The Journal of CPRI,
Vol. 5, No. 1, March 2009 pp. 57–65

Optimum Cost of Generation for Maximum Loadability Limit of Power System Using Multi-agent Based Particle Swarm Optimisation (MAPSO)

A Shunmugalatha* and Dr S Mary Raja Slochanal**

To estimate voltage stability, Maximum Loadability Limit (MLL) is one approach. MLL is the margin between the operating point of the system and the maximum loading point. The optimum cost of generation for MLL of power system can be formulated as an optimisation problem, which consists of two steps namely, computing MLL and the optimum cost of generation for MLL. This paper utilises the newly developed Evolutionary Multi-agent Based Particle Swarm Optimization (MAPSO) in solving this optimisation problem. Details of the implementation of the proposed method to modified IEEE 30-bus system, IEEE 57-bus system and IEEE 118-bus system are presented. Simulation results show that the proposed approach converges to a better solution much faster, which proves the loadability and applicability of the proposed method.

***Key words**: economic load dispatch, maximum loadability limit, multi-agent system, particle swarm optimisation and voltage stability*

NOMENCLATURE

θ_{ij} - Voltage angle difference between bus i and j (rad)

B_{ij} - Transfer susceptance between bus i and j (p.u.)

G_{ij} - Transfer conductance between bus i and j (p.u.)

f - Total real power demand of the system

N_o - Set of number of total buses excluding slack bus

N_B - Set of number of total buses

N_D - Set of number of load buses

N_G - Set of number of generator buses

N_i - Set of number of buses adjacent to bus i, including bus i

N_T - Set of number of transformer branches

N_V^{lim} - Set of number of buses violating voltage limits

P_{Di} - Real power demand at bus i (p.u.)

P_{Gi} - Real power generation at bus i (p.u.)

P_S - Real power at slack bus (p.u.)

Q_{Di} - Reactive power demand at bus i (p.u.)

Q_{Gi} - Reactive power generation at bus i (p.u.)

T_k - Tap position of transformer k

V_i - Voltage magnitude of bus i(p.u.)

V_{PQ} - Voltage vectors of PQ buses (p.u.)

V_{PV} - Voltage vectors of PV buses (p.u.)

V_S - Voltage magnitude of slack bus. (p.u.)

$P_{d\,max}$ - Maximum loadability limit (p.u.)

$F_{cj}(P_j)$ - Fuel cost function of unit j

P_{jmin} - Minimum real power output of unit j

P_{jmax} - Maximum real power output of unit j

F – Total cost of generation ($ /hour)

*Associate Professor / EEE, K.L.N College of Engineering, Pottapalayam 630611, INDIA
Email: Surya_subramanian@yahoo.com
**Prof. and HOD / EEE, Thiagarajar College of Engineering, Madurai 625 015, INDIA
Email: smrseee@tce.edu

1.0 INTRODUCTION

The problem of voltage stability is one of the main concerns in the operation of power system. Maximum loadability limit is the margin between the operating point of the system and the maximum loading point. The maximum loadability limit problem has been formulated as a non-linear optimisation problem with a mixture of discrete and continuous variables. The main objective of economic load dispatch is to minimise the fuel cost of generation while satisfying the load demand.

Various mathematical techniques to solve maximum loadability limit can be categorised as:

- Continuation Power Flow method (CPF)
- Successive Quadratic Programming (SQP)
- Interior Point method (IP) and
- Repetitive Power Flow solution (RPF).

If the system is already near the maximum loading point, the continuation power flow technique [1] may face some convergence problems. The SQP [2] approach uses the second order derivatives to improve the convergence rate. These methods become too slow as the number of control variables becomes very large. Interior point methods [2] are computationally efficient. However, if the step size is not chosen properly, the sub-linear problem may have a solution that is unfeasible in the original non-linear domain. Another technique is the repetitive power flow solution [3]. Increasing the load on the system in steps in some direction and solving the load flow at each step until the load flow solution diverges. The divergence of the load flow [4] does not represent the maximum loading point. In general, conventional optimisation methods that are not able to locate global optimum, can only lead to a local optimum and sometimes result in divergence.

