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Economic Dispatch with Line Flow Constraints Using Hybrid PSO and IPSO Techniques

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Abstract *– This paper presents an Improved Particle Swarm Optimization (IPSO) to solve the Economic Dispatch (ED) problem with line flow constraints, bus voltage limits and generator operating constraints. In the proposed IPSO method, a new velocity strategy equation is formulated suitable for large scale system and the features of the Constriction Factor Approach (CFA) are also incorporated into the proposed approach. Different evolutionary programming (EP) techniques such as Classical EP (CEP), Fast-EP (FEP) and Mean of Classical and Fast EP (MFEP) have different features and their combination with PSO may become more effective to find the optimal solution. Combining the advantages of CEP, FEP and MFEP in the PSO method called hybrid PSO. The proposed approach compares the results obtained from hybrid PSO, Conventional Particle Swarm Optimization (PSO), Evolutionary Programming (EP) techniques such as CEP, FEP and MFEP. In this paper, the proposed IPSO, hybrid PSO, PSO and EP techniques such as CEP, FEP, MFEP methods have been tested on IEEE-14, 30, 118-bus and also on 66-bus Indian utility system. Results show that the proposed method is very competent in solving ED problem in comparison with other existing methods.*

Keywords **–** Cauchy mutation, evolutionary programming, Gaussian mutation, line flow constraints, particle swarm optimization.

1. INTRODUCTION

Economic Dispatch (ED) pertains to optimum generation of generating units in an interconnected power system to minimize the cost of generation subject to relevant system constraints. In this paper the line flow and voltage constraints, which are important for any practical implementation of ED, are taken into consideration. In the past, many mathematical programming methods and optimization techniques have been applied to solve the ED problem. These methods include lambda iteration method [1], base point, participation factor, gradient method etc. However, the base case operating constraints line flow limits and load bus voltage magnitude limits are not considered in these methods. Ringlee *et al*. [2] solved a non-convex ED problem using Dynamic Programming (DP) but this has disadvantage, namely the computational requirements of the DP based method depend on the size of the discrete capacity step (10 MW,20 MW) used. With a capacity step 1MW, which is the usual accuracy required in the ED schedule. Dommel *et al.* [3] presented a Non-Linear Programming (NLP) technique to solve Optimal Power Flow (OPF) problem in which the line flow constraints and voltage limits are included. Nanda *et al.* [4] have developed an algorithm to solve the ED problem with line flow constraints using modified coordination equations. Linear Programming methods are fast and reliable, but the main disadvantage is the piece-wise linear cost approximation. NLP methods have a problem of convergence and algorithm complexity.

Stochastic searching algorithms such as Simulate Annealing (SA) [5] and Hopfield neural network methods [6] have also been used to solve the non-convex ED problem. However, these methods require external training routines. Baskar *et al.* [7] proposed a participation factor in conjunction with the Improved Lambda based Genetic Algorithm (GA) to solve ED problem but this has disadvantage that the line flow limits are not considered and it leads to over load on the lines. Though meta heuristic algorithms such as GA have been employed to solve ED problems, recent research has identified some deficiencies in GA performance. The premature convergence of GA degrades its performance and reduces its search capability that leads to a higher probability toward obtaining local minimum. Sinha *et al.* [8] proposed Evolutionary Programming (EP) techniques for ED problem. However, the line flow limits and load bus voltage magnitude limits are not considered in these methods. Venkatesh *et al.* [9] proposed an EP based ED problem with line flow constraints. Somasundram *et al.* [10] proposed a security constrained Economic Dispatch using EP method. Aruldoss *et al.* [11] proposed a modified hybrid EP-Sequential Quadratic Programming (SQP) approach to solve ED problem. In this approach, the best features of EP and SQP are exploited.

