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Contingency Constrained Economic Load Dispatch Using Particle Swarm Optimization Embedded with Evolutionary Programming for Security Enhancement

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Abstract: This study presents a Contingency Constrained Economic Load Dispatch (CCELD) using proposed Particle Swarm Optimization embedded with Evolutionary Programming (PSO-EP), conventional Particle Swarm Optimization (PSO), Evolutionary Programming (EP) techniques such as Classical EP (CEP), Fast-EP (FEP) and Mean of Classical and Fast EP (MFEP) to alleviate line overloading. Power system security enhancement deals with the task of taking remedial action against possible network overloads in the system following the occurrences of contingencies. Line overload can be removed by means of generation re-dispatching. The proposed approach employs conventional Particle Swarm Optimization embedded with Evolutionary Programming (PSO-EP) techniques. So that positive features of both techniques are exploited. The proposed method combines the advantages of different EP and PSO techniques to solve the ELD problem with contingency constraints. The solution obtained is quite encouraging and it has stable convergence characteristics. The CCELD problem is a twin-objective function viz. minimization of fuel cost and minimization of severity index. This proposed PSO-EP based CCELD approach generates higher quality solution in terms of optimal cost, minimum severity index than the other methods. Simulation results on IEEE 30 and 118 bus test systems are presented and compared with the results of other approaches.

Key words: Particle Swarm optimization, evolutionary programming, Gaussian mutation, contingency constraints, overload alleviation, twin-objective function

INTRODUCTION

With the continued increase in demand for electrical energy with little addition to transmission capacity, security assessment and control have become important issues in power system operation. Security assessment deals with determining whether or not the system operating in a normal state can withstand contingencies (such as outage of transmission lines, generators etc.) without any limit violation. If the present operating state is found to be insecure, action must be taken to prevent limit violation in the contingency state. Rerouting of power flow in the system can alleviate transmission line overload. A change in line flow can be caused by an appropriate change in generation schedule. In Udupa *et al.* (2001), a fuzzy-set-theory-based approach has been proposed for overload alleviation through real power generation rescheduling. A generation shift sensitivity factor was used to determine the change in generation required at a generator bus bar. Although, these approaches are fast in rescheduling the power generation, it may lead to overloading in other lines. In Lima *et al.* (2003) and Kumar and Parida (2005) mixed-integer linear programming has been applied to identify the location of the phase shifter and FACTS devices in handling inequality constraints. In Momoh *et al.* (2001), a rule based Optimal Power Flow (OPF) with phase shifter has been proposed to alleviate the line overload. The principal of shortcoming of a rule based approach is that the construction of rules requires extensive help from the skilled knowledge of engineers. Also, it does not provide a continuous fabric over the solution space. In Devaraj and Yegnanarayana (2005), a Genetic Algorithm (GA) based algorithm has been proposed for OPF problem for security enhancement. In this method, line overload is removed by means of generation re-dispatching and adjustment of phase shifting transformer. Recent research shows that the premature convergence of GA (Gaing, 2003) degrades its performance and reduces its search capability. In Somasundram and Kuppusamy (2005) and Venkatesh *et al.* (2003), Evolutionary Programming (EP) based security constrained ELD proposed and the

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Cauchy, mean of Gaussian and Cauchy mutations are not considered. The contingency constraints are not taken into the problem formulation. In Pancholi and Swarup (2002), PSO based security constrained Economic Load Dispatch (ELD) proposed to solve system under normal state (without contingencies). The proposed Particle Swarm Optimization embedded with Evolutionary Programming (PSO-EP) based Contingency Constrained Economic Load Dispatching (CCELD) solution gives the optimal settings of all controllable variables for a static power settings loading condition. CCELD problem for security enhancement is solved using the following techniques and necessary software has been developed using MAT lab:

- Classical Evolutionary Programming (CEP) with gaussian mutation with scaled cost (Sinha *et al*., 2003).
- Fast Evolutionary Programming (FEP) with cauchy mutation with scaled cost (Sinha *et al*., 2003).
- Mean of Classical and Fast Evolutionary Programming (MFEP) with Mean of gaussian and cauchy mutation with scaled cost (Sinha *et al*., 2003).
- Conventional Particle Swarm Optimization (PSO).
- Proposed Particle Swarm Optimization embedded with Evolutionary Programming (PSO-EP).

