Electric Field Modeling of Plate-Type Electrostatic Separators Using Optimum Charge Simulation Method

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***Abstract*- A novel combination of genetic algorithms (GA) and the charge simulation method (CSM) is proposed for enhancing the computation precision of electric fields associated with plate-type electrostatic separators; a new recycling technology of electrical and electronics waste. An algorithm is developed to, automatically, arrive at optimal arrangement of the simulating charges and their locations in order to eliminate dependency on the user judgment and experience. Accurate results for the electric field computation, compared with earlier published techniques, are realized for several design parameters of the separator. Experiments carried out for determination of detachment fields of small metallic particles (steel spheres of radius, r_p, 0.501 mm) confirmed the validity of the numerical simulation. The present work shows that the coupled GA-CSM algorithm can be an efficient and flexible design tool for accurate field computations of the electrostatic separation equipment.**

I. Introduction

The principle of the charge simulation method (CSM) is easy to implement and suitable for potential and field solutions of open boundary problems [1- 7]. The method, simply, computes the simulating charge magnitudes by satisfying the boundary conditions at a selected number of contour points along the electrodes surfaces. The basic equations of CSM for given boundary conditions are

$$[P]\,[Q] = [V] \tag{1}$$
$$[F_X][Q] = [E_X] \tag{2}$$
$$[F_Y][Q] = [E_Y] \tag{3}$$

Where [P] is the potential coefficient matrix, [Q] is the column vector of unknown charges; [V] is the column vector of known potentials at the contour points. $[F_X]$ and $[F_Y]$ are the electric field intensity coefficients between the simulation charges and the electric field intensity components at the point where the electric field intensity is required in a Cartesian coordinate system. $[E_X]$ and $[E_Y]$ are the components of the electric field intensity at the same point. Given a particular configuration, the coefficients [P] will be determined by the location of the charges and the contour points. Once Eq.(1) is solved for the values of the simulating charges, then it will be used again to calculate the potentials at a set of check points such that a pre-specified accuracy criteria is satisfied. Eqns. (2) and (3) can then be used to calculate the electric field intensity, analytically, at any given point.

As CSM accuracy depends on the values and locations of the simulating charges, the CSM programs for a particular application become case specific and depend on experience and judgment of the user. Appropriate arrangements of fictitious charges and contour points are indispensable to obtain accurate solutions and several optimization methods were proposed to deal with these considerations [4, 5]. In fact, the arrangement of the simulation charges and contour points, both efficiently and accurately, may take hours of computational time to reach a reasonable accuracy [6, 7]. It is necessary to, further, investigate more efficient automatic arrangement methods of the simulating charges and assess the solution accuracy.

Plate-type electrostatic separator is a new environmental-friendly technology for the recycling of electrical and electronics equipment waste known as E-Waste [8, 9]. The optimum operation of these separators can be achieved only by appropriate design of the electrode system [8, 9]. Several design parameters are of importance in this regard including: the slope and length of the high-voltage electrode and the gap distance. Numerical computation and analysis of the electric field for different configurations is a vital tool for the design and development of these separators [10-13].

The study presents an algorithm that couples genetic algorithms and the charge simulation method in order to, automatically, determine the optimal locations and values of simulating charges in the CSM. Within each GA generation, a call is made to the CSM to obtain the positions and values of the simulating charges. The GA then modifies these variables such that the accumulated square error (ASE) of the potential values along the high voltage electrode is minimized. The algorithm was developed in the MATLAB environment. The effectiveness of the algorithm is demonstrated for electric field computations of plate-type electrostatic separators. The results of the numerical computations were confirmed by experiments for determination of the detachment field of small metallic particles (steel spheres of radius, r_p, 0.501 mm) from the plate for different design parameters. The present work shows that the coupled GA-CSM algorithm can be an efficient design tool for accurate field computations of the electrostatic separation equipment and can serve as the basis for the design of a laboratory plate-type electrostatic separator.