Particle Swarm Optimization (PSO), first introduced by Kennedy and Eberhart, is one of the modern heuristic algorithms. It was developed through simulation of a simplified social system, and has been found to be robust in solving continuous non-linear optimization problems. Gaing [12] has presented a PSO technique for ED problem considering the generator

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constraints. The PSO technique can generate high-quality solutions within shorter calculation time and stable convergence characteristics than other stochastic methods. Pancholi *et al*. [13] proposed a PSO for security constrained ED problem. Yoshida *et al*. [14] proposed a PSO for reactive and voltage control (VVC) considering voltage security assessment. The feasibility of their method is compared with Reactive Tabu System (RTS) and enumeration method on practical system, and the results are quite promising. Baskar *et al*. [19] proposed an IPSO method to solve Security Constrained ED problem suitable for Indian utility system and the results obtained from the proposed method are compared with various EP and conventional PSO methods. The suitability of the proposed method is not discussed and investigated on large IEEE systems with and without line flow constraints. Moreover, the results obtained from hybrid PSO method are not compared with the proposed method and other EP methods. In this paper, the performance of the conventional PSO method improved by using hybrid PSO and Improved PSO methods. In hybrid PSO, EP techniques such as CEP, FEP and MFEP are embedded with conventional PSO method and the results are quite encouraging compared with other various EP and PSO techniques. ED problem is solved using the following techniques and necessary software has been developed using MAT lab:

1. CEP with Gaussian Mutation with scaled cost [8]
2. FEP with Cauchy Mutation with scaled cost [8]
3. MFEP with Mean of Gaussian and Cauchy Mutation with scaled cost
4. Conventional Particle Swarm Optimization (PSO)
5. PSO Embedded with CEP, FEP and MFEP (hybrid PSO)
6. Proposed Improved Particle Swarm Optimization (IPSO)

2. PROBLEM FORMULATION

Optimization of cost of generation has been formulated based on classical ED problem with line-flow and voltage constraints. For a given power system network the fuel cost is minimized with the following constraints.

Subject to the following constraints:

$$Min\ F_T(P) = \sum_{i=1}^{n} F_i(P_i) \quad (1)$$

(i) Power- balance constraint

$$\sum_{i=1}^{n} P_{gi} = P_d + P_l \quad (2)$$

(ii) The power flow equation of the power network

$$g(|v|, \theta) = 0 \quad (3)$$

where,

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

(iii) The inequality constraint on real power generation P_{gi} of each unit i

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \quad (4)$$

(iv) The inequality constraint on voltage of each PQ bus

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (5)$$

(v) Power limit on transmission line

$$MVAf_{p,q} \le MVAf_{p,q}^{\max} \quad (6)$$

Total fuel cost of generation F_T in terms of control variables on generator power can be expressed as

$$F(P_i) = \sum_{i=1}^{n} \left(a_i P_i^2 + b_i P_{gi} + c_i\right) \ \text{\$/hr} \quad (7)$$

3. OVERVIEW OF EP AND PSO

Four decades earlier, EP was proposed for evolution of finite state machines, In order to solve prediction task. Since then, modification 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 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 evolutionary search. Cauchy mutation based EP called FEP [8], which demonstrated better performance than CEP in converging to a near global optimum point but not all FEP success can be attributed to its greater ability to escape local minima by using Cauchy mutation. Fast EP using weighted mean of Gaussian and Cauchy mutation MFEP, advantages of Gaussian and Cauchy mutation can be exploited. This method out performs other EP methods such as, CEP and FEP in all the benchmark functions studied.

PSO is population based optimization method first proposed by Kennedy and Eberhart [16]. It can be used to solve a wide range of different optimization problems. Like Evolutionary algorithms, PSO technique conducts search among a population of particles. Corresponding to individuals each particle represents a candidate solution to the problem at hand. In a PSO system, particle changes the position by flying around in a multidimensional search space until computational limitations are exceeded. In PSO a particle is defined as many point in hyperspace. For each particle, at the current time step, a record is kept of the position, velocity and the best position obtained in the search so far. Figure 1 shows the general flowchart of PSO method.

