OPTIMIZATION DESIGN OF HIGH VOLTAGE SUBSTATION GROUND GRID BY USING PSO & HS ALGORITHMS

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Abstract: *this paper presents methods for optimization of substation ground grid. the parameters, rules & restrictions for design of substation ground grid according to IEEE80 standards described, authors write a program in MTLAB to design the substation ground grid according to standard and develop this program by adding a cost objective function to minimize and customize design. Two optimization algorithms described and used for this purpose, particle swarm optimization (PSO) and harmony search algorithm (HS).A real example used to compare the effect of using these algorithms.*

Keywords: *Substation Ground Grid; PSO Algorithms; HS Algorithms; Optimization*

ABBREVIATIONS

In table.1 all abbreviations that are used in this article are clarified.

TABLE 1.
ABBREVIATIONS

Symbol	Description	Symbol	Description
ρ	Soil resistivity, Ω·m	L_c	Total length of grid conductor, m
ρ_s	Surface layer resistivity, Ω·m	L_M	Effective length of $Lc + LR$ for mesh voltage,m
$3I_0$	Symmetrical fault current in substation for conductor sizing, A	L_R	Total length of ground rods, m
A	Total area enclosed by ground grid, m²	L_r	Length of ground rod at each location, m
C_S	Surface layer derating factor	L_S	Effective length of $Lc + LR$ for step voltage, m
d	Diameter of grid conductor, m	L_T	Total effective length of grounding system conductor, including grid and ground rods, m
D	Spacing between parallel conductors, m	L_x	Maximum length of grid conductor in x direction, m
D_f	Decrement factor for determining *IG*	L_y	Maximum length of grid conductors in y direction, m
D_m	Maximum distance between any two points on the grid, m	n	Geometric factor composed of factors *na*, *nb*, *nc*, and *nd*
E_m	Mesh voltage at the center of the corner mesh for the simplified method, V	n_R	Number of rods placed in area A
E_s	Step voltage between a point above the outer corner of the grid and a point 1 m diagonally outside the grid for the simplified method, V	R_g	Resistance of grounding system, Ω
E_{step50}	Tolerable step voltage for human with 50 kg body weight, V	S_f	Fault current division factor (split factor)
E_{step70}	Tolerable step voltage for human with 70 kg body weight, V	t_c	Duration of fault current for sizing ground conductor, s
$E_{touch50}$	Tolerable touch voltage for human with 50 kg body weight, V	t_f	Duration of fault current for determining decrement factor, s
$E_{touch50}$	Tolerable touch voltage for human with 70 kg body weight, V	t_s	Duration of shock for determining allowable body current, s
h	Depth of ground grid conductors, m	$CO1$	Cost of one meter of conductor ($/m.mm²)
h_s	Surface layer thickness, m	$CO2$	Cost of burring in depth one meter of conductor in ($/m.m)
I_G	Maximum grid current that flows between ground grid and surrounding earth (including dc offset), A	$CO3$	Cost of weld for one junction ($)
I_g	Symmetrical grid current, A	$CO4$	Cost of each rod ($)
K	Reflection factor between different	K_{ii}	Corrective weighting factor that adjusts for the

	resistivities		effects of inner conductors on the corner mesh, simplified method
K_h	Corrective weighting factor that emphasizes the effects of grid depth, simplified method	K_m	Spacing factor for mesh voltage, simplified method
K_i	Correction factor for grid geometry, simplified method	K_s	Spacing factor for step voltage, simplified method

1. INTRODUCTION

Many researchers are used different search algorithms and technical software for solving power system problems [1-9]. The ground system is one of main parts of power electric systems. Power networks designers follow two main idea in their designing, first continuity in power electricity flows to consumers and second make a safe zone for consumers and staffs from power plants to the last point of power network in using electricity. One of items that helps designer to achieve this goals is proper design of earthing and grounding grid systems. In generally design of erthing systems follow safety for people and safety for equipment.

Role of earthing system in working electrical equipment is very important. The earthing system makes a condition that when a fault or short circuit occurred, the fault current leaded to ground and the equipment remain safe.

A Substation is one of main parts of power network and also ground grid is one of main part of substations too. So the design of substation ground grid is very important. For designing earthing systems, IEEE published IEEE80 standard [10]. Nowadays it is main reference of this designing. In this standard all descriptions and general methods of earthing design is described that in this paper some of them is mentioned too.

