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Solution to Non-Convex Economic Power Dispatch Problems with Generator Constraints by Charged System Search Algorithm

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Abstract – *Today along with an increase in the need for electrical energy, economic power dispatch problem has become one of the most important issues in the operation of power systems. In this study, the solution of the economic power dispatch problems with valve point effects and prohibited operating zones which consider ramp rate limits of the generators as well as the present power limits have been found by the charged system search (CSS) algorithm. In the solution of the problems, the transmission line losses have been calculated by using B loss matrices.*

The CSS method has been applied to the 15 generator test system in literature for economic power dispatch problem with prohibited operating zones and power generation limit and it has been applied to 30 bus 6 generator (IEEE) test system in literature for non-convex economic power dispatch problem with valve point effect under different constraints. The best solution values found for both of the test systems have been compared with the solution values found by the application of different methods in literature and the results have been discussed.

***Keywords**: Non-Convex Economic Power Dispatch, Prohibited Operating Zones, Ramp-Rate Limits, Valve-Point Effects, Charged System Search Algorithm*

Nomenclature

F_{Total}	Total fuel cost rate, ($/h)
$F_i\left(P_i\right)$	Fuel cost rate of the i^{th} generation unit, ($/h)
P_i	Active generation of the i^{th} unit, (MW)
P_i^{min}, P_i^{max}	Lower and upper active generation limits of the i^{th} unit respectively, (MW)
DR_i, UR_i	Fall and rise active generation limits of the i^{th} unit respectively, (MW)
P_{load}, P_{loss}	Total system active load and loss respectively, (MW)
pz_i	The number of the prohibited operating zone of the i^{th} generation unit
a_i, b_i, c_i	The cost function coefficients of the i^{th} generation unit
e_i, f_i	The i^{th} generation unit cost function coefficients showing valve point effect
q_i	The amount of magnitude of charge for each CP
p_{ij}	Determines the probability of each CP's movement towards the others
k_a	The acceleration coefficient
k_v	The velocity coefficient

I. Introduction

The increasing need for the electrical power increases, day by day, the significance of the economic power dispatch problem that must be solved in order to make the power generation units operate more efficiently. The fact that the cost of the fuel used in power generation reaches a considerable amount on generation costs leads companies that generate power to use the fuel more efficient. Thence, economical operations of the power generation systems have come into question. Economic power dispatch problem is known as the meeting of the present load in the system by the generation units under system limits with the minimum total fuel cost. In the solution of these kinds of problems, the solution of the problems are simplified by ignoring some limits such as ramp rate limits belonging to generators, prohibited operating zones and valve-point effects. These kinds of problems are known as simplified economic power dispatch problems partially carrying the characteristics of the real problems. Therefore, with the addition of the aforementioned limits economic power dispatch problems become much closer to real problems. In this way, economic power dispatch problems with additional limits are transformed to non-linear optimization problems with more limits. The non-convex economic power dispatch problems with prohibited operating zones and valve point effect are nonlinear problems the optimal solution of which is rather difficult to find.

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In the literature search, particle swarm optimization and improved particle swarm optimization algorithms (NAPSO, FAPSO, MPSO, IPSO, PSO, APSO, SPSO, PC-PSO, SOH-PSO, DSPSO-TSA, SA-PSO) [1]-[8], improved honey bee mating optimization algorithm (HBMO, IHBMO) [9], genetic algorithm (GA) [10], evolutionary programming (EP) [11] and fast computation evolutionary programming algorithms (QEA, IQEA) [12], mixed integer quadratic programming approach (MIQP) [13], artificial immune system optimization algorithm (AIS) [14], simulated annealing (SA), tabu search (TS) and multiple tabu search (MTS) algorithms [15], differential evolution (DE) [16] and modified differential evolution algorithms (MDE) [17], artificial bee colony optimization method (ABC) [18] and civilized swarm (CSO), society-civilization optimization algorithm (SCA) [19] and direct search method (DSM) [20] have been applied to nonlinear economic power dispatch problems with prohibited operating zones.

In literature non-convex valve point effect economic power dispatch problems have been solved with many new hybrid search optimization algorithms (MSG-HS, GA-APO, NSOA, UHGA, GA-PS-SQP, FCASO-SQP, SOA-SQP) [21]-[26], differential evolution and modified differential evolution algorithms (DE, SADE-ALM, MDE, CDE) [27]-[31], particle swarm optimization and improved particle swarm optimization algorithms (PSO, APSO, GCPSO, MPSO) [32]-[36], artificial bee colony optimization method (ABC) [37], [38], evolutionary programming and improved evolutionary programming algorithms (EP, IEP) [39], genetic algorithm and improved genetic algorithm approaches (GA, IGA-MU, CGA-MU, SARGA) [40], [41], self-organizing migrating strategy and cultural self-organizing migrating strategy optimization methods (SOMA, CSOMA) [42], chaotic shuffle frog leaping algorithm (CMSFLA) [43], modified group search optimizer method (MGSO) [44], dynamic adaptive bacterial foraging algorithm (DABFA) [45], mixed integer linear programming (MILP) [46], tabu search and multiple tabu search algorithms (TS, MTS) [47], enhanced cross-entropy method (ECE) [48], artificial immune system optimization algorithm (AIS) [49], pattern search method (PS) [50] and gravitational search algorithm (GSA) [51].

In this study, the charged search system (CSS) algorithm has been used for the solution of the economic power dispatch problem with prohibited operating zones and power generation limit, and for the solution of the non-convex economic power dispatch problem with valve point effect. The CSS algorithm has been applied to both economic power dispatch problems for the first time in this study.

II. Economic Power Dispatch Problem

The solution of economic power dispatch problem is found by the minimization of the total fuel cost under system limits. And, this is the purpose function of the optimization problem given in Eq. (1) [51]:

$$min\, F_{Total} = min\sum_{i=1}^{N} F_i\left(P_i\right) \quad \left(\$/h\right) \tag{1}$$

In Eq (1), F_{Total} shows total fuel cost and P_i is taken as MW. The fuel cost function belonging to the thermal generation units has been shown in Fig. 1.

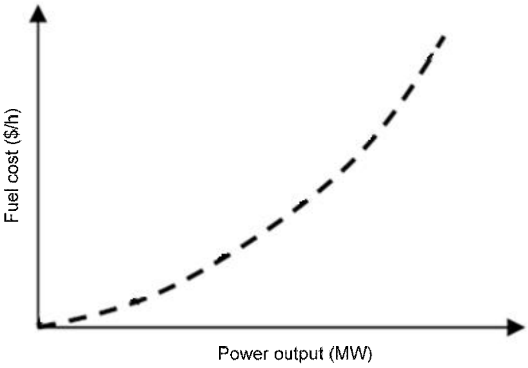

Fig. 1. The fuel cost function of the normal generation units

The graphic shown in the figure is a convex fuel cost function and as represented in equation (2). It has been taken as second-order degrees function of active power generation for each unit [1], [53]:

$$F_i\left(P_i\right) = a_i + b_i P_i + c_i P_i^2 \quad \left(\$/h\right) \tag{2}$$

In the equation, $F_i\left(P_i\right)$ shows the fuel cost function of the i^{th} generation unit, a_i, b_i and c_i show respectively the cost function coefficients of the i^{th} generation unit, and P_i shows the output power of the i^{th} generation unit.