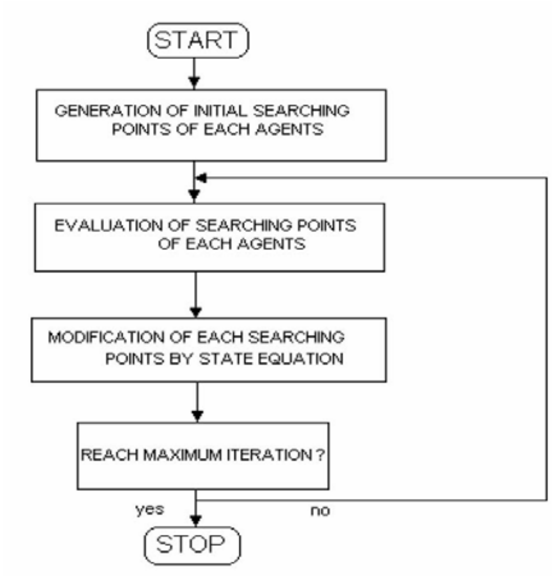

Fig. 1. General flow chart of PSO method.

4. HYBRID PSO METHOD

In the hybrid PSO, EP methods such as Classical EP (CEP), Fast EP (FEP) and Mean of Classical and Fast EP (MFEP) are embedded with conventional PSO. In CEP, FEP and MFEP Gaussian, Cauchy and mean of Gaussian and Cauchy mutations are used, respectively. The proposed hybrid PSO method is embedded with three mutation (Gaussian, Cauchy and mean of Gaussian and Cauchy) operations of EP search. All the three mutation operations create new searching points from the same parent and the better one has been chosen for the next generation. EP methods such as CEP, FEP and MFEP have different features and their combination with PSO may become more effective to find the optimal solution. In the proposed hybrid PSO method, the positive features of both PSO and EP techniques are exploited and are employed to solve ED problem. The proposed hybrid PSO method is better than the other EP methods and conventional PSO method, but the hybrid PSO method takes higher computational time because three mutation operations are involved in the hybrid PSO method. However, the results of the hybrid PSO method are quite encouraging and promising.

5. DEVELOPMENT OF THE PROPOSED IPSO METHOD

The main differences between the proposed IPSO and the conventional PSO methods are:

1. In the proposed IPSO method, a new velocity strategy equation is formulated suitable for a large scale system and a scaling factor β is introduced in Equations 9 and 10, which enhances the convergence characteristics and reduces the damping effect in the search procedure of the conventional PSO. Different values of β are tried on the proposed method; β=0.01 gives better results than other values. In the new velocity strategy equation the upper and lower velocity limits are proportional to minimum and maximum capacity limits of all the generators so that velocity limits are automatically adjusted with the number of generating units and are well suited for the large system. Moreover, the scaling factor β is used to get smooth variation in velocity.
2. In the proposed method, Constriction Factor Approach (CFA) is incorporated into the velocity equation of the PSO. The basic system equation (Velocity equation) [15] of conventional PSO can be considered as a kind of difference equations. Therefore, the system dynamics and search procedure can be analyzed by the eigen value analysis. The CFA utilizes the eigen value analysis and controls system behaviour by which the system behaviour has the following features:
   i. The system does not diverge in a real value region and finally converge and
   ii. The system can search different regions efficiently.

The velocity of CFA PSO can be expressed as given below:

$$v_{id}^{t+1} = K * \begin{pmatrix} v_{id}^{(t)} + c_1 * Rand() * \left(pbest_{id} - S_i^t\right) \\ + c_2 * Rand() * \left(gbest_d - S_i^t\right) \end{pmatrix} \qquad (8)$$

where,

$$K = \frac{2}{\left|2 - \phi - \sqrt{\phi^2 - 4 * \phi}\right|}$$

φ = C1 + C2; φ >4; i=1, 2, 3…. n; d=1, 2, 3…m.

