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Accelerated Particle Swarm Optimization-based Approach to the Optimal Design of Substation Grounding Grid

***Abstract**. This article presents an application of the Accelerated Particle Swarm Optimization based approach to minimize the cost of grounding grids in high voltage substations while maintaining the legitimacy of safety necessities. The cost effectiveness and the constraints of ground potential rise, step and touch potentials are adapted to formulate optimized solutions for the grounding grid planning problem. The proposed approach attempts to calculate the optimal values of the grounding conductor lengths, cross sectional area, number of vertical rods, and depth of conductor burial while respecting a set of constraints within pre-set acceptable limits. Several test cases of grounding grid planning, some of them for real projects, are demonstrated to validate the proposed method. The superiority and efficacy of Accelerated Particle Swarm Optimization have been acknowledged in terms of grounding grid cost minimization, stable performance and short CPU computational time.*

***Streszczenie.** W artykule zaprezentowano wykorzystanie algorytmu rojowego do minimalizacji kosztów sieci uziemiającej w podstacji wysokiego napięcia. Zaproponowany algorytm optymalizuje długość przewodu uziemiającego, liczbę prętów i głębokość przy założonych kryteriach. Przedstawiono wyniki symulacji i eksperymentu. (Optymalizacja projektowania sieci uziemiającej w podstacji wysokonapięciowej z wykorzystaniem algorytmów rojowych)*

Keywords: Accelerated Particle Swarm Optimization, Cost Minimization, Grounding Grid, Safety Criteria.
Słowa kluczowe: algorytmu rojowe, sieć uziemiająca, optymalizacja.

1. Introduction

A grounding system is one of the most important items inside power plants and substation systems. Poor design methods and simplified calculations can lead to high erection costs and unsafe conditions. A grounding network dissipates electrical fault currents into the earth without producing harmful potential gradients that could be fatal to humans. To ensure fault currents are dissipated in a safe manner, three parameters must be calculated: GPR, step, and touch potentials [1]. Substation safety criteria are different in different countries, with two main approaches being adopted. American and European methods assess "step" and "touch" potentials, while the UK focus is given to evaluating the GPR [2-3]. The GG is regularly done at the foundation stage of substation design and, firstly, its design purpose is considered suitable for both the human safety and equipment protection [4]. The voltage changes and call the number step conductors earth system to determine efficiency in reducing conductors increased contact and step potentials provided the tolerance values, has been compared to evaluate safety was demonstrated [5]. The concept of optimal design of a GG in a two layer soil structure has been initially introduced [6]. More recently, GAs applied to optimize the design of grounding grids were successfully demonstrated [7-10]. The study on compression ratio and its relationship with the conductors and the voltage step was to contact and appropriate compression ratio achieved with minimal contact voltage compared with the values of tolerance not to evaluate safety was studied [11-13]. The advantage of GA optimization of the network with the purpose of minimizing voltage contact is presented [14]. An application of GA and PSO methods is discussed and presented for the research of optimal design of the GG [15].

In this article, an APSO algorithm is applied to optimize the design of grounding grids of HV substations. The standard recognized shapes by IEEE Std. 80-2000 are incorporated within the proposed method. All the calculations of important factors for the GG design are executed based on latest edition of ANSI/IEEE Std. 80-2000. However, the optimization practice is carried out using APSO-based approach. The algorithm has been tested and validated using several test cases and some of them are for real projects.

2. Overviews of Some Important Terms for the Design of GG

2.1 Tolerable Step and Touch potentials

In the procedure of designing the GG system, safety criteria is first calculated to specify a safety level, then the maximum touch and step potentials are calculated to compare with the safety criteria in order to assess whether it is safe to work on the area of substation. The tolerable step and touch potentials [2] are calculated by Eq. (1);

$$\mathrm{E}_{\mathrm{Tolerable}}^{\mathrm{Weight}} = [1000 + \mathrm{K}_1 \times \mathrm{C}_\mathrm{S} \times \rho_\mathrm{S}] \times \frac{\mathrm{K}_2}{\sqrt{\mathrm{t}_\mathrm{S}}} \qquad (1)$$
$$\mathrm{C}_\mathrm{S} = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_\mathrm{S}}\right)}{2\mathrm{h}_\mathrm{s} + 0.09}$$

Table I tabulated the values for K_1 *and* K_2 for step and touch potentials with weights of 50 and 70 kg for tolerable step and touch potentials.

