12.5 %. It is found that further increase in the diameter of the grading ring has an effect of increasing the maximum voltage deviation beyond the 12.5 % value which is an acceptable value. However the electric field on the corona ring and grading ring surface is more with grading ring diameter of 1200 mm compared to the case with ring diameter of 1300 mm. Hence, the ring diameter of 1300 mm is considered as the safe value which prevents corona discharge.

4.4 Effect of Grading Ring Tube Diameter on Voltage Distribution

The voltage drop across the sections is computed with tube diameters of 150 mm, 125 mm and 100 mm with the optimum grading ring diameter and the position obtained in the earlier steps. The values are shown in Table 4 below. The percentage deviation of voltage drop across each section from the average value is less than 12.5 % for all the cases. However, with the grading ring diameters of 125 mm and 100 mm, the electric field on the surface of the ring has increased and hence the ring diameter of 150 mm is considered as optimum.

4.5 Effect of Pedastal Height on Voltage Distribution

In the last step of optimization, the computations are continued with different pedestal heights. The pedestal heights considered are 3.5 m, 4 m and 4.5 m and the results are presented in Table 5. The optimized dimensions of ring diameter of 1300 mm, tube diameter of 150 mm and position of 5466 mm are considered for each of the pedestal heights. From the results presented in Table 5, it is clear that the deviation of voltage drop across top section from the average voltage drop increases and that of the bottom section reduces by increasing the pedestal height from 3.5 m to 4.5 m. It is also noticed that the deviation of voltage drop of the section (which is more stressed) from the average voltage drop is 12.53 %, 11.72 % and 11.89 % with pedestal heights of 3.5 m, 4 m, and 4.5 m respectively. These percentage values are less than the acceptable deviation of 15 % [1] across all the sections. This makes it very clear that the ring diameter of 1300 mm, tube diameter of 150 mm and ring position of 5466 mm results into a more uniform voltage distribution which is acceptable across all the units.

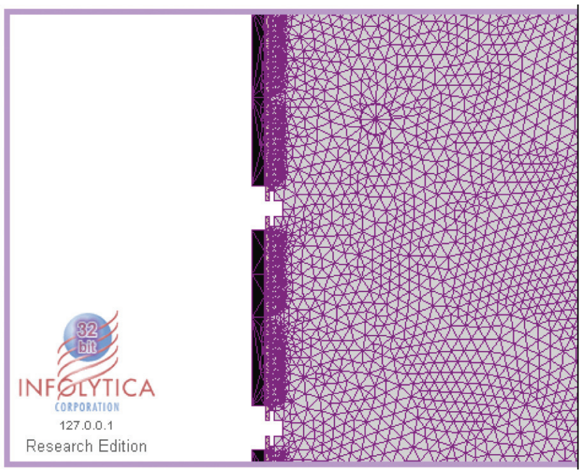
TABLE 4

EFFECT OF GRADING RING TUBE DIAMETER ON VOLTAGE DISTRIBUTION. GRADING RING DIAMETER=1300 mm, RING POSITION=5466 mm, PEDESTAL HEIGHT=3.5 m

Unit	% voltage deviation across each section with respect to average voltage drop		
	Tube Diameter of the grading ring in mm		
	150	125	100
1	8.66	11.12	11.92
2	3.74	4.49	3.76
3	–7.71	–7.97	–8.25
4	–11.67	–12.16	–12.50
5	–5.32	–6.32	–6.04
6	12.54	11.00	11.29

TABLE 5			
EFFECT OF PEDESTAL HEIGHT ON VOLTAGE DISTRIBUTION GRADING RING DIAMETER=1300 mm RING POSITION=5466 mm AND GRADING RING TUBE DIAMETER=150 mm			
Unit	**% voltage deviation across each section with respect to average voltage drop**		
	Pedestal height in mm		
	3.5	4	4.5
1	8.66	10.26	11.73
2	3.73	4.78	5.92
3	–7.72	–7.45	–7.03
4	–11.67	–11.72	–11.89
5	–5.33	–8.90	–7.17
6	12.53	7.33	8.50

Figure 2 shows the FEM model indicating the optimized dimensions of the grading rings along



FEM GRID USED FOR THE SIMULATION ARRESTER

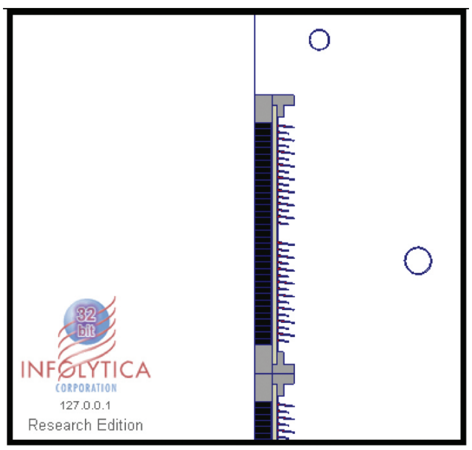


FIG. 2 FEM MODEL SHOWING THE OPTIMAL GRADING RING DIMENSIONS OF 624 kV

Figure 3 shows the equipotential contours and with the FEM GRID used for the study. electric field shaded regions around the arrester. Figures 4 and 5 show the voltage and electric field variation, along the axial length of the arrester from top to bottom section of the arrester. These figures are for the final optimized dimensions of the grading ring keeping the other dimensions of the arrester unchanged. The same figures also show the voltage and electric field distribution comparison with and without the grading ring.