For example, If φ=4.1, then K=0.73. As φ increases above 4.0, K gets smaller. For example if φ=5.0 then K=0.38 and damping effect is even more pronounced. The convergence characteristics of the system are controlled by φ. CFA of PSO ensures the convergence of the search procedure based on the mathematical theory. The amplitude of each agent's oscillation decreases as it focuses on a previous best point. The above modification makes the proposed approach superior to other approaches.

Proposed Approach

Using above concepts, the search procedure of the proposed IPSO based ED is given below.

STEP 1: Initialize randomly the individual of the population according to the limits of each generating unit (except slack bus) including individual dimensions, searching points and velocities. The new velocity strategy equation is formulated and the maximum and minimum velocity limits of each individual are calculated using Equations 9 and 10.

$$V_d^{\max} = \left(\frac{P_d^{\max} - P_d^{\min}}{2}\right) * \beta \qquad (9)$$

$$V_d^{\min} = \left(\frac{P_d^{\max} - P_d^{\min}}{2} \right) * \beta \qquad (10)$$

where,

$$P_d^{\max} = \sum_{i=1}^{n} P_i^{\max}$$

$$P_d^{\min} = \sum_{i=1}^{n} P_i^{\min}$$

i=1, 2…n, where, β =0.01

STEP 2: Compute slack bus generator vector, losses and line flows using Newton-Raphson load flow method for the above generators.

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 F_T using Equation 11.

$$F_T^* = F_T + K_1 \sum_{i=1}^{nl} \left(I_i - I_i^{\max} \right)^2 + K_2 \left(P_{G1} - P_{G1}^{\lim} \right)^2 + K_3 \sum_{i=1}^{N} \left(V_{Li} - V_{Li}^{\lim} \right)^2 \qquad (11)$$

The second term in Equation 11 becomes zero during no violation in voltage, line flow and slack bus capacity limits and it gets value of non zero only if limits are violated.

STEP 4: Among the population the minimum augmented fuel cost value is taken as the best value. The best-augmented fuel cost value in the population is denoted as the gbest. Remaining individuals are assigned as the pbest.

STEP 5: Modify the member velocity V of the each individual real power generating unit P_{gi} using Equation 8.

STEP 6: Check the limits on velocity using:

$$If \quad V_{id}^{(t+1)} > V_d^{\max}, then \quad V_{id}^{(t+1)} = V_d^{\max}$$

$$If \quad V_{id}^{(t+1)} < V_d^{\min}, then \quad V_{id}^{(t+1)} = V_d^{\min} \qquad (12)$$

STEP 7: Modify member position of each individual Pgi using Equation 13.

$$Pg_{id}^{(t+1)} = Pg_{id}^{(t)} + V_{id}^{(t+1)} \qquad (13)$$

STEP 8: $Pg_{id}^{(t+1)}$ must satisfy the capacity limits of the generator and given by:

$$Pg_{id}^{(t+1)} > Pg_{id}^{\max}, then \quad Pg_{id}^{(t+1)} = Pg_{id}^{\max}$$

$$Pg_{id}^{(t+1)} < Pg_{id}^{\min}, then \quad Pg_{id}^{(t+1)} = Pg_{id}^{\min} \qquad (14)$$

STEP 9: Modified member positions in step 8 are taken as initial value for N-R load flow method. Compute slack bus power loss and line flows using N-R load flow method.

STEP 10: Calculate the augmented fuel cost using (11) and gbest and pbest values are assigned. If the gbest value is better than gbest value in Step 4 current value is set to gbest. If pbest value is better than pbest value in Step 4 current value is set to pbest.

STEP 11: If the iteration reaches the maximum go to Step 12, otherwise go to Step 4 and the gbest and pbest values are in Step 4 replaced by latest gbest and pbest values from Step 10.

STEP 12: Individual that generates the latest gbest value is the optimal generation of each unit with minimum fuel cost and satisfying all the constraints.