Recently, evolutionary techniques have been developed to solve the MLL problem. The PSO technique [5,6] can generate high quality solutions within short calculation time and have more global searching ability at the beginning of the run and a local search near the end of the run. A Hybrid Particle Swarm Optimisation (HPSO) [7] that adds the breeding and subpopulation process of GA to PSO, has the potential to reach a better optimum solution than the standard PSO. A Multi-agent technique (MAS) [8] can be applied to solve the maximum loadability problem. PSO incorporated multi-agent [9] has been proved to converge at better optimal solutions when compared with the above methods. The MLL of power system and the optimum cost of generation [10] for modified IEEE 30-bus, IEEE 57-bus and IEEE 118-bus systems are evaluated using MAPSO. The results indicate that the MAPSO is capable of undertaking a global search with a faster convergence rate and the feature of robust computation. It is capable of handling all types of variables either real or integer and also capable of obtaining global optimum of the objective function.

2.0 MATHEMATICAL FORMULATION

The first objective is to maximise the active power load applied to the transmission network. The second objective is to find the optimum cost of generation for the maximum loadability limit.

2.1 Objective I

$$\textit{Maximise} \quad f \tag{1}$$

Where f is the loading factor, which represents the increase in the system load from base case without violating the voltage limit. The maximisation of the above function is subjected to a number of constraints:

$$0 = P_{Gi} - P_{Di} - V_i \sum_{j \in N_i} V_j \left(G \right.$$
$$0 = Q_{Gi} - Q_{Di} - V_i \sum_{j \in N_i} V_j \left(C \right. \tag{2}$$

$$V_i^{\lim} \le V_i \le V_i^{\max} \qquad i \in$$
$$T_k^{\min} \le T_k \le T_k^{\max} \qquad k \tag{3}$$

where power flow equations are equality constraints and the bus voltage restrictions, and the transformer tap setting restrictions are inequality constraints. In non-linear optimisation problems, the constraints are considered by generalising the objective function using penalty terms. Voltages of PQ buses (Vpq) are constrained by adding them as penalty term to the objective function. The above problem is generalised as:

(4)

Where λ_{vi} is the penalty factor.

V_i^{lim} is defined as:

$$V_i^{\lim} = V_i^{\max} \quad for$$
$$V_i^{\lim} = V_i^{\min} \quad for \qquad (5)$$

2.2 Objective II

Minimise (6)

$F_1 = f \sum_{i \in N_V} \lambda_{vi} (V_i$ $\quad F_2 = \sum_{j=1}^{n} F_{cj}(P_j)$

Where $F_{cj}(P_j)$ is the fuel cost function of unit j and P_j is the real power generated by the unit j, subject to power balance constraints.

$$P_{d\max} = \sum_{j=1}^{n} P_j - P_L \qquad (7)$$

Where P_{dmax} is the maximum loadability limit and P_L is the transmission loss. The generator capacity constraint is given by:

$$P_{j\min} \le P_j \le P_{j\max} \text{ for j = 1, 2, 3, ……n} \qquad (8)$$

Where $P_{j\ min}$ and $P_{j\ max}$ are the minimum and maximum real power output of unit j. The fuel cost function of the generating unit j is given by:

$$F_{cj}(P_j) = a_i P_j^2 + b_i P_j + c_i \qquad (9)$$

Where , b_i and c_i are the fuel cost coefficients of unit j.

3.0 MULTI-AGENT BASED PARTICLE SWARM OPTIMISATION (MAPSO)

3.1 Particle Swarm Optimisation (PSO)

In PSO, each single solution is called as "particle" in the search space. All particles have fitness values and have velocities, which direct the flying of the particles. The particle updates its velocity and position with the following equations:

$$V_{id} = V_{id} + C_1{*}rand(){*}(P_{id} - X_{id}) + C_2{*}rand(){*}(P_{gd} - X_{id}) \qquad (10)$$

$$V_{id} = W{*}V_{id} + C_1{*}rand(){*}(P_{id} - X_{id}) + C_2{*}rand(){*}(P_{gd} - X_{id}) \qquad (11)$$

$$X_{id} = X_{id} + V_{id} \qquad (12)$$

Where V_{id} is the particle velocity.

