Grading ring parameters optimization for 220 kV metal-oxide arrester using 3D-FEM method and bat algorithm

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Abstract
Aging of metal oxide surge arresters is mainly affected by the high electric stress near the high voltage electrode. It has been observed that the distribution of voltage and electric field along an arrester is non-uniform. In this paper, the effect of grading ring geometrical parameters is investigated in order to achieve a more uniform electric field and voltage distribution. A 3D finite element method was employed based on COMSOL MULTIPHYSICS software to calculate these latter. The optimal design of grading ring is achieved by minimizing the electric field along the active column of varistors using a reduced number of simulations based on the Taguchi design and a bat algorithm. Initially, simulation results for a single grading ring were analysed. By using an optimal design of the single ring, the electric field is reduced by 42% in the top of the 220 kV metal oxide surge arrester and the voltage distribution can be improved. It was proposed to install an additional ring at the top of the metal oxide surge arrester. Simulation results shows that using of an optimal design of grading rings, the distribution of voltage and electric field along the surge arrester can be made as uniform as possible.

1 INTRODUCTION
A metal oxide surge arrester (MOSA) is the most important device for power system protection against switching and lightning over-voltages; it is installed closely to the equipment being protected from rapid surge current [1]. Today, installed MOSA are almost nonlinear metal oxide arresters without gaps due to high-energy absorption capability and highly nonlinear V-I characteristic of ZNO varistors.

The distribution of voltage and E-field along an arrester under normal operating conditions has been observed non-uniform [2]. This non-uniformity should be kept to a minimum in order to avoid damage the upper parts of the arresters which the ZNO discs placed near HV electrode are more stressed than the remaining discs by excessive electric fields and hence thermal stresses leading to faster thermal ageing of these highly stressed discs [3, 4].

In other words, the ring is a metal device usually circular in shape, installed to modify electrostatically the voltage distribution along the surge arrester [5]. Surge arresters of system voltages about 145 kV and over and if their length exceeds 1.5 to 2 meters, and usually for arresters made up of several units, grading rings are absolutely essential with one or more metallic rings suspended down from the top of the arrester [6–8]. For very high system voltages, additional rings are used to prevent external corona from the upper metallic flange and from the line terminal [6].

E-field distribution along varistor column is an important factor that needs to be taken into account during designing of metal oxide surge arresters (MOSA). Recently, finite element method (FEM) has been increasingly employed in all fields of engineering to aid in simulating various practical problems, including electric field analysis [9–11]. For this reason, FEM software’s such as Maxwell [12, 13] and FEMM 4.2 [14] were used to investigate the design of the grading ring for a MOSA.

He et al [15] applied 3D finite-element method (FEM) and circuit-analytic method to analyse and improve the potential distribution of the 1000-kV MOA. The influences of the grading ring and mounting height of the MOA on the potential distribution are also discussed.

Grading ring height was optimized between 75% and 86% of the total arrester length [4, 16]. It was found that placing spacers...
The E-field and voltage distribution of a 624 kV rated voltage polymeric surge arrester with varying the grading ring parameters and height of pedestal were studied [17]. Acceptable value for the voltage deviation of 12% to 15% is considered for the grading ring parameters optimization. The commercially available 2D Elecnet software based on FEM was employed.

He et al have proposed a combined method of electrical field and electric circuit in order to analyse potential distribution of suspended-type metal oxide surge arresters [18]. After installing grading ring, the voltage distribution has been improved and the maximum voltage ratio is reduced from 1.24 without ring to 1.04.

According to these studies cited previously, they have not optimized the dimensions of grading ring of the arrester's by artificial intelligence methods. Only, investigations were performed to see the effect of different ring parameters on voltage distribution and electric field.

Otherwise, several studies have been carried out to optimize the corona ring parameters in order to control the electric field stress on the insulator surface [19–23]. Corona rings are employed in insulator to avoid corona discharge activity caused by high electric stress near the end fittings [19, 24]. Artificial intelligence methods such as PSO, artificial fish swarm algorithm (AFSA), response surface methodology (RSM) and other methods have been performed for the optimization of the corona ring parameters [19, 23, 24].

In this paper, the E-field along the axis central of 220 kV MOSA with and without grading rings is studied by 3D FEM using Comsol Multiphysics software. The effect of a single grading ring parameters namely position of the grading ring from HV electrode \( (H) \), ring radius \( (R) \) and ring tube thickness \( (T) \) are analysed.