6. EXAMPLE AND DISCUSSIONS

A comparative study of CEP, FEP, MFEP, Conventional PSO, hybrid PSO and Proposed IPSO was performed on IEEE 14, 30, 118-bus and 66-bus Indian utility system. The upper and lower voltage limits at all the bus bars except slack were taken as 1.01 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. Software has been developed in Mat Lab to solve ED problem using EP techniques (CEP, FEP, MFEP), conventional PSO, hybrid PSO and proposed IPSO methods, and tested on 2.66 GHz Pentium IV, 256 MB RAM personal computer. The cost coefficients are taken from [13] for IEEE 14, 30, 118 bus system and Indian utility system [7]. For implementing the Evolutionary Programming techniques and PSO techniques, population size = 20, Maximum number of generations = 100, is taken and the optimal solution was obtained in 50 trails.

Example 1

The summarized results of IEEE 14 -bus system are given in Table 1 provides of ED results obtained by various optimization methods and the complete line flow results with and without line flow constraints using hybrid PSO given in Table 2. The proposed IPSO method complete line flow results with and without line flow constraints given in Table 3. The star marked line was over loaded with economic generation schedule when the line flow constraints are not considered. For IEEE 14 bus system [13] demand of 259 MW is taken. The results clearly show that the ED using IPSO method is superior over hybrid PSO, conventional PSO, CEP, FEP and MFEP methods.

Table 1. Summary of results of IEEE 14 bus system with line flow constraints.

Method	P1 (MW)	P2 (MW)	P3 (MW)	Losses (MW)	Optimum Fuel Cost $/hr
CEP	92.72	78.90	94.42	7.06	1103.9
FEP	147.35	30.89	89.26	8.51	1108.0
MFEP	91.42	76.02	98.60	7.08	1099.6
PSO	87.99	89.07	88.72	6.93	1114.9
hybrid PSO [16]	110.31	58.03	98.14	7.49	1092.9
Improved PSO	114.44	52.18	100.00	7.62	1091.2

Table 2. Line flow results of hybrid PSO IEEE 14-bus.

Line Desig	Base Case Line Flow in pu	Line Flow With Constraints in pu	Line Flow Without Constraints in pu	Max. Line Flow in pu
1-2	1.5821	0.5608	1.1031**	1.0000
1-5	0.7561	0.3269	0.5069	1.0000
2-3	0.7333	0.6382	0.6606	1.0000
2-4	0.5612	0.3690	0.4142	0.5000
2-5	0.4155	0.2201	0.2611	0.5000
3-4	0.2374	0.3248	0.3041	0.5000
4-5	0.6295	0.6290	0.6497	1.0000
4-7	0.2948	0.1225	0.1764	0.5000
4-9	0.1602	0.0690	0.0955	0.5000
5-6	0.4594	0.2243	0.1466	0.5000
6-11	0.0845	0.2444	0.1900	0.5000
6-12	0.0822	0.1003	0.0942	0.5000
6-13	0.1929	0.2702	0.2442	0.5000
7-8	0.1782	0.1840	0.1796	0.5000
7-9	0.2881	0.1722	0.1976	0.5000
9-10	0.0637	0.1494	0.1002	0.5000
9-14	0.0992	0.0754	0.0659	0.5000
10-11	0.0438	0.2053	0.1517	0.5000
2-13	0.0182	0.0369	0.0303	0.5000
13-14	0.0606	0.1631	0.1288	0.5000

Table 3. Line flow results of IPSO- IEEE 14-bus.