Table 1. Values of K_1 and K_2

Tolerable potential	Weight=50 kg		Weight=70 kg	
	K_1	K_2	K_1	K_2
Step	6	0.116	6	0.157
Touch	1.5	0.116	1.5	0.157

The actual touch potential, mesh potential, or transferred voltage should be less than the maximum allowable touch potential, $\mathrm{E}_{\mathrm{touch}}$, to ensure safety. Generally, touch potentials represent a much more serious hazard than step potential; these are the usual basis for design.

2.2 Sizing of Grounding Conductors

The minimum size of the grounding conductor is expressed and calculated using Eq. (2).

$$\mathrm{A}_{\mathrm{kcmil}} = \mathrm{I}_\mathrm{F}.\mathrm{K}_\mathrm{C}.\sqrt{\mathrm{t}_\mathrm{C}} \quad \text{and} \qquad (2)$$
$$\mathrm{A}_{\mathrm{mm}^2} = \frac{\mathrm{A}_{\mathrm{kcmil}} \times 1000}{1973.52}$$

The common material constants (K_C) can be obtained [2].

2.3 Ground Resistance

Ground resistance of the substation primarily depends on soil resistivity, area available and grid configuration [16-18]. Estimation of the total resistance to remote earth is one of the first steps in determining the size and basic layout of a grounding system. Sverak [16] has developed the formula to take into account the effect of grid depth.

$$R_g = \rho\left[\frac{1}{L_t} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}}\right)\right] \tag{3}$$

However, Schwarz [17] proposed a formula to combine the resistance of the grid, rods, and mutual ground resistance to calculate the total system resistance as follows;

$$R_g = \frac{R_c R_r - R_m^2}{R_c + R_r - 2R_m} \tag{4}$$

2.4 Ground Potential Rise

The maximum electrical potential that a substation GG may attain relative to a distant grounding point assumed to be at the potential of remote earth is called GPR. The GPR is calculated as follows;

$$\begin{gathered} GPR = I_G . R_g \\ I_G = S_F . C_P . D_F . I_F \end{gathered} \tag{5}$$

2.5 Maximum Actual Mesh and Step Potentials

As per ANSI/IEEE Std. 80 [2], the formulas to calculate maximum step potential and maximum mesh/touch potential are expressed in Eq. (6) and Eq. (7), respectively.

$$E_s = \frac{\rho . K_s . K_i . I_G}{L_s} \tag{6}$$

$$E_m = \frac{\rho . K_m . K_i . I_G}{L_m} \tag{7}$$

Step potential depends on grid geometry irregularity factor K_i, spacing factor K_s, grid depth and current per meter length of the conductor [2, 19].The mesh voltage depends on resistivity of the soil, conductor spacing, number of meshes, current per meter length of the conductor and depth at which the grid is buried, while parameters such as the conductor diameter and the thickness of the surfacing material have less impact [2, 20]. Nevertheless, step potential is one of the important criteria for the safety of the person [1].

3. Problem Formulation and Objective Function

The increase in number of meshes and use of ground rods of varying length with horizontal grid makes the surface potential distribution more favorable for personal safety. It also decreases the grid resistance and ground potential rise which enhances the reliability of controlling devices. However, the cost will be a concern. To have the optimal design of grounding grid with minimum cost of installation and purchasing, the objective function has to be minimized while satisfying a set of safety criteria and other constraints;

$$\text{Minimise}\ \{L_C \times C_c + N_r \times L_r \times C_r + h \times A \times C_{ex}\} \tag{8}$$

Subject to the following constraints;

3.1 Safety Criteria Constraints

These safety criteria include actual mesh and step potentials which must be less than values of the corresponding tolerable potentials;

$$\begin{gathered} E_{mesh-Actual} < E_{touch-tolerable} \\ E_{step-Actual} < E_{step-tolerable} \end{gathered} \tag{9}$$

3.2 Grounding Resistance

For most transmission and other large substations, the ground resistance is usually about 1 Ω or less. In smaller distribution substations, the usually acceptable range is from 1 Ω to 5 Ω, depending on the local conditions.