Based on 3D-FEM simulation results combined with Taguchi design, an objective function consists of a mathematical relationship between the maximum E-field magnitudes and grading ring parameters and their interactions is established.

Then, grading ring parameters are optimized using bat algorithm in order to reduce the E-field in the top of the arrester and improved the voltage distribution.

Bat algorithm is among the most powerful algorithms for optimization compared to other methods such as GA and PSO as well as HS (Harmony Search) [25, 26]. It is becomes a simple and efficient algorithm to solve many continuous optimization problems [27]. Teodoro et al [28] were made a comparison between BA and several algorithms such as: sequential quadratic programming (SQP), GA, GA-SQP, ACO, PSO for the mono-objective problem. The result found in this study by BA after 30 runs is the best compared to the other methods. According to [29], the obtained results show that the Bat algorithm is has also a favourable convergence speed compared to the most of other metaheuristic techniques.

Bat algorithm has been implemented using JAVA Script software. An improvement was recorded on the distribution of the voltage and the electric field along the surge arrester. It was considered that this improvement is not sufficient, for this purpose, it has been proposed to install an additional ring in order to make the voltage distribution as uniform as possible and to reduce the electric field value in the top of arrester. Also, double ring parameters have been optimized using bat algorithm in the same way for a single ring. Furthermore, the optimized parameters are verified by 3D model of the surge arrester using COMSOL MULTIPHYSICS.

### 2 | MODELING DETAIL OF THE MOSA

The structure of the studied 220 kV polymeric metal oxide surge arrester is shown in Figure 1. The arrester considered for this study is made of two 110 kV MOSA units in series with a total height about 2 m. The arresters unit 110 kV consists of 32 ZnO varistors having a diameter of 71 mm and thickness of 20.5 mm. A fiberglass reinforced plastic (FRP) with their inner and outer diameters are 73 and 86 mm. The maximum outer diameter of the shed is 202 mm, and the diameter of the silicone rubber cylinder is 94 mm. All metal parts in the studied arrester are made of aluminium alloy [30].

3D finite element method was employed via software COMSOL MULTIPHYSICS 4.3 to calculate the E-field and potential distribution. We simulated the polymeric surge arrester under dry and clean conditions. The high voltage (HV) electrode is carried to a potential of \( (220 \times \sqrt{2}) \)/\( \sqrt{3} \) kV while the lower electrode carried to a null potential (0 V).

The air box around the designed arrester was also drawn to observe the electric field distribution surrounding the test object.

After assembling the full geometry, material properties were assigned to each domain, also boundary conditions in the
geometry model, and the model was meshed into smaller elements for effective computation. Because the ZnO column is the most important part which determines the arrester’s behaviour, extremely fine mesh elements were applied on the area of the varistors in Ref [31, 32]. According to these references, the air domain surrounding the arrester is less important in determining the electrical properties of the arrester; for this purpose a coarser mesh has been applied to this area, and finally, fine mesh for the rest of all areas of the model. Therefore, the size of the mesh elements has substantial effect on the simulation time and also to ensure the accuracy of the calculation.

In our study, an investigation was performed to see the effect of the air box size surrounding the studied MOSA on the distribution of the electric field. Figure 2 presents the E-Field distribution along the central axis of the studied MOSA without grading ring for different radius of the air box. The radial distance is defined as the distance between the central axis and the arrester. In our case, Figure 2 gives the E-Field distribution along the central axis which means that the radial distance is zero. From this figure, we can see that the maximum value of the electric field in the top of arrester corresponds to a minimum air box radius \(R_{AB} = 1300 \text{ mm}\) and it is inversely proportional. Therefore, the choice of the air box size should not be done randomly, and it should be based on a reference or standard in order to obtain an accurate results.

The chosen size of the air box around the studied arrester having a height about 1.5x the total height of the arrester [5].

