Design of Outdoor Insulation Sheds of ZnO Surge Arresters Aiming at Electric Field Distribution on Surface ZnO Pills Column Using 2-D FEM and Fuzzy Multiobjective

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Abstract-- In this paper, the optimal design of a metal oxide surge arrester with appropriate distribution of electric field of the Zinc Oxide pills using intelligent algorithms and numerical analysis of 2-dimenional Finite Element Method (FEM) is studied in electrostatic situation. This paper has presented a fuzzy multiobjective model and DE and PSO algorithms to prevention of premature aging of ZnO pills column. This formulation incorporates two objectives: minimization of maximum of electric field on ZnO column surface and minimization of porcelain housing volume. Parameters of designing are length and thickness outdoor insulation sheds. The proposed approach used for two case for to valuation objectives. With uniform distribution of the electric field, the ZnO pills lifetime increases and the cost of operation and maintenance decreases. Also, by reducing the volume of porcelain insulation, the manufacture cost of surge arrester reduces. All other requirements and constraints that must be considered in the design of insulation elements are also satisfied.

Keywords: Electric Field, Finite Elemnt Method (FEM), optimization methods, surge arrester, Zinc Oxide (ZnO).

I. INTRODUCTION

Surge arrester is a protective device that damps over-voltages caused by lightning and prevents damages to the network and its equipment. On one hand, damages to system equipment impose heavy costs on the electricity industry, and on the other hand, interrupt the supply of electrical energy needed by consumers. Major disorders of the metal oxide surge arresters are the electrical and thermal disorders in the static mode. The advanced type of surge arresters, known as Metal Oxide Arrester (MOA), is made of pills of oxide metals such as Zinc Oxide (ZnO) which have non-linear properties. MOA is without an air gap and is always subject to the network voltage, so a leakage current passes through it and heats it gradually. If the arrester's shape, size and the materials of its various parts are not designed properly, it will be burnt. On the other hand, designers are interested in identifying and considering important factors which are effective on the maximum electric field intensity of MOA, by which excessive inside and outside potential gradient can be avoided. Without this, serious damages to the insulation system of the arrester are quite possible.

Most papers have considered the design of the transient model of oxide pills [1-5], but this paper is focused on the electrostatic design of MOA. In MOA, the pills located at the bottom and the top of the resistor column are subject to more wear and early aging, because of the way they are located in the network and because of the concentration of electric field on them. In order to gain a uniform distribution of electric field, suitable size and geometry of different parts of the arrester, e.g. grading ring, spacer, FRP, etc. is needed. Paper [6] presents suitable location of spacers and grading ring in two 220 kV and 400 kV arresters. In [7] influence spacer numbers and grading ring design parameters on voltage distribution and leakage current analyzed in metal oxide surge arrester. Also in paper [8,9] reduced maximum electric field and improved voltage distribution of grading ring with grading ring parameters. In [10] several 230 kV insulator strings with different porcelain and glass units were simulated and their electric fields and voltage distributions were calculated and compared together, to investigate the effect of insulator types on these quantities.

The location and dimensions of grading ring is studied also we presented optimal design of grading ring [11]. Also we in

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[12] 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.