X_{id} is the current particle solution.

W is the inertia weight.

P_{id} pbest.

P_{gd} gbest.

rand () is a random number between (0,1).

C_1 and C_2 are learning factors, usually

$C_1 = C_2 = 2$.

Population size = 50;

Maximum iterations = 150.

Suitable selection of the inertia weight results in lesser iterations on an average to find a sufficient optimal solution.

3.2 Hybrid PSO

In PSO, if a particle's current position coincides with the global best position and if their previous velocities are very close to zero, then all the particles will stop moving. This may lead to a premature convergence of the algorithm known as stagnation. To avoid this problem, HPSO incorporates the breeding and subpopulation process of GA into PSO, which allows the search to escape from local optima and to search in different zones of the search space. The breeding and subpopulation process is employed by the following equations:

$$child_1 = x_1 * parent_1 \quad (13)$$

$$child_2 = x_1 * parent \quad (14)$$

where x_1 is a random value between 0 and 1.

$$child\left(\bar{V}_1\right) = \frac{parent\left(\bar{V}_1\right)}{\left|\bar{V}_1 +\right.} \quad (15)$$

$$child\left(\bar{V}_2\right) = \frac{parent\left(\bar{V}_1\right) +}{\left|\bar{V}_1 +\right.} \quad (16)$$

Parent 1 is the best particle 1.
Parent 2 is the best particle 2.
V_1 is the velocity of parent 1.
V_2 is the velocity of parent 2.

3.3 Multi-agent Based Particle Swarm Optimisation (MAPSO)

Multi-agent System (MAS) is a computational system in which several agents work together to achieve goals. First, a lattice-like environment is constructed with each agent fixed on a lattice point as in Fig. 1. The size of L is L_{size} X L_{size}, where L_{size} is the total number of particles for PSO and is an integer.

1,1	1,2	....	1,Lxx
2,1	2,2	....	2,Lxx
.....	....	....	....
Lxx1	Lxx2	....	Lxx,Lxx

FIG. 1 STRUCTURE OF THE ENVIRONMENT

The neighbours of $\alpha_{i,j}$, $N_{i,j}$ are defined as follows:

$$N_{i,j} = \{\alpha_{i^1,j}, \alpha_{i,j^1}, \alpha_{i^2,j} \quad (17)$$

Where

$$i^1 = \begin{cases} i-1 & i \neq 1 \\ L_{size} & i = \end{cases}$$

$$i^2 = \begin{cases} i+1 & i \neq \\ 1 & i = I \end{cases}$$

$$j^1 = \begin{cases} j-1 & j \neq \\ L_{size} & j = \end{cases}$$

$$j^2 = \begin{cases} j+1 & j \neq \end{cases}$$

From (17), each agent has four neighbours with whom the agent can sense. Suppose that competition and cooperation operator is performed on the agent $\alpha_{i,j}$ and M in $N_{i,j} = (m_1, m_2 \ldots\ldots\ldots\ldots m_n)$ is the agent with maximum fitness value among the neighbours of $N_{i,j}$, namely $m \in N_{i,j}$ and $\forall \varepsilon \in N_{i,j}$ then $f(\varepsilon) \leq f(m)$. If agent $\alpha_{i,j}$ satisfies (18), it is a winner. Otherwise, it is a loser.

$$F(\alpha_{ij}) \geq f(m) \quad (18)$$

If $\alpha_{i,j}$ is a winner, it can still live in the same location of the search space. If it is a loser, a new agent will occupy its lattice point determined by:

$$\alpha_k' = m_k + rand\ (0,1)\ (m_k \quad (19)$$

where rand (0,1) is a uniform random value in the range [0,1]. If $\alpha_k' \geq X_{maxk}$, then $\alpha_k' = X_{maxk}$. If $\alpha_k' \leq X_{mink}$, then $\alpha_k' = X_{mink}$. Making use of the agent-agent interactions and evolution mechanism of PSO, MAPSO realises the purpose of optimising the value of objective function.