Then, the influence of mesh size was investigated in the case of the arrester without ring. Analyses results and comparisons included four different meshes type: extra fine, Fine, coarse and extra coarse are presented in Table 1. It is observed that the 3D-FEM model simulation with the extra fine mesh generate the most accurate results, because it has a smallest error compared to the other type of mesh. This error was extracted directly from Comsol Multiphysics. The computing time of simulation in this case is 433 s for 45 iterations, on the other hand for the extra coarse mesh is 21 s for 28 iterations with the highest calculation error. The results show that the choice of mesh type has a significant effect on the simulation time and also to ensure the accuracy of the calculation. When using the extra fine mesh, the simulation is time and memory consumed and was failed in some cases with variation of grading ring dimensions. In this case the accuracy is a little bit improved compared to the case using finer mesh, where it is shown that considerable computation efficiency is achieved in terms of CPU time in conjunction with low memory consumed without losing accuracy (see Table 1). For that reasons finer mesh elements is adopted. Finer mesh elements were applied on the all area with their tetrahedron shape. The potential is concentrated in the HT electrode and the varistors near this electrode, as well as the grading ring. Therefore almost all areas are important for our study.

The electric field along the central axis of the arrester particularly close to the energized end fittings in the top unit of arrester must be minimized, for this purpose three structural parameters of a single grading ring are considered: the position of the grading ring from HV electrode \(H\), the grading ring radius \(R\) and the thickness of the grading ring tube \(T\) as shown in Figure 3.

**TABLE 1** Comparison results for different mesh type

| Mesh type   | Nbr of Elements | Nbr of iterations | Computing time [s] | Error       |
|------------|----------------|-------------------|-------------------|-------------|
| Extra fine | 3148019        | 45                | 433               | 6,1.10^{-5} |
| Fine       | 1189888        | 36                | 97                | 7,6.10^{-5} |
| Coarse     | 392291         | 30                | 33                | 3,1.10^{-4} |
| Extra coarse | 246896     | 28                | 21                | 9,6.10^{-4} |
Grading ring dimensions differ from a manufacturer to another. Table 2 summarizes some used rings and their dimensions for 245 kV surge arresters.

In order to reduce the number and the simulations time performed to optimize the grading ring parameters, an optimal design requires a smaller number of simulations is adopted based on the model L9 of Taguchi. Therefore, we choose three values for each parameter \((H, R, T)\). Grading ring parameters to be studied and their variation ranges are indicated in Table 3.

In addition, there are no standards for the design and the placement of the grading rings by manufacturers \([4,12,16,33-35]\). According to the author of the reference \([7, 8]\), a grading ring should be installed in quarter of the total arrester length from top in order to achieve an acceptable axial distribution of the electric potential, power losses and temperatures.

The dry arc distance is reduced if the position of the ring from end \((H)\) increased over 500 mm; this distance is related to total length of the metal oxide surge arrester. It is the distance to respect in order to avoid arcing. According to reference \([36]\), the arc distance must be \(>1.10\) m for a voltage of 225 kV. For this reason, we choose three positions of grading ring from HV electrode: \(H (0, 250 \) and 500 mm).

To avoid any contact between the shed and the ring, the inner radius of ring must be superior to the larger shed radius of 101 mm. three variation ranges are chosen \((200, 300 \) and 400 mm). In this study, we note that the increase of the ring radius beyond 400 mm has practically no effect on the maximum E-field.

Three ring tube thickness variation ranges are chosen \((20, 50 \) and 80 mm). We note that low thickness leads to high E-field. The excessive increasing of tube thickness beyond 80 mm is not economical, and makes the ring more bulky and is subjected to mechanical stresses \([12, 13, 24]\).

A combined method based on 3D FEM and Taguchi design is opted in order to obtain the objective function. The optimization problem is achieved by minimizing the electric field using a BAT algorithm.

### 3 BAT ALGORITHM

Bat algorithm (BA) has been proposed by Yang in 2010 \([25]\). It is a recent metaheuristic optimization algorithm inspired by the echolocation behaviour of bats \([26, 27]\). The bats use sonar echoes to build a precise image of their surroundings in order to detect prey and avoid obstacles \([26, 27, 38]\).

The three idealized rules used of developing the bat algorithm are \([25]\):

1. All bats use echolocation to sense distance, and they also ‘know’ the difference between food/prey and background barriers in some magical way.
2. Bats fly randomly with velocity \(\mathbf{v}_t\) at position \(\mathbf{x}_t\) with a fixed frequency \(f_{\text{min}}\), varying wavelength \(\lambda\) and loudness \(A_0\) to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission \(r \in [0, 1]\), depending on the proximity of their target.
3. We assume that the Loudness varies from a large positive value \(A_0\) to a minimum constant value \(A_{\text{min}}\); it can vary in many ways.

