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Research Article

A More Uniform Electric Field Distribution on Surge Arresters through the Optimal Design of Spacer and Fiber Glass Layer

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Abstract: In this study, the optimal design of spacers and fiber glass layer of a metal oxide surge arrester is presented in order to achieve a more uniform electric field distribution, inside and outside the arrester. This is done by using intelligent algorithms and numerical analysis, i.e., Finite Element Method (FEM). The introduced method can be used in order to determine the optimal dimensions of spacers and fiber glass layer so that the electric field distribution is optimized and the lifetime of highly stressed ZnO blocks in the vicinity of HV electrode is increased. In order to verify the results, Differential Evolution (DE) and Particle Swarm Optimization (PSO) algorithms are used.

Keywords: Electric field, Finite Element Method (FEM), optimization methods, surge arrester

INTRODUCTION

Metal Oxide Arresters (MOA) have been used extensively in high voltage power systems for providing protection for the insulation devices in power apparatus against dangerous over voltages. The lifetime of these arresters is dependent on their steady state performance. It has been observed in practice that the voltage distribution on the arrester is quite non-uniform. As a result, the discs at the top share a higher voltage and hence higher thermal stresses, than the remaining discs. This leas to a faster electric field aging of the discs at the top. To overcome this problem efforts are generally made to make the electric field distribution on the arrester as uniform as possible.

The transient analysis of MOA is investigated in some studies (He *et al.*, 2003a, b; Csendes and Hamann, 1981; Han *et al.*, 2005; Kumar and Mogaveera, 2002); but the present study focuses on electrostatic analysis of MOA. In MOA, the ZnO blocks placed near HV electrode, are highly stressed by excessive electric fields existed in the vicinity of the HV electrode. In other words, the electric field distribution is non-unifrom along the axis of the Metal Oxide Varistors (MOVs) and causes a faster aging of the varistors placed near the HV electrode. Spacers and Fiberglass Reinforce Plastic (FRP) layers are well known means to uniform the voltage distribution on the arresters. In order to gain a uniform distribution of electric field, proper geometry and size of Spacer and FRP layer is needed.

The electric field and voltage distribution on MOA are analyzed in studies (Vahidi *et al.*, 2004a, b, 2005). Vahidi *et al.* (2005), the location of spacers and grading ring is studied also we presented optimal design of grading ring (Aghaebrahimi *et al.*, 2012). However, in this study an algorithm for optimal design of the size and the geometry of Spacers and FRP in MOA to uniform the electric filed distribution along the axis of arrester is presented. The electric field is calculated by Finite Element Method (FEM) based software; then, Differential Evolution (DE) and Particle Swarm Optimization (PSO) algorithms are used to obtain the optimum size of Spacers and FRP layer for a better electric field distribution. As shown in Fig. 1, the design parameters which are to be optimized in order to uniform the electric field distribution, inside and outside of arrester, are P1, P2 and P3, in which P1 and P2 are the distance between up Spacer and down Spacer and the center of the arrester, respectively and P3 is the FRP layer's radius measured from the center of the arrester.

The aim of this study is to have the optimal design for these parts of MOA, using iteration theory and evolutionary algorithm. Electric field calculations are done using FEM and various geometric parameters of the insulation materials are considered in order to achieve optimal distribution of electric field, with a general default form of the surge arrester. In addition, the calculation of the electric field is done by COMSOL Multiphysics software package which has the ability to be connected to MATLAB software package (Farin, 1997).

This optimization method represents a universal method of optimization for various objective functions related to the arrester and other devices (Kitak *et al.*, 2005, 2009; Hesamzadeh *et al.*, 2008). This approach, thus, is not only not limited to the purpose of optimizing

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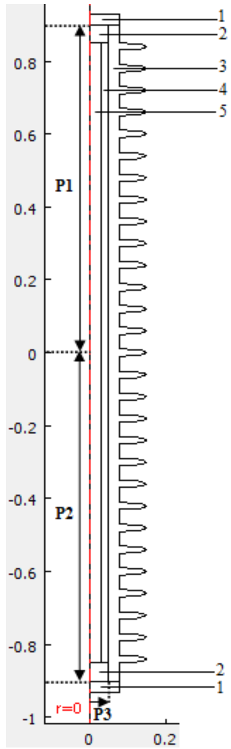

Fig. 1: 2-D cut model of MOA and the defined optimization parameters (1: electrode, 2: spacer, 3: porcelain housing, 4: FRP, 5: ZnO block)

the geometry of distribution of the electric field, but can also be performed by regarding the properties of the material used and various types of surrounding insulation materials. The results of Differential Evolution (DE) and Particle Swarm Optimization (PSO) algorithms applied to the case study optimization problems will be shown and it can be seen that the proposed method is effective and acceptable for an optimal field distribution on the column of ZnO pills.