The results of the proposed PSO-EP method are compared with evolutionary techniques such as CEP, FEP, MFEP and conventional PSO. The results show that the proposed PSO-EP out performs the other methods by giving the optimal solution with zero severity index

Severity index: The severity of a contingency to line overload may be expressed in terms of the following severity index, which express the stress on the power system in the post contingency.

$$\text{Severity index } I_{s1} = \sum_{1 \in L_o}^{n} \left(\frac{S_1}{S_1^{max}} \right)^{2m} \tag{1}$$

The line flows in Eq. (1) are obtained from Newton-Raphson load flow calculations. While using the above security index for security assessment, only the overloaded lines are considered to avoid masking effects. IEEE 30 and 118 bus systems are considered in this work and we have fixed the value of m as 1.

Problem formulation: The formulation of the CCELD problem is a twin objective function (minimization of fuel cost and severity index):

$$\text{Min}F_T(P) + \text{Min}(I_{s1}) \tag{2}$$

During security control, the prime task of the power system operator would be to remove the line overload. Hence, the minimum severity index is taken as the objective function. The minimization problem is subjected to the following constraints:

- Power balance constraint

$$\sum_{i=1}^{n} P_{gi} = P_d + P_l \tag{3}$$

- Power flow equation of the power network

$$g(|v|, \theta) = 0 \tag{4}$$

Where,

$$g(|v|,\theta) = \begin{vmatrix} P_i(|v|,\theta) - P_i^{net} \\ Q_i(|v|,\theta) - Q_i^{net} \\ P_m(|v|,\theta) - P_1^{net} \end{vmatrix} \begin{matrix} \leftarrow \text{For each PQ bus i} \\ \leftarrow \text{For each PV bus m,} \\ \text{not including the ref. bus} \end{matrix}$$

- Inequality constraint on real power generation P_{gi} of each unit i,

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \tag{5}$$

- Inequality constraint on voltage of each PQ bus

$$V_i^{min} \le V_i \text{ (with single line pq out) } \le V_i \tag{6}$$

- Power limit on transmission line

$$MVA_{pq}^{min} \le MVA_{pq}\text{(with single line pq out)}MVA_{pq}^{max} \tag{7}$$

Total fuel cost of generation F_T in terms of control variables on generator powers is expressed as:

$$F_t(P) = \sum_{i=1}^{n} a_i P_i^2 + b_i P_{gi} + c_i \tag{8}$$

Overview of EP and PSO: Four decades earlier EP was proposed for evolution of finite state machines, in order to solve a prediction task. Since then, several modifications, enhancements and implementations have been proposed and investigated. Mutation is often implemented by adding a random number or a vector from a certain distribution (e.g., a gaussian distribution in the case of classical EP (CEP) to a parent. The degree of variation of gaussian mutation is controlled by its standard deviation, which is also known as a 'strategy parameter' in an evolutionary search. Cauchy mutation based EP, called Fast EP (FEP), which demonstrated better performance than CEP in converging to a near global optimum point, but not all FEP successes can be attributed to its greater ability to escape local minima by using cauchy mutation. In MFEP, the weighted mean of gaussian and cauchy mutation with an objective of having step size greater than gaussion and smaller than cauchy mutations are used, so that advantages of gaussian as well as cauchy mutation are exploited.

PSO is a population based optimization method first proposed by Kennedy and Eberhart (1995). According to the background of PSO and simulation of swarm of bird, Kennedy and Eberhart (1995) developed a PSO concept. PSO is basically developed through simulation of bird flocking in 2 dimensional spaces. The position of each agent is represented by XY axis position and also the velocity is expressed by Vx (velocity of X axis) and Vy (velocity of Y axis). Modification of the agent (particle) position is realized by the position and velocity information. Bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. This information is analogy of personal experiences of each agent. Moreover, each agent knows the best value so far in the group (gbest) among pbests. This information is analogy of knowledge of how other agents around them have performed. Each agent tries to modify its position using the following information:

- The current position (x, y).
- The current velocities (Vx, Vy).
- The distance between the current position and pbest.
- The distance between the current position and gbest.