Line Desig	Base Case Line Flow in pu	Line Flow With Constraints in pu	Line Flow Without Constraints in pu	Max. Line Flow in pu
1-2	1.5821	0.7625	1.1182**	1.0000
1-5	0.7561	0.3424	0.4480	1.0000
2-3	0.7333	0.6187	0.6275	1.0000
2-4	0.5612	0.3278	0.3455	0.5000
2-5	0.4155	0.1714	0.1854	0.5000
3-4	0.2374	0.3439	0.3358	0.5000
4-5	0.6295	0.6594	0.6769	1.0000
4-7	0.2948	0.1037	0.1305	0.5000
4-9	0.1602	0.0690	0.0726	0.5000
5-6	0.4594	0.2841	0.2031	0.5000
6-11	0.0845	0.2639	0.2362	0.5000
6-12	0.0822	0.1026	0.0994	0.5000
6-13	0.1929	0.2797	0.2663	0.5000
7-8	0.1782	0.1861	0.1832	0.5000
7-9	0.2881	0.1673	0.1749	0.5000
9-10	0.0637	0.1676	0.1419	0.5000
9-14	0.0992	0.0821	0.0730	0.5000
10-11	0.0438	0.2243	0.1973	0.5000
12-13	0.0182	0.0393	0.0359	0.5000
13-14	0.0606	0.1753	0.1579	0.5000

** - line violation.

Example 2

The summarized results of IEEE 30 -bus system given in Table 4 provides of ED results obtained by various optimization methods. For IEEE 30 bus system demand of 283.4MW is taken. Line flow limits, bus voltage limits, capacity limit constraints, power balance equation are taken in to consideration. The results clearly show that the proposed IPSO outperforms the other methods.

Example 3

The results of IEEE 118-bussystem given in Table 5 and it provide the ED results obtained by various optimization methods. For IEEE 118 system demand of 4242MW is taken. This example shows that the proposed method is suitable for large scale system.

Example 4

Sixty-six bus Indian utility system [7] demand of 1250 MW is taken and the complete bus results are shown in Table 6 line flow constraints are taken into consideration while solving ED problem using CEP, FEP, MFEP, conventional PSO, hybrid PSO and IPSO. Minimum fuel cost obtained in the proposed IPSO method and there is no limit violation in the optimum schedule, this fact demonstrates the proposed algorithm reliable, stable convergence and also suitable for practical system. Figure 2 shows that the convergence nature of IPSO and PSO approaches. It clearly shows that the cost oscillations in the PSO are completely reduced in the proposed method. Proposed method gives stable convergence and avoids local minimum.

Table 4. Summary of IEEE 30-bus system with line flow constraints.

Method	P1 (MW)	P2 (MW)	P3 (MW)	Losses (MW)	Optimum Fuel Cost $/hr
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	95.589	96.74	98.42	7.49	1199.3
hybrid PSO [16]	129.19	66.27	96.20	8.28	1185.2
Improved PSO	136.30	59.87	95.68	8.46	1184.2

Table 5. Summary of IEEE 118-bus system with line flow constraints.

Unit Power Output (MW)	CEP	FEP	MFEP	PSO	Hybrid PSO[16]	Improved PSO
P1	522.45	434.76	185.82	357.67	328.11	278.65
P2	56.98	144.77	134.34	179.83	180.00	165.09
P3	214.06	180.70	314.48	320.00	162.45	241.63
P4	219.14	336.81	276.26	239.27	263.71	272.53
P5	91.30	57.68	63.70	100.00	100.00	100.00
P6	88.58	38.24	96.37	109.00	110.00	68.29
P7	164.19	194.90	250.87	277.21	50.00	55.69
P8	32.21	109.98	110.28	115.69	150.00	137.70
P9	214.23	185.35	184.44	243.55	250.00	250.00
P10	148.88	248.50	224.38	204.33	260.00	260.00
P11	330.36	394.61	478.66	271.25	253.78	267.63
P12	408.67	387.58	290.49	228.13	347.66	370.45
P13	501.19	101.03	447.23	461.21	525.88	487.59
P14	430.02	545.92	389.96	485.27	395.25	400.20
P15	34.10	60.31	44.53	20.004	20.00	100.00
P16	373.24	495.99	512.69	531.8	438.83	424.35
P17	329.46	283.63	144.80	202.51	350.00	313.55
P18	130.02	73.83	132.65	139.85	138.69	139.37
P19	65.12	77.67	73.70	38.40	20.00	20.61
Losses	112.49	110.36	113.72	283.00	101.70	111.30
Optimum Fuel Cost $/hr	22061	22704	21927	23015	21849	21705

Table 6. Summary of 66-bus Indian utility system with line flow constraints.