Various papers are written in case of earthing or ground grid of substations. In some papers effect of two or more layers of soil is studied [11-14]. In some other papers the effect of some parameters in improvement of grounding system specification are studied for example the effect of number of rods [15-16]. In the pass of time in studies and papers noticed to optimization of earthing systems in several ways. Variable space technique was a good method to design grounding grid systems of substations [17-19] that we will consider it too. This techniques generally are based on trial and error methods. After a while in last decade of 20 century new smart optimization and heuristic methods were studied and used for erthing system design like genetic algorithm [20-22] particle swarm optimization [23-28] and other optimization methods [29-31]. In this paper try to introduce another heuristic method as Harmony search algorithm and compare its ability with PSO and space variable techniques.

In design of substations minimizing the cost is very important so in this paper an objective cost function will be defined and will be optimized.

The steps and procedures that will be followed in this paper is as below:

1- Define a real constructed ground grid of a big substation
2- Re calculate and re design this system according to IEEE80 standard.
3- Program a MTLAB code to calculate grounding grid of substation by variable space technique.
4- Define an objective cost function to be optimized
5- Describe the PSO algorithm and flowchart and program a MATLAB code to optimize objective cost function.
6- Describe the HS algorithm and flowchart and program a MATLAB code to optimize objective cost function.
7- Compare the results of each step with main substation and select the best method.

2. CONVENTIONAL OPTIMIZATION METHOD

2.1. Variable Space Technique

Design of grounding grid system of power substation is described here, the sequence of design stage is according to IEEE80 standard, so the parameters are identified table 1, variable space technique is a trial and error procedure, and this procedure could be divided in 12 stages:

- **Stage 1:** The property map and general location plan of the substation and area to be grounded, soil resistivity should be specified.

- **Stage 2:** Size the earthing grid conductor. The fault current $3I_0$ should be the maximum expected future fault current that will be conducted by any conductor in the grounding system, and the time, *tc*, should reflect the maximum possible clearing time (including backup).

$$I_f = 3I_0 = 3\frac{I_{3\phi}}{2+\frac{x_0}{x_1}} \qquad (1)$$

$$A_{\min} = 0.5I_f \times \sqrt{\frac{10000t_c \times a_r \times \rho_r}{TCAP \times Ln(1+\frac{T_{m(mesh)} - T_a}{T_a + K_0})}} \qquad (2)$$

- **Stage 3:** The tolerable touch and step voltages should be determined.

$$E_{touch-70} = (1000 + 1.5C_s\rho_s)\frac{0.157}{\sqrt{t_s}} \qquad (3)$$

$$E_{step-70} = (1000 + 6C_s\rho_s)\frac{0.157}{\sqrt{t_s}} \qquad (4)$$

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \quad (5)$$

- Stage 4: The preliminary estimation will be done and the conductor loop, number of rods and locations, initial estimates of conductor spacing based on the current *IG* will be specified.

- Stage 5: Calculation of the preliminary resistance of the grounding system in uniform soil:

$$Rg = \frac{R_1 R_2 - R_m^2}{R_1 + R_2 - 2R_m} \quad (6)$$

$$R_1 = \frac{\rho}{\pi . L_C}\left[\ln\left(\frac{2L_C}{a'}\right) + \frac{k_1 L_c}{\sqrt{A}} - K_2\right] \quad (7)$$

$$R_2 = \frac{\rho}{2n_r \pi . L_r}\left[\ln\left(\frac{4L_r}{b}\right) - 1 + \frac{2K_I L_r}{\sqrt{A}}\left(\sqrt{n_r} - 1\right)^2\right] \quad (8)$$

$$R_m = \frac{\rho}{\pi . L_C}\left[\ln\left(\frac{2L_C}{L_r}\right) + \frac{k_1 L_c}{\sqrt{A}} - K_2 + 1\right] \quad (9)$$

Where:

$$k_1 = -0.04\left(\frac{a}{b}\right) + 1.41 \quad (10)$$

$$k_2 = 0.15\left(\frac{a}{b}\right) + 5.5 \quad (11)$$

$$n_a = \frac{2.L_C}{L_P} \quad (12)$$

$$n_b = \sqrt{\frac{L_P}{4\sqrt{A}}} \quad (13)$$

$$n_c = \left[\frac{L_x L_y}{A}\right]^{\frac{0.7A}{L_x L_y}} \quad (14)$$

$$n_d = \frac{D_m}{\sqrt{L_x{}^2 + L_y{}^2}} \quad (15)$$

$$n = n_a n_b n_c n_d \quad (16)$$

- Stage 6: Determines the current *IG:*

$$I_G = I_f . S_f . D_f . C_p \quad (17)$$

- Stage 7: Check the GPR. If the GPR of the preliminary design is below the tolerable touch voltage, no further analysis is required.