The power equality limit in the lossy system has been taken as in Eq. (3):

$$\sum_{i=1}^{n} P_i - P_{load} - P_{loss} = 0 \tag{3}$$

The operation border values of the thermal generation units have been given in Eq. (4):

$$P_i^{min} \le P_i \le P_i^{max} \tag{4}$$

The power losses of the system occurring in the transmission line are calculated with B loss matrices by using equation (5) [1], [21], [52], [53]:

$$P_{loss} = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i \cdot B_{ij} \cdot P_j + \sum_{i=1}^{n} B_{0i} \cdot P_i + B_{00} \tag{5}$$

The expressions between equation (1) and (5) are the equations valid for both economic power dispatch problems which have been solved in the study. The expressions used for the different limits added to the problems have been given additionally in the following parts.

II.1. Economic Power Dispatch Problem with Prohibited Operating Zones and Ramp Rate Limits

The solution of economic power dispatch problem with prohibited operating zones which considers the ramp rate limits of the generators as well as the present power limits is found by the minimization of the total fuel cost under system limits. Since there are prohibited zones in these kinds of problems where generation cannot be carried out, the cost curve increases as broken oscillations as is seen in Fig. 2 [1], [2].

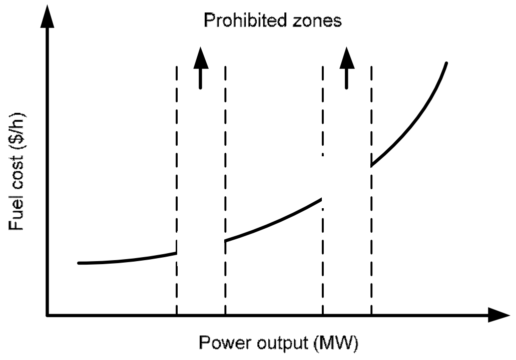

Fig. 2. The fuel cost function of the generation units with prohibited operating zones

In this problem, different from the traditional economic power dispatch problem, the sudden ramp rate limit of the output power of the generators happen in defined limits. Thus, the generation units cannot be decreased or increased to any operation value out of these limits. Therefore, the transmissions between the operation values of all generation units depending on the system are limited by the ramp rate limits given in Eq. (6) [1]-[4]:

$$P_i^0 - P_i \le DR_i \quad \text{ve} \quad P_i - P_i^0 \le UR_i \tag{6}$$

In the equation, P_i^0 shows the power that the generation unit generated in the previous step, DR and UR shows the fall and rise border values respectively. When the ramp rate limit values belonging to generation values are applied to operation border values of the units given in equation (4), equation (4) turns into the following equation:

$$\begin{gathered} max\left(P_i^{min}, P_i^0 - DR_i\right) \le P_i \le min\left(P_i^{max}, P_i^0 + UR_i\right) \\ i = 1,2,\ldots,N_G \end{gathered} \tag{7}$$

In the economic power dispatch problems with prohibited operating zones broken fuel cost curves shown in Fig. 2 are used. Thence, in the solution of the economic power dispatch problem with prohibited operating zones the operation border values of the generation units in equation (4) are used as shown in Eq. (8) [2]:

$$P_i \in \begin{cases} P_i^{min} \le P_i \le P_{i,1}^l \\ P_{i,j-1}^u \le P_i \le P_{i,j}^l \quad j = 2,3,\ldots,pz_i \\ P_{i,pz_i}^u \le P_i \le P_i^{max} \end{cases} \tag{8}$$

In the equation, $P_{i,j}^u$, $P_{i,j}^l$ show respectively lower and upper limits of the prohibited operating zones of the i^{th} generation units as MW and pz_i shows the number of the prohibited operating zone of the i^{th} generation unit.

II.2. Non-Convex Economic Power Dispatch Problem with Valve-Point Effects

When the input-output curve of the non-convex economic power dispatch problem with valve point effect is compared with the equality in equation (2), it is very different. The inclusion of the valve point effect as well to the fuel cost of the generation unit makes the presentation of the fuel cost more appropriate. For the non-convex economic power dispatch problem with valve point effect the fuel cost function belonging to generation units has been shown in Fig. 3 [24].

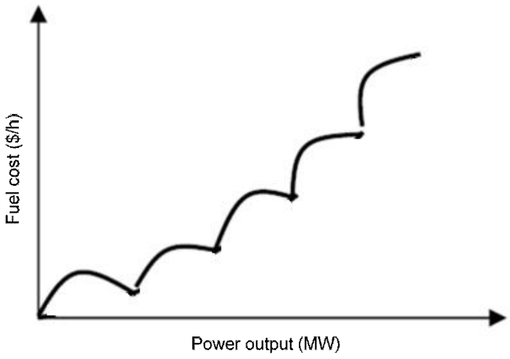

Fig. 3. The fuel cost function of the generation units with valve point effect

As shown in Fig. 3, since valve point results in sinusoidal surges, the fuel cost function contains non-linear higher arrays. Therefore, in the studies done to be able to consider the valve point effects instead of equation (2), the non-convex cost function in the following equation has been used. [21], [24], [53]:

$$\begin{gathered} F_i\left(P_i\right) = a_i + b_i P_i + c_i P_i^2 + \\ + \left| e_i \cdot sin\left(f_i\left(P_i^{min} - P_i\right)\right)\right| \ \left(\$/h\right) \end{gathered} \tag{9}$$

here, different from the Eq. (2), e_i and f_i are the i^{th} generation unit cost function coefficients showing valve point effect.

III. The Charged Search System Algorithm

Charged System Search (CSS) algorithm has been proposed for the first time by Kaveh and Talatahari in 2010 [54]. This algorithm is growing and its application is extending various optimization problems. The charged system search algorithm (CSS) depends on Coulomb and Gauss laws and movement governing motion laws of Newtonian mechanics.

This algorithm can be considered as a multi-agent approach in which each agent is a charged particle (CP). Each CP is assumed as a sphere with radius a and having a proper charge density and can be expressed as below [54]-[65]:

$$q_i = \frac{fit(i) - fitworst}{fitbest - fitworst}, \ i = 1,2,...,N \tag{10}$$

In the expression, $fitbest$ and $fitworst$ are the best and worst fitness value of all particles; $fit(i)$ is the fitness of agent i; and N is the total number of CPs.