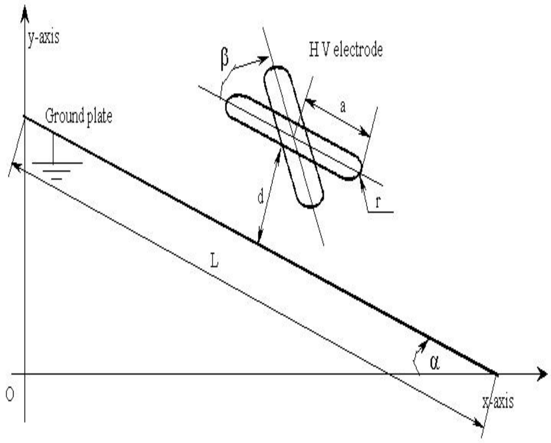


Figure 1 Electrode arrangement of a plate-type electrostatic separator.

II. METHOD OF ANALYSIS

The electrode configuration of the separator under study is presented in 2-D coordinates in Fig. 1. The high voltage electrode has a tubular-profile with length 2a, rotation angle β, radius r and gap distance d from the ground plate. The ground plate has length l and inclination angle $\alpha=60^o$. The electrode potential is 1 p.u. Figure 2 shows the arrangement of the simulating charges inside the electrode with the image effect taken to simulate the ground plate. The simulating charges are placed inside the electrode on a hypothetical surface parallel to the electrode surface as shown in Fig.3. Three optimization parameters C_1, C_2, C_3 are considered as shown in Fig.3.

An algorithm which couples genetic algorithms and the charge simulation method is developed, in the MATLAB environment, in order to determine the optimal values of the optimization parameters such that the accumulated square error (ASE) of the potential values along the electrode surface is minimized.

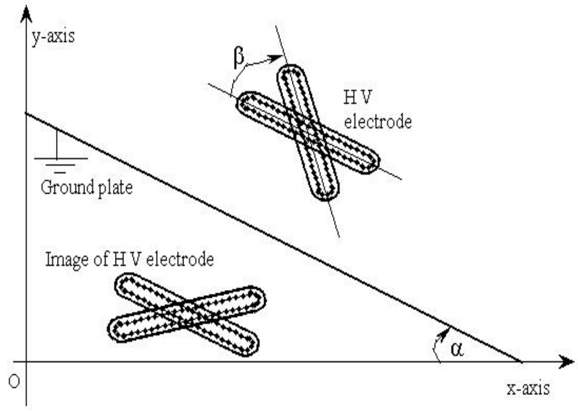


Figure 2 The CSM representation of the electrode system and its image.

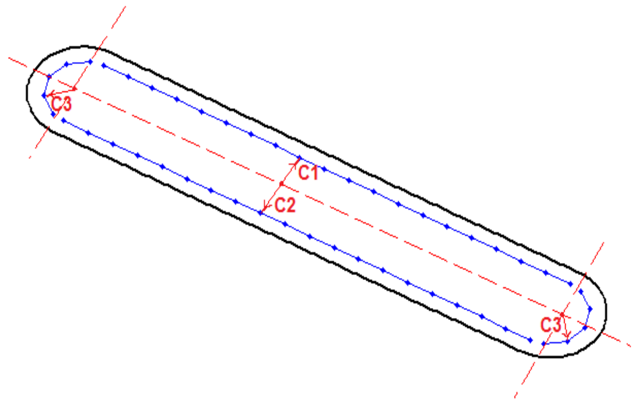


Figure 3 The optimization parameters (C_1, C_2, C_3) for the arrangement of the simulating charges in the CSM.

The ASE is obtained by evaluating errors at N_h check points uniformly distributed along the surface of the electrode. The objective function, FF, (fitness function); thus, has the form:

$$FF = \sum_{j=1}^{Nh} \left[V - v_j\right]^2 \tag{4}$$

Where V is the electrode voltage (1 p.u), v_j is the potential obtained by the CSM at the check point j, and N_h is the total number of check points.