$$R_g \le R_{Target} \tag{10}$$

3.3 Maximum Allowed Ground Potential Rise

Recommended practices provided the limits of the GPR, which is typically 5000V for most substations.

$$GPR \le GPR_{max} \tag{11}$$

3.4 Spacing between Adjacent Conductors

The separation between the conductors in x and y directions should be uniform and proportional to the grid dimensions.

$$D_{x,min} \le D_x \le D_{x,max} \tag{12}$$

$$D_{y,min} \le D_y \le D_{y,max} \tag{13}$$

3.5 Depth of Earth Grid Conductor

The grid burial depth influences the step and touch potentials significantly. The touch voltage decreases, due mainly to the reduced grid resistance and corresponding reduction in the GPR. However, for very large increases in depth, the touch potential may actually increase. The typical variations of burial depth found within the industry (i.e. approximately 0.5-1.5 m) and the change in grounding resistance with depth are negligible for uniform soil.

$$h_{\ min} \le h \le h_{\ max} \tag{14}$$

Finally, the mathematical model can be formulated as general constrained optimization problem as follows;

$$\begin{gathered} \text{Minimize}\ \{F(x,u) = GG\_Cost\} \\ S.t.\ \begin{cases} g(x,u) = 0 \\ h(x,u) \le 0 \end{cases} \end{gathered} \tag{15}$$

Where $F(x,u)$ is the objective function; $g(x,u)$ and $h(x,u)$ are the set of equality and inequality constraints, respectively. x is the state variables and u is the vector of continuous and discrete control variables. The control variables are the spacing between adjacent conductors (continuous variable), depth of burial (continuous variable), number of rods (integer number and continuous variable), and grounding conductor cross sectional area (discrete variable).

4. Overview of the PSO Algorithm

The PSO is an optimization technique and was first introduced in the year 1995 by Kennedy and Eberhart [21]. PSO has been recognized as an EC technique and has features of both GA and ES [22-24]. The standard PSO uses both the current global, $gbest$ and the individual best, $pbest$.The modification of the particle's position can be mathematically modeled according the following;

$$\begin{gathered} v_i^{k+1} = w \times v_i^k + \alpha . r(\dots) \times \left(pbest_i - s_i^k\right) + \beta . r(\dots) \\ \times \left(gbest - s_i^k\right) \end{gathered} \tag{16}$$

The parameters α and β are the learning parameters, which can typically be taken as, say, $\alpha \approx \beta \approx 2$.

The following weighting function is usually utilized;

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times iter \tag{17}$$

Using the above equation, a velocity, which gradually gets close to $pbest$ and $gbest$ can be calculated. The current position (searching point in the solution space) can be modified as follows;

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{18}$$

Fig. 1 shows a concept of modification of a searching point by PSO algorithm and each agent changes its current position in a solution space using the integration of vectors as shown in Fig. 2.

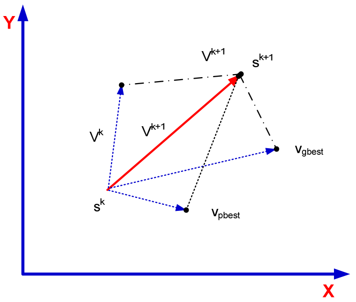

Fig. 1 Concept of modification of a searching point according to PSO algorithm

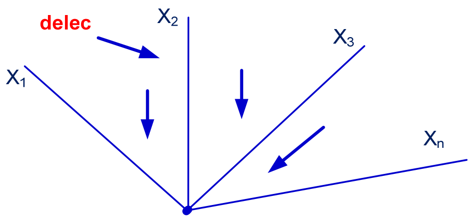

Fig. 2 Concept of searching with agents in a solution space

4.1 Accelerated PSO

A simplified version which could accelerate the convergence of the algorithm is to use the global best only. Thus, in the APSO [24], the velocity vector is generated by a simpler formula as:

(19) $$v_i^{k+1} = v_i^k + \alpha.r(\dots) + \beta.\left(gbest - s_i^k\right)$$

This is equivalent to introduce an implicit mass to stabilize the motion of the agents, and thus the algorithm is likely to converge more quickly.
In order to increase the convergence even further, the update of the location can written in a single step, as;

(20) $$s_i^{k+1} = (1-\beta).s_i^k + \beta.gbest + \alpha.(r(\dots) - 0.5)$$

This simpler version will give the same order of convergence [25]. Typically, $\alpha = 0.1 \sim 0.5$, while $\beta = 0.2 \sim 0.7$ is sufficient for most applications, though $\alpha \approx 0.2$ and $\beta \approx 0.4$ can be taken as the initial values for most unimodal objective functions.