$$GPR = R_g . I_G \quad (18)$$

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\ln\left(1 + \frac{1}{h\sqrt{20A}}\right)\right] \quad (19)$$

- Stage 8: The calculation of the mesh and step voltages for the grid as designed can be done by the approximate analysis techniques:

$$E_s = \frac{\rho . K_s K_i I_G}{L_s} \quad (20)$$

$$E_{Mesh} = \frac{\rho . K_m K_i I_G}{L_M} \quad (21)$$

$$K_i = 0.644 + 0.148n \quad (22)$$

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}\left(1 - 0.5^{n-2}\right)\right] \quad (23)$$

$$L_M = L_c + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right] \times L_R \quad (24)$$

$$K_{ii} = \frac{1}{(2n)^{\frac{2}{n}}} \quad (25)$$

$$K_h = \sqrt{1+h} \quad (26)$$

- Stage 9: Control the mesh voltage and tolerable touch voltage. There will be two situation, if the computed mesh voltage is lower than the tolerable touch voltage, the design may be complete. But if the computed mesh voltage is higher than the tolerable touch voltage, the design should be revised.

-Stage 10: If the touch and step voltages are lower than tolerable voltages, the design is completed. If not, the preliminary design should be revised.

-Stage 11: If either the step or touch voltage are higher than tolerable voltage then the grid design should be revised by Smaller conductor spacings, larger conductor size, additional ground rods, etc.

- Stage 12: Add further rods or earthing near electrical equipment according to their criteria if all other requirements are satisfied.

All 12 above stages are shown in fig.1

3. A REAL SAMPLE

3.1. Description

Steel factories are one of the main power network consumers. All times steel factories have a main substation. For this article a 400/34.5KV substation in a steel factory in Iran is selected. This substation is designed and constructed.

The main parameters of grounding grid system of this substation is specified in table 2. and table 3.

3.2. Redesign Ground Grid of Sample with Variable Space Technique

In this part by using the flow diagram and 12 described stages, a program is written in MATLB, by running this program the output of ground grid substation are recalculated and compared with constructed ground grid. The important parameters of result are listed in the table

4.

As cleared in this table with this technique size of grid conductor, number of conductor in each side and also length of total conductor is decreased, so it will be an economized design.

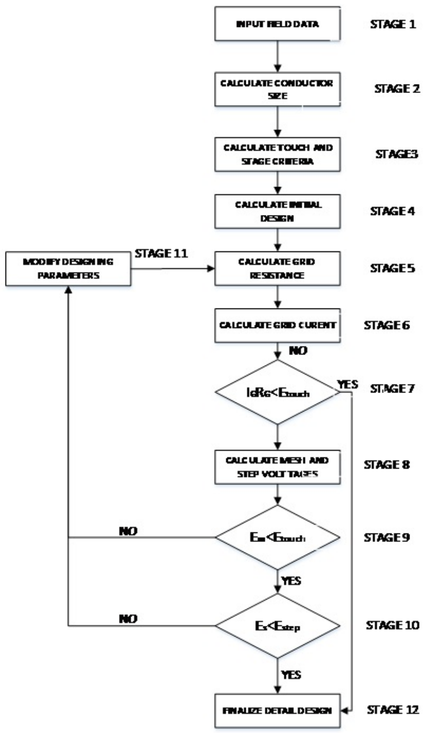

Figure. 1. Algorithm for designing substation ground grid according to IEEE 80.

TABLE 2.

INPUT DATA OF STUDIED SAMPLE

Symbol	Description/Value
Name of Substation	PASARGAD steel
Location	Iran
Voltage Level	400/34.5 kV
Used Conductor Name	stranded annealed soft copper
L_x	228 m
L_y	154 m
P	60 Ω·m
P_s	3000 Ω·m
$3I_0$	50KA
t_s	0.5s
h	0.5 m
h_s	*0.15m*
L_r	*3m*
n_R	*30*

TABLE 3.