This modification is represented by the concept of velocity. Velocity of each agent could be modified by the following equation

$$v_{id}^{t+1} = w * v_i^{(t)} + c_1 * \text{rand}() * (\text{pbest}_{id} - p_{id}) + c_2 * \text{rand}() * (\text{gbest}_d - p_{id}) \tag{9}$$

i =1, 2,........n; d = 1, 2,................ m

Where,

n : The population size.
m : The number of units.
w : Value is set using.

$$w = w_{max} - \frac{w_{max} - w_{min}}{\text{iter}_{max}} * \text{iter} \tag{10}$$

Where,

W_{max} = 0.9
W_{min} = 0.4

Using the above equation, a certain velocity, which gradually gets close to pbest and gbest, can be calculated. The current position can be modified by the following equation

$$S_{id}^{t+1} = S_{id}^{t} + V_{id}^{t+1} \tag{11}$$

The first term of the right hand side of Eq. (9) is corresponding to diversification in the search procedure. The second and third terms of that are corresponding to intensification in the search procedure. The PSO method has a well-balanced mechanism to utilize diversification and intensification in the search procedure efficiently.

Proposed PSO-EP method: The proposed approach integrates 3 mutation (gaussion, cauchy and mean of gaussion and cauchy) operations of EP search. All the 3 mutation operations are created new searching points from the same parent and better one chosen for next generation. So that, positive features of EP and PSO techniques are exploited.

The search procedure of the proposed PSO-EP method is given.

Step 1: Initialize randomly the individual P_{gi} of the population according to the limit of each unit (except slack bus) including individual dimension, searching points and velocities. Initial velocity limits of each individual is as:

$$V_d^{max} = 0.5P_d^{max}, V_d^{min} = -0.5P_d^{min}$$

Step 2: Compute slack bus vector (Ps), losses and line flows using N-R load flow method with (n-1) lines are considered.

Step 3: To account for slack unit limit violation, branch power flow limit violation and voltage limit violation, the total operating cost is augmented by non-negative penalty terms K_1, K_2 and K_3. Calculate augmented cost using Eq. (12) and severity index calculated using Eq. (1). Augmented cost F_T^*:

$$F_T^* = F_T + K_1 * \sum^{n1} \left(I_i - I_i^{max}\right)^2 + K_2 * \left(P_{g1} - P_{g1}^{lim}\right)^2 + K_3 \sum_{i=1}^{N} \left(I_{ij} - I_{Li}^{lim}\right)^2 \tag{12}$$

Step 4: Among the population the minimum augmented cost value with minimum severity index is taken as the gbest value. Remaining individuals are assigned as the pbest.

Step 5: Modify the member velocity V of the each individual P_{gi} using Eq. (9) and Eq. (10).

Step 6: Check the limits on velocity using Eq. (13).

$$\begin{aligned}&\text{If } V_{id}^{(t+1)} > V_{d}^{max}, \text{then } V_{id}^{(t+1)} = V_{d}^{max}\\&\text{If } V_{id}^{(t+1)} > V_{d}^{min}, \text{ then } V_{id}^{(t+1)} = V_{d}^{min}\end{aligned} \tag{13}$$

Step 7: Modify member position of each individual P_{gi} using Eq. (14)

$$Pg_{id}^{(t+1)} = Pg_{id}^{(t)} + V_{id}^{(t+1)} \tag{14}$$

Step 8: $Pg_{id}^{(t+1)}$ is to satisfy the capacity limits of the generator and it is given by Eq. (15).

$$\begin{aligned}&\text{If } Pg_{id}^{(t+1)} < Pg_{id}^{max} \text{ then, } Pg_{id}^{(t+1)} = Pg_{id}^{max}\\&\text{If } Pg_{id}^{(t+1)} < Pg_{id}^{min} \text{ then, } Pg_{id}^{(t+1)} = Pg_{id}^{min}\end{aligned} \tag{15}$$

Step 9: Modified member positions in step 8 are taken as initial value for N-R load flow with (n-1) lines. Calculate the augmented fuel cost using Eq. (12) and severity index using Eq. (1).

Step 10: Among the population the minimum augmented fuel value with minimum severity index is taken as the gbest value. Remaining individuals are assigned as the pbest. If the current gbest value is better than the gbest value in Step 4 current value is set to the gbest. If the current pbest value is better than the pbest value in Step 4 current value is set to pbest.