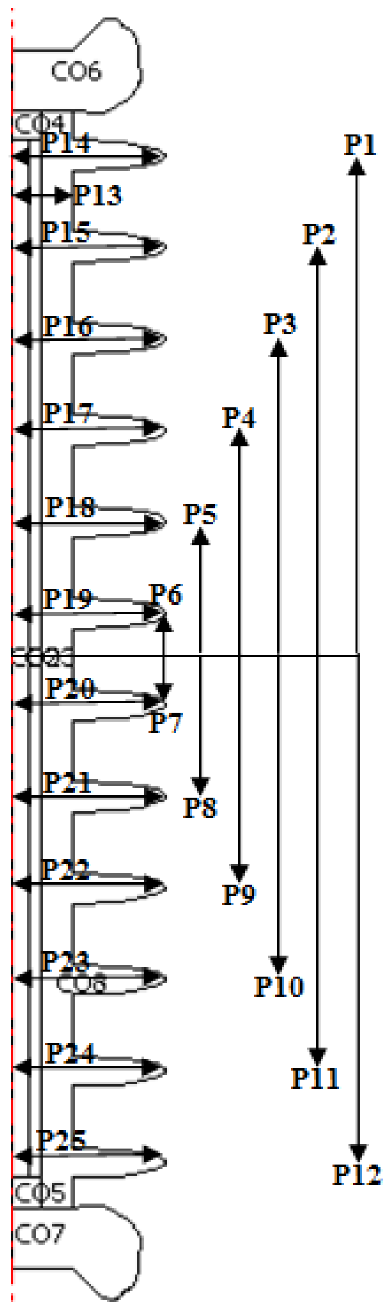

Fig. 1. 2-D cut model of MOA and the defined optimization parameters

The aim of this paper 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 geometry 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 [13]. Design parameters are P1 to P25 and are shown in Fig. 1 that P1-P12 and P14-P25 are length and thickness of porcelain housing sheds respectively, P13 is internal thickness of porcelain housing.

This optimization method represents a universal method of optimization for various objective functions related to the arrester. This approach, thus, is not only not limited to the purpose of optimizing 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. The optimization based on maximum electric field only caused volume of porcelain housing increase that for this reason, another objective function provided as volum of porcelain housing. Therefore Method of fuzzy multiobjective for solution of proposed problem.

Firstly, in this paper, model problem formulation of proposed method and constrains are presented. The second section provided computation method of electric field by COMSOL Multiphysics package and intelligent algorithms. In next part program description and constraints handling presented. Finally, the four and five parts the numerical results and conclutions expressed, respectively

II. Problem Formulation ‘s Model and Its Constraints

A. Objective Function

In this optimization problem, the aim is to obtain an electric field distribution on the surface of ZnO block. Intitially regarding to maximum electric filed as objective function, porcelain housing volume is increase. manufacturer requirement will satisfied ranging from economic and technical by increasing the volume. So, volume as second objective is considered. Goals not listed from a gender and they cann’t combined usually. Now problem is multiobjective that in this research used from fuzzy multiobjective for its solution which can be described as follows:

$$Objective \quad function = -\left(w_1 \cdot \vec{\mu}_{Etot} + w_2 \cdot \vec{\mu}_{Volume}\right) \tag{1}$$

Where w_1 and w_1 are non-negative weight factors and $w_1 + w_2 = 1$. $\vec{\mu}_{Etot}$ represents the value of membership function for minimization maximum electric field on ZnO column surface and $\vec{\mu}_{Volume}$ is the value of membership function to minimizing porcelain housing volume. Membership functions in following Fig. 2.:

$$\vec{\mu}_{Etot} = Exp\left(\frac{Etot_{\min} - Etot}{Etot_{\min}}\right) \tag{2}$$

$$\vec{\mu}_{Volume} = Exp\left(\frac{Volume_{\min} - Volume}{Volume_{\min}}\right) \tag{3}$$

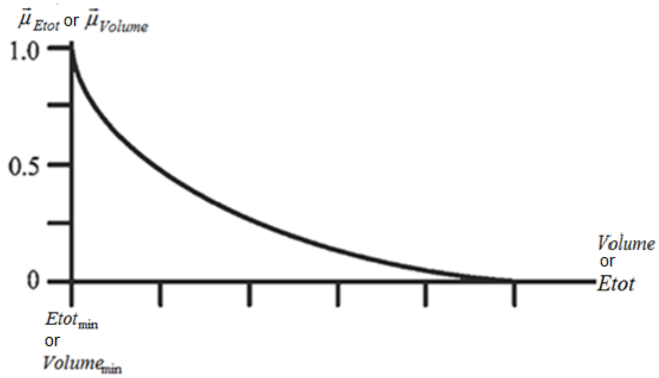

Fig. 2. Membership function diagram

B. *Constraints*

The constraint that must be considered in the process of arrester design is the dielectric strength of the insulation. Therefore, the maximum electric field on the external surface of the porcelain insulator must be less than the electric strength of the air, i.e. 2.4 kV/mm.

Two other constraints are related to the design variables and are as follows:

$$P1 + |P2| \leq 2400 \tag{4}$$

$$P_{\min} < P < P_{\max} \tag{5}$$

Relationship (4) shows the length of the arrester which should not exceed the limit and relationship (5) presents the range of each parameter. $P_{\min}$ and $P_{\max}$ are the lower and the upper limits of design parameters, respectively.