4.0 ALGORITHM FOR OPTIMUM ALLOCATION OF GENERATION FOR MLL USING MAPSO

The objective function is to maximise the load and minimise the cost of generation using MAPSO. Load is assumed as the particle to be optimised for Objective I and real power generation cost is assumed as the particle to be optimised for Objective II. Either maximum number of iterations or the maximum value of load without violating the voltage constraints is set as a stopping criterion. Following is the MAPSO algorithm for optimum cost of generation for MLL of power system:

Step 1: Input the parameters of the system and the algorithm and specify the lower and upper boundaries of each variable.

Step 2: Generate a lattice-like environment and initialise randomly each agent.

Step 3: Evaluate the fitness value of each particle based on the Newton–Raphson power flow analysis.

Step 4: Update the time counter t = t +1.

Step 5: Perform the neighbourhood competition and cooperation operator on each agent. Agents with maximum fitness value will survive.

Step 6: Execute PSO operator on those surviving agents according to equations (11) and (12).

Step 7: Evaluate the fitness value of those surviving agents based on the Newton-Raphson power flow analysis.

Step 8: Find the best agent with the maximum fitness value.

Step 9: If one of the stopping criteria is satisfied, then go to Step 10. Otherwise go to Step 4.

Step 10: Output the agent with the maximum fitness value in the last generation.

Step 11: For the MLL obtained in Step 9, obtain the optimum cost of generation with the objective function [equation (6)] subjected to the constraints [equations (7) and (8)] using MAPSO.

5.0 NUMERICAL RESULTS

From the literature [1], [2], [7], it is understood that MAPSO to maximum loadability limit outperforms the techniques namely Interior Point Algorithm, Continuation Power Flow method, Particle Swarm Optimisation and Hybrid Particle Swarm Optimisation. To verify the effectiveness and efficiency of the proposed method, it has been applied to the modified IEEE 30-bus, IEEE 57-bus and IEEE 118-bus systems [11] using MATLAB programming language 7.0 and the program was run on a Pentium-IV, 2.6 GHz processor to evaluate the optimum cost of generation for the MLL. The lower voltage magnitude limits at all buses are 0.95 p.u. and the upper limits are 1.1 p.u. for all the PV buses and 1.05 p.u. for all the PQ buses and the reference bus.

The initial load, total generations and power losses for modified IEEE 30-bus system are given are follows:

P_{load} = 1.8920 p.u; Q_{load} = 1.0720 p.u.

$\Sigma\, P_G$ = 1.9164 p.u; $\Sigma\, Q_G$ = 1.0041 p.u.

P_{loss} = 0.0244 p.u; Q_{loss} = 0.0899 p.u.

MLL for modified IEEE 30-bus system by RPF is 2.4596 p.u.

The initial load, total generations and power losses for IEEE 57-bus system are given as follows:

P_{load} = 12.5 p.u; Q_{load} = 3.364 p.u.

$\Sigma\, P_G$ = 12.7866 p.u; $\Sigma\, Q_G$ = 3.2108 p.u.

P_{loss} = 0.27864 p.u; Q_{loss} = 1.2167 p.u.

MLL for IEEE 57-bus system by RPF is 13.759 p.u.

The initial load, total generations and power losses for IEEE 118-bus system are given as follows:

P_{load} = 42.42 p.u; Q_{load} = 14.38 p.u.;

$\Sigma\, P_G$ = 43.7486 p.u; $\Sigma\, Q_G$ = 7.9568 p.u.;

P_{loss} = 1.32863 p.u; Qloss = 7.8379 p.u.

MLL for IEEE 118-bus system by RPF is 55.146 p.u.

The adopted parameters in the algorithms are given in Table 1. The objective function with voltage i.e., equation (4) is used. Owing to the randomness in PSO, HPSO and MAPSO approach, the algorithms are executed 30 runs when applied to the test system. For comparison purposes, the MLL obtained by PSO, HPSO and MAPSO for modified IEEE 30-bus system, IEEE 57-bus system and IEEE 118-bus system are tabulated in Tables 2, 3 and 4 respectively.