In the present genetic algorithm, the bit sequences of the individuals of the ''0th generation'' and the initial conditions are created by using uniform random numbers. The calculations are terminated when a pre-specified number of generations is reached. Details of GA operations and implementations are given in [14-16]. The sequence of the proposed GA-CSM algorithm is as follows:

1. Determine the domain for the optimization parameters.
2. GA generates initial uniform random values for C_1, C_2, C_3.
3. For each call to the CSM routine by GA, the CSM will produce the ASE error for this set of optimization parameters.
4. The GA will then evaluate the fitness function and modify the optimization parameters to minimize the ASE error.
5. Steps 3-4 are repeated for a prespecified number of generations.

III. EXPERIMENTAL PROCEDURE

An experimental model is set up to simulate a plate-type electrostatic separator as shown in Fig.4. A Hipotronics dc high voltage supply model 800pl- 10mA, 0-80kV is used. The high voltage electrode, made of stainless steel, has a tubular profile of length 150 mm and end radius 13 mm. The grounded electrode is a metal plate of length 380mm and width 350 mm. The electrode can be inclined at an angle between 0-30^o with respect to the horizontal plane. The set up is used to measure the detachment voltages of small metallic particles and compare with the corresponding computed values in order to validate the numerical procedure described above. The particles used are steel spheres of average radius, r_p, 0.501 mm and average mass 3.75 mg. The gap between the electrodes was d = 35 mm with α =0 and β = 0. Particles were positioned at x = 120 mm and x = 190 mm on the surface of the plate, in contact with which they charge by conductive induction. Another set of experiments was carried out for α =0 and β = 15^o where the particles were positioned at x = 190 mm and x = 240 mm. The voltage applied to the electrode system was progressively increased at a rate of 1 kV s^{-1} until the particles detach from the plate. The detachment voltage U_{dexp} was read on an electrostatic voltmeter and compared with the predicted numerical value U_{dnum} which is determined as follows [10]:

$$U_{dnum}(x) = (E_d / E_{num}(x))U_{num} \qquad (5)$$

where $E_{num}(x)$ is the computed electric field strength at point x, for the applied voltage U_{num} , and the detachment field strength E_d is evaluated from; [10],

$$E_d = 0.241(1/r_p)\,[(m\,g/\varepsilon)\cos\alpha]^{1/2} \qquad (6)$$

For the case when the plate electrode is horizontal, i.e. α = 0, the detachment electric field strength becomes

$$E_d = 0.241(1/r_p)\,[(m\,g/\varepsilon)\,]^{1/2} \qquad (7)$$

where m is the mass of the particle, g = 9.81 ms^{-2}, ε being the permittivity of air and α is the local slope of the inclined plate.

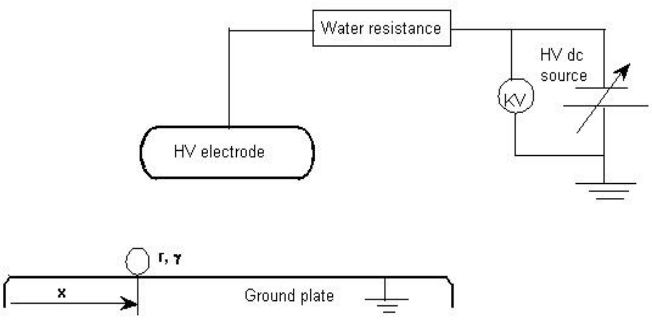


Figure 4 Schematic representation of the experimental set-up.

Table 1 CSM and GA Parameters

Number of optimization variables (C1, C2, C3)	3
Total Number of simulating line charges (N_t)	50
Total Number of contour points (N_c)	50
Total Number of check points (N_h)	200
Voltage of HV electrode (p.u.)	1
Number of bits per variable (N_2) (bits)	14
Population size	4
Mutation rate	0.20
Number of generations N_g	500
Range for C1	0.01r- 0.9r
Range for C2	0.01r- 0.9r
Range or C3	00.01r- 0.9r
Using roulette wheel selection and single point crossover.	