III. ELECTRIC FIELD CALCULATION AND OPTIMIZATION ALGORITHMS

A. *Electric Field Calculation*

Electric field calculation is done using COMSOL Multiphysics software package. The design process is such that in COMSOL field calculation, the geometry of arrester is implemented by initial random values which are produced by optimization algorithm in MATLAB. Then, the type of meshing and the study mode (here: electrostatic), boundary conditions, dielectric constants of different used materials are determined. Next, the type of differential equation consisting of 2-D finite element method is determined. After that, the file of the case study model is reviewed, and the basic parameters are corrected, if problems such as overlapping sub-domains are observed. A mesh is developed according to the finite element type and the meshing of the arrester is completed. The number of finite elements is different in each calculation stage based on the model's geometry for each production. Now with determined method, the static partial differential equation problem is solved by a linear or non-linear method. Finally, the outputs required, such as the total electric field, the electric potential, etc., can be recalled. The flowchart of the above steps is shown in Fig. 3.

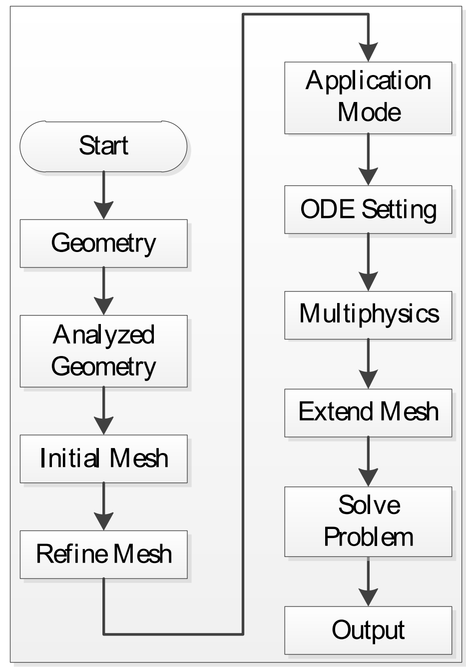

Fig. 3. The flowchart of COMSOL Multiphysics software s calculations

B. *Particle Swarm Optimization*

PSO is a population-based intelligent algorithm introduced by Eberhart and Kennedy [14]. Each particle in PSO is a candidate solution in multidimensional space of the problem. Candidate solutions have two main parts, current position (P_i) and current velocity (V_i), which are expressed by:

$$\begin{aligned} P_i &= \left(p_i^1, p_i^2, \ldots, p_i^{ns}\right) \\ V_i &= \left(v_i^1, v_i^2, \ldots, v_i^{ns}\right) \end{aligned}, \tag{6}$$

where ns is the dimension of the problem and i is the iteration index. The new position of each particle is created by its current position and new velocity. New velocity is produced by four factors, the current velocity and position, the particle's best position (*PBest*), and the best position among all of particles in all iterations (*GBest*). Therefore, new velocity is obtained as follows:

$$V_{i+1} = wV_i + r_1 \cdot (PBest_i - P_i) + r2 \cdot (GBest - P_i) \tag{7}$$

where ω is the particle inertia coefficient, r_1 and r_2 are random numbers between 0 and 1, respectively. The new position of the particle is obtained by:

$$P_{i+1} = P_{i+1} + V_{i+1}. \quad (8)$$

The process is continued until convergence criteria are met.

C. Differential Evolution algorithm

Original DE algorithm is a simple population based evolutionary computational algorithm for global optimization .It is one of the accurate and fast meta-heuristic optimization algorithms that was introduced in 1995s by Price and Storn [15]. This evolutionary algorithm begins the search process by initial random population. DE includes three main operators, namely, mutation, crossover, and selection. Also, it has three control parameter, namely, population size (*np*), scaling coefficient (*F*), and crossover probability (*CR*). In the subsequent sections, the implementation details of the DE are described [16].

1) Initialization: The DE algorithm searches in parallel using a group of members similar to the other evolutionary based heuristic optimization techniques. Each member corresponds to a candidate solution to the problem. In an *n*-dimensional search space, the structure of member *k* is represented as vector $X_k = (x_{k,1}, x_{k,2}, \cdots, x_{k,n})$ where the dimension represents the number of components. In the first stage of the DE optimization process, initial population contains *np* members should be created randomly.