TABLE 1

PARAMETER VALUES FOR GA, PSO, HPSO AND MAPSO

Parameter	IEEE 30-bus / IEEE 57-bus / IEEE 118-bus		
	PSO	**HPSO**	**MAPSO**
No. of variables	24 /50 /64	24 /50 /64	24 /50 /64
Population size	50	50	50
No. of iterations	100	100	100
C_1	2	2	2
C_2	2	2	2
W	0.3 to 0.95	0.3 to 0.95	0.3to0.95
Competition and cooperation operator	-	-	0 to 1
Crossover probability	-	0.05	-
Mutation probability	-	0.1	-

TABLE 2

COMPARISON OF MLL FOR MODIFIED IEEE 30-BUS SYSTEM

By RPF, MLL is 2.4596 p.u.

Algorithm	$P_{d\ max}$ (p.u.)	% rise of MLL (%)	Convergence iteration number / Time (sec)
PSO	2.601	5.7489	37 / 61.3615
HPSO	2.603	5.8487	24 / 39.8020
MAPSO	2.608	6.0359	21 / 34.3359

From Tables 2 to 4, it is found that for the proposed MAPSO method, MLL has been increased when compared with PSO and HPSO. Also for this proposed MAPSO method, number of iterations for convergence and the average execution time compared to PSO and HPSO is very less.

TABLE 3

COMPARISON OF MLL FOR IEEE 57-BUS SYSTEM

BY RPF, MLL IS 13.759 P.U.

Algorithm	$P_{d\ max}$ (p.u.)	% rise of MLL (%)	Convergence iteration number / Time (sec)
PSO	14.04	2.035	39 / 67.2340
HPSO	14.06	2.2021	29 / 58.1046
MAPSO	14.07	2.2603	23 / 54.3210

TABLE 4

COMPARISON OF MLL FOR IEEE 118-BUS SYSTEM

BY RPF, MLL IS 55.146 P.U.

Algorithm	$P_{d\ max}$ (p.u.)	% rise of MLL (%)	Convergence iteration number / Time (sec)
PSO	56.443	2.3519	41 / 69.9055
HPSO	56.445	2.3555	30 / 51.1500
MAPSO	56.449	2.3628	23 / 39.2150

Based on the percentage of MLL and time for convergence, the results are tabulated and compared. From the results obtained, it is obvious that by means of MAPSO, the MLL for modified IEEE 30-bus system is 2.60806 p.u. with the convergence time of 34.3359 seconds, for IEEE 57-bus system it is 14.070 p.u with the convergence time of 54.321 seconds and for IEEE 118-bus system it is 56.449 p.u with the convergence time of 39.2150 seconds.

It is also observed that our proposed MAPSO method converges nearly 1.787 times faster than PSO and 1.159 times faster than HPSO for modified IEEE 30-bus system, 1.2377 times faster than PSO and 1.06965 times faster than HPSO for IEEE 57-bus system, 1.3667 times faster than PSO and 1.3043 times faster than HPSO for IEEE 118-bus system.

The convergence characteristics for PSO, HPSO and MAPSO for modified IEEE 30-bus system, IEEE 57-bus system and IEEE 118-bus system are given in Figs. 2, 3 and 4 respectively.