Main steps of Bat algorithm can be summarized as the pseudo-code shown in Figure 4.

Initializing the bat population is performed randomly in this Algorithm, with each bat \((b_i)\) is defined by its position \((\mathbf{x}_i)\), velocity \((\mathbf{v}_i)\), frequency \((f_i)\), loudness \((A)\) and the emission pulse rate \((\xi)\) in a d-dimensional search space. Let \((Np)\) be number of bats in the echolocation, and \((\ell)\) is the number of iterations.

New solution generation or motion of virtual bats is performed by updating their frequency, velocity which is proportional to frequency and position according to the following equations \([25, 26]\):

\[
f_i = f_{\text{min}} + (f_{\text{max}} - f_{\text{min}}) \times \pi \quad (1)
\]

\[
\xi_{i}^{\prime} = \xi_{i}^{-1} + \left[\xi_{i}^{-1} - \xi_{\text{best}}\right] f_i \quad (2)
\]

\[
\mathbf{x}_i^{\prime} = \mathbf{x}_i^{-1} + \mathbf{v}_i \quad (3)
\]

Where \(\pi \in [0, 1]\) indicates a random vector drawn from a uniform distribution, \(f_i\) is a frequency value corresponding to the \(i\)th bat used for seeking its prey, \(f_{\text{min}}\) and \(f_{\text{max}}\) are minimum and maximum frequency values respectively, and \(\xi_{i}^{\prime}\) is the velocity of the \(i\)th bat at \(\ell\)th time step, \(\xi_{\text{best}}\) is the obtained best solution after comparing all solutions among the \(Np\) bat.

A solution is selected from the best current solutions and then for local search, we apply the random walk on bats with

| TABLE 2 | Grading ring dimensions for 245 kV surge arresters |
|---------|-----------------------------------------------|
| Grading ring dimensions | \(H [\text{mm}]\) | \(R [\text{mm}]\) | \(T [\text{mm}]\) |
| Ref [33] | 160 | 200 | / |
| Ref [34] | 381 | 320 | 48 |
| Ref [12] | 1724* | 425 | 65 |
| Ref [35] | 800 | 400 | / |
| Ref [4] | 80% \(H\) arrester | / | 100 |
| Ref [16] | 75% \(H\) arrester | 400 | / |

*the ring position was calculated from bottom electrode.

| TABLE 3 | Grading ring parameters |
|---------|-------------------------|
| Parameters | \(H [\text{mm}]\) | \(R [\text{mm}]\) | \(T [\text{mm}]\) |
| Variation ranges | 0 | 200 | 20 |
| 250 | 300 | 50 |
| 500 | 400 | 80 |
**Bat Algorithm:**

**Input:** Bat population \( x_i = (x_{i1}, ..., x_{ip}) \), for \( i = 1, 2, ..., Np \), velocity \( (v_i) \), frequency \( (f_i) \), loudness \( (A_i) \), pulse rate \( (r_i) \) and the maximum number of iteration \( (MaxIt) \).

**Output:** The best solution \( x_{\text{best}} \) and its corresponding fitness value \( f(x_{\text{best}}) \)

1. Initialize the bat population \( x_i (i = 1, 2, ..., Np) \)
2. Evaluate fitness for each bat \( f(x_i) \)

```plaintext
while (t < MaxIt) do
    for i = 1 to Np do
        Generate new solutions by adjusting frequency, and updating velocities and locations/solutions [equations (1) to (3)]
        if (rand < r_i) Select a solution among the best solutions
        Generate a local solution around the selected best solution
    end if
    Generate a new solution by flying randomly
    if (rand < A_i and f(x_i) < f(x_{\text{best}})) Accept the new solutions
        Increase rand reduce A_i
    end if
end for
Rank the bats and find the current best \( x_{\text{best}} \)
end while
Display results
```

**FIGURE 4** Pseudo-code of Bat algorithm

their pulse emission rates \( r_i \) smaller than the random number in order to generate a new solution for each Bat as follows [25, 26]:

\[
x_{\text{new}} = x_{\text{old}} + \epsilon A^t
\]  

(4)

Where \( \epsilon \in [-1; 1] \) is a random number and represents direction and intensity of random-walk and \( A^t \) is the average loudness of all the bats at time \( t \). At each iteration of the algorithm, the loudness \( A_i \) is decreased and the rate \( r_i \) is increased with the following equations:

\[
A_i^t = \alpha A_i^{t-1}
\]

(5)

\[
r_i^t = r_i^0 \left( 1 - \gamma^{t-1} \right)
\]

(6)

Where \( 0 < \alpha < 1 \) and \( \gamma > 0 \) are constants [25, 37]. At the initialization step of the algorithm, each bat has a different random loudness \( A_0 \) which is in \([1, 2]\) and random pulse emission rates \( r_0 \) which is in \([0, 1]\).