Step 11: $Pg_{id}^{(t+1)}$ is created from each individual by adding to each component Pg_{id}, a gaussian random variable with 0 mean and standard deviation proportional to scaled cost values:

$$Pg_{id}^{(t+1)'} = Pg_{id} + N_i\ (0,\ \sigma_i^2) \tag{16}$$

where, N $(0,\sigma i^2)$ represents a gaussian random variable with 0 mean and standard deviation σi,

$$\sigma i = \beta * \frac{f_i}{f_{i\ min}} (Pgi_{max} - Pgi_{min}) \tag{17}$$

Check capacity limits of the generating units using Eq. (15), replacing

$$Pg_{id}^{(t+1)}$$

by

$$Pg_{id}^{(t+1)'}$$

Step 12: Modified member positions in step11 are taken as initial value for N-R load flow with (n-1) lines. Calculate the augmented fuel cost using Eq. (12) and severity index using Eq. (1).

Step 13: Among the population the minimum augmented cost value with minimum severity index is taken as the gbest value. Remaining individuals are assigned as pbest. If the current gbest value is better than the gbest value in Step 10 current value is set to the gbest. If the current pbest value is better than the pbest value in Step 10 current value is set to pbest.

Step 14:

$$Pg_{id}^{(t+1)''}$$

is created using Cauchy mutation (FEP) using Eq. (18).

$$Pg_{id}^{(t+1)''} = Pg_{id} + \sigma_i^2\, C_i(0,1) \tag{18}$$

Ci is a Cauchy random variable with a scale parameter with t = 1 centered at zero.

Check capacity limits of the generating units using Eq. (15), replacing

$$Pg_{id}^{(t+1)}$$

by

$$Pg_{id}^{(t+1)''}$$

Step 15: Modified member positions in step14 are taken as initial value for N-R load flow with (n-1) lines. Calculate the augmented fuel cost using Eq. (12) and severity index using Eq. (1).

Step 16: Among the population the minimum augmented cost value with minimum severity index is taken as the gbest value. Remaining individuals are assigned as pbest. If the current gbest value is better than the gbest value in Step 13 current value is set to the gbest. If the current pbest value is better than the pbest value in Step 13 current value is set to pbest.

Step 17:

$$Pg_{id}^{(t+1)'''}$$

is created using Mean of the gaussian and cauchy mutation using Eq. (19).

$$Pg_{id}^{(t+1)'''} = Pg_{id} + \sigma i/2\{Ci\ (0,1) + Ni\ (0,1)\} \quad (19)$$

Check capacity limits of the generating units using Eq. (15), replacing

$$Pg_{id}^{(t+1)}$$

by

$$Pg_{id}^{(t+1)'''}$$

Step 18: Modified member positions in step17 are taken as initial value for N-R load flow with (n-1) lines. Calculate the augmented fuel cost using Eq. (12) and severity index using Eq. (1).

Step 19: Among the population the minimum augmented cost value with minimum severity index is taken as the gbest value. Remaining individuals are assigned as pbest. If the current gbest value is better than the gbest value in Step 16 current value is set to the gbest. If the current pbest value is better than the pbest value in Step 16 current value is set to pbest.

Step 20: If the iteration reaches the maximum and severity index equal to zero go to step 21, otherwise goto Step 4 and the gbest and pbest values in Step 4 replaced by latest gbest and pbest values from Step 19.

Step 21: Individual that generates the latest gbest value is the optimal generation of each unit with minimum fuel cost and zero severity indexes satisfying all the constraints.

RESULTS AND DISCUSSION

This study presents the detail of results of the study, carried out on IEEE test system for security enhancement. Contingency analysis was conducted under base load conditions to identify the harmful contingencies. Here, top 2 severe contingencies are severe taken for security enhancement. If the algorithm relieves overload on top 2 severe contingencies, then, the algorithm can relieve overload on lines for less severe contingencies. The proposed method and different EP techniques based CCELD algorithm are applied to obtain the optimal control variables in the IEEE 30 and IEEE 118 bus system (1996) under contingency. The upper and lower voltage limits at all the bus except slack bus, were taken as 1.05 and 0.95, respectively. The slack bus bar voltage was fixed to its specified value of 1.06 p.u. The line flows were computed using Newton-Raphson method and line loading limits 120 % of base case were considered. For implementing the EP and PSO methods, population size = 20, maximum number of generations =100. The proposed methods were applied to alleviate overloads under line outage through generator rescheduling. The proposed algorithm code was written in MAT LAB and executed on a PC with a Pentium-IV.