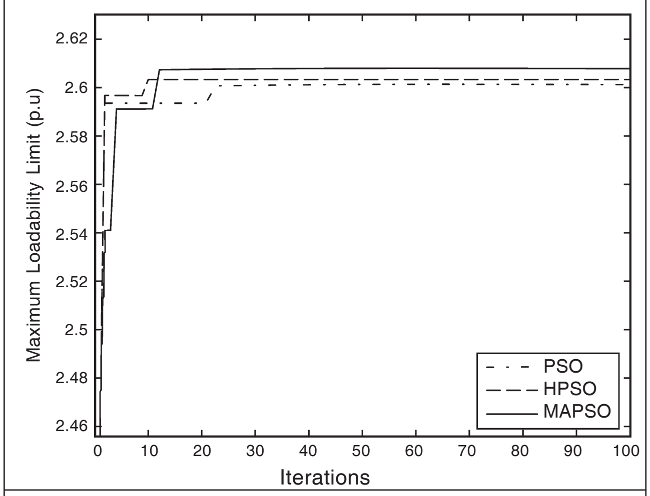

FIG.2. CONVERGENCE CHARACTERISTICS FOR MODIFIED IEEE 30-BUS SYSTEM

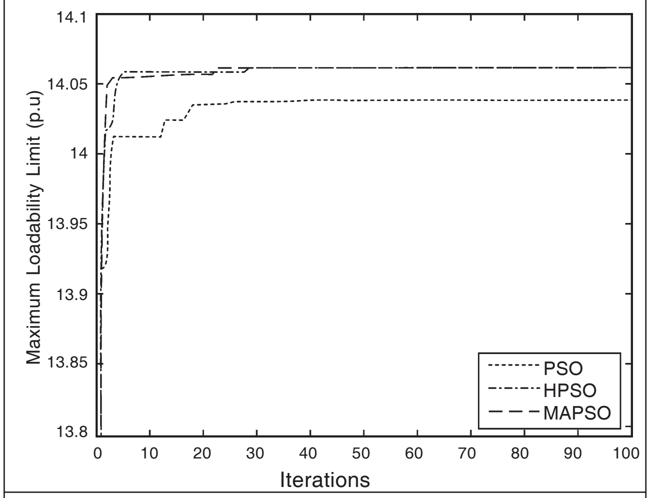

FIG. 3 CONVERGENCE CHARACTERISTICS FOR IEEE 57-BUS SYSTEM

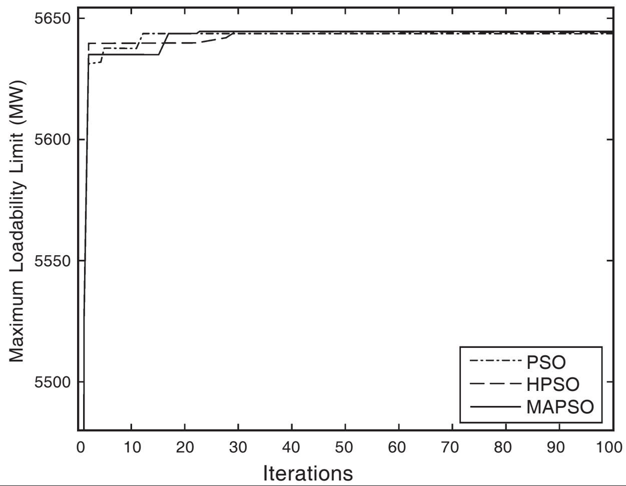

FIG. 4 CONVERGENCE CHARACTERISTICS FOR IEEE 118-BUS SYSTEM

The optimum cost of generation for MLL of modified IEEE 30-bus, IEEE 57-bus and IEEE 118-bus systems are tabulated in Tables 5 to 7 respectively.

TABLE 5

OPTIMUM COST OF GENERATION FOR MLL OF MODIFIED IEEE 30-BUS SYSTEM

Unit	P_g λ method	P_g GA	P_g HPSO	P_g MAPSO
1	150.77	226.3	202.30	362.08
2	114.27	58.26	43.193	57.834
3	46.787	64.05	50.888	34.715
6	114.27	77.22	58.379	0
8	526.36	547.85	541.44	550.00
9	114.27	85.728	100.00	0
12	362.60	349.48	410.00	401.57
F $/h	48543.8	48377	48068	47695

TABLE 6

OPTIMUM COST OF GENERATION FOR MLL OF IEEE 57-BUS SYSTEM

Unit	P_g λ method	P_g GA	P_g HPSO	P_g MAPSO
1	56.413	67.253	56.426	53.4753
2	71.615	63.030	73.166	80.0000
13	26.052	24.731	22.034	23.2287
22	60.343	52.097	52.096	46.5546
23	25.130	14.281	25.784	29.3892
27	25.130	38.905	30.839	27.6977
F_{cost} ($/hr)	868.86	862.20	852.85	851.07

From Tables 5 to 7, it is observed that the optimum cost of generation obtained by MAPSO is comparatively reduced when compared with λ iteration method, GA and HPSO. The power savings by MAPSO method are 2.05%, 1.75% and 10.45% for the modified IEEE 30-bus system, IEEE 57-bus system and IEEE 118-bus system when compared with the conventional λ iteration method.