IV. RESULTS AND DISCUSSION

Employing the data given in Table 1, the computations are carried out using the developed algorithm for a separator model with dimensions l = 0.380m, a = 0.075m, r = 0.013m, α = 60^o, β = 30^o. Figure 5 shows the convergence of the fitness function for d=a/2 and β = 0 in one case and β = 30^o in another. The algorithm works its way smoothly into convergence in both cases. Faster and better convergence is observed for the case β = 0 than β = 30^o which may be due to the highly non uniform field distribution in the latter case. For β = 0, the optimal values of the three parameters C1, C2, C3 were found to be 0.414, 0.419, 0.543r and for β = 30^o these values were 0.137, 0.519, 0.513r respectively. Influence of varying the mutation rate on convergence is shown in Fig. 6 where a value of 0.2 provided the best convergence in this case. Two selection methods were considered; roulette wheel selection and tournament selection [16] and both produced similar results after about 50 generations as shown in Fig. 7. Figure 8 shows the computed potential errors, upon convergence, to be less than 0.08%. Relatively larger errors occurred at and close to the electrode rounded edges (points 80 to 100 and points 180 to 200) while lesser errors occurred along the flat parts of the electrode. A contour potential plot in the gap is shown in Fig.9.

The variation of the electric field strength at the surface of the plate for β=0, and various gap distance d, is presented in Fig. 10. As d decreases higher electric field strength is realized; however the active region, zone where the electric field is approximately uniform, decreases. For a fixed d, the distribution of the electric field strength varies with the electrode angle as shown in Fig. 11. Accurate field modulation, both magnitude and shape, is useful for the detachment of larger and heavier particles [10]. The influence of the electrode length is shown in Fig.12. It extends the uniform field zone more significantly as the gap distance d gets smaller as shown in Fig12b. However, in Fig12a, it allows more selectivity along the rising and falling parts of the distribution; which may be needed for some particles of closer sizes and/or masses [10]. These distributions are found to be in good agreement when compared with those obtained earlier using the boundary element method [10], which further confirms the accuracy of the developed GA-CSM algorithm.

The measured detachment voltages U_{dexp} for the two sets of measurements are given in Tables 2&3 for β=0 and β= 15^o respectively. The results are the average of 10 experiments with the range of the measured values between brackets.

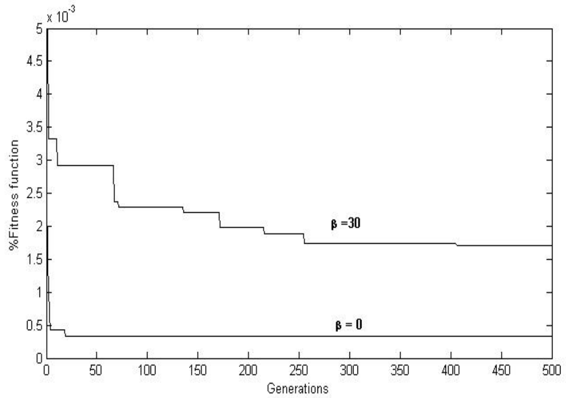


Figure 5 Convergence of the fitness function for β= 0, β = 30^{o}.

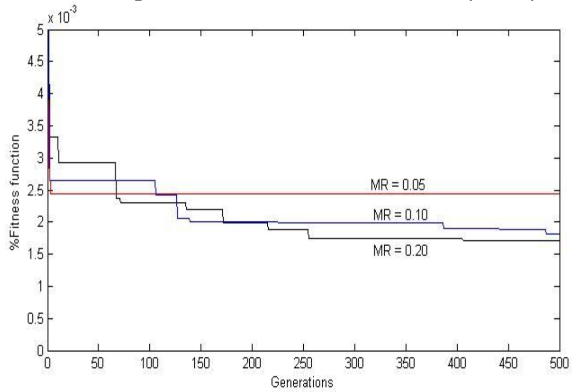


Figure 6 Influence of varying mutation rate on convergence.

