4. PSO BASED COUPLED LOAD FLOW

4.1. INTRODUCTION

Traditional load flow algorithms [1]-[8], [42], [43] determine the normal solutions as the iterative methods are started by initializing the variables close to their normal solutions. The normal solutions are operable solutions. Solutions other than normal one are inoperable; but such solutions exist mathematically. A power system having N number of buses may have 2^N-1 solutions out of which only one is normal and the rest are low voltage inoperable solutions. Such low voltage solutions, though does not appear in operable power systems, give valuable information regarding the closeness of the system to the voltage stability limit. Methods have been developed to determine such low voltage solutions [16], [17].

Active and reactive power flows in power system are determined by the nodal voltages and phase angles. The interdependence between these quantities, however, varies. The well known decoupled property is valid if the node voltages are close to their rated values. Load flows based on decoupling principle are thus unable to determine the low voltage solutions. The PSO based load flow developed in the previous chapter also suffers from this limitation.

In this chapter the author proposes another PSO based load flow that can determine multiple load flow solutions. The PSO algorithm alone, however, cannot find the low voltage solutions unless supported by the local network based load flow proposed in chapter two. Simple PSO technique, however, can find normal solution in the proposed new method of implementation though at the cost of much greater number of generations compared to the decoupled algorithm.

The new algorithm does not make any simplified assumption in respect of the coupling between the power system quantities. Hence, to differentiate this algorithm with that proposed in the previous chapter, the new algorithm will be termed as the coupled algorithm. The learning factors c1, c2 of the PSO algorithm play a very crucial role in the convergence of the new method. The author has proposed an adaptive variation of the learning factors and this has been found to be very effective in the performance of the proposed algorithm.

4.2 DEVELOPMENT OF THE ALGORITHM

In the coupled algorithm particles are formed by a complete set of the load flow variables. Thus the pbest or the gbest solutions need not be constructed as in case of the decoupled algorithm, they are rather selected based upon the closeness of the solution strings from their final values. In the new formulation, a complete solution string is considered as an inseparable set of elements and are updated simultaneously using a single updating rule. This is quite different from the method adopted in the previous case where elements were updated separately. In case of the decoupled algorithm active and reactive power mismatches of the individual buses were used to update the phase angle and voltage of an individual bus using the update equation of the PSO. In sharp contrast to it, the total mismatch of the system computed as the sum of the squares of the active and reactive power mismatches of the individual buses are used to update a whole solution string. Therefore, the update rule here applies on the whole string simultaneously, but in the previous algorithm, the update was performed separately for individual variables. At each iteration the updated values of the voltages and phase angles are used to compute the active and reactive power mismatches at the buses. The sum of the squares of individual bus error are then used to assess the quality of a solution string. Lower the value of the objective function, better is the quality of the solution string. And when this value is close to zero, it may be said that the solution string has achieved the converged values.

The coupled algorithm thus solves the power flow problem by minimizing the sum of the squares of the bus active and reactive power mismatches, which thus works as the single objective function. At every iteration, the population having the lowest value of the objective function is the pbest solution and the global minimum value of the objective function corresponds to the gbest solution. The solution algorithm is shown in the flowchart of Fig. 4.1.