CONSTRUCTED STUDIED SAMPLE

Symbol	Description/Value
Size of grid conductor	$120mm^2$
D	*12m*
n_a	*20*
n_b	*14*
$L_{conductor}$	*6272m*
E_s	*503V*
E_m	*855V*
E_{step70}	*3026V*
$E_{touch70}$	*908V*

TABLE 4.

COMPARE NEW CALCULATION RESULT WITH CONSTUCTED

Symbol	Constructed	New calculation result-variable space technique
Size of grid conductor	$120mm^2$	$95mm^2$
D	*12m*	*14m*
n_a	*20*	*17*
n_b	*14*	*12*
$L_{conductor}$	*6272m*	*5354m*
E_s	*503V*	*510V*
E_m	*855V*	*974V*
E_{step70}	*3026V*	*3315V*
$E_{touch70}$	*908V*	*995V*

4. META HEURISTIC OPTIMIZATION METHOD

In this part try to optimize an object function with Meta heuristic algorithms like PSO & HS.

4.1. Objective Function

It is possible to select many objective functions to be optimized, but in grounding system cost of grounding systems is very important for clients and they tend to pay the minimum money. So according to this criteria an objective cost function is defined and the goal is minimize this function.

Cost of grounding grid system could be divided to four main parts:

1- Cost of grounding grid conductor, it is related to size and length of used conductor.
2- Cost of burring the conductor, it is related to depth of burring conductor, length of conductor or length of burring path.
3- Cost of weld in crossover of earth conductors, the cost of weld is related to number of conductors in each sides.
4- Cost of Rods, it is related to number and specification of Rods.

According to these the objective function is defined:

$$OBJ.\mathrm{COST}.\mathrm{FUNC} = CO1.\mathrm{A}_c.(N_x.L_y + N_y.L_x) + CO2.h.(N_x.L_y + N_y.L_x) + CO3.N_x.N_y + CO4.N_r \quad (27)$$

4.2. PSO Algorithm

The PSO algorithm (Particle Swarm Optimization) was developed as optimization algorithm in the year 1995 by Kennedy and Eberhart. It gets its characteristics from nature such as bird or fish schooling.

Particle swarm optimization is similar but much simpler than known genetic algorithm. It is very useful and it has good answer contiguity.

This algorithm searches the space of an objective function by adjusting the trajectories of individual agents, called particles, as these trajectories form piecewise paths in a quasi-stochastic manner. [32] Each particle is attracted toward the position of the current global best g* and its own best location x in history, while at the same time it has a tendency to move randomly.

When a particle finds a location that is better than any previously found locations, then it updates it as the new current best for particle i. There is a current best for all n particles at any time t during iterations. The aim is to find the global best among all the current best solutions.

The modification of the particle's position can be modeled as below:

$$v_i^{k+1} = w.v_i^k + \alpha.r(...).(Pbest_i - s_i^k) + \beta.r(...).(gbest_i - s_i^k) \quad (28)$$

Where:

$\alpha + \beta = 4$ and P is related to best location of each particle and g is related to global best location.

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}}.iter \quad (29)$$

Velocity according to Pbest and gbest can be calculated. Current position can be obtained:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (30)$$

The use of this algorithm for minimize objective function is shown in fig. 2.

4.3. HS Algorithm

Harmony search algorithm, developed by Z. W. Geem et al. in 2001. This algorithm generated by pitch adjustment, randomization.

Harmony search can be explained in more detail with the aid of the discussion of the improvisation process by a musician. When a musician is improvising, he or she has three possible choices:

1- Play any famous piece of music (a series of pitches in harmony) exactly from his or her memory;
2- Play something similar to a known piece (this is equivalent to adjusting the pitch slightly);
3- Compose new or random notes.

It could be an idea for making an algorithm (HS). In searching for best answer of objective function 3 positions may be occurred, the answer is good and it is best answer, the answer isn't the best answer and there should be a random change in some inputs and generate new answer or the answer isn't the best answer and there will be a total random change in and inputs and generate new answer.

HS algorithm includes a number of optimization parameters, such as the harmony memory (HM), the harmony memory size (HMS), the harmony memory considering rate (HMCR), and the pitch adjusting rate (PAR).

The stages in the procedure of harmony search are as follows:

-Stage1: Initialize the problem and algorithm parameters.
-Stage2: Initialize the harmony memory (HM).
-Stage3: Improvise a new harmony from the HM.
-Stage4: Update the HM. If the New Harmony is better, include it in harmony memory.
-Stage5: Repeat Stages 3 and 4 until the termination criterion is satisfied.