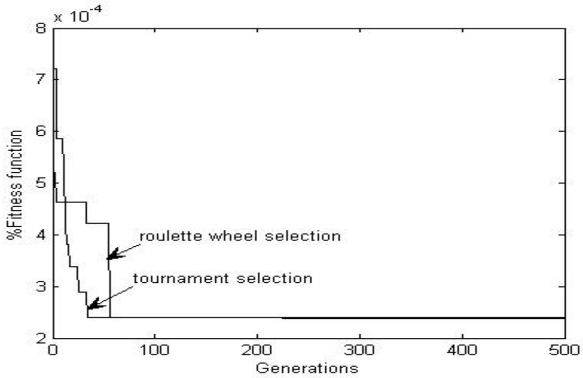


Figure 7 Influence of the selection method on convergence.

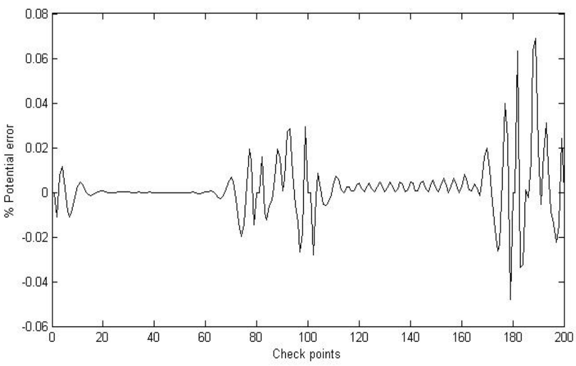


Figure 8 Percentage potential errors at the check points for d= (3/4)a , α = 60^{0}, β = 30^{0} .

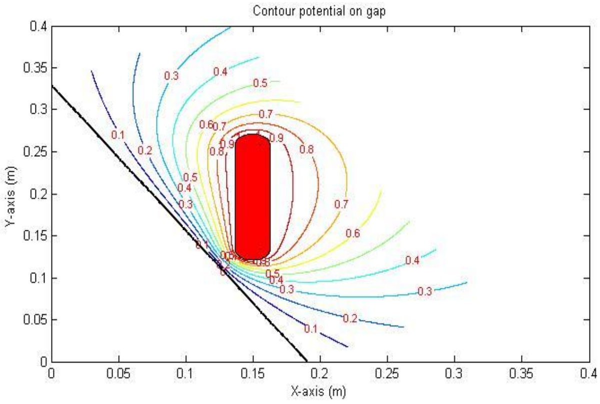


Figure 9 Equipotential contours for d = (2/3)a, α = 60^{0}, β = 30^{o}

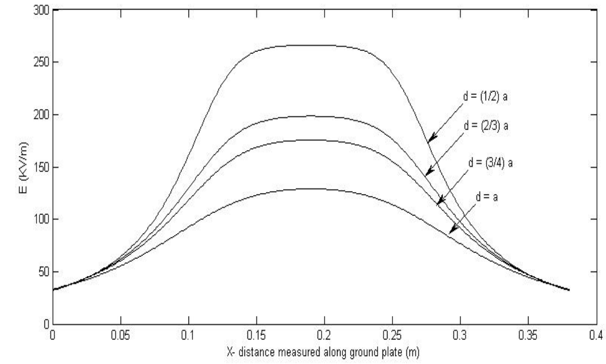


Figure 10 Variation of the electric field along the plate, for α = 60^{o}, β = 0, U = 10 kV for various gap distance d.