(21) $$\alpha = 0.7^k$$

The details of the implementation of APSO to achieve the optimal design of high voltage substation are illustrated in the flow chart shown in Fig. 3.

5. Test Cases, Numerical Results and Discussions

To evaluate the performance of the proposed method, two test cases to be presented and demonstrated. Case 1is for real case of a project located in United Arab Emirates in the field of Umm Al Nar independent water and power (Abu Dhabi-based).However, the second case is for 33/11 kV package substation (Al Wathba South – Abu Dhabi) with 1.8 kA grounding grid current.

The proposed method developed and implemented in MATLAB platform [26] to run the proposed methodology. In all optimization runs, the parameter settings to execute APSO; the population size is 15, and the maximum cycles is 150. The type of grounding conductor material is assumed to be Copper hard-drawn, bare circular and the ambient temperature is 40°C used in the two test cases reported in this article.

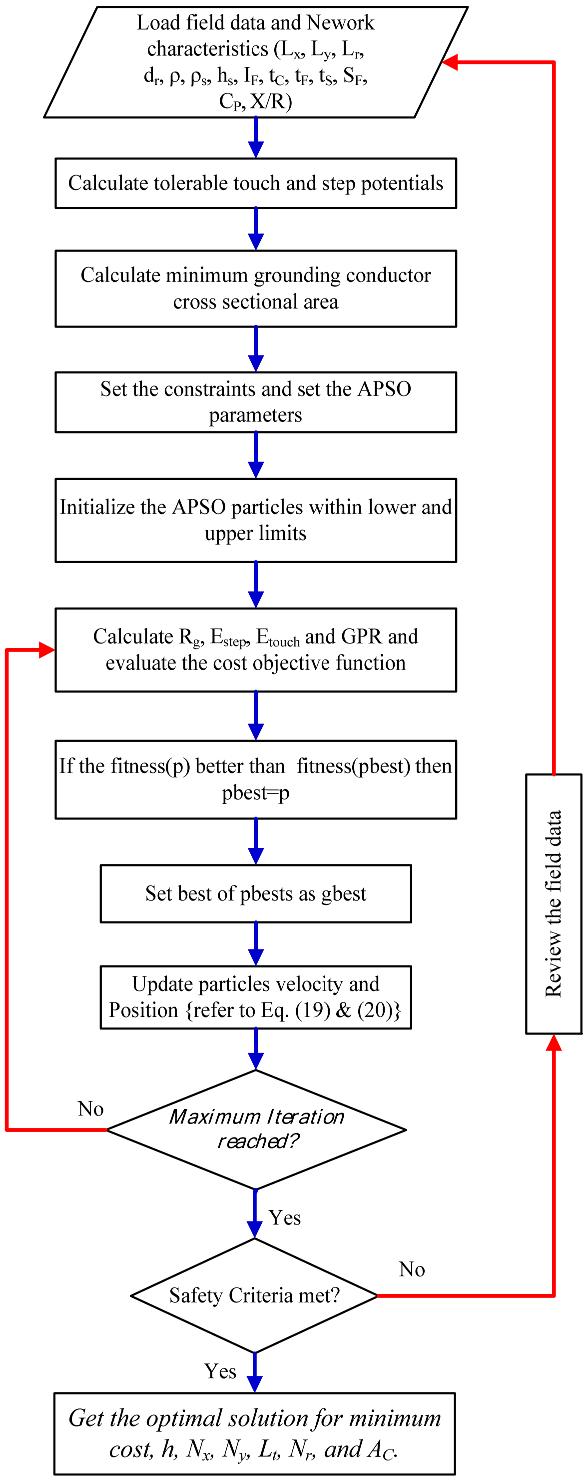

Fig. 3 APSO algorithm and the GG optimization flow chart

The upper and lower limits of control variables are proposed in compliance with recommended practices as follows; $D_x \in [2.5, 30]$, $D_y \in [2.5, 30]$, $A_C \in [A_{min}, 630]\ mm^2$, $N_r \in [0, A/(L_r)^2]$ and $h \in [0.5, 1.5]m$. A_{min} can be calculated using the formula defined in Eq. (2). The rate for the cost of the grounding conductors including the installation expenses and other fittings are tabulated in Table II for different conductor cross sectional areas. The price of vertical rod including installing cost is assumed to be 60 $/m. However, the excavation constants are 25 $/m^3 and 50

$/m^3 for soft-medium soil and rocky soil, respectively. Accurate design of a grounding system requires an accurate assessment of the site's soil conditions. Roughly, the soil with resistivity's of 500 Ω.m and below is being considered as soft-medium soil type. However, soil with higher resistivity's is being considered as rocky type. The field and network data for cases 1 and 2 are depicted in Table 3. The minimum grounding conductors cross sectional areas are 300 mm^2, and 240 mm^2 for the cases 1, and 2, respectively as recommended by the project specifications.