PROBLEM ‘S MODEL AND CONSTRAINTS

Objective function: The aim of the proposed optimization algorithm is to obtain the uniform electric field distribution along ZnO blocks. Therefore, the objective function is defined as follows:

$$\text{Objective function} = \min\,(E_{max}/E_{mean}) \tag{1}$$

where E_{max} and E_{mean} are the maximum and average of the electric field existed along arrester axis, respectively.

Problem constraints: The constraint that must be considered in design of arrester is the dielectric strength of insulation housing. Therefore, the maximum electric field on surface of the porcelain housing must be equal or less than the electric strength of the air, i.e., 2.4 kV/mm. In the other words:

$$E_{max} < 2.4\text{kV/mm} \tag{2}$$

The rest constraints are defined considering the limits relative to arrester’s dimensions. They can be defined as:

$$P_{1-\min} < P_1 < P_{1-\max} \tag{3}$$

$$P_{2-\min} < P_2 < P_{2-\max} \tag{4}$$

while,

$$P_1 + |P_2| < 2400\ mm \tag{5}$$

and

$$P_{3-\min} < P_3 < P_{3-\max} \tag{6}$$

where $P_{1\text{-min}}$ and $P_{2\text{-min}}$ are the height of ZnO block and $P_{3\text{-min}}$ is the ZnO block's radius. Due to design considerations, $P_{1\text{-max}}$ and $P_{2\text{-max}}$ are arrester's height. Relationship (5) expressed by Hinrichsen (2001). Also, $P_{3\text{-max}}$ is the radius of the arrester's porcelain housing.

OPTIMIZATION ALGORITHMS

In order to check the accuracy of the obtained results, two different optimization algorithms, Differential Evolution (DE) and Particle Swarm Optimization (PSO), are used. Each particle in PSO or each solution in the initial population of DE will be a candidate for the final solution of the problem. The general steps of the optimization process are as follows:

Step 1 : Initializing the population
A sample string in defining the initial population is as follows:

P1 P2 P3

Step 2 : Evaluating the initial population by FEM
Step 3 : Creating the new solutions
Step 4 : Constraint handling
Step 5 : Selection
Step 6 : If the convergence criterion is satisfied exit, else: go to step 3

The flowchart of above steps is given in Fig. 2.

The arrester is modeled and simulated in COMSOL software to calculate the electric field distribution.

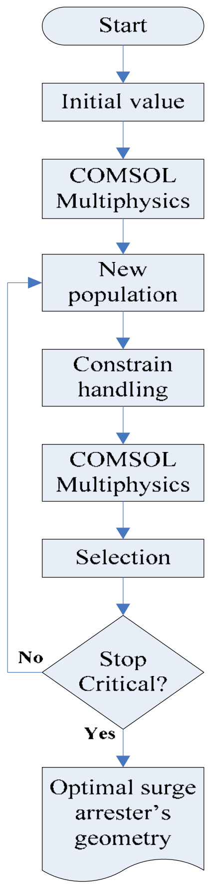

Fig. 2: The flowchart of optimal design of a 220 kV MOA

Then, the obtained results are transferred to MATLAB in order to evaluate the objective function (1). Considering the initial value of parameters and calculated quantities, new values for parameters are produced by the intelligent algorithm. This process continues until the optimization algorithm converges to the optimum values of Spacers and FRP layer parameters, i.e., P1 to P3.

Whenever the calculated values of P1, P2 and P3 exceed their relative limits, they will be fixed in bounds by a probability of 0.7 and a new feasible solution is created and is replaced by a probability of 0.3.