4 | RESULTS AND DISCUSSION

4.1 | FEM simulation without grading ring

Initially, the electric field and voltage distribution are computed along the central axis of the metal oxide surge arrester without grading ring.

Figure 5 shows the E-field distribution, it is clearly indicated that the E-field at the HV electrode of the surge arrester reaches a maximum value located at the same triple point height and decreases rapidly then after. So the top discs near the HV electrode are more stressed [2, 12].

Figure 6 shows the distribution of the electric potential along the studied MOSA without grading ring. The high electric potential strength areas are concentrated on the top of arrester close to the energized end. It is shown that the voltage distribution along the arrester is not uniform because of the effect of the stray capacitances to the earth and to the HV electrode [3].

4.2 | FEM simulation with grading ring

In order to examine the influence of ring parameters \((H, R, T)\) on the axial distribution of the E-field, 3D-FEM simulation is carried out. The electric field variation is plotted as a function of two ring parameters, while the third parameter is kept at a fixed value.

Figure 7 shows the maximum E-field in the top discs of arrester which located at the same triple point height for different \( H \) and \( R \) chosen previously while keeping ring tube thickness at \( T = 50 \) mm. It is noticed that increasing the ring position firstly decreases strongly the E-field to reach a minimum.
value before increasing again. On the other hand, increasing ring radius \( R \) increases the E-field.

Figure 8 shows the maximum E-field for different \( T \) and \( H \) with \( R = 300 \) mm. It can be seen that increasing the ring tube thickness has an effect of reducing the E-field.

Figure 9 shows the effect plots of ring radius and ring tube thickness on the E-field value. It can be seen that the minimum E-field is correspondent to ring radius value equal to 200 mm and to ring tube thickness value equal to 80 mm. The increase of the ring radius has an increasing influence on the E-field.

According to these obtained results, the optimum value of \( H \) that corresponds to a minimum value of the E-field varies in the interval \([300–400]\) mm.

In addition, the electric field is reduced, if the ring is closer to shed, and if the ring tube thickness is at the chosen maximum value.

Therefore, grading ring parameters should be optimized to obtain better electric field distribution along the MOSA.

## 4.3 Optimization of the grading rings parameters based on BAT algorithm

The main objective of the optimization of grading ring geometrical parameters is to reduce maximum E-Field along 220 kV MOSA and improve its distribution.

In this paper, the optimization process is based on BAT algorithm. Indeed, the optimization problem can be formulated as mentioned in Equation (7).

\[
 f (x_1, x_2, x_3) = E (H, R, T) \tag{7}
\]

Where \( x_1, x_2, x_3 \) corresponds to \( H, R \) and \( T \) respectively,
- \( E \): E-field [kV/cm].
- \( H \): grading ring position from HV electrode [mm].
- \( R \): grading ring radius [mm].
- \( T \): the thickness of the grading ring tube [mm].

In order to obtain the objective function which can evaluate relationship between maximum electric field strength and grading ring structure parameters, a combined method based on 3D FEM and Taguchi design is opted.

In our study, Taguchi design which allows using Response Surfaces Modelling (RSM) is opted and it is considered as a statistical method for modelling of problems in which different variables affect the desired response. It allows determining
an appropriate approximation function representing the relationship between the response and independent variables [19, 39–41].

The Taguchi method is one of the best experimental methodologies used to find the minimum number of experiments to be performed within the permissible limit of factors and levels. With the plans of experiments, we obtain the maximum information with the minimum of experiences. Thus the marriage of design of experiments with optimization of control parameters to obtain best results is achieved in the Taguchi Method. Results of these experiments analyzed and fitted to a second-order polynomial using regression analysis as given by the following form [19, 41]:

\[
Y = a_0 + \sum_{i=1}^{3} a_i X_i + \sum_{i=1}^{3} a_{ii} X_i^2 + \sum_{i<j}^{3} a_{ij} X_i X_j \quad (8)
\]

where:
- \(Y\) represents the wanted response.
- \(a_0, a_i, a_{ii}, a_{ij}\) are the regression coefficients.
- \(X_i\) : Represents the input variables related to the considered parameters.
- \(X_i^2\) : Represents the square of the variables and \(X_i, X_j\) represents the interaction between variables.