As depicted in Tables 5-6; which are self-explanatory, all the constraint parameters of the GG design obeys the IEEE Std. 80-2000 requirements. The results of safety characteristics obtained for case 1 is better than those calculated during real project design with being paid better net saving. The proposed approach was able to reduce the cost of GG by 31.21%, and 55.68% for the cases 1 and 2, respectively as indicated in Table 4.

Table 2. Proposed cost rates for ground conductors including installing fees

Area (mm^2)	Cost ($/m)	***Area (mm^2)***	Cost ($/m)
1.5	2.250	***95***	66.300
4	3.375	***120***	70.125
6	4.725	***150***	110.175
10	7.125	***185***	147.375
16	10.875	***240***	179.85
25	18.375	***300***	282.675
35	24.525	***400***	321.750
50	34.65	***500***	360.375
70	47.025	***630***	472.500

These obtained values are comparable and demonstrate the accuracy of the proposed method with significant reductions in the GG overall cost and at the same, satisfying the tolerable safety criteria. Moreover, it might be noted; the computational time of APSO method is very short, and considerably competitive.

It is worth pointing out that the APSO is much simpler compared with many PSO variants, as the APSO uses only two parameters, and the mechanism is simple to understand.

Table 3. Input Data for the test cases for land, soil characteristics and network data

Item	**Case 1**	**Case 2**
Body weight (kg)	50	70
ρ_s (Ω-m)	3000	3000
h_s (m)	0.2	0.1
ρ (Ω-m)	15	5.81
t_S (s)	3.0	1.0
t_F (s)	3.0	1.0
t_C (s)	3.0	1.0
$(L_x \times L_y)$ m	340 × 160	29 × 22
L_r (m)	3.0	3.6
d_r (m)	0.0172	0.02
h (m)	1.5	1
I_f (kA)	40.0	1.80
$\frac{X}{R}$	0.33	0
S_F	1	1
C_P	1	1

Table 4. Optimal values for the design of cases 1 and 2 compared to the real project calculations

Item	***Case 1***		***Case 2***	
	Project Design	***Proposed Approach***	***Project Design***	***Proposed Approach***
N_x	*6*	*8*	*7*	*2*
N_y	*13*	*16*	*5*	*2*
N_r	*0*	*0*	*50*	*0*
$L_C + L_r (m)$	*4,120*	*5,280*	*493*	*102*
$h\ (m)$	*1.5*	*0.5*	*1*	*0.5*
$A_{min} (mm^2)$	*300*	*300*	*240*	*300*
Cost ($)	***$3,204,621***	***$2,172,524***	***$83,043***	***$36,807***
Net Saving%	***---***	***32.21%***	***---***	***55.68%***
CPU time (s)	***---***	***0.87***	***---***	***0.79***

Table 5. Case 1: Results for safety characteristics of GG design – Weight is 50 kg