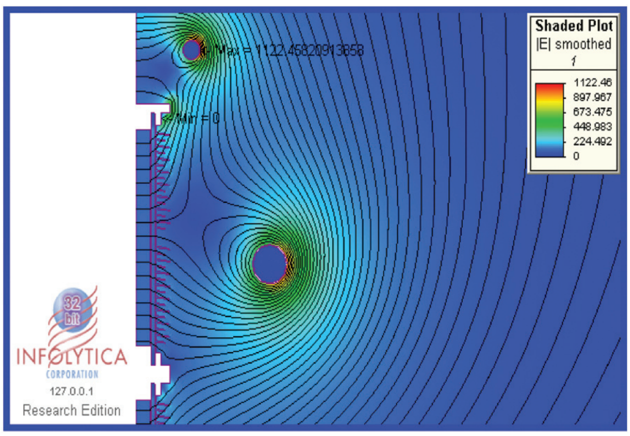


FIG. 3 AN EXPANDED VIEW OF EQUIPOTENTIAL LINES AND SHADED ELECTRIC FIELD DISTRIBUTION OF 624 kV ARRESTER

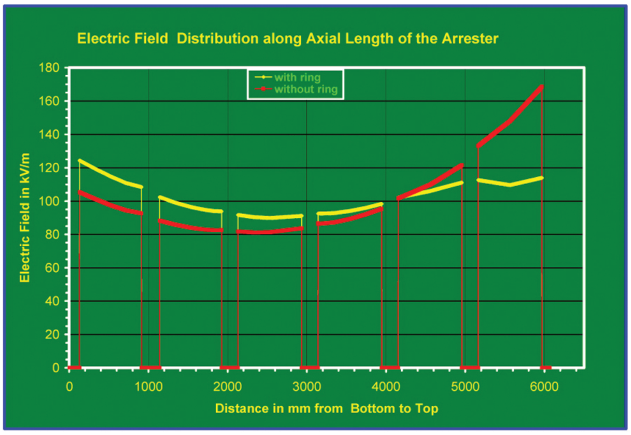


FIG. 4 COMPUTED VOLTAGE DISTRIBUTION ALONG THE AXIAL LENGTH OF THE 624 kV ARRESTER

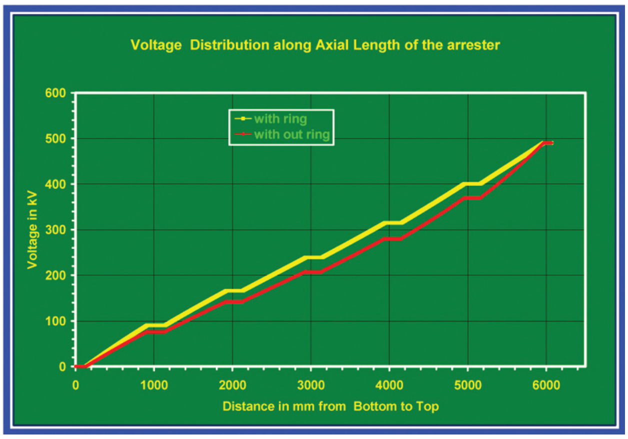


FIG. 5 COMPUTED ELECTRIC FIELD DISTRIBUTION ALONG THE AXIAL LENGTH OF THE 624 kV ARRESTER

5.0 CONCLUSIONS

- The following conclusions are drawn from the above study.
- The position of the ring is found to have a greater influence on the voltage distribution. The voltage distribution improves when the position of the ring is moved towards ground. However, the distribution becomes nonuniform once again beyond a certain position of the ring. Thus, there exists an optimum position at which the voltage drop across all the units is within the acceptable value of 12–13 %.
- Higher is the ring diameter, more is the voltage non uniformity and vice versa.
- The tube diameter does not affect the voltage distribution much but the electric field on the ring surface itself increases, indicating the existence of minimum tube diameter to avoid corona.
- The increasing pedestal height has an effect on making the voltage distribution more uniform. In this study, the ring diameter and the position are optimized to take care of range of pedestal heights ranging from 3.5 m to 4.5 m.

The results of all the optimization cases considered have yielded the following optimized dimensions for the grading ring:

Optimal Grading Ring dimensions

Grading ring diameter	:	1300 mm
Grading ring pipe diameter	:	150 mm
Grading ring position	:	5466 mm from

bottom most point of the arrester to the center of the ring

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