The initial positions of CPs in search space are determined randomly and equation (11) is used for determination:

$$x_{i,j}^{(o)} = x_{i,min} + rand_{ij}\left(x_{i,max} - x_{i,min}\right), \ i = 1,2,...,N \tag{11}$$

In this equation, $x_{i,j}^{(o)}$, determines the initial value of i^{th} variable for j^{th} CP; $x_{i,\min}$ and $x_{i,\max}$ are the minimum and the maximum allowed values for i^{th} variable; $rand_{ij}$ is a randomly generated number within the interval $[0,1]$. The initial velocities of charged particles are taken as below:

$$v_{i,j}^{(o)} = 0, \ i = 1,2,...,N \tag{12}$$

Each CP applies a force on other CPs according to Coulomb law. The magnitude of this force is proportional with the distance between CPs for the CP within the sphere while it is inversely proportional with square of the distance between particles for a located CP outside the sphere.

These forces may come out as attracting or repelling and can be found with the ar_{ij} force parameter defined as below:

$$ar_{ij} = \begin{cases} +1 & k_t < rand_{ij} \\ -1 & k_t > rand_{ij} \end{cases} \tag{13}$$

The $+1$ value in the expression shows that the force is attracting and the -1 value shows that the force comes out as repelling and k_t is the parameter controlling the effect of force type coming out. Usually the force coming out as attracting, gathers the CPs in a certain area within the search area while the repelling force tries to distribute CPs. p_{ij}, determines the probability of each CP's movement towards the others:

$$p_{ij} = \begin{cases} 1 & \dfrac{fit(i) - fitbest}{fit(j) - fit(i)} > rand \vee fit(i) > fit(j) \\ 0 & else \end{cases} \tag{14}$$

As a result the force coming out can be defined as below:

$$F_j = \sum_{i,i \neq j} \left(\frac{q_i}{a^3} r_{ij} i_1 + \frac{q_i}{r_{ij}^2} i_2 \right) ar_{ij} p_{ij} \left(X_i - X_j \right) \quad \begin{cases} j = 1,2,...,N \\ i_1 = 1, \ i_2 = 0 \Leftrightarrow r_{ij} < a \\ i_1 = 0, \ i_2 = 1 \Leftrightarrow r_{ij} > a \end{cases} \tag{15}$$

where, F_j is the resultant force value acting on j^{th} CP; r_{ij} is the distance between two charged particle and is defined as follows:

$$r_{ij} = \frac{\left\| X_i - X_j \right\|}{\left\| \left(X_i - X_j \right)/2 - X_{best} \right\| + \varepsilon} \tag{16}$$

where, X_i and X_j, are the positions of i^{th} and j^{th} CPs respectively. X_{best} is the position of best current CP and ε is a small positive number taken to prevent singularity. As a result the resultant forces and motion laws determine the new positions of CPs. At this stage each CP moves towards its new position with the influence of occurring forces and its previous velocity as below:

$$X_{j,new} = rand_{j1} \cdot k_a \cdot \frac{F_j}{m_j} \cdot \Delta t^2 + + rand_{j2} \cdot k_v \cdot V_{j,old} \cdot \Delta t + X_{j,old} \tag{17}$$

$$V_{j,new} = \frac{X_{j,new} - X_{j,old}}{\Delta t} \tag{18}$$

where, k_a is the acceleration coefficient; k_v is the velocity coefficient controlling the influence of the previous velocity; $rand_{j1}$ and $rand_{j2}$ are two random numbers distributed to the sequence uniformly within $[0,1]$ interval. If each CP moves out of the search space, its position is corrected by handling approach based on harmony search. Besides charged memory is used for recording the best results. The flowchart of CSS algorithm has been given in Fig. 4 [55].

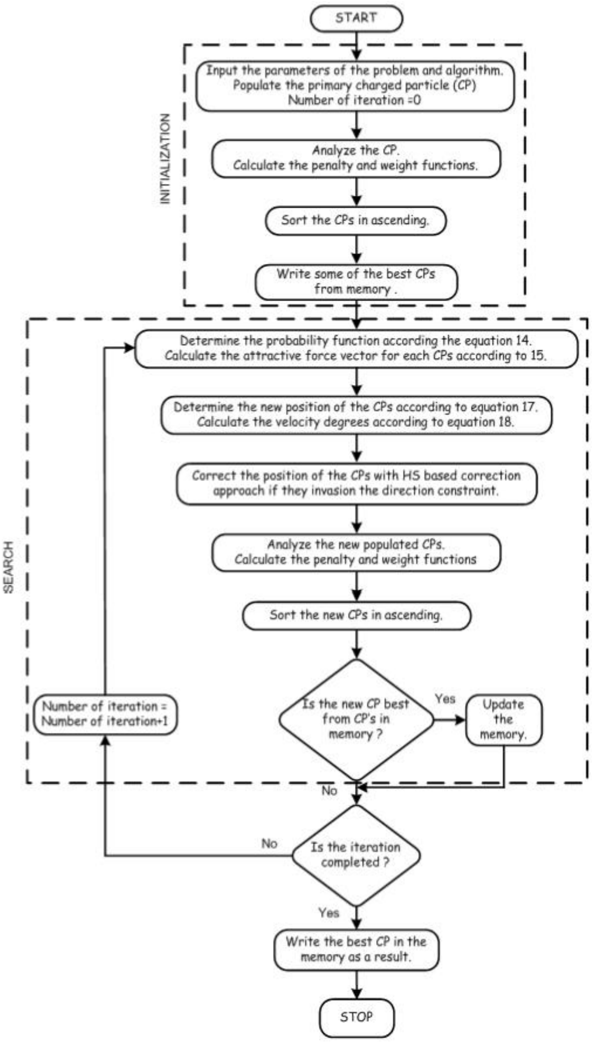

Fig. 4. The flowchart of the CSS

IV. The Application of the CSS Algorithm to the Economic Power Dispatch Problems

In this section the application of the CSS algorithm to the economic power dispatch problems has been told.

At first, all charged particles are formed randomly. For the determined total charged particle number (N), $P_i,\ i \in N_G$ values with i parameter are assigned randomly by using the equation below. The assigned values are in $N_G - 1$ number [2]:

$$P_i = P_i^{min} + rand\left[0,1\right] \times \left(P_i^{max} - P_i^{min}\right) \tag{19}$$

In this equation, $rand\ [0,1]$ is a random number distributed uniformly between zero and one. In order to provide the active power equality limit given in equation (3) it is important to form CPs. Therefore, the l^{th} depended generator (swing bus), the generation power of which is P_l is selected randomly. The value of the depended generator power P_l^{old} is taken as $P_{loss}^{old} = P_{loss}^{first} = 0$ and calculated by using equation (20) [1], [10]:

$$P_l^{old} = P_{load} + P_{loss}^{old} - \sum_{i \in N_G, l \notin N_G} P_i \tag{20}$$

After finding P_l^{old}, P_{loss}^{new} is calculated from equation (5). According to this, the value of P_l^{new} is calculated again from the following equation:

$$P_l^{new} = P_l^{old} + P_{loss}^{new} - P_{loss}^{old} \tag{21}$$

At the end of the transaction, the error tolerance is controlled from equation (22), and when E is under TOL_E value, the fault rate determined in equation (3) is provided. In a way, loss minimization is also done in these transactions:

$$E = \left| P_{loss}^{new} - P_{loss}^{old} \right|, \quad E \le TOL_E \tag{22}$$

In this case, it is checked if P_l^{new} value provides the Eq. (4) constraint. If it does, the objective function value is computed by using these solution values proposed by CP, and thus the first place where the CP will be sent has been determined. If Eq. (4) constraint isn't provided, equation (19) equality is turned back and random assignment transaction is repeated. These steps are repeated until the number of the charged particle in N number, which is proper to all constraints, is completed.