Item	***Tolerable value***	***Project Design***	***Proposed Approach***	***Remarks***
E_{Step}	*1052.17*	*46.749*	*118.589*	*Pass*
E_{Touch}	*313.271*	*312.749*	*293.543*	*Pass*
R_g	*≤5 Ω*	*0.032*	*0.0315*	*Pass*
GPR	*≤5000 V*	*1280.2*	*1258.82*	*Pass*

Table 6. Case 2: Results for safety characteristics of GG design – Weight is 70 kg

Item	***Tolerable Value***	***Project Design***	***Proposed Approach***	***Remarks***
E_{Step}	*644.67*	*11.063*	*42.550*	*Pass*
E_{Touch}	*2107.66*	*24.381*	*128.091*	*Pass*
R_g	*≤5 Ω*	*0.1069*	*0.1556*	*Pass*
GPR	*≤5000 V*	*192.449*	*280.163*	*Pass*

6. Conclusions

In this manuscript, an APSO-based approach for the optimal design of the grounding grids has been proposed and implemented. The proposed method has been tested and within the recommended grounding parameters, so it is easy to judge the safety of the substation. The obtained results show the importance of the proposed algorithm to explore the grid optimal parameters that satisfy safety requirements and achieve the optimum design for the GG with significant reductions in the cost aspects. The accuracy and reliability of the proposed approach have been validated using several test systems. The numerical results illustrate its effectiveness, applicability, good performance, and the computational CPU is noticeable as well.

Nomenclatures & Symbols

C_S	The reduction factor
ρ_S	The resistivity of crushed rock
ρ	The uniform resistivity of the soil
h_s	The thickness of the crushed layer material
t_C	The fault-clearing time
K_1, K_2	The constant factors for step and touch potentials
I_F	The maximum RMS current (include for future growth)
K_C	The conductor material constant
t_F	The duration of fault current (between 0.25 to 3 s)
t_S	The duration for shock exposure
A_{mm^2}	The conductor cross section in mm^2
A_{kcmil}	The conductor cross section in $kcmil$
A	The total area enclosed by the grounding grid
L_t	The total buried length of conductors includes rods
h	The depth of the grid
R_c	The ground resistance of grid conductors
R_r	The ground resistance of all ground rods
R_m	The mutual ground resistance between the group of grid conductors
R_g	The grounding resistance
S_F	The fault current division factor
C_P	The corrective projection factor
D_F	The decrement factor for the entire duration of fault
I_G	The grounding grid current
K_i	The correction factor for the grid geometry
K_s	The spacing factor for the step voltage
E_s	The step potential
E_m	The mesh potential
C_c	The price of conductor/unit length including installation cost
N_r	The number of vertical rods
C_r	The cost of vertical rod/unit length including rod

	installation cost
C_{ex}	The cost of soil excavation
D_x	The spacing between conductors in x-direction
$D_{x,min}$	The lower limit for spacing in x-direction
$D_{x,max}$	The upper limit for spacing in x-direction
N_x	The number of conductors in x-direction
L_y	The length of grounding grid in y-direction
D_y	The spacing between conductors in y-direction
$D_{y,min}$	The lower limit for spacing in y-direction
$D_{y,max}$	The upper limit for spacing in y-direction
N_y	The number of conductors in y-direction
L_x	The length of grounding grid in x-direction
h_{min}	The lower limit for the grounding grid depth
h_{max}	The upper limit for the grounding grid depth
k	The pointer of iterations
v_i^k	The velocity of agent i at iteration k
w	The weighting function
α, β	The acceleration coefficients
$r(\ldots)$	Random number between 0 and 1
s_i^k	Current position of agent i at iteration k
$pbest_i$	The personnel best of agent i
$gbest_i$	The global best of the group
w_{min}	Initial weight
w_{max}	Final weight
$iter_{max}$	Maximum iteration number
$iter$	Current iteration number
s^k	The current searching point
s^{k+1}	The modified searching point
v^k	The current velocity
v^{k+1}	The modified velocity
v_{pbest}	The velocity based on $pbest$
v_{gbest}	The velocity based on $gbest$

Abbreviations

PSO	Particle swarm optimization
APSO	Accelerated particle swarm optimization
GA	Genetic algorithm
ES	Evolutionary strategy
EC	Evolutionary computational
GPR	Ground potential rise
GG	Grounding grid
RMS	Root mean square
HV	High Voltage

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