2) Mutation: After the population is initialized, the operators of mutation, crossover and selection create the population of the next generation. At the generation *t*, the process for creation of a mutant solution (Y_k) for each parent (X_k) in the population can be expressed as follows:

$$Y_k(t) = X_{r3}(t) + F \cdot (X_{r1}(t) - X_{r2}(t)) \ , \quad k = 1, 2, \cdots, np \quad (9)$$

where vector indices *r*1, *r*2, and *r*3 are randomly chosen, which $r1, r2, \text{and } r3 \in \{1, \ldots, np\}$ and $r1 \neq r2 \neq r3 \neq k$. X_{r1}, X_{r2}, and X_{r3} are selected members for each parent vector. *F* is a user-defined constant known as the 'scaling factor', which is a positive and real number. The usual choice for *F* is a number between 0 and 1.

3) Crossover: In order to increase the diversity of the population, the crossover process is employed. At the generation *t*, the crossover operator creates a new solution (child) (Z_k) using each parent (X_k) and its related mutant vectors (Y_k) as follows:

$$z_{kj}(t) = \begin{cases} y_{kj}(t) & \text{if } rand \le CR \text{ or } j = jrand \\ x_{kj}(t) & \text{otherwise} \end{cases}, \quad \text{for } j = 1, \ldots, n \quad (10)$$

where *CR* is 'crossover probability' which is a user-defined value usually selected from within the range [0, 1]. *CR* controls the diversity of the population and helps the algorithm to escape from local optima. *rand* is a uniformly distributed random number within the range (0, 1) generated a new for each component *j*. Here, $jrand \in [1, 2, \ldots, n]$ and ensures that the trial vector gets at least one parameter from the mutant vector.

4) Selection: To keep the population size constant over subsequent generations, the selection operator is applied to determine which one of the child and the parent will survive in the next generation. This operator compares the fitness of the parent and the corresponding child and the fitter of the two solutions is then allowed to advance into the next generation. The selection process can be expressed as,

$$X_k(t+1) = \begin{cases} Z_k(t) & FIT(X_k(t)) \ge FIT(Z_k(t)) \\ X_k(t) & \text{otherwise} \end{cases} \quad (11)$$

where $FIT(.)$ is the fitness function.

5) Stopping Criteria: The overall optimization process is terminated if the iteration approaches to the predefined maximum iteration or other predetermined convergence criterion is satisfied.

IV. Program Description and Model Evaluation

A. Program Steps

Each particle in PSO or each solution in the initial population of DE is a candidate for final solution of the problem. Program steps are as follows:

Step 1: Initializing the population

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

P1	P2	P3	…	P25

Step 2: Evaluating the initial population by COMSOL Multiphysics software package

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. 4. In this proposed method, the initial contour parameters are generated by PSO nad DE and the model of the generated design is simulated in COMSOL Multiphysics environment. The calculated components of the electric field and the required quantities for calculation of objective function are sent to PSO and DE. By having the previous and updated calculated parameters, the parameters of next step are generated by this optimization algorithms. This procedure continues until it converges to an optimal contour which its conditions for different parts of the Surge arrester will be discussed in the following section.

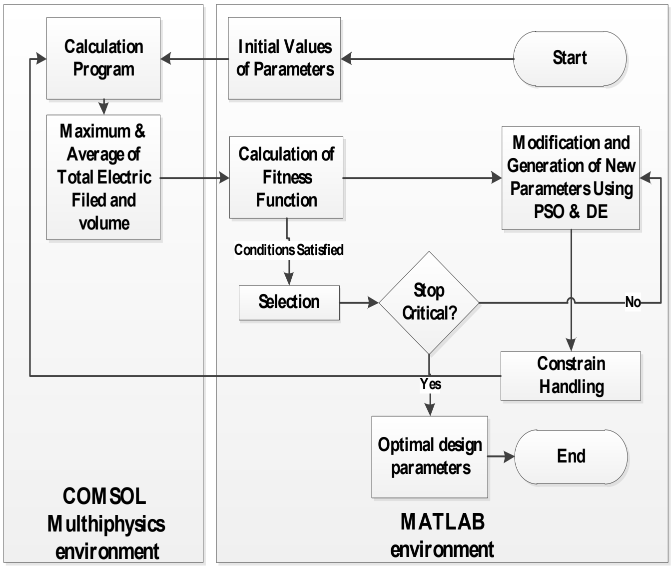

Fig. 4. The flowchart of a 220 kV MOA design

B. Constraint Handling

P1 is created randomly and P12 is generated according to P1 (equation 12) for satisfying the maximum MOA length.

$$P12 = rand(P1, 2.4) \tag{12}$$

Also, for satisfying equation (12), the solutions which violate the up/down bounds are 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.