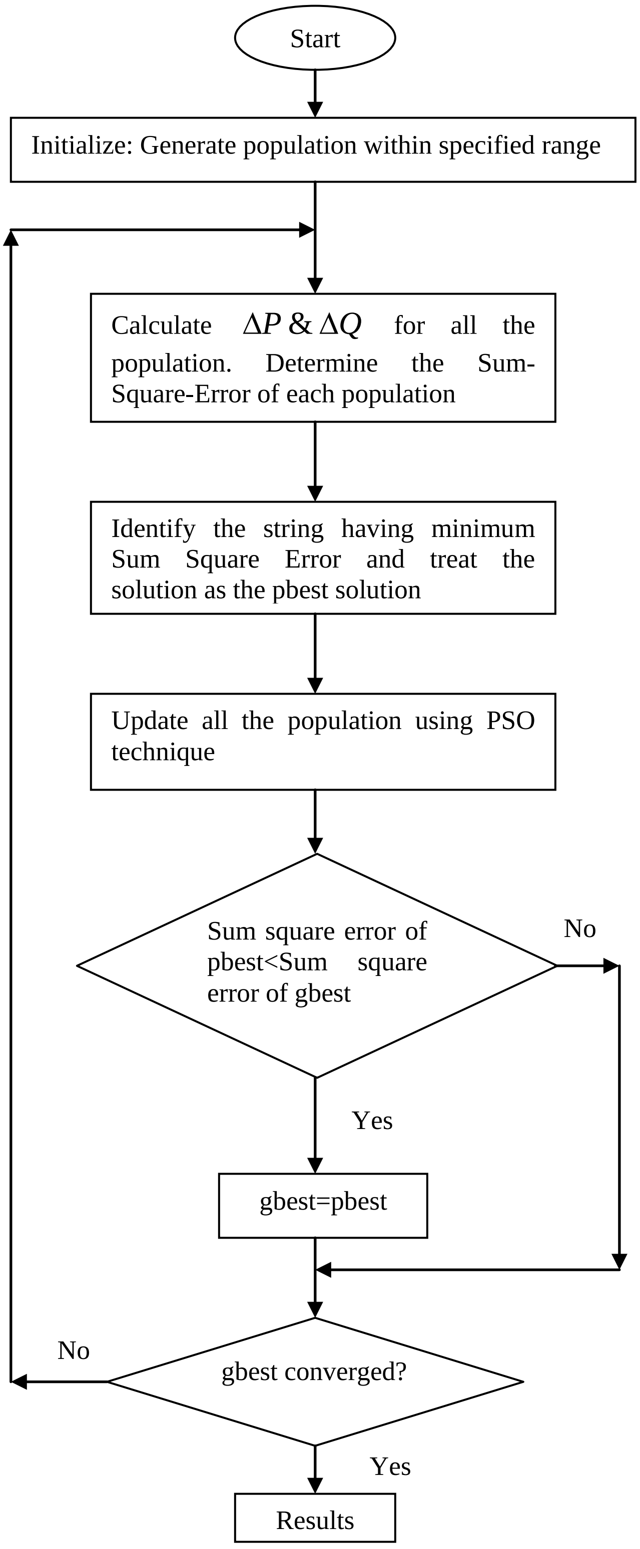

Fig. 4.1: Flowchart of the PSO based Coupled Algorithm

4.3. PARAMETER SETTINGS

Like the PSO based decoupled algorithm, parameters are appropriately set to get the desired results in case of the proposed algorithm.

Learning factors play a very important role in the performance of the PSO algorithm. If c1 & c2 are not selected properly the PSO algorithm might not converge at all. If c1 & c2 are kept constant or generated randomly within the specified range, the PSO based coupled load flow algorithm does not converge. For constant or randomly generated learning factors, the entire population soon become identical with the power mismatch values sufficiently large.

The proposed load flow converges only if the learning factors are made adaptive depending upon the objective function value of the individual population with respect to the objective function of the pbest and the gbest solutions. For the p^{th} solution individual constriction factors c_1^p and c_2^p (superscript p is used to indicate the population number) are designed as:

$$c_1^p = \frac{\text{Sum Square Error of } p^{th} \text{ Population}}{\text{Sum Square Error of pbest Solution}} \tag{4.1}$$

$$c_2^p = \frac{\text{Sum Square Error of } p^{th} \text{ Population}}{\text{Sum Square Error of gbest Solution}} \tag{4.2}$$

During initial iterations c1, c2 assume higher values as the individual population error (objective function value) will generally be large. But, as the convergence approaches, all the solution strings will approach the gbest and pbest solutions making the sum square error of individual solution very close to that of the pbest or gbest solutions. Thus c_1^p and c_2^p will be approaching unity as the convergence is approached.

For the normal solution the range of values from which voltage magnitudes and phase angles are randomly initialized are 0.9 to 1.1 p.u. and –0.01 to –0.4 radian respectively. For assured and faster convergence of the proposed PSO based coupled power flow algorithm, velocities of the agents are to be limited to certain maximum values. These values, determined empirically, for voltage magnitudes and phase angles are 0.05 p.u. and 0.25 radian respectively.

In the PSO based coupled algorithm, w is not adaptive like the decoupled algorithm. If the adaptive weighting function instead of conventional weighting function is used, then this method could be converged but takes more number of generations for the same population size. Conventionally weighting factor w is taken as w=0.5+rand/2 [25], [30], [35]. This type of random selection of w gives better result than adaptive w.

4.4. RESULTS FOR THE PSO BASED COUPLED ALGORITHM

Test results showing the number of generations required to converge to the normal power flow solutions are given in Table 4.1 for different test systems like 5 bus [41], 11 bus, IEEE 14 bus, IEEE 30 bus, IEEE 57 bus and IEEE 118 bus. Table 4.1 shows that Simple PSO based algorithm needs larger population size and larger number of iterations to achieve convergence.

Table 4.1

Test results of The PSO based coupled algorithm

Test system →	5 bus	11 bus	IEEE 14 bus	IEEE 30 bus	IEEE 57 bus	IEEE 118 bus	Population Size ↓
Number of Generations	93	892	441	998	1419	2232	100
	61	634	393	578	889	1465	200
	49	448	218	387	706	1032	300
	22	129	102	248	518	764	500
	15	63	47	103	246	449	800
	08	31	27	48	73	224	1000

For standard IEEE 30 bus test system with 800-population size, variations of the maximum values of c1 and c2 are shown in Fig. 4.2 and 4.3 respectively. It is observed that initially maximum values of c1 & c2 in the whole population are greater than 10. But the values gradually decrease as the iteration progresses. At the end of the iteration the maximum values of the constriction factors becomes near 2. Variations of the average values of c1 and c2 are shown in Fig. 4.4 and 4.5 respectively for a population size of 800.

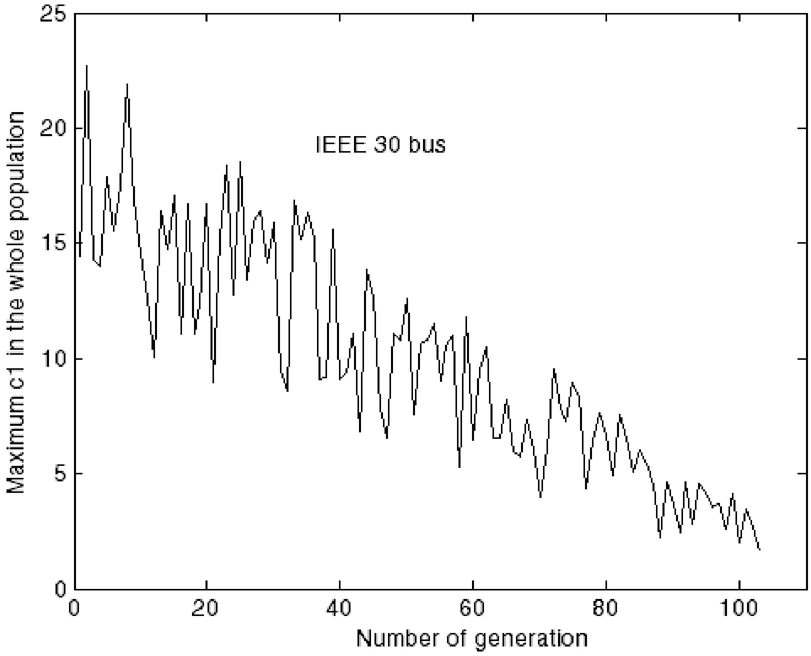

Fig. 4.2: Variation of the maximum value of c1 in the whole population for normal solution using PSO based coupled algorithm