The use of this algorithm for minimize objective function is shown in fig. 3.

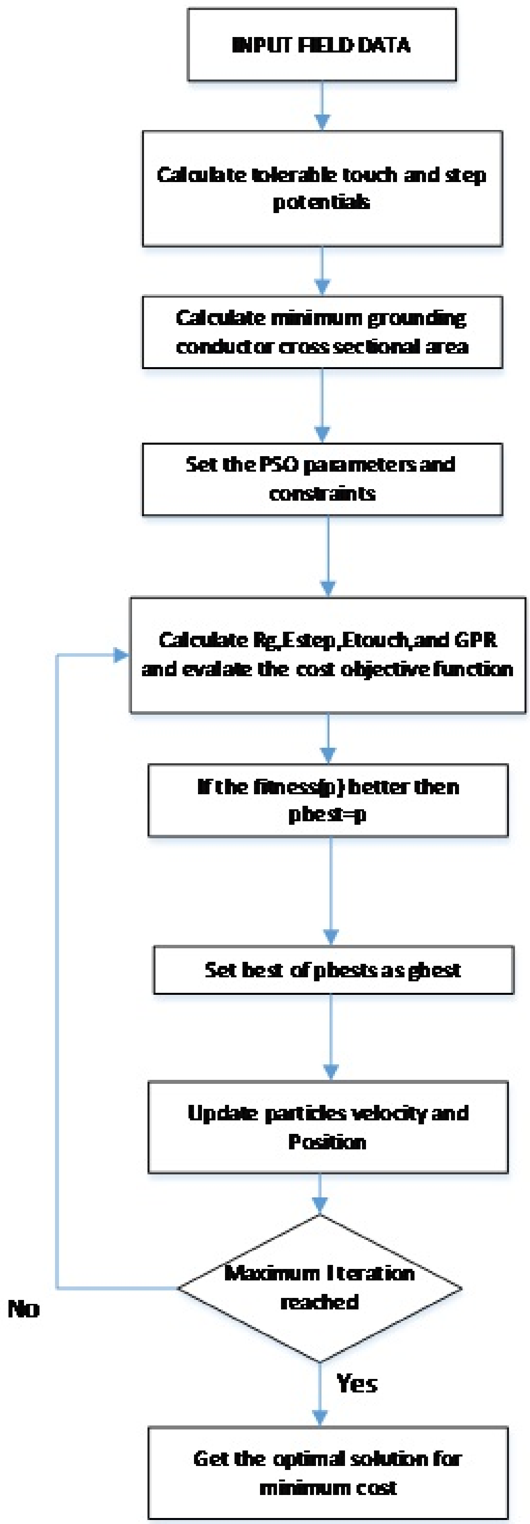

Figure 2. PSO algorithm for objective function.

5. OPTIMIZATION RESULT

In this part the results of optimization for sample project and objective function will be shown.

Two other programs in MATLAB software are written according to mentioned PSO and HS algorithms. Input data of studied sample are mentioned In table 5 and the result of calculations and output of program are shown in

table 6. and table 7. according to PSO and HS algorithms. Also the result are calculated according to variable space technique and mentioned in table 8.
Total price and other parameters of constructed ground grid of substation are calculated and shown in table 9.