V. NUMRICAL RESULTS

A. The Studied System

Simulation of the design of a sample arrester has been done to show the abilities of the proposed method. The studied arrester is a 220 kV ZnO arrester, the data of which are presented in [17]. Also, dielectric constants of different domains of the arrester are presented in Table 1. All of the electric field values are based on a one per unit applied voltage. In this paper weight factor values intented for two states that as following:

$$\begin{aligned} &case1: \; w_1 = w_2 = 0.5 \\ &case2: \; w_1 = 0.7, w_2 = 0.3 \end{aligned} \tag{13}$$

TABLE I

RELATIVE PERMITTIVITY OF MOA 'S VARIOUS PARTS

domain	ZnO block	Porcelain housing	Spacer
ε_r	150	3.6	10^3
domain	FRP	Electrodes	Grading ring
ε_r	4.6	10^6	10^3

Initial values of design parameters, the defined range of variation for them and the optimum values of PSO and DE algorithms for each of them with a population (NP) of 150 and 200 iterations are shown in Table 2. According to Table 2, sufficient and permissible domains exist for search algorithms to achieve the absolute optimum.

TABLE 2

OPTIMIZED VALUES OF DESIGN PARAMETERS FOR DE AND PSO

Par.	In.	Min	Max	Optim. DE		Optim. PSO	
				Case1	Case2	Case1	Case2
P1	0.82	0.73	0.85	0.82	0.82	0.73	0.73
P2	0.62	0.59	0.70	0.59	0.60	0.70	0.59
P3	0.52	0.45	0.56	0.48	0.53	0.52	0.52
P4	0.37	0.30	0.42	0.41	0.36	0.30	0.31
P5	0.22	0.16	0.27	0.19	0.22	0.16	0.17
P6	0.07	0.02	0.13	0.02	0.13	0.13	0.13
P7	-0.07	-0.13	-0.02	-0.12	0.07	-0.02	-0.02
P8	-0.22	-0.27	-0.16	-0.17	0.27	-0.16	-0.16
P9	-0.37	-0.42	-0.30	-0.39	0.40	-0.42	-0.41
P10	-0.52	-0.56	-0.45	-0.48	0.49	-0.60	-0.45
P11	-0.62	-0.70	-0.59	-0.59	0.62	-0.62	-0.70
P12	-0.82	-0.85	-0.73	-0.73	0.83	-0.85	-0.77
P13	0.10	0.06	0.12	0.06	0.06	0.06	0.09
P14	0.30	0.07	0.20	0.08	0.08	0.08	0.12
P15	0.30	0.07	0.20	0.08	0.08	0.08	0.12
P16	0.30	0.07	0.20	0.08	0.08	0.08	0.12
P17	0.30	0.07	0.20	0.08	0.08	0.08	0.12
P18	0.30	0.07	0.20	0.08	0.08	0.08	0.20
P19	0.30	0.07	0.20	0.08	0.08	0.08	0.12
P20	0.30	0.07	0.20	0.08	0.08	0.08	0.19
P21	0.30	0.07	0.20	0.08	0.08	0.08	0.12
P22	0.30	0.07	0.20	0.08	0.08	0.08	0.12
P23	0.30	0.07	0.20	0.08	0.08	0.08	0.20
P24	0.30	0.07	0.20	0.08	0.08	0.08	0.12
P25	0.30	0.07	0.20	0.08	0.08	0.08	0.12

Results simulation of fuzzy multiobjective presented in Table 3. Objective function values compared for case1 and case2 and DE and PSO algorithms. Values maximum electric field on ZnO column surface and volume of porcelain housing provided in four modes. As shown, DE algorithm reached suitable optimal solution than PSO algorithm.

Fig. 5 is showing Convergence diagram of fuzzy multiobjective of DE algorithm for case1 and case2. Also Convergence diagram of PSO is providing in Fig. 7.