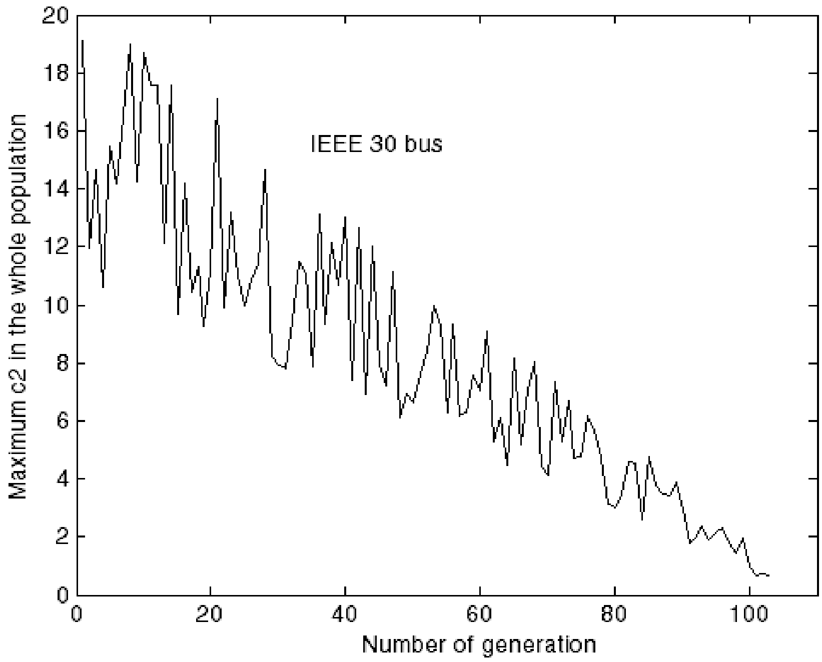

Fig. 4.3: Variation of the maximum value of c2 in the whole population for normal solution using PSO based coupled algorithm

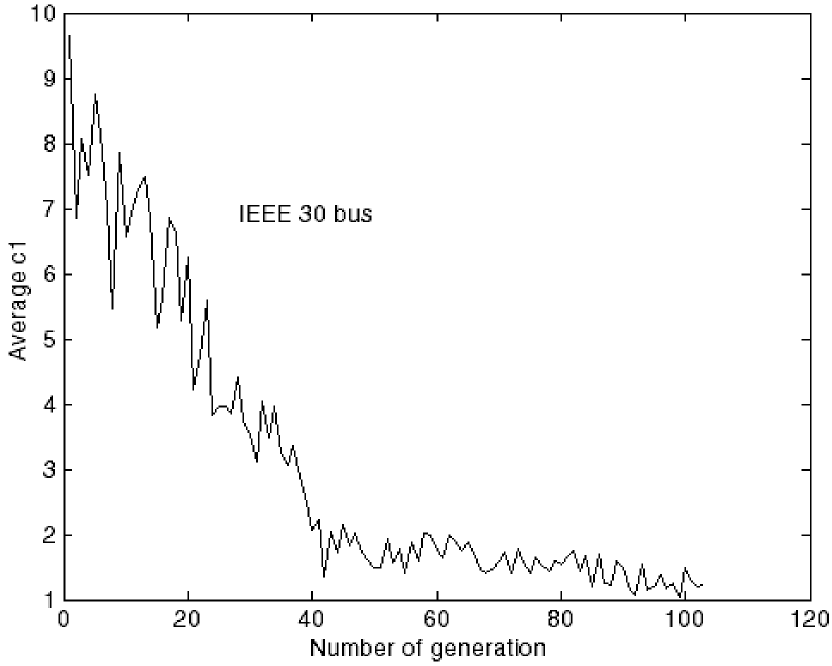

Fig. 4.4: Variation of the average value of c1 for normal solution using PSO based coupled algorithm

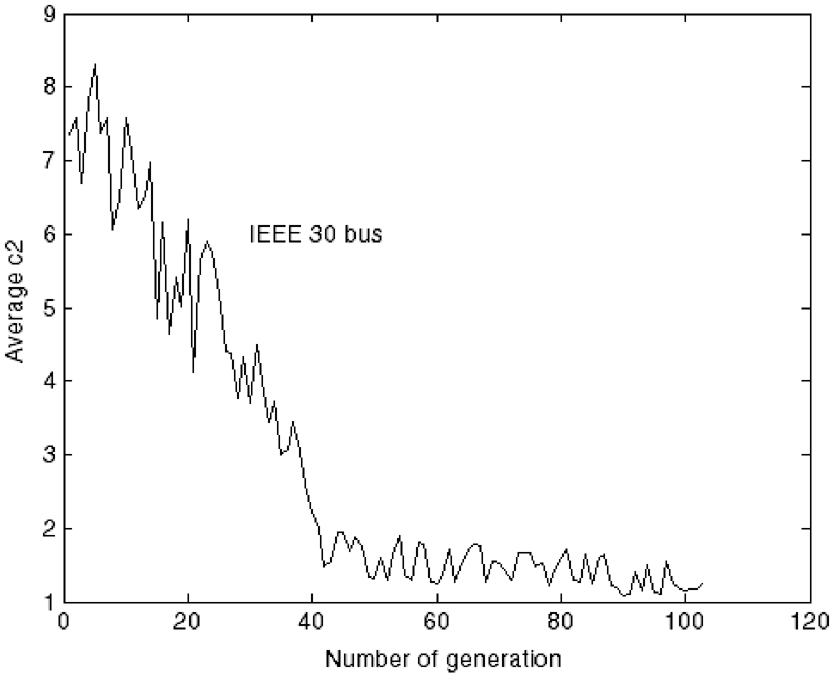

Fig. 4.5: Variation of the average value of c2 for normal solution using PSO based coupled algorithm

It is to be noted that the proposed load flow algorithm fails to converge with constant values for c1 & c2 (taken 1.5). Convergence characteristic of the power flow for constant c1 & c2 is shown in Fig. 4.6.