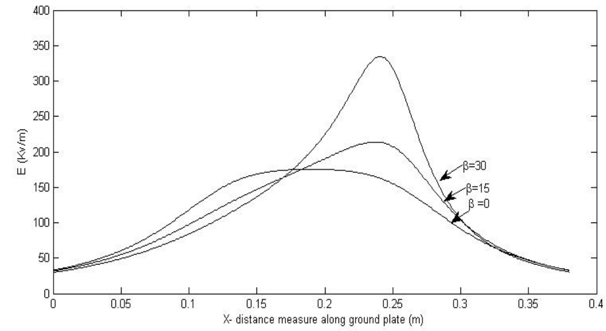
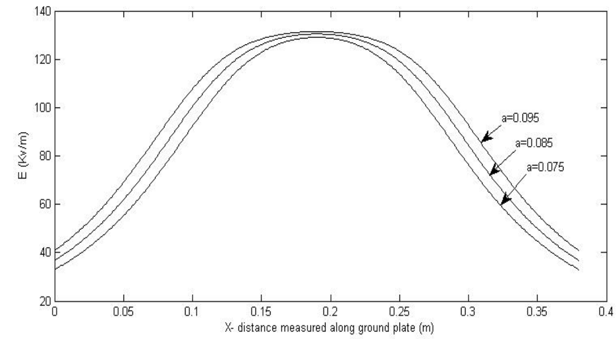
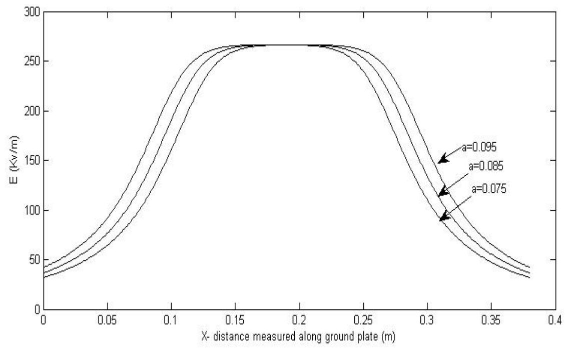


Figure 11 Variation of the electric field along the plate, for α = 60^{o}, d = (3/4) a, U = 10 kV for various electrode angle β.



(a) d = 0.075m



(b) d = 0.0375m

Figure 12 Variation of the electric field along the plate, for $\alpha = 60^0$, $\beta = 0$,U = 10 kV for various electrode lengths a.

The results are in good agreement with the computed predictions. The errors were relatively higher for experiments with $\beta = 15^o$ probably due to a slight imprecision in the positions of the particles, the electrode inclination angle and/or in the determination of the average mass employed for the computation of the detachment voltage U_d. Nevertheless, the results demonstrate the effectiveness of the proposed numerical algorithm in accurate modeling of the electric fields of the plate type electrostatic separators; in predicting the detachment voltage of metallic particles at different positions on the plate and for different inclination angles of the electrode.

Table 2 Comparison between experimental U_{dexp} and predicted U_{dnum} detachment voltages for $\alpha = \beta = 0$ and d =35 mm.

	Position x	
	120 mm	190 mm
U_{dexp} (kV)	43.1(40-47)	33.2(30-36)
U_{dnum} (kV)	42.2823	34.3431
Error (%)	1.94	3.32

Table 3 Comparison between experimental U_{dexp} and predicted U_{dnum} detachment voltages for $\alpha = 0$, $\beta = 15^o$ and d =35 mm.

	Position x	
	190 mm	240 mm
U_{dexp} (kV)	32.1(30-35)	22.2(19-24)
U_{dnum} (kV)	33.2473	21.3445
Error (%)	3.43	4.03

VI. CONCLUSIONS

A new approach to the optimization of the charge simulation method using genetic algorithms has been presented. The proposed algorithm offers flexibility and accuracy for determination of the optimal locations of simulating charges and their magnitudes. Accurate results are achieved for several design parameters of the plate-type electrostatic separator including: the slope and length of the high-voltage electrode and the gap distance. Comparison with previously published techniques also confirmed the adequacy of the present approach. A simplified experimental set up was constructed to model a laboratory type separator and results for the detachment voltages of small spherical particles compared well with those computed using the proposed algorithm. The present work shows that the GA can be a useful tool to, automatically, determine the appropriate arrangement of fictitious charges of the charge simulation method for accurate field computations of plate type electrostatic separators. The approach is general and can be extended to other electrostatic equipment configurations.

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