Method	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	Losses (MW)	Optimum Fuel Cost $/hr
CEP	555.28	308.53	298.29	114.63	26.63	16,139.4
FEP	529.48	316.98	311.24	119.11	26.72	15,634.4
MFEP	421.09	481.25	324.24	56.00	32.49	14,985.6
PSO	479.16	353.99	324.28	120.00	27.33	14,789.6
hybrid PSO [16]	478.88	354.34	324.22	120.00	27.34	14,784.6
Improved PSO	473.24	357.32	326.99	120.00	27.45	14,714.6

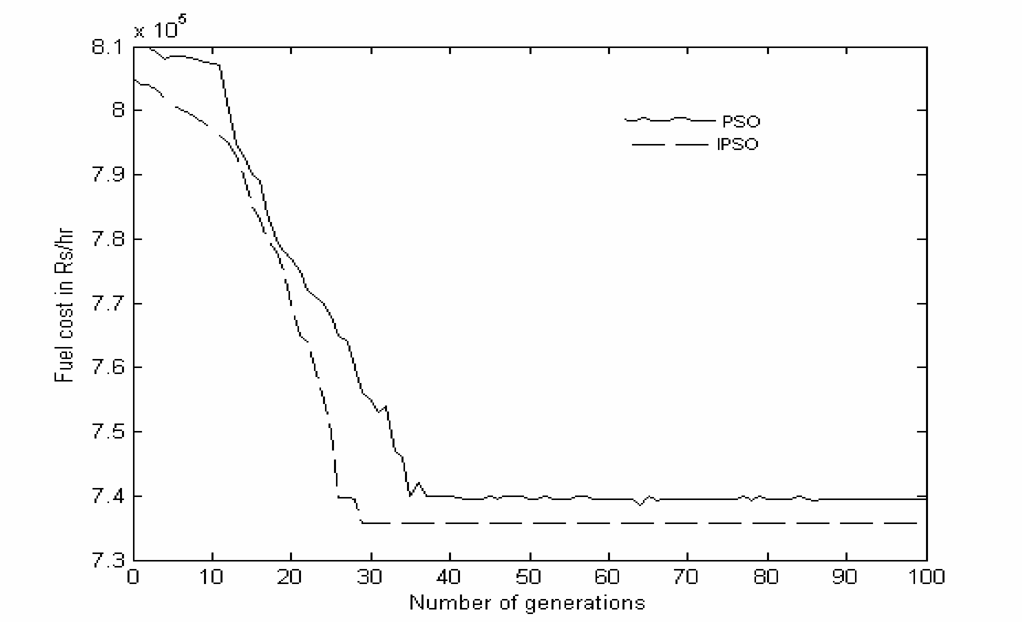

Fig. 2. Solution convergence patterns of the PSO and IPSO for 66 bus Indian utility system.

7. CONCLUSION

The EP techniques such as CEP, FEP, MFEP, conventional PSO, hybrid PSO and Improved PSO algorithms were tested on IEEE 14, 30, 118 systems and 66-bus practical utility Indian systems and the results were presented. The MVA line flow limits of the test system were incorporated and the over load lines were observed. In the proposed IPSO method, the performance of the conventional PSO is greatly improved by using a new velocity strategy equation, which is suitable for large system and the Constriction Factor Approach (CFA) is incorporated into the velocity equation. The proposed method has been demonstrated to have superior features, including stable convergence characteristic and avoids premature convergence. The convergence characteristics of IPSO method are stable and it avoids the premature convergence.

NOMENCLATURE

P_i^{net}, Q_i^{net}	Specified real and reactive powers for PQ bus i
P_i , P_m^{net}	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 powers allowed at generator i
V_i^{min} , V_i^{max}	Minimum and maximum voltages 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 coefficients
n	Number of particles in a group
m	Number of members in a particle
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

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