Thus, the initial pool composed of CPs in N number has been formed. After the initial pool is formed, the transaction steps of CSS algorithm is moved on to.

First of all, the fitness of all CPs in the initial population is calculated. The separation distance between them (r_{ij}) is computed according to equation (16), the probability of their moving towards each other (p_{ij}) is computed according to equation (14). Then, for the j^{th} CP in the system, the resultant force is calculated by using equation (15). Each CP in the population moves towards its new position with the resultant forces and its previous velocity.

Their new position and velocity values are determined respectively according to equation (17) and (18). When the CPs in N number are put into their new positions, it is controlled if the proposed solution of each CP provides the equation (4) constraint.

If it does, an iteration has been completed by calculating the new fitness values. If the newly found solution (CP) violates the constraints, the values are pulled to the borders according to equation (23), and the transaction is completed by calculating the fitness of the new CPs again:

$$P_i = \begin{cases} P_i^{min} & if \quad P_i < P_i^{min} \\ P_i^{max} & if \quad P_i > P_i^{max} \end{cases} \tag{23}$$

In the present study, along with all the transactions mentioned, the solutions obtained for the economic power dispatch problem with prohibited operating zone at the end of every iteration have been checked if they have provided the equation (7) constraint. If the constraint has been provided, the transactions have been carried on, if it has been violated, the transaction has been completed by pulling the obtained solutions to the borders by hand.

These steps are repeated until the determined iteration number is completed. In this study, maximum iteration number has been determined as stopping criterion. When this number is reached, the algorithm is stopped and the individual with the highest compatibility is accepted as the solution.

V. Sample Problem Solutions

The CSS algorithm has been applied to 15 generator test system with prohibited operating zone and power generation limit present in literature for $P_{load} = 2630 \ MW$ load demand, and it has been applied to 30 bus 6 generator (IEEE) non-convex test system with valve point effect for $P_{load} = 283.4 \ MW$ load demand. In the present study, the fault tolerance in equation (20) has been taken as $TOL_E = 1 \times 10^{-3} \ MW$.

The values used in the solution of both problems; the CSS parameters total charged particle number has been taken as $N = 25$, acceleration coefficient as $k_a = 0.5$, velocity coefficient as $k_v = 0.5$, control parameter as $k_t = 0.8$ an undefined expression has been taken as $\varepsilon = 10^{-6}$. 100 iteration number has been determined as algorithm stopping criterion.

V.1. Economic Power Dispatch Problem with Prohibited Operating Zones and Ramp Rate Limits

15 generator test system has been solved 50 times with the CSS algorithm for $P_{load} = 2630MW$ load demand. The cost function coefficients used in the problem, ramp-rate and active power generation limits have been given in Table I; B loss matrix values used in the calculation of the energy transmission line losses have been given in Table II and prohibited operating zones have been given from MW type in Table III. [1], [2], [5].

In the solutions done 50 times the total fuel cost values obtained by CSS algorithm for 15 generator test system have been shown in Fig. 5.

After the application of the CSS to 15 generator test system, the obtained changes of the total fuel cost according to iteration numbers have been given in Figure 6, changes of the generated powers according to iteration numbers have been given in Fig. 7 and changes of the transmission line losses according to iteration numbers have been given in Fig. 8 respectively.

For the application of the CSS algorithm to both test systems, a program in MATLAB R2010a software has been developed. This program has been run on a computer with Intel Core i7-2760QM 2.40 GHz processor and 8 GB RAM memory.

Maximum and minimum fuel cost values obtained by the application of the CSS to 15 generator test system 50 times, the generation powers in which these values have been obtained, transmission line losses and the time in which these values have been obtained, have been given in Table IV.

TABLE I
THE COST FUNCTION COEFFICIENTS OF THE GENERATION UNITS, RAMP-RATE AND ACTIVE POWER GENERATION LIMITS (CASE I)

Bus No	a	b	c	UR (MW/h)	DR (MW/h)	P^0 (MW)	P^{min} (MW)	P^{max} (MW)
1	0.000299	10.1	671	80	120	400	150	455
2	0.000183	10.2	574	80	120	300	150	455
3	0.001126	8.8	374	130	130	105	20	130
4	0.001126	8.8	374	130	130	100	20	130
5	0.000205	10.4	461	80	120	90	150	470
6	0.000301	10.1	630	80	120	400	135	460
7	0.000364	9.8	548	80	120	350	135	465
8	0.000338	11.2	227	65	100	95	60	300
9	0.000807	11.2	173	60	100	105	25	162
10	0.001203	10.7	175	60	100	110	25	160
11	0.003586	10.2	186	80	80	60	20	80
12	0.005513	9.9	230	80	80	40	20	80
13	0.000371	13.1	225	80	80	30	25	85
14	0.001929	12.1	309	55	55	20	15	55
15	0.004447	12.4	323	55	55	20	15	55

TABLE II
B LOSS MATRIX VALUES (CASE I)