On the whole, it is clear that multi-agent based PSO converges at a better optimum solution with less average execution time.

TABLE 7

OPTIMUM COST OF GENERATION FOR MLL OF IEEE 118-BUS SYSTEM

Unit	$P_g\lambda$ method	P_gGA	P_gHPSO	P_gMAPSO
1	41.559	25.807	47.295	100
4	41.559	98.729	61.803	55.2395
6	41.559	92.180	37.422	31.1532
8	41.559	9.482	70.773	64.8176
10	468.70	409.14	342.87	398.531
12	88.533	59.316	80.738	77.1159
15	41.559	57.674	80.360	59.5010
18	41.559	99.805	58.013	46.2515
19	41.559	79.863	50.310	37.6082
24	41.559	52.493	46.809	73.2484
25	229.14	280.90	113.65	121.830
26	327.05	264.67	301.64	0.0
27	41.559	91.007	20.119	76.6049
31	7.2909	4.707	14.113	7.6790
32	41.559	58.162	64.253	50.6618
34	41.559	2.248	31.286	68.4668
36	41.559	53.959	87.184	62.3006
40	41.559	30.01	70.129	7.8764
42	41.559	42.033	57.430	61.0728
46	19.79	35.363	17.333	0.7754
49	212.48	249.02	164.03	219.319
54	49.995	46.874	92.432	42.7234
55	41.559	33.92	66.977	26.4969
56	41.559	24.536	47.820	99.8282
59	161.44	223.34	178.74	212.823
61	66.649	56.422	132.18	209.06
62	41.559	28.544	52.427	41.8845
65	407.25	222.70	391.81	319.295
66	408.29	431.88	492.00	353.083
69	537.86	595.83	569.72	749.615
70	41.559	15.152	47.401	33.4655
72	41.559	19.648	51.494	77.5198
73	41.559	90.811	10.000	24.1238
74	41.559	10.655	43.276	11.7850
76	41.559	68.915	74.676	20.3018
77	41.559	9.677	28.611	0.0
80	496.82	372.26	363.93	0.0
85	41.559	5.572	35.739	15.8541
87	4.1662	16.774	9.6416	29.6803
89	632.22	521.09	465.92	496.212
90	41.559	92.473	50.956	27.6528
91	41.559	27.566	51.070	25.1910
92	41.559	43.695	41.304	10.9833
99	41.559	11.730	11.661	0.0
100	262.47	244.64	100.42	164.067
103	41.662	19.844	26.834	54.0115
104	41.559	83.187	71.162	48.9523
105	41.559	69.599	70.686	66.5837
107	41.559	18.866	42.408	37.0275
110	41.559	9.775	27.228	23.9712
111	37.496	10.901	54.016	117.638
112	41.559	99.805	27.590	56.6561
113	41.559	8.113	0.0000	29.1009
116	41.559	11.339	96.602	89.2037
F $/h	197462.1	186530	186470	176820

6.0 CONCLUSION

The algorithm named Multi-agent Based Particle Swarm Optimisation is applied to estimate the optimum cost of generation. From the results obtained, it is concluded that this algorithm is an efficient way of reducing the computational effort required to compute the maximum loadability limit. It also reduces the cost of generation for the same. It is obvious from the simulation study that this approach is simple, easy to implement and converges at a faster rate and can be used for other optimisation problems as well.

7.0 ACKNOWLEDGEMENT

The authors are grateful to the Principal and the Management of Thiagarajar College of Engineering, Madurai and K L N College of Engineering, Pottapalayam for providing all facilities for this research work.

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