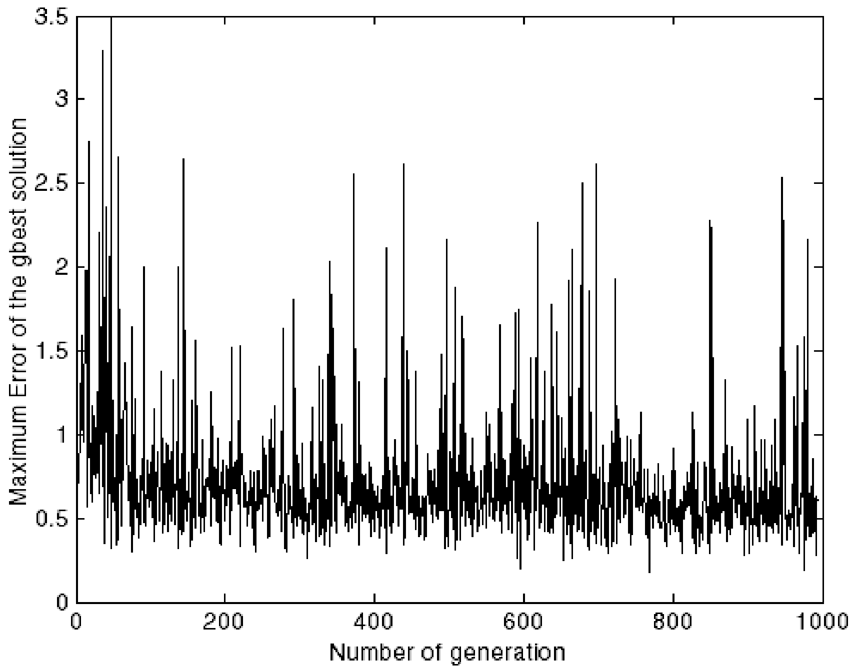

Fig. 4.6: Convergence characteristics for constant c1 & c2 for coupled algorithm with the 1000 population size for IEEE 30 bus test system

The variation of reactive power mismatch at bus number 30 for conventional w and the proposed adaptive w are shown in Fig. 4.7 and Fig. 4.8 respectively for IEEE 30 bus test system with 800-population size for the PSO based coupled algorithm. From the figures given below it is observed that smooth reduction in error occurs using conventional w, whereas, the adaptive weighting function as proposed in chapter 3 results in slower decay of the power mismatch values. The convergence characteristics become sluggish in case of adaptive w.

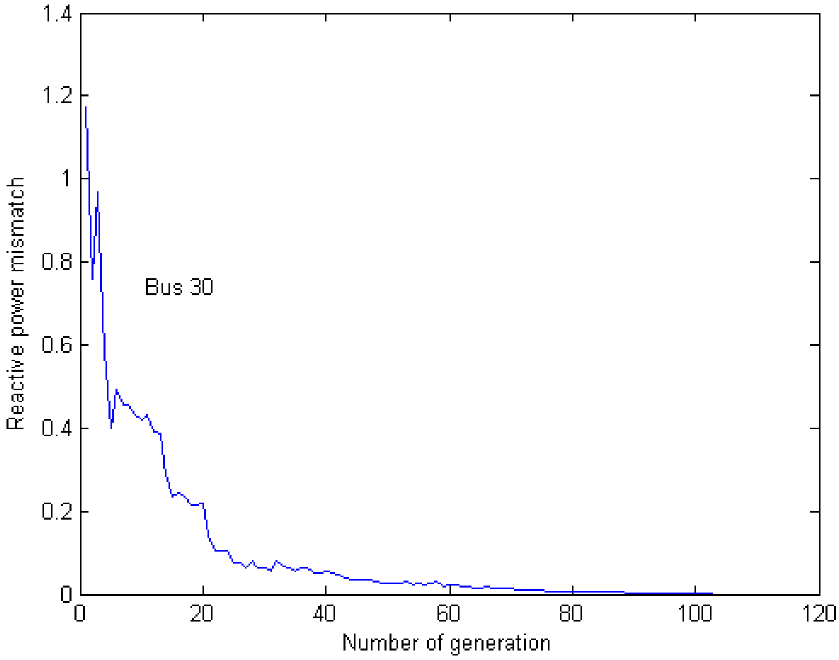

Fig. 4.7: Variation of error of bus 30 for IEEE 30 bus test system for 800 population size using conventional ‘w’