B-coefficients

$$[B] = 0.001 * \begin{bmatrix} 1.4 & 1,2 & 0,7 & -0,1 & -0,3 & -0,1 & -0,1 & -0,1 & -0,3 & -0,5 & -0,3 & -0,2 & 0,4 & 0,3 & -0,1 \\ 1.2 & 1,5 & 1,3 & 0,0 & -0,5 & -0,2 & 0,0 & 0,1 & -0,2 & -0,4 & -0,4 & 0,0 & 0,4 & 1,0 & -0,2 \\ 0.7 & 1,3 & 7,6 & -0,1 & -1,3 & -0,9 & -0,1 & 0,0 & -0,8 & -1,2 & -1,7 & 0,0 & -2,6 & 11,1 & -2,8 \\ -0.1 & 0,0 & -0,1 & 3,4 & -0,7 & -0,4 & 1,1 & 5,0 & 2,9 & 3,2 & -1,1 & 0,0 & 0,1 & 0,1 & -2,6 \\ -0.3 & -0,5 & -1,3 & -0,7 & 9,0 & 1,4 & -0,3 & -1,2 & -1,0 & -1,3 & 0,7 & -0,2 & -0,2 & -2,4 & -0,3 \\ -0.1 & -0,2 & -0,9 & -0,4 & 1,4 & 1,6 & 0,0 & -0,6 & -0,5 & -0,8 & 1,1 & -0,1 & -0,2 & -1,7 & 0,3 \\ -0.1 & 0,0 & -0,1 & 1,1 & -0,3 & 0,0 & 1,5 & 1,7 & 1,5 & 0,9 & -0,5 & 0,7 & 0,0 & -0,2 & -0,8 \\ -0.1 & 0,1 & 0,0 & 5,0 & -1,2 & -0,6 & 1,7 & 16,8 & 8,2 & 7,9 & -2,3 & -3,6 & 0,1 & 0,5 & -7,8 \\ -0.3 & -0,2 & -0,8 & 2,9 & -1,0 & -0,5 & 1,5 & 8,2 & 12,9 & 11,6 & -2,1 & -2,5 & 0,7 & -1,2 & -7,2 \\ -0.5 & -0,4 & -1,2 & 3,2 & -1,3 & -0,8 & 0,9 & 7,9 & 11,6 & 20,0 & -2,7 & -3,4 & 0,9 & -1,1 & -8,8 \\ -0.3 & -0,4 & -1,7 & -1,1 & 0,7 & 1,1 & -0,5 & -2,3 & -2,1 & -2,7 & 14,0 & 0,1 & 0,4 & -3,8 & 16,8 \\ -0.2 & 0,0 & 0,0 & 0,0 & -0,2 & -0,1 & 0,7 & -3,6 & -2,5 & -3,4 & 0,1 & 5,4 & -0,1 & -0,4 & 2,8 \\ 0.4 & 0,4 & -2,6 & 0,1 & -0,2 & -0,2 & 0,0 & 0,1 & 0,7 & 0,9 & 0,4 & -0,1 & 10,3 & -10,1 & 2,8 \\ 0.3 & 1,0 & 11,1 & 0,1 & -2,4 & 1,7 & -0,2 & 0,5 & -1,2 & -1,1 & -3,8 & -0,4 & -10,1 & 57,8 & -9,4 \\ -0.1 & -0,2 & -2,8 & -2,6 & -0,3 & 0,3 & -0,8 & -7,8 & -7,2 & -8,8 & 16,8 & 2,8 & 2,8 & -9,4 & 128,3 \end{bmatrix}$$

$$[B_0] = 0.001 * [-0.1 \quad -0.2 \quad 2.8 \quad -0.1 \quad 0.1 \quad -0.3 \quad -0.2 \quad -0.2 \quad 0.6 \quad 3.9 \quad -1.7 \quad 0.0 \quad -3.2 \quad 6.7 \quad -6.4]$$

$$[B_{00}] = 0.0055$$

TABLE III
PROHIBITED OPERATING ZONES (CASE I)

Bus No	Zone-I	Zone-II	Zone-III
2	[185 - 225]	[305 - 335]	[420 - 450]
5	[180 - 200]	[305 - 335]	[390 - 420]
6	[230 - 255]	[365 - 395]	[430 - 455]
12	[30 - 40]	[55 - 65]	-

The optimal solutions obtained by CSS for 15 generator test system have been given in Table V together with other results in literature. When Table V is examined, it is clearly seen that for 15 generator test system, the minimum total fuel cost values obtained by the algorithm proposed in this study are better than the results in literature. For the 15 generator test system, CSS method has caught approximately 2.2275 $/h less cost value than EA, IQEA and MIQP algorithms which obtain the best results in literature.

V.2. Non-Convex Economic Power Dispatch Problem with Valve-Point Effects

30 bus 6 generator (IEEE) test system has been solved 50 times with CSS method for $P_{load} = 283.4\ MW$ load demand. There are 41 transmission lines and 21 load bus in the test system. The one-line diagram of the system has been given in Fig. 9.

The cost function used in the solution of the test system and active power generation limits have been given in Table VI and B loss matrix values have been given in Table VII [21], [22], [39].

Maximum and minimum fuel cost values obtained by the application of the CSS to 30 bus 6 generator test system 50 times, the generation powers in which these values have been obtained, transmission line losses and the time in which these values have been obtained, have been given in Table VIII.

In the solutions done 50 times the total fuel cost values obtained by CSS algorithm for 30 bus 6 generator test system have been shown in Fig. 10. The graphics obtained by the application of the CSS to 30 bus 6 generator test system and showing the changes of the total fuel cost, the generated powers and the transmission line losses according to iteration numbers have been given in Figs. 11, 12, 13 respectively.

TABLE IV
MAXIMUM AND MINIMUM VALUES OBTAINED FOR 50 TRIALS (CASE I)

Bus No	CSS	
	Min	Max
P_1 (MW)	455.0000	455.0000
P_2 (MW)	455.0000	454.3090
P_3 (MW)	130.0000	130.0000
P_4 (MW)	130.0000	130.0000
P_5 (MW)	234.1410	223.8810
P_6 (MW)	460.0000	457.3560
P_7 (MW)	465.0000	465.0000
P_8 (MW)	60.0000	60.0000
P_9 (MW)	25.0000	25.0000
P_{10} (MW)	29.6018	56.5816
P_{11} (MW)	77.6733	72.6289
P_{12} (MW)	79.9374	72.0790
P_{13} (MW)	25.0000	25.0000
P_{14} (MW)	15.0004	15.0000
P_{15} (MW)	15.0003	15.0000
$\sum P_i$ (MW)	2656.3542	2656.8360
P_{loss} (MW)	26.3430	26.8351
F_{total} ($/h)	32542.742551	32553.393263
Time (sn)	0.8097	0.8446

TABLE V

THE RESULTS IN LITERATURE AND THE OPTIMAL SOLUTION VALUES OBTAINED BY THE PROPOSED CSS (CASE I)

Methods	Best cost ($/h)	Worst cost ($/h)	Average cost ($/h)
NAPSO [1]	32548.585876	32548.5904	32548.5869
FAPSO [1]	32659.794	32676.07	32663.19
MPSO [2]	32738.4177	-	-
IPSO [3]	32709	-	32784.5
PSO [4]	32858	33031	32989
APSO [5]	32742.77	-	32976.6812
SPSO [6]	32798.69	-	-
PC_PSO [6]	32775.36	-	-
SOH_PSO [6]	32751.39	32945	32878
DSPSO_TSA [7]	32715.06	32730.39	32724.63
SA_PSO [8]	32708	-	-
HBMO [9]	32637.6219	32676.07	32663.19
IHBMO [9]	32552.4613	32554.6649	32552.8961
GA [10]	33063.54	33337	33228
EA [11]	32544.97	-	-
QEA [12]	32548.48	32806.89	32679.54
IQEA [12]	32544.97	32699.56	32575.35
MIQP [13]	32544.97	-	32544.97
AIS [14]	32854	32892	32873.25
TS [15]	32762.12	32842.71	32822.84
MTS [15]	32716.87	32796.13	32767.4
SA [15]	32786.4	33028.95	32869.51
ESO [16]	32640.86	32710	32620
DE [16]	32588.865	32641.419	32609.851
MDE [17]	32917.87	33245.54	33066.76
ABC [18]	32707.85	32708.27	32707.95
CSO [19]	32588.9189	32796.7792	32679.8775
SCA [19]	32867.025	33381.0607	33138.302
CSS	**32542.7425**	**32553.3932**	**32548.8942**