Differential Evolution algorithm: Differential Evolution algorithm (DE) is one of the most high speed and accurate and at the same time simplest, algorithms for solving mathematical problems. It was proposed by Storn and Price (1995). In recent years, many studies have been done by DE (Coelho and Mariani, 2006; Chiou, 2009; Bhattacharya and Chattopadhyay, 2010; Duvvuru and Swarup, 2011). This evolutionary algorithm starts the search process by an initial random population. There are three operatives of crossover, mutation and selection and three controlling parameters of population size (NP), scale Factor (F) and Crossover Rate (CR). DE steps are as follows:

- **Initial population generation:** The initial population consists of NP members, created randomly such that each member is in the feasible region. The structure of member *i* in the problem with dimension *D* is expressed by:

$$X_i = (x_{i,1}, x_{i,2}, \cdots, x_{i,D})$$

- **Mutation:** A new solution of Y_i in each iteration *t* is created as follows:

$$Y_i(t) = X_{r3}(t) + F \cdot (X_{r1}(t) - X_{r2}(t)) \quad i = 1, 2, \cdots, NP \tag{7}$$

where r_1, r_2, r_3 ε[1, NP] are three random unequal integers and *F* is a positive and real number, which is considered 0.5 in most problems.

- **Crossover:** The new solution Z_i is created by combination of X_i and Y_i as follows:

$$z_j(t) = \begin{cases} y_j(t) & \text{if } rand \le CR \text{ or } j = jrand \\ x_j(t) & \text{otherwise} \end{cases} \tag{8}$$

- **Selection:** If the fitness of the new solution is better than that of the previous solution, the new solution replaces the old one, otherwise, the previous solution is kept:

$$X_i(t+1) = \begin{cases} Z_i(t) & if \ fit(X_i(t)) \ge fit(Z_i(t)) \\ X_i(t) & \text{otherwise} \end{cases} \tag{9}$$

where fit (.) shows the solution's fitness.

- **Stop conditions:** The searching process continues until the convergence criteria are satisfied. The iteration number is usually selected as the convergence criterion.

Particle Swarm Optimization: Particle Swarm Optimization (PSO) is a population-based optimization algorithm that proposed by Kennedy and Eberhart (1995). The main idea in PSO algorithm is the modeling and simulation of the group movement and behavior of birds in search for food. Each particle in PSO is considered as a candidate solution for solving the problem in multi-dimensional search spaces.

Each particle has two components of X_i (current position) and V_i (current velocity) in n-dimensional problem search space as follows:

Table 1: Relative permittivity of various parts of arrester

Relative permi.	ZnO	Porcelain housing	Spacer	FRP	Electrode
ε_r	150	3.6	10^3	4.6	10^6

Table 2: Optimization values of design parameters, calculated by optimization algorithms

Parameter	Min (mm)	Max (mm)	Init. (mm)	Optim. DE (mm)	Optim. PSO (mm)
P1	861	1539	900	1200	1199.8
P2	-861	-1539	-900	-1199.7	-1199.6
P3	31	79	50	69	68.6

Table 3: Values of objective function and maximum electric field

	No optim.	Optim. DE	Optim. PSO
Objective function value	2.1514	1.8731	1.8734
Maximum electrical field value [p.u.]	1.4002	1.1410	1.1406

$$X_i(t) = \left(x_i^1(t), x_i^2(t), \dots, x_i^n(t)\right)$$
$$V_i(t) = \left(v_i^1(t), v_i^2(t), \dots, v_i^n(t)\right) \quad (10)$$

where, n is the dimension of the problem and t is the iteration index.

The new position of each particle is created by its current position and its new velocity. Also, the new velocity is produced by four factors, i.e., current velocity, current position, best previous position of the particle (P_{best}) and the best position among all of particles in all iterations (G_{best}). Therefore, the new velocity is obtained as follows:

$$v_{i,j} = \omega \cdot v_{i,j} + c_1 r_1(\cdot)\left[pbest_{i,j} - x_{i,j}\right] + c_2 r_2(\cdot)\left[gbest_j - x_{i,j}\right] \quad (11)$$

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \times iter \quad (12)$$

In Eq. (11), $pbes_{i,j}$ is the jth dimension of particle i's best position and $gbest_j$ is the jth dimension of the best position among group's particles. Also, ω is the particle inertia coefficient, ω_{max} and ω_{min} are the final and initial values of inertia coefficient, respectively, iteris the current iteration, $iter_{max}$ is the number of all iterations, c_1 and c_2 are acceleration coefficients, r_1 and r_2 are random numbers between 0 and 1 and i and j are the particle and its dimension indices respectively. The new position of the particle is obtained by:

$$x_{i,j+1} = x_{i,j} + v_{i,j} \quad (13)$$

NUMRICAL RISULTS

The proposed method has been applied to the design of the grading ring of a real arrester. The voltage rating of the arrester is 220 kV. All other data are as presented by Hinrichsen (2001).