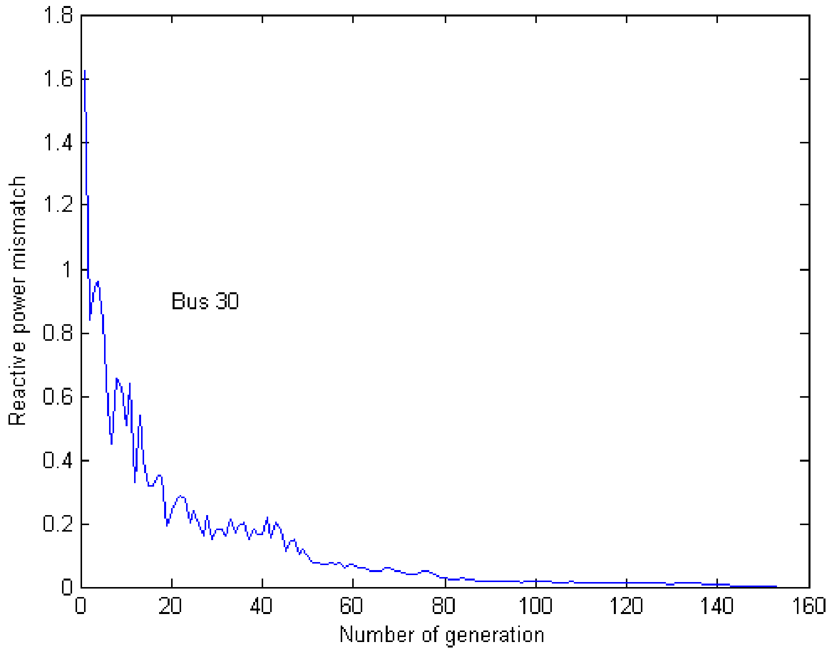

Fig. 4.8: Variation of error of bus 30 for IEEE 30 bus test system for 800 population size using adaptive ‘w’

The convergence characteristics for the gbest solution are shown for different test systems through Fig. 4.9 to Fig.4.14 for the coupled algorithm to obtain normal solution for a population size of 800.

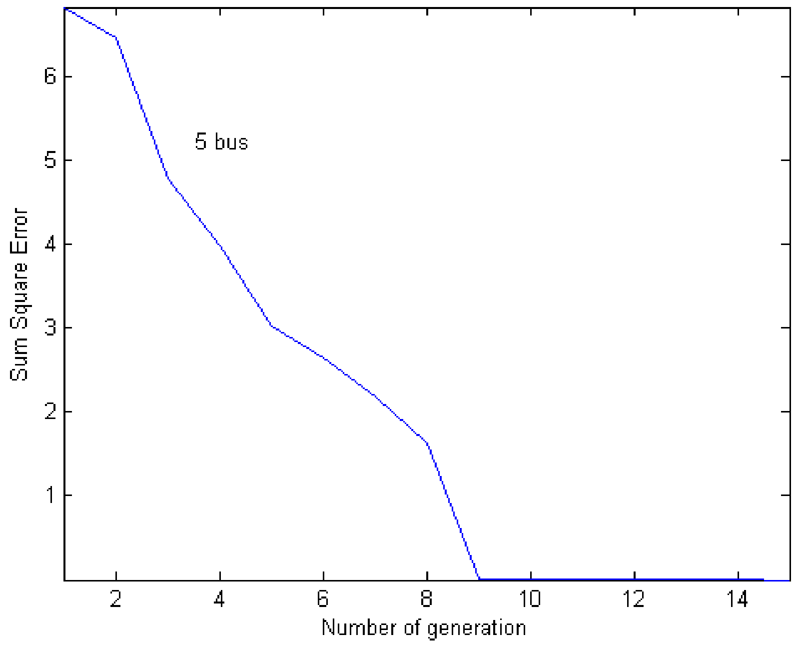

Fig. 4.9: Convergence characteristic of 5 bus for the PSO based coupled algorithm with the population size of 800

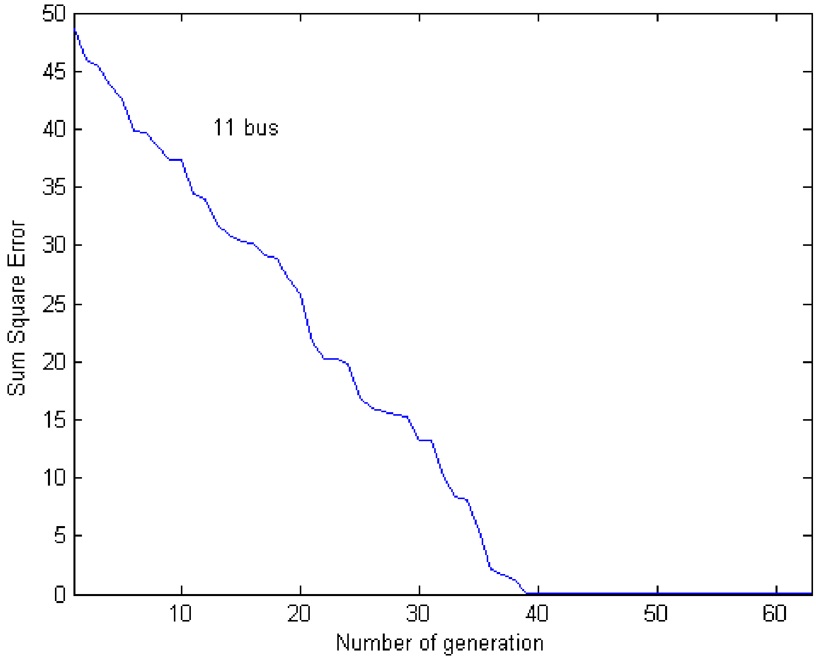

Fig. 4.10: Convergence characteristic of 11 bus for the PSO based coupled algorithm with the population size of 800