TABLE VI

THE COST FUNCTION COEFFICIENTS OF THE GENERATION UNITS AND ACTIVE POWER GENERATION LIMITS (CASE II)

Bus No	1	2	5	8	11	13
a	150.0	25.0	0.0	0.0	0.0	0.0
b	2.00	2.50	1.00	3.25	3.00	3.00
c	0.0016	0.0100	0.0625	0.00834	0.025	0.025
e	50.0	40.0	0.0	0.0	0.0	0.0
f	0.0630	0.0980	0.0	0.0	0.0	0.0
P_{min} (MW)	50	20	15	10	10	12
P_{max} (MW)	200	80	50	35	30	40

TABLE VII

B LOSS MATRIX VALUES (CASE II)

B-coefficients

$$[B]=\begin{bmatrix} 0.0224 & 0.0103 & 0.0016 & -0.0053 & 0.0009 & -0.0013 \\ 0.0103 & 0.0158 & 0.0010 & -0.0074 & 0.0007 & 0.0024 \\ 0.0016 & 0.0010 & 0.0474 & -0.0687 & -0.0060 & -0.0350 \\ -0.0053 & -0.0074 & -0.0687 & 0.3464 & 0.0105 & 0.0534 \\ 0.0009 & 0.0007 & -0.0060 & 0.0105 & 0.0119 & 0.0007 \\ -0.0013 & 0.0024 & -0.0350 & 0.0534 & 0.0007 & 0.2353 \end{bmatrix}$$

$$[B_0]=[-0.0005 \quad 0.0016 \quad -0.0029 \quad 0.0060 \quad 0.0014 \quad 0.0015]$$

$$[B_{00}]=0.0011$$

TABLE VIII

MAXIMUM AND MINIMUM VALUES OBTAINED FOR 50 TRIALS (CASE II)

Bus No	CSS	
	Min	Max
P_1 (MW)	199.5997	199.6018
P_2 (MW)	20.0000	21.5903
P_5 (MW)	23.9210	17.4977
P_8 (MW)	17.8954	25.0861
P_{11} (MW)	17.5657	14.1640
P_{13} (MW)	14.5648	17.8270
$\sum P_i$ (MW)	293.5466	295.7669
P_{loss} (MW)	11.0554	12.3676
F_{total} (R/h)	921.8674	935.1469
Time (sn)	0.525	0.516

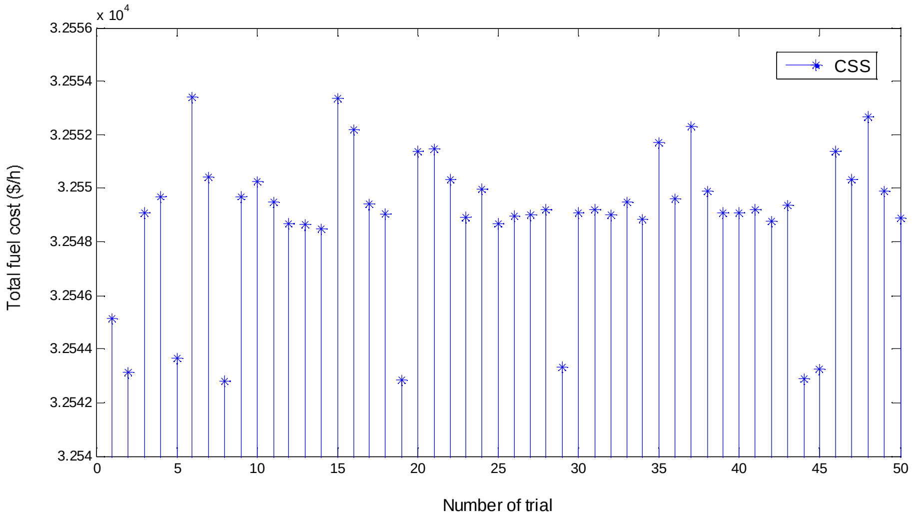

Fig. 5. The total fuel cost values obtained for 50 trials (Case I)

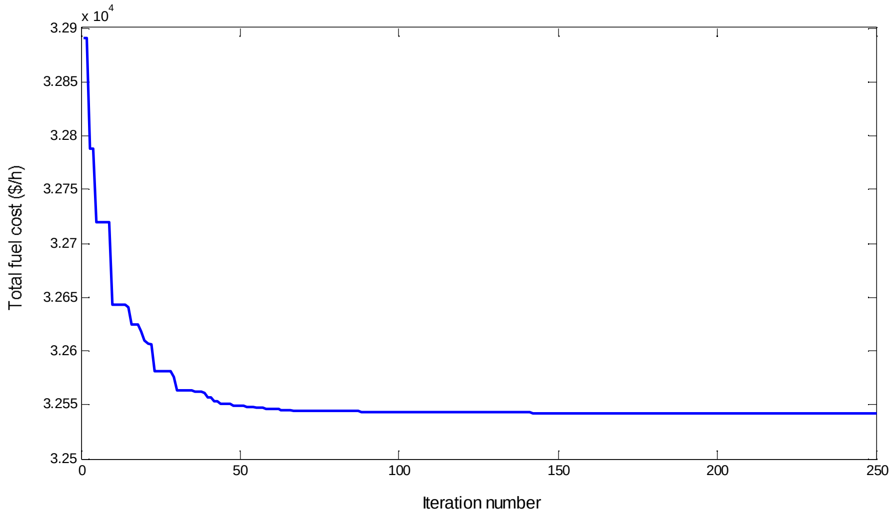

Fig. 6. Changes of the total fuel cost according to iteration numbers (Case I)

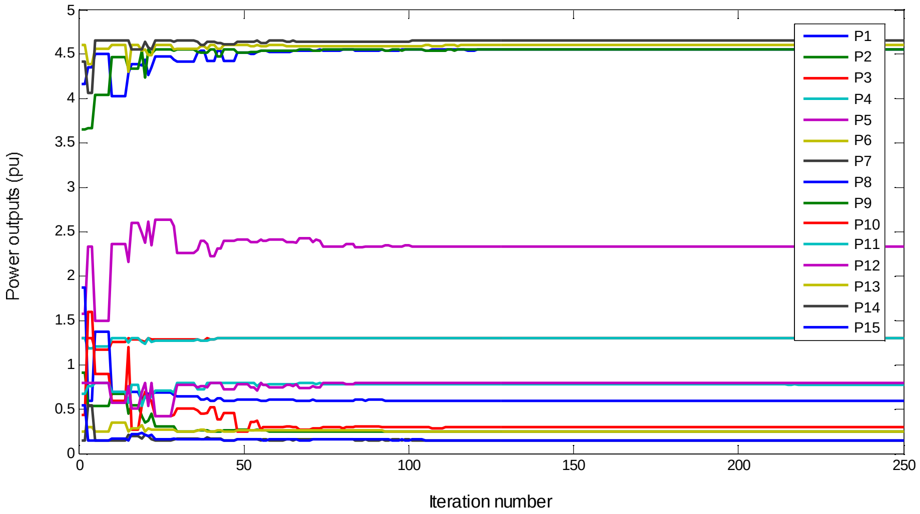

Fig. 7. Changes of the generated powers according to iteration numbers (Case I)