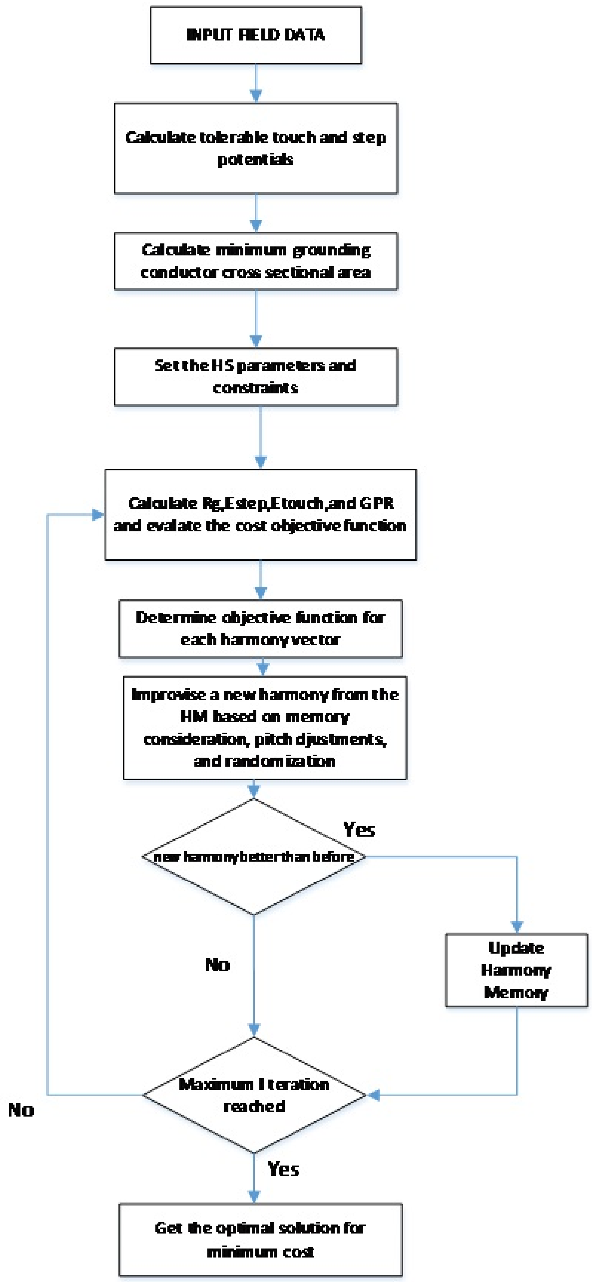

Figure 3. HS algorithm for objective function.

According to these calculation and above tables it is cleared that use of PSO or HS algorithm help the designer to find an optimum cost for design of ground grid of this substation.

In table 5 input data of calculation and optimization is defined. For this calculation length and diameter or rods are constant and in the optimization there are not any change in the length or diameter of rods. It is true approximately, because generally in substations rods with 3 m length are used and the diameter of rods doesn't have more effect on the results.

For PSO optimization population size is defined 10 and maximum iteration is defined 1000 iterations.

The PSO algorithm is very fast and has good convergence to the answer.

TABLE 5.
INPUT DATA OF STUDIED SAMPLE

Symbol	Description/Value
Name of Substation	PASARGAD steel
Location	Iran
Voltage Level	400/34.5 kV
Used Conductor Name	stranded annealed soft copper
L_x	228 m
L_y	154 m
ρ	60 Ω·m
P_s	3000 Ω·m
$3I_0$	50KA
t_s	0.5s
h_s	*0.15m*
L_r	*3m*
CO1	$0.1\$/(m.mm^2)$
CO2	*6$/(m.m)*
CO3	*3$*
CO4	*40$*

TABLE 6.
CALCULATION RESULT (CALCULATING BY PSO ALGORITHM)

Symbol	New calculation result-PSO Algorithm
Size of grid conductor	$95mm^2$
h	*0.28m*
D	*13m*
n_a	*19*
n_b	*13*
n_r	*13*
$L_{conductor}$	*5890m*
E_s	*830V*
E_m	*990V*
E_{step70}	*3315V*
$E_{touch70}$	*995V*
Total price	*67111$*

TABLE 7.
CALCULATION RESULT (CALCULATING BY HS ALGORITHM)

Symbol	New calculation result-PSO Algorithm
Size of grid conductor	$95mm^2$
h	*0.65m*
D	*14m*
n_a	*17*
n_b	*12*
n_r	*27*
$L_{conductor}$	*5354m*
E_s	*407V*
E_m	*953V*
E_{step70}	*3315V*
$E_{touch70}$	*995V*
Total price	*73435$*

In table 6 result of using PSO algorithm is shown. According to this result and compare with main result of constructed substation (table 8) by this new calculation designer could achieve to %31 cost saving in grounding grid system.

TABLE 8.
CALCULATION RESULT (CALCULATING BY VARIABLE SPACE TECHNIQUE.)

Symbol	New calculation result-PSO Algorithm
Size of grid conductor	$95mm^2$
h	0.5
D	14m
n_a	17
n_b	12
n_r	30
$L_{conductor}$	5357m
E_s	510V
E_m	974V
E_{step70}	3315V
$E_{touch70}$	995V
Total price	68730$

Running PSO algorithm and program could give the similar result and it is one positive point of using this algorithm for this problem.