The dielectric constants of different parts of the arrester are presented in Table 1. All of the electric field values are in the form of per unit, based on the values of the applied voltage. The initial values of design parameters, the range of permissible variation of each parameter and the resultant optimum values, calculated by PSO and DE optimization methods, are presented in Table 2. The initial dimensions of Spacers and Fiber glass layer are those used in conventional design and presented in the catalog. Based on the results, in order to uniform the electric field on ZnO block, the optimal height for the upper spacer and lower spacer is 350 mm (1200-850) and 349.7 mm (1199.7-850) respectively. The 850 mm is the height of ZnO block from the origin of the vertical axis in Fig. 1. Also, the optimum value for P3, which is the radius of the Spacer and is directly related to the FRP layer, is found to be equal to 69 mm and its optimum thickness is found to be equal to 39 mm.

The optimization parameters of DE method, which are the Number of Population (NP), the scale Factor (F) and the crossing constant (CR), are equal to 100, 0.5 and 0.9, respectively. The parameters of PSO method, which are the Number of Particles (NP), the individual learning coefficient C1 and the group learning coefficient C2, are equal to 100, 1 and 1, respectively. Figure 3 shows the convergence processes of the two mentioned optimization algorithms during 100 iterations.

Table 3 presents the minimum values of the objective function (1) calculated by DE and PSO methods and the maximum electric field existing along the arrester axis with the initial dimensions of Spacers and FRP layer and with the optimized dimensions calculated by the proposed method. According to Table 3, the maximum electric field on ZnO varistors with initial parameters is equal to 1.4002 p.u. which can be decreased to 1.1410 p.u. (for DE) by using the dimensions determined for Spacers and FRP layer by the proposed optimization method.

With the optimization algorithm presented in this study, in addition to achieving a more uniform distribution of the electric field along the arrester axis, the high stresses imposed on the ZnO varistors located in the vicinity of the HV electrode could be prevented too. This leads to an increase in the lifetime of ZnO

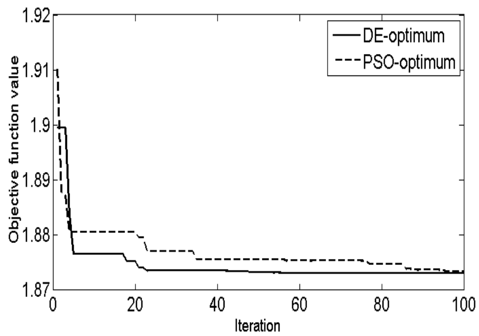

Fig. 3: Convergence of DE and PSO algorithms

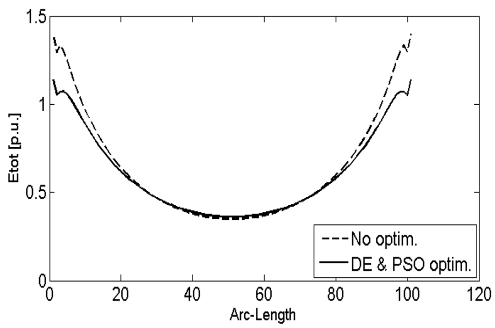

Fig. 4: Electric field contour of the surface of ZnO block for initial parameters and with DE and PSO optimizations

varistors due to the reduction of aging which takes place inside these blocks.

Figure 4 shows the electric field contour on the surface of ZnO block for initial parameters and with DE and PSO optimizations. The decrease in the maximum value of the electric field, as a result of the optimization procedure, is quite clear.

CONCLUTION

In this study, the optimal design of the surge arrester's Spacers and Fiber glass layer, regarding the field distribution on the zinc oxide tablet and using PSO and DE algorithms, was studied. The simultaneous use of geometry parameters display, producing a newly developed mesh and numerical calculation methods, with the help of finite element analysis and intelligent algorithms, is found to be reliable. Also, the major task in the arrester's design is its optimization process. Regarding the studied test sample, it has been proved that both DE and PSO algorithms are reliable and completely applicable for modeling the arrester elements and other fast electromagnetic components.

The numerical results show that arrester elements have a direct effect on the voltage gradient and with suitable design, the lowest concentration of electric field on the surface of considered parts (here: ZnO block) can be achieved. Also, the proposed method is a general-purpose method of modeling not only for the surge arrester, but also for other power system insulation elements.

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