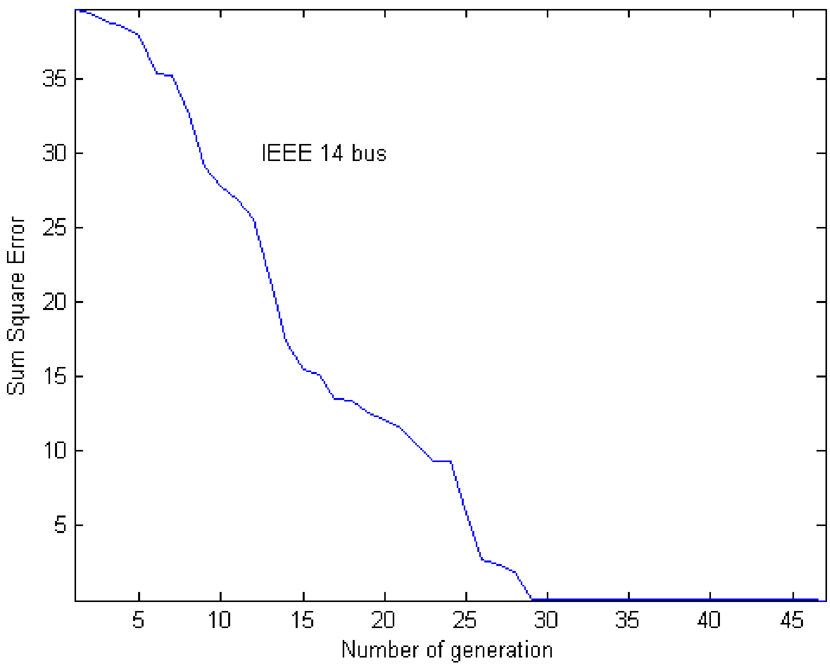

Fig. 4.11: Convergence characteristic of IEEE 14 bus for the PSO based coupled algorithm with the population size of 800

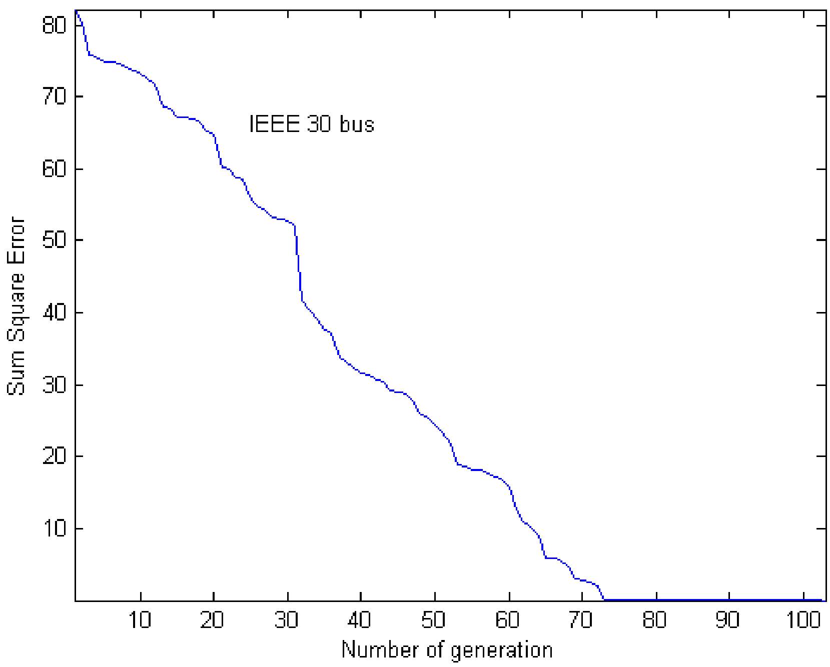

Fig. 4.12: Convergence characteristic of IEEE 30 bus for the PSO based coupled algorithm with the population size of 800

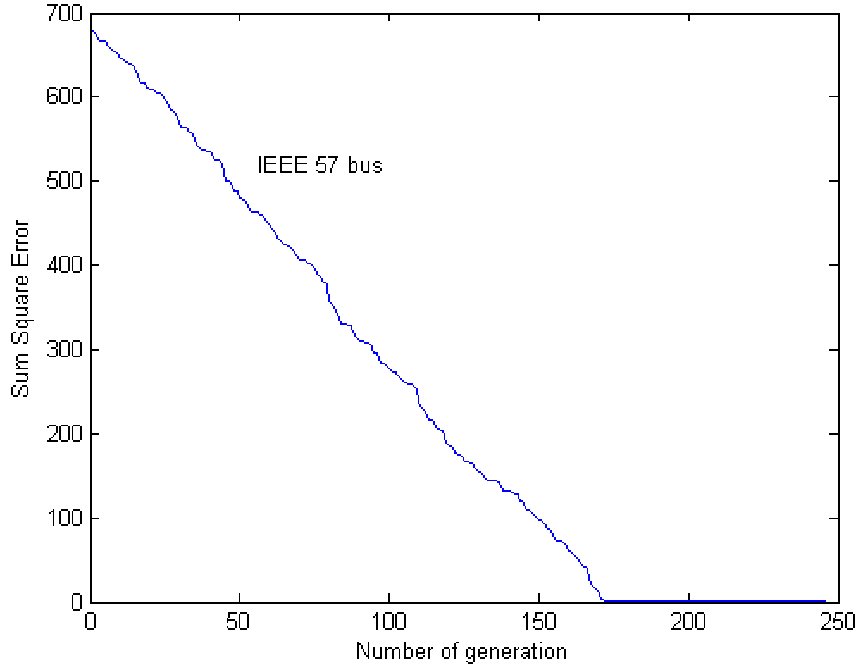

Fig. 4.13: Convergence characteristic of IEEE 57 bus for the PSO based coupled algorithm with the population size of 800