Example 1: Over load alleviation in IEEE 30-bus system: The generator and transmission line data relevant to the system are taken from (Saadat, 1999). Here the contingency is considered for base load condition to identify severe contingencies. The CEP, FEP, MFEP, PSO and proposed PSO-EP methods have been applied to obtain the optimal fuel cost in the IEEE 30 bus system under normal condition. Table 1 Shows that the results of IEEE 30 bus system under normal condition (contingency constraints are not considered). From the contingency analysis, it was found that line outages 1-3 and 3-4 have resulted in overload on other lines. The power flow on the overloaded lines and the calculated value of severity index for each contingency are given in Table 2. Two line outages 1-3 and 3-4 are the severe and the CEP, FEP, MFEP, PSO and proposed PSO-EP methods are applied to alleviate the line overload. All the methods give zero severity indexes but minimum fuel cost obtained in the proposed PSO-EP based CCELD. Results clearly show that the proposed PSO-EP based CCELD algorithm gives minimum fuel cost and zero severity indexes than other EP and PSO methods (Table 3). The generation schedule for various methods is given in Table 4.

Example 2: Over load alleviation in IEEE 118 bus system: In this case, proposed algorithm is used for corrective control under a contingency state. Contingency analysis was conducted under base-load conditions to identify the harmful contingencies. From the contingency analysis, it was found that line outages 8-5 and 64-65 have resulted in overload on other lines. The power flow on the overloaded lines and the calculated value of severity index for each contingency are given in Table 5. In this case, the proposed algorithm was applied to alleviate the line overload under contingency condition in the IEEE 118 bus system. The test system has 54 generator buses and 186 transmission lines (Devaraj and Yegnanarayana, 2005; IEEE 118 bus system, 1996). Contingency analysis was conducted on the system and the top 2 severe-contingency cases are produced in Table 5 along with the overloaded lines and the severity index. The CEP, FEP, MFEP, PSO and proposed PSO-EP based CCELD

Table 1: Summary of IEEE 30 bus system under normal condition

Methods	P1 (MW)	P2 (MW)	P3 (MW)	Losses (MW)	Optimum fuel cost ($\$ h^{-1}$)
CEP	118.81	79.34	96.22	10.78	1186.9
FEP	114.59	77.36	99.26	7.82	1184.8
MFEP	112.08	78.59	100.48	7.78	1184.5
PSO	95.58	96.74	98.42	7.49	1199.3
Proposed PSO-EP	129.19	66.27	96.20	8.28	1185.2

Table 2: Base-case solution of IEEE 30 bus system

Line outage	Over load line	Line flow (MVA)	Line flow limit (MVA)	Severity index
1-3	1-2	270.86	125	7.584
	2-4	86.623	75	
	2-6	93.527	75	
3-4	1-2	267.94	125	7.414
	2-4	85.391	75	
	2-6	92.570	75	

Table 3: Summary of results of IEEE 30 bus system with contingency constraints

Methods	Line outage	Min. severity index	Min. fuel cost ($\$ h^{-1}$)
CEP	1-3	0	1241.1
FEP		0	1233.4
MFEP		0	1245.1
PSO		0	1231.4
PSO-EP		0	1223.0
CEP	3-4	0	1229.7
FEP		0	1242.0
MFEP		0	1240.6
PSO		0	1237.0
PSO-EP		0	1227.9

Table 4: Generation Schedule of IEEE 30 bus (line outage of 1-3)

Generation MW	CEP	FEP	MFEP	PSO	Proposed PSO-EP
P1	103.18	117.40	96.07	121.94	97.24
P2	111.13	83.73	92.95	97.40	100.43
P3	80.59	93.10	105.75	75.86	99.11
Losses	11.46	10.89	11.39	11.82	13.49
Minimum fuel cost ($\$ h^{-1}$)	1241.1	1233.40	1245.10	1231.40	1223