In table. 7 result of using HS algorithm is shown. For HS algorithm HS-size (Length of solution vector) was 10, maximum attempt was 10000, HM Accepting Rate was 0.95 and Pitch Adjusting rate selected as 0.4. Using of HS algorithm has %24 cost saving in grounding grid system but in compare with PSO some items should be mentioned.

1- Running PSO algorithm is faster than HS algorithm.
2- PSO algorithm has better convergence in answer for this problem. Running several times of two program has different but acceptable answer for HS algorithm but PSO algorithm for this problem generally converge to a specific answer.
3- HS algorithm is a random algorithm and the effect of history in final answer isn't very much. But in PSO algorithm history term has a good effect to converge to final answer.
4- HS algorithm is suitable for continuous area. In discrete problems like this problem the effect of random working of algorithm is visible. This problem via the step size of cables needs suitable algorithm for discrete area.
5- HS algorithm is simple to program.
6- Both PSO and HS algorithms had good effect in optimizing this problem. The accuracy and reliability of the proposed approach have been validated using several test systems.

In Table 8 & 9, table 3 is repeated and also the total price is calculated, in designing grounding grid use of variable space technique is suitable, But using meta heuristic optimization methods has better effect in optimization.

6. CONCLUSION

Using meta heuristic optimization methods like PSO or HS algorithm has good effect on cost minimization of ground grid of substations. In these algorithms with Assumption the constraint of IEEE80 standard and good objective function could achieve a good optimized design.

Using faster and more accurate algorithms may be suitable in continuing this way.

TABLE 9.
CALCULATION RESULT OF CONSTRUCTED GRID

Symbol	New calculation result-PSO Algorithm
Size of grid conductor	$120mm^2$
h	0.5
D	14m
n_a	20
n_b	14
n_r	30
$L_{conductor}$	6272m
E_s	503V
E_m	855V
E_{step70}	3026V
$E_{touch70}$	908V
Total price	96120$

REFERENCES

[1] Jazebi, S. Vahidi, B. "Reconfiguration of distribution networks to mitigate utilities power quality disturbances", *Electric Power System Research*, **91**: 9-17 (2012).

[2] Vahidi, B. Ghaffarzadeh, N. Hosseinian, S. H. "A wavelet-based method to discriminated internal faults from inrush currents using correlation coefficient", *International Journal of Electrical Power & Energy Systems*, **32**(7): 788-793 (2010).

[3] Vahidi, B. Jannati, M. Hosseinian, S. H. "A novel approach to adaptive single phase autoreclosure scheme for EHV power transmission lines based on learning error function of ADALINE", *Simulation*, **84**(12): 601-610 (2008).

[4] Hejazi, H. A. Araghi, A. R. Vahidi, B. Hosseinian, S. H. Abedi, M. Mohsenian Rad, H. "Independent distributed generation planning to profit both utility and DG investors", *IEEE Transactions on Power Systems*, **28** (2): 1170-1178 (2013).

[5] Fereidouni, A. R. Vahidi, B. Hosseini Mehr, T. Tahmasbi, M. "Improvement of low frequency oscillation damping by allocation and design of power system stabilizers in the multi-machine power system", *International Journal of Electrical Power & Energy Systems*, **52**(7): 207-220 (2013).

[6] Fereidouni, A. R. Vahidi, B. Hosseini Mehr, T. "The impact of solid state fault current limiter on power network with wind-turbine power generation", *IEEE Transactions on Smart Grid*, **4** (2): 1188-1196 (2013).

[7] Vahidi, B. Arabshahi, M. M. "Teaching current tests on surge arresters to undergraduate students using MATLAB–SIMULINK", *Computer Applications in Engineering Education*, **20**: (3): 391-399 (2012).

[8] Naghizadeh, R. N. Jazebi, S. Vahidi, B. "Modeling hydro power plants and tuning hydro governors as an educational guideline", *International Review on Modelling and Simulations (I. RE. MO. S.)*, **5** (4): 1780-1790 (2012).