We keep the same variation ranges of studied parameters (\(H, R, T\)) of the Table 3.

We adopted the experimental design L9 of Taguchi orthogonal array as shown in Table 4. It’s the most suitable orthogonal array for experimentation [39]. Numerically computed results obtained by 3D FEM of Table 4, relating to the studied configurations of grading ring parameters such as \(H, R, T\) and its corresponding maximum E-field are used to find the objective function.

The objective function consists of a mathematical relationship between the maximum E-field magnitudes and grading ring parameters and their interactions. For this reason, statistical software MINITAB 18 was employed.

It can be presented according to the following equation:

\[
E = 3,063 - \left( \frac{2911.3H}{-67R + 13440T} - \frac{49H^2}{56T^2} - \frac{4H.T}{4.H.T} \right) \times 10^{-6} \quad (9)
\]

where:
- \(E\): E-field [kV/cm].
- \(H\): grading ring position from HV electrode [mm].
- \(R\): grading ring radius [mm].
- \(T\): the thickness of the grading ring tube [mm].

Note that the advantage of BAT algorithm is a very fast program, the Bat algorithm enables rapid convergence to an accurate solution. It is a simple and efficient algorithm.

The optimum value of the electric field is achieved (1.87 kV cm < sp > -1 <)/sp > as shown in Figure 10. From this figure, it can be seen that the objective function achieves its minimal value after a few numbers of iterations (5th iterations) and then any change can happen. The optimal value corresponds to the minimum value on the 100 iterations in Figure 10.

The optimized dimensions of grading ring are: grading ring position \(H = 310\) mm, radius of grading ring \(R = 200\) mm, and grading ring tube thickness \(T = 80\) mm.

In order to validate the powerful and the reliability of the optimization method used and to check accuracy of the obtained results, two different optimization algorithms, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) are utilized for comparison with a Bat algorithm. This comparison was made for the same studied MOSA, and the optimal design of grading ring is achieved by minimizing the same used objective function mentioned in Equation (9) for the same number of iterations.

The obtained results are shown in Table 5. From these results, we can notice that the BAT, PSO, and GA methods almost lead to the close results. The E-Field value optimized by Bat algorithm corresponds to the minimum value compared to the other methods, which means that the Bat algorithm produces more accuracy results. It’s our goal to get the minimum value.

Furthermore, the BAT approach possesses less computation time than the other two algorithms as shown in Table 5. We note

### TABLE 4 Numerically computed results for a single ring

| \(H\) [mm] | \(R\) [mm] | \(T\) [mm] | \(E\) (kV cm\(^{-1}\)) |
|---|---|---|---|
| 0  | 200  | 20  | 2.83  |
| 0  | 300  | 50  | 2.55  |
| 0  | 400  | 80  | 2.37  |
| 250 | 200  | 50  | 2.10  |
| 250 | 300  | 80  | 1.95  |
| 250 | 400  | 20  | 2.38  |
| 500 | 200  | 80  | 1.99  |
| 500 | 300  | 20  | 2.37  |
| 500 | 400  | 50  | 2.15  |
TABLE 5 Grading ring parameters optimization for different optimization algorithm

| Parameters | $H$ [mm] | $R$ [mm] | $T$ [mm] | $E$ (kV cm$^{-1}$) | Computation time [s] |
|------------|-----------|-----------|-----------|-------------------|----------------------|
| BAT        | 310       | 200       | 80        | 1.87              | 5                    |
| PSO        | 325       | 200       | 80        | 1.91              | 12                   |
| GA         | 341       | 203       | 80        | 1.96              | 45                   |

Figure 11 E-field distribution along the central axis of the surge arrester

that choice of the objective function based on the 3D FEM and Taguchi design is minimized the computation time.

Then, these optimized parameters are verified by FEM. We insert these parameters into the 3D model of the surge arrester, in order to see the distribution of the electric field and the voltage along the surge arrester.

Figure 11 shows the E-field distribution along the central axis of the 3D surge arrester with optimized grading ring; it is clearly observed that the E-field at the HV electrode of the surge arrester have been reduced by nearly 42%. The optimized grading ring installation improves the electric field distribution along the surge arrester.