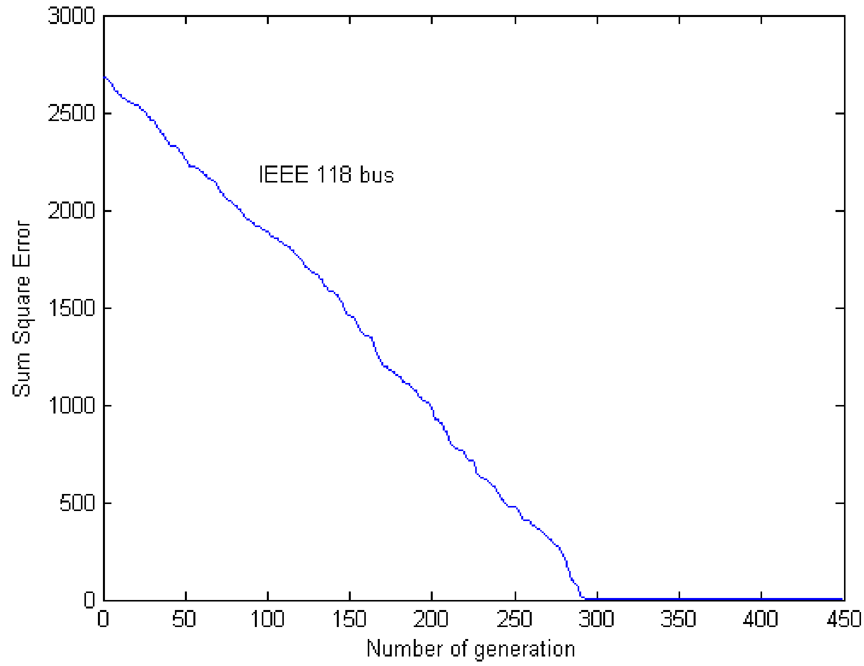

Fig. 4.14: Convergence characteristic of IEEE 118 bus for the PSO based coupled algorithm with the population size of 800

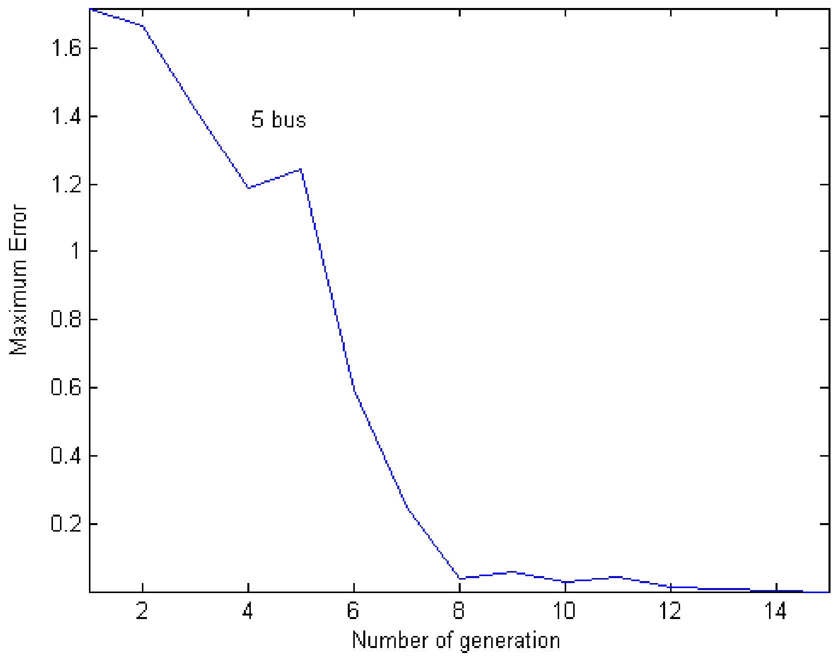

Fig. 4.15: Variation of the maximum error with the number of generation of 5-bus test system for PSO based coupled algorithm

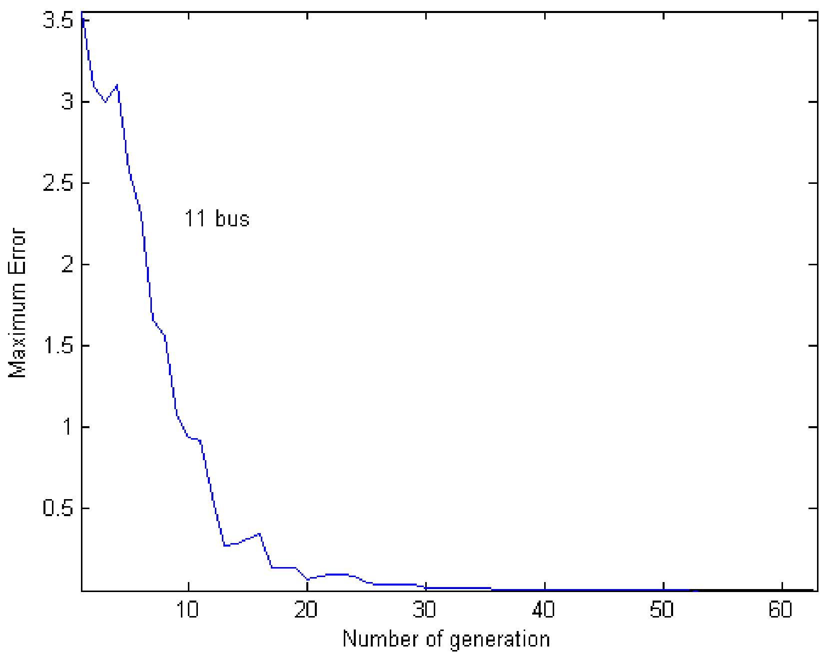

Fig. 4.16: Variation of the maximum error with the number of generation of 11-bus test system for PSO based coupled algorithm