[9] Mohammadi, M. Vahidi, B. "Model of corona for transient study", TENCON 2005-2005 IEEE Region 10 Conference, (2005).
[10] ANSI/IEEE Std. 80-2000, Guide for Safety in AC Substation Grounding, IEEE Inc., 2000, New York.80-2000, Agosto 2000.
[11] Dawalibi, F. Mukhedkar, D. "Optimum design of substation grounding in a two layer earth structure-Part I analytical study", *IEEE Transactions on Power Apparatus and Systems*, **PAS-94**(2): 252-261 (1975).
[12] Dawalibi, F. Mukhedkar, D. "Behaviour of grounding systems in multilayer soils: a parametric analysis", *IEEE Transactions on Power Delivery*, **9**(1): 334-342 (1994).
[13] Puttarach, A. Chakpitak, N. Kasirawat, T. Pongsriwat, C. "Substation grounding grid analysis with the variation of soil layer depth method," IEEE PES International Conference Power Tech, Lausanne, witzerland, pp.1881-1886, (2007).
[14] Puttarach, A. Chakpitak, N. Kasirawat, T. Pongsriwat, C. "Analysis of substation ground grid for ground potential rise effect reduction in two-layer soil," proc. EECTI International Conference, Chinag Rai, Thailand, (2007).
[15] Dawalibi, F. Mukhedkar, D. "Optimum design of substation grounding in a two layer earth structure, part III: study of grounding grids performance and new electrode configuration", *IEEE Transactions on Power Apparatus and Systems*, **PAS-94**(2): 267-272 (1975).
[16] Dawalibi, F. Mukhedkar D. "Influence of ground rods on grounding grids", *IEEE Transactions on Power Apparatus and Systems*, **PAS-98**(6): 2089-2098 (1979).
[17] Sverak, J. G. "Optimized grounding grid design using variable spacing technique", *IEEE Transactions on Power Apparatus and Systems*, **PAS-95**(1): 362-374 (1976).
[18] Ioannis G. Stathopulos, I. "Estimation of multilayer soil parameters using GA", *IEEE Trans Power Del*, **20**(1): 100–106 (2005).
[19] Costa, M. C. Filho, M. L. P. Mirechal, Y. Coulomb, J. Cardoso, J. R. "Optimization of grounding grids by response surfaces and GA", *IEEE Trans Magn*, **39(3):** 1301-1304 (2003).
[20] Otero, A. F. Cidrbs J. Garrido, C. "GA-based method for grounding grid design," Proc. of the IEEE Int Conference on Evolutionary Computation, pp. 120-123, (1998).
[21] Covitti, A. Delvecchio, G. Fusco, A. Lerario, F. Neri, F. "Two cascade genetic algorithms to optimize unequally spaced grounding grids with rods", International Conference on EUROCON 2005, pp. 1533-1536, (2005).
[22] He, Z. Wen, X. Wang. J. "Optimization design of substation grounding grid based on genetic algorithm", The Third International Conference on natural computation, WuHan, pp. 140-144, (2007).
[23] Clerc, M. Kennedy, J. "The particle swarm – explosion, stability, and convergence in a multidimensional complex space," *IEEE Trans. Evol. Comput*. **6**(1): 58-73 (2002).
[24] Kennedy, J. Eberhart, R. "Particle swarm optimization," in Proc. IEEE Int. Conf. Neural Networks, pp.1942-1948, (1995).
[25] Shi, Y. Eberhart, R. "A modified particle swarm optimizer," in Proc. IEEE Int. Conf. Evolutionary Computation, pp.69-73, (1998).
[26] Nuno, J. Lopes, F. "Optimization design of substation grounding grid", https://fenix.tecnico.ulisboa.pt/downloadFile/395143513401/resumo.pdf
[27] EL_Fergany, A. "Accelerated particle swarm optimization-based approach to the optimal design of substation grounding grid", *Przeglad Elektrotechniczny*, **89**(7): 30-31 (2013).
[28] Lee, C. Y. Shen, X. "Optimal planning of ground grid based on particle swam algorithm", *World Academy of Science, Engineering and Technology*, **3**(12): 30-37 (2009).
[29] Heimbach, M. Grcev, L. D. "Grounding system analysis in transients programs applying electromagnetic field approach," *IEEE Trans. On Power Delivery*, **12**(1): 186-193 (1997).
[30] Xu, H. Wen, X. Sh. Huang, L. "Optimization design of grounding grid of large substation", *High voltage engineering*, **31**(12): 63-65 (2005).
[31] Gao, Y. Zeng, R. Liang, X. He, J. "Safety analysis of grounding grid for substations with different structure", PowerCon 2000, Perth WA, pp. 1487-1492, (2000).
[32] Yang, X-She. "Engineering optimization, an introduction with metaheuristic applications", Published by John Wiley & Sons, Inc., Hoboken, New Jersey, (2010).