Figure 12 illustrates the distribution of the electric potential along the studied metal oxide surge arrester with optimized grading ring. It is shown that the voltage distribution along the arrester is improved compared to the case without ring; this improvement is well clear up in Figure 13. This figure shows that before the installation of grading ring, the half of the applied voltage (90 kV) is supported only by 500 mm of the surge arrester length. While by using the optimized grading ring, this distance is increased to reaches almost 700 mm of the surge arrester length and that means improving the voltage distribution.

From these obtained results, it was considered that this improvement is not sufficient. For this purpose, it has been proposed to install an additional ring in order to make the voltage distribution as uniform as possible and to reduce the electric field value in the top of arrester. The proposed additional ring has a large geometric dimension compared to the first ring as shown in Figure 14 [6, 33, 42].

Figure 12 Distribution of the electric potential for a surge arrester with optimized grading ring

Figure 13 Electric potential distribution along the central axis of the surge arrester

According to some simulation tests, the dimensions of small ring have been fixed to new values different from the ring dimensions in the first case where there is only one ring, and the dimensions of the large ring were allowed to vary, three levels for each parameter are chosen as shown in Table 6.

As already said, there are two rings used to improve the distribution of the voltage and the electric field, a small ring and a large ring. The thickness of the small ring was set at 30 mm. The increase in the thickness beyond this value will increase the electric field to the metal flanges in the middle of the arrester and make its distribution no uniform. The value of $H_1$ is fixed at 150 mm. Also, we chose the same minimum distance between
the shed and ring. Therefore, we chose the radius of the small ring at 175 mm. These chosen values always remain our own proposal.

Table 7 shows the nine studied configurations of grading rings and its corresponding highest E-field, distributed according to the model L9 of Taguchi orthogonal array.

The obtained objective function in this case is as follows:

\[
E = 3,047 - (383.3H_2 - 89.R_2 + 15190.T_2 - 4.H_2^2 - R_2^2 - 44.T_2^2 - 3.H_2.R_2.19.H_2.T_2).10^{-6}
\]

(10)

**TABLE 7** Numerically computed results for two rings

| \(H_2\) [mm] | \(R_2\) [mm] | \(T_2\) [mm] | \(E\) [kV cm\(^{-1}\)] |
|-------------|-------------|-------------|-----------------|
| 200         | 200         | 20          | 2,18            |
| 200         | 300         | 50          | 1,93            |
| 200         | 400         | 80          | 1,78            |
| 350         | 200         | 50          | 1,77            |
| 350         | 300         | 80          | 1,64            |
| 350         | 400         | 20          | 1,85            |
| 500         | 200         | 80          | 1,81            |
| 500         | 300         | 20          | 1,78            |
| 500         | 400         | 50          | 1,63            |
rings. It is shown that the voltage distribution along the arrester is uniform; this uniformity is well clear up in Figure 17, where it is shows that the applied voltage is distributed on both units of MOSA almost by equality.

5 | CONCLUSION

The 3D finite element method was used to calculate the voltage distribution and electric field distribution of the 220 kV surge arrester. The effects of grading ring parameters are analysed. A combined FEM and Bat algorithm was used to conduct the optimization process for grading ring parameters.

The optimal design of the grading ring is achieved by minimizing the electric field along the active column of varistors using a bat algorithm, and the objective function of this algorithm is based on Taguchi design which allows using response surfaces modelling (RSM). Then the optimized parameters are verified by 3D-FEM. A good agreement has been reached between the results of this last and the Bat algorithm.

The obtained results show that using an optimal design of a single grading ring, the electric field is reduced by 42% in the top of the 220 kV MOSA and the voltage distribution can be improved.

In order to obtain a better distribution of the voltage and the electric field along the arrester, an additional ring has been proposed. This proposed additional ring has a large geometric dimension compared to the first ring. The dimensions of the small ring have been fixed, and the dimensions of the large ring were allowed to vary. Simulation results show that using an optimal design of double rings, the voltage distribution can be made as uniform as possible and the electric field is reduced by 53% to avoid damage of varistors. To make certain the validity of the proposed approach, it is intended, as a future work, to introduce the experimental verification which is very important in this kind of research work.

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FIGURE 17 Electric potential distribution along the central axis of the surge arrester
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