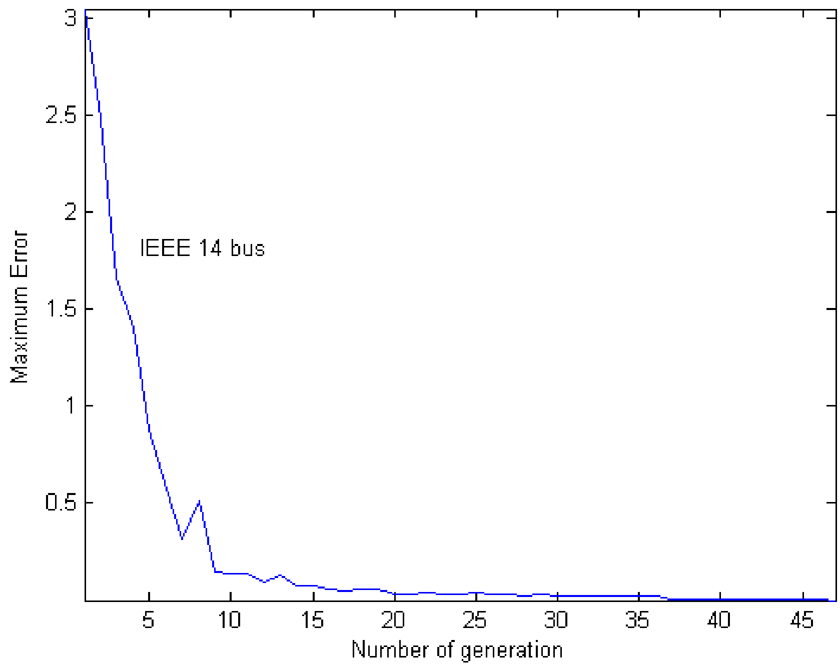

Fig. 4.17: Variation of the maximum error with the number of generation of IEEE 14 bus test system for PSO based coupled algorithm

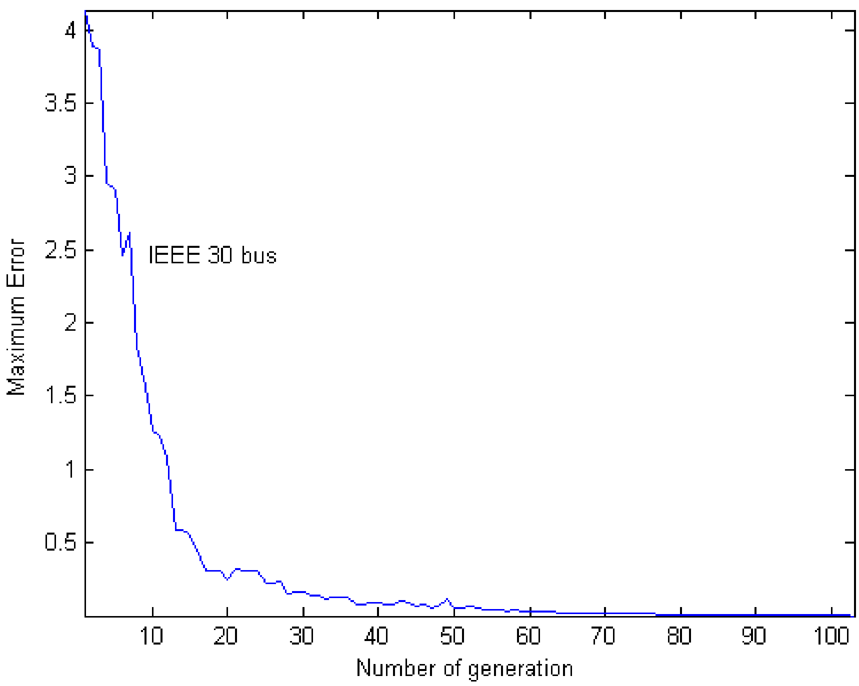

Fig. 4.18: Variation of the maximum error with the number of generation of IEEE 30 bus test system for PSO based coupled algorithm

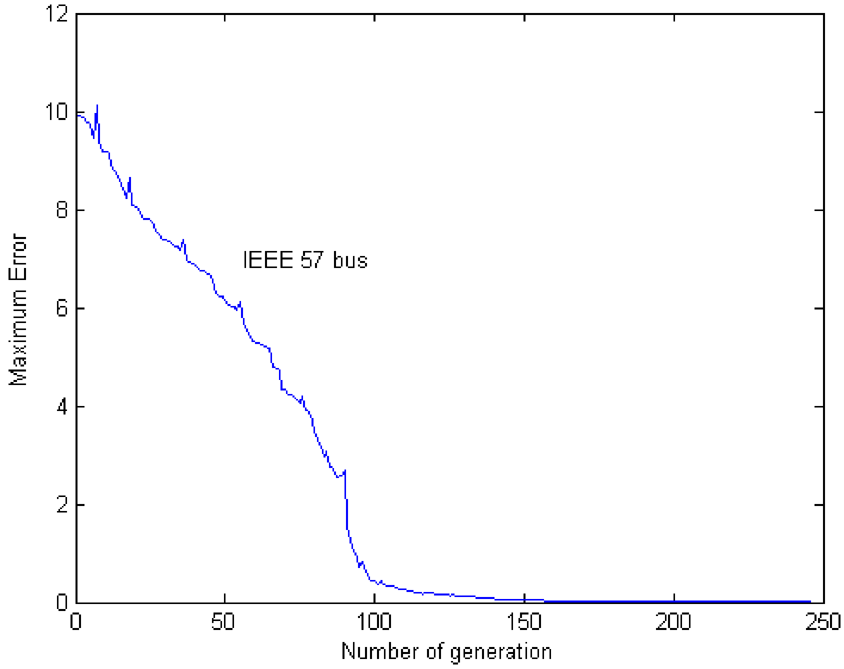

Fig. 4.19: Variation of the maximum error with the number of generation of IEEE 57 bus test system for PSO based coupled algorithm