Table 5: Base case solution of IEEE 118 bus systems

Outage line	Over loaded line	Line flow (MVA)	Line flow limit (MVA)	Severity index
8-5	12-14	107.20	100	6.2001
	13-15	103.07	100	
	12-16	143.65	130	
	15-17	223.48	200	
	16-17	160.22	130	
64-65	65-66	172.79	100	4.1715
	66-67	108.90	100	

Table 6: Summary of results of IEEE 118 bus with contingency constraints

Methods	Line outage	Minimum severity index	Minimum fuel cost ($\$ h^{-1}$)
CEP	8-5	1.1	22213
FEP		0	23528
MFEP		2.105	23882
PSO		0	22115
PSO-EP		0	22124
CEP	64-65	0	22712
FEP		0	24042
MFEP		0	24045
PSO		0	21996
PSO-EP		0	21945

Table 7: Generation schedule IEEE 118bus (line outage of 8-5)

Generation MW	CzEP	FEP	MFEP	PSO	Proposed
P1	184.97	401.98	420.77	55.0	377.33
P2	134.19	162.26	170.74	180.0	180
P3	314.14	219.64	200.97	320.0	319.99
P4	275.25	400.92	84.84	162.09	40
P5	63.68	43.21	62.2	100	99.99
P6	96.33	89.49	70.92	110	110
P7	250.41	89.06	98.22	300	299.03
P8	110.21	105.57	67.74	150	30
P9	184.06	178.16	244.68	250	250
P10	224.15	225.64	250.23	260	228.19
P11	475.24	213.81	168.04	490	205.95
P12	289.64	243.27	422.47	100	373.16
P13	503.94	632.36	793.89	434.8	305.14
P14	388.74	540.46	476.2	550.0	493.37
P15	44.51	76.79	53.24	100	99.96
P16	509.06	573.54	509.48	209.67	410.32
P17	144.63	80.29	208.04	350	350
P18	132.59	105.28	82.11	140	138.83
P19	73.64	28.61	22.58	130	87.57
Losses	157.37	168.34	165.35	149.6	146.07
Minimum Fuel Cost ($\$ h^{-1}$)	22213	23528	23882	22115	22124

algorithm was applied to reschedule the generator output with objective function of minimum fuel cost and minimum severity index. Table 6 clearly shows that the proposed PSO-EP based algorithm gives best results than the other EP and PSO techniques. Table 7 shows that generation schedule of IEEE 118 bus system using various methods.

CONCLUSION

This study has proposed EP and PSO techniques based Contingency Constrained Economic Load Dispatch. The application of these tools for scheduling the power system during contingencies has been presented. The line overloads were relieved through rescheduling of the generators with minimum fuel cost. The proposed PSO-EP based algorithm yields better results than the other methods and stable convergence. The proposed PSO-EP based algorithm well suitable for obtaining the solution of CCELD problem.

Appendix A: List of symbols

P_i, Q_i : Calculated real and reactive powers for PQ bus i.
P_i^{net}, Q_i^{net} : The specified real and reactive powers for PQ bus i.
P_i, P_i^{net} : The calculated and specified real powers for PV bus m.
$|V|$, ϕ : Voltage magnitude and phase angles of different buses.
$P_{gi}^{min}, P_{gi}^{max}$: Minimum and Maximum value of real power allowed at generator I.
I_{s1} : Flow in line l (MVA)

S_l^{max} : Rating of the line l (MVA)
L_o : Set of overloaded lines
P_{gi}^{min} : $\sum_{i=1}^{n} P_{gi}^{max},\ P_d^{max} = \sum_{i=1}^{n} P_i^{max}$
V_i^{min}, V_i^{max} : Minimum and Maximum voltage at bus i.
$MVAf_{p,q}^{max}$: Maximum rating of transmission line connecting bus p and q.
K_1 : Line loading penalty factor
K_2 : Penalty factor for slack bus generation.
K_3 : Penalty factor for bus voltages
a_i, b_i, c_i : Cost co-efficient
t : Pointer of iterations.
C1, C2 : acceleration constant is equal to 2.
Rand (), rand () : uniform random value (0, 1).
$V_i^{(t)}$: Velocity of the particle i at iteration t.
S_i^t : Current position of particle i, at iteration t.
$iter_{max}$: Max number of iterations (generations).
iter : Current iteration number.

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