TABLE 3

COMPARE FAZZY MULTIOBJECTIVE OF PSO AND DE VALUES FOR TWO CASE

Algorithm Type		Objective function	Electrical field	Volume
DE	Case1	-0.96	1.03	0.07
	Case2	-0.95	1.03	0.08
PSO	Case1	-0.97	1.07	0.06
	Case2	-0.64	1.07	0.73

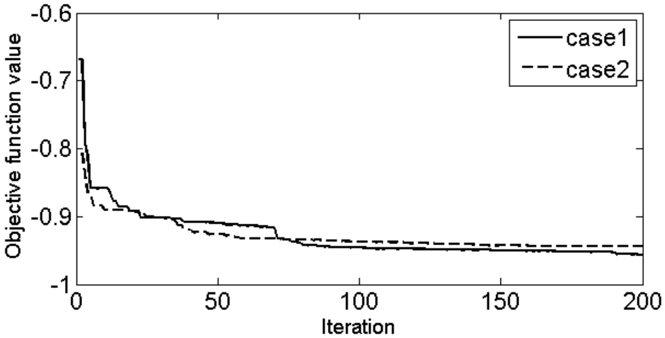

Fig.5. Fuzzy multiobjective convergence characteristics of DE for case1 and case2

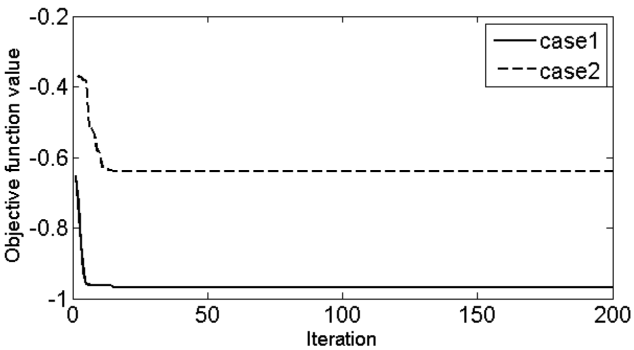

Fig.6. Fuzzy multhiobjective convergence characteristics of PSO for case1 and case2

TABLE 4

RESULTS OF ELECTRIC FIELD QUANTITY BEFORE AND AFTER DESIGNING

Electric field	initial	DE	PSO
Maximum	1.0089	0.9459	0.9618
Minimum	0.4099	0.4282	0.4255
Average	0.6129	0.6067	0.6072

According to Table 4, values of maximum, minimum and average of electric field on ZnO column surface compared before and after optimal designin. The maximum of electric field on the ZnO pills with the initial parameters is equal to 1.0089 per-unit and the optimization with NP=100, F=0.3 and CR=1 for DE algorithm and NP=100, C1=0.9 and C2=0.9 for PSO algorithm leads to 0.9459 and 0.9618 per-unit, respectively. With this design approach, the premature wear of the tablets which are exposed to electric field concentration can be avoided. Electric field contour of the ZnO pills surface compared before and after the designin in Fig. 7.

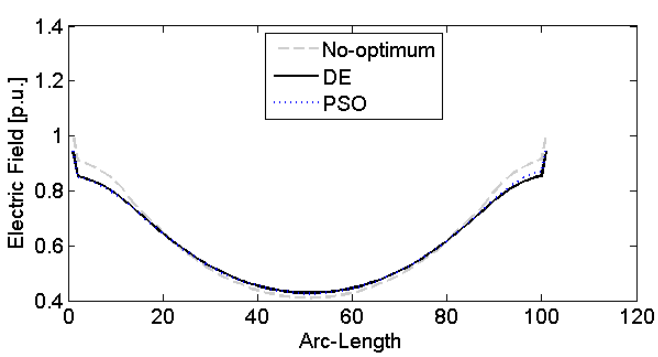

Fig. 7: Electric field contour of the surface of ZnO block for initial parameters and with DE and PSO optimizations

VI. CONCLUSIONS

This paper has presented a fuzzy multiobjective model and DE and PSO algorithms to prevention of premature aging of ZnO pills column. This formulation incorporates two objectives: minimization of maximum of electric field on ZnO column surface and minimization of porcelain housing volume. Based on problem designing considerations, fuzzy membership functions related to the objectives are proposed. As result, the information provided by the multiobjective model has been shown to be more useful than the traditional single objective optimal solutions.

In this paper, the optimal design of the surge arrester regarding the field distribution on the zinc oxide pills column, using PSO and DE algorithms is studied. The simultaneous use of geometry parameters display, producing a newly developed mesh, numerical calculation methods with the help of finite element analysis and intelligent algorithms is found to be reliable. Also, the major the major task in the arrester's design is its optimization process. Regarding the studied test system, 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.

We obtain a more uniform distribution of electric field by applying this method.

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