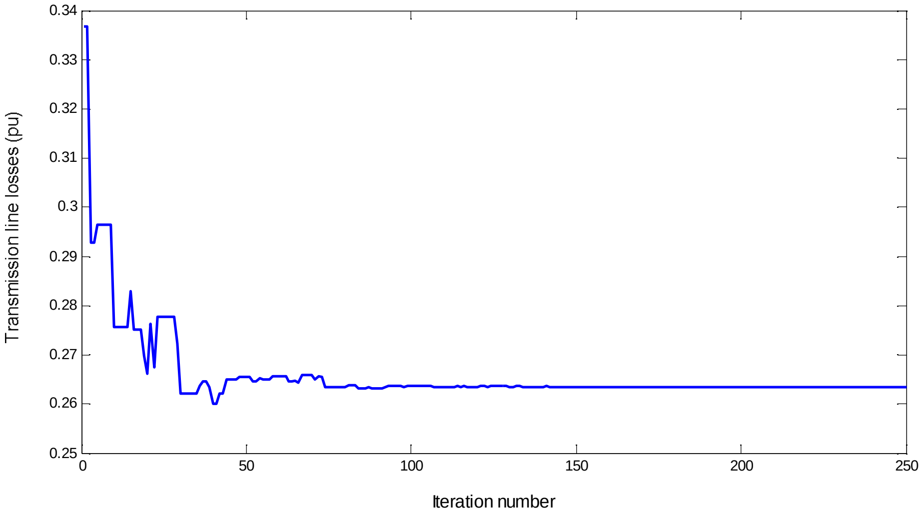

Fig. 8. Changes of the transmission line losses of the system according to iteration numbers (Case I)

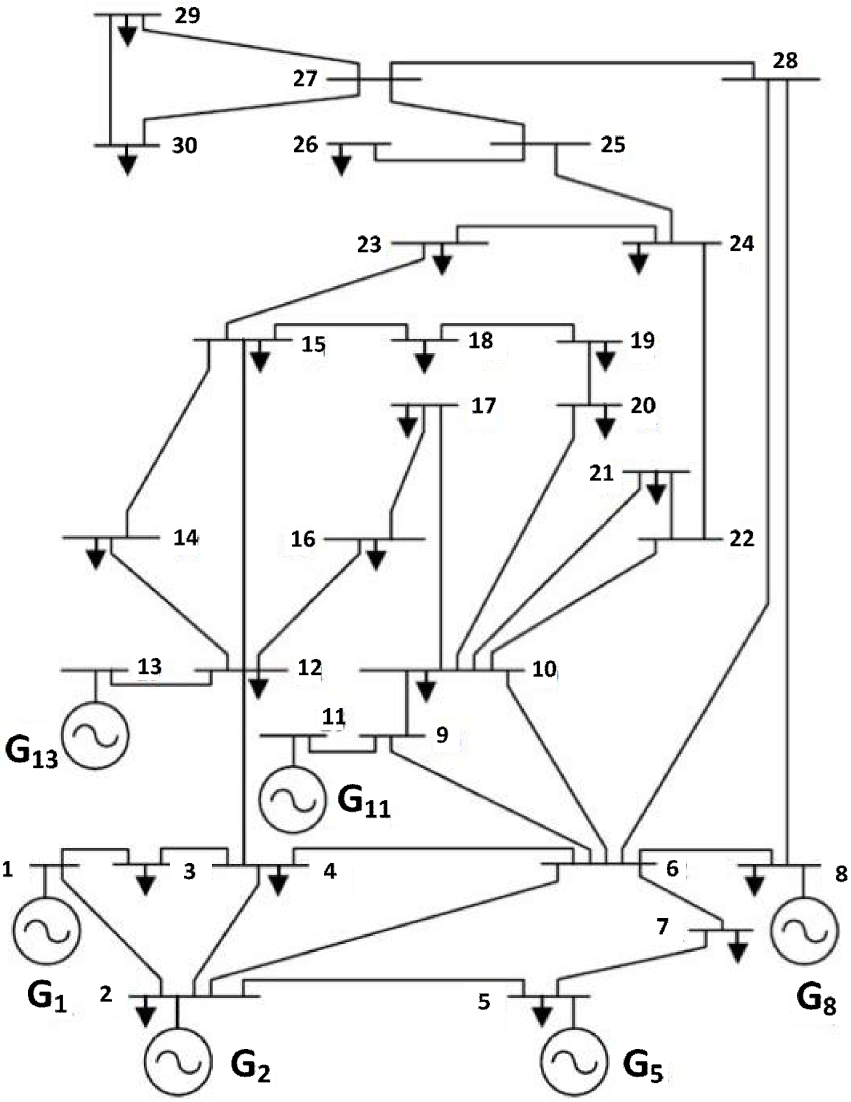

Fig. 9. One-line diagram for the sample power system (Case II)

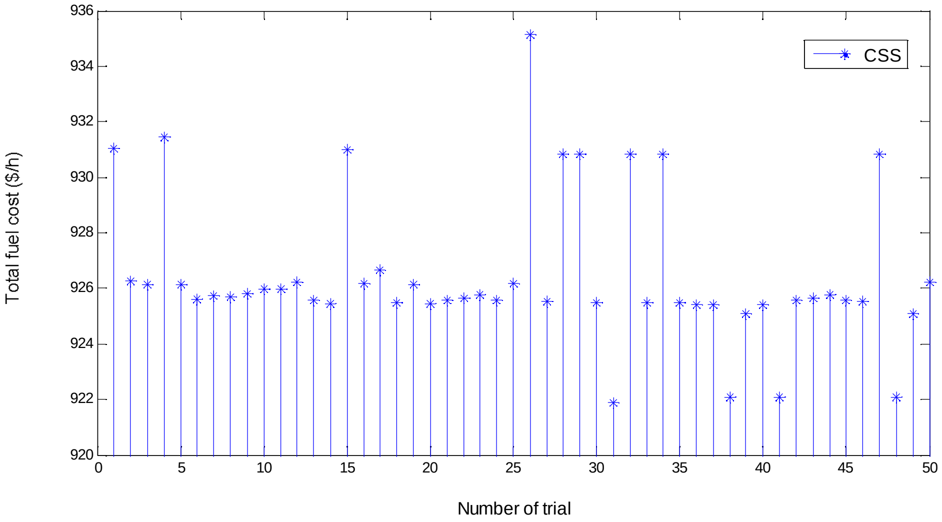

Fig. 10. The total fuel cost values obtained for 50 trials (Case II)

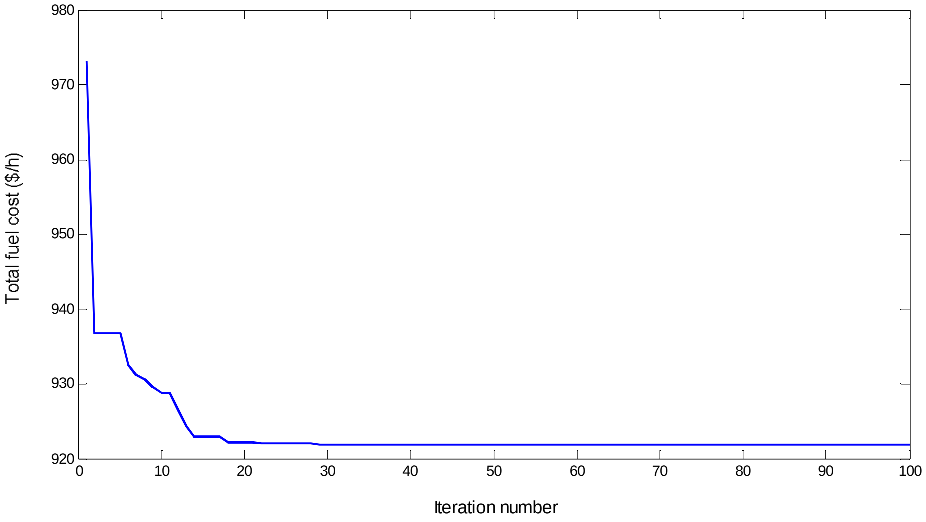

Fig. 11. Changes of the total fuel cost according to iteration numbers (Case II)

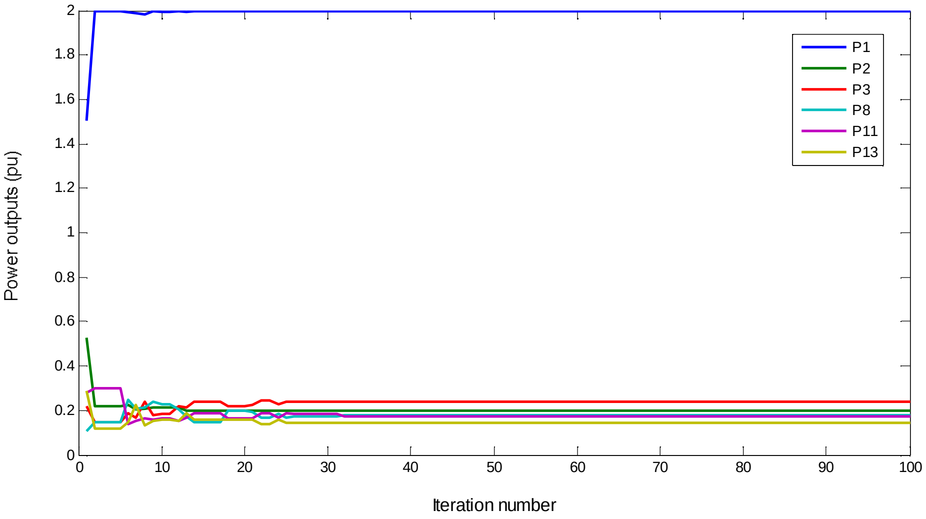

Fig. 12. Changes of the generated powers according to iteration numbers (Case II)

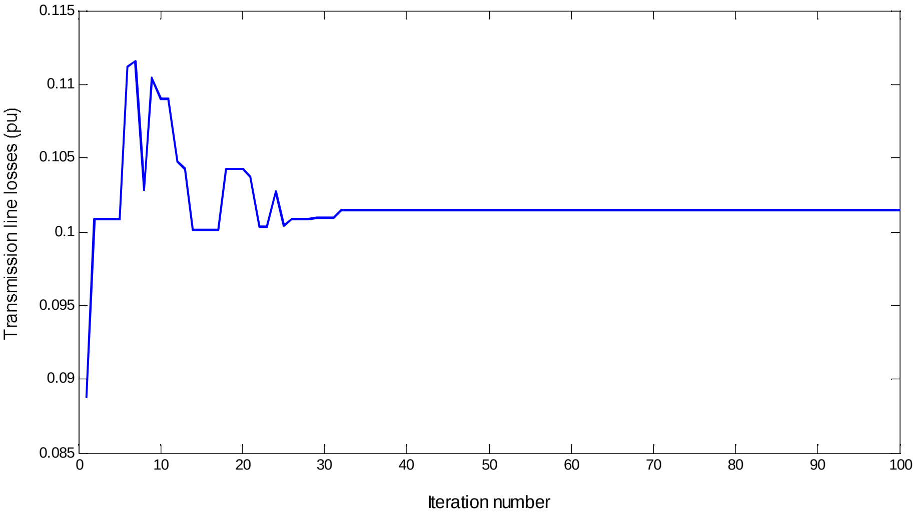

Fig. 13. Changes of the transmission line losses of the system according to iteration numbers (Case II)

The optimal solutions obtained by CSS for 30 bus 6 generator test system have been given in Table IX together with other results in literature.

When Table IX is examined, it is clearly seen that for 30 bus 6 generator test system, the minimum total fuel cost values obtained by the algorithm proposed in this study are better than the results in literature. For the 30 bus 6 generator test system the solution of which has been done, CSS method has caught approximately 3.7736 $/h less cost value than MSG-HS algorithm which is the best result in literature.

TABLE IX
THE RESULTS IN LITERATURE AND THE OPTIMAL SOLUTION VALUES OBTAINED BY THE PROPOSED CSS (CASE II)

Methods	Best Cost ($/h)	Average Cost ($/h)	Worst Cost ($/h)
MSG-HS [21]	925.641	926.851	928.599
GA [22]	996.0369	-	1117.1285
GA-APO [22]	996.0369	-	1101.491
NSOA [22]	984.9365	-	992.4815
DE [27]	963.0010	-	-
SADE_ALM [28]	944.031	954.8	964.794
PSO [32]	925.7581	926.388	928.427
ABC [38]	928.437	-	-
EP [39]	955.508	957.709	959.379
IEP [39]	953.573	956.46	958.263
ITS [39]	969.109	977.17	985.533
TS-SA [39]	959.563	962.889	966.023
TS [47]	956.498	958.456	960.261
CSS	**921.8674**	**926.4595**	**935.1469**

VI. Conclusion

In this study the CSS algorithm has been applied to 15 generator test system for the solution of the economic power dispatch problem with prohibited operating zone and it has been applied to 30 bus test system of IEEE for the solution of the non-convex economic power dispatch problem with valve-point effect. It has been seen that the results obtained by the proposed algorithm have converged to the results in literature and have given better results than many of the compared methods.

The CSS algorithm, which is based on population-base electromagnetic Coulomb and Gauss laws with the basic motion law from Newton mechanic, is a strong algorithm emerged in recent years. In this study, traditional CSS algorithm has been used. The CSS algorithm can be rendered more determined and stronger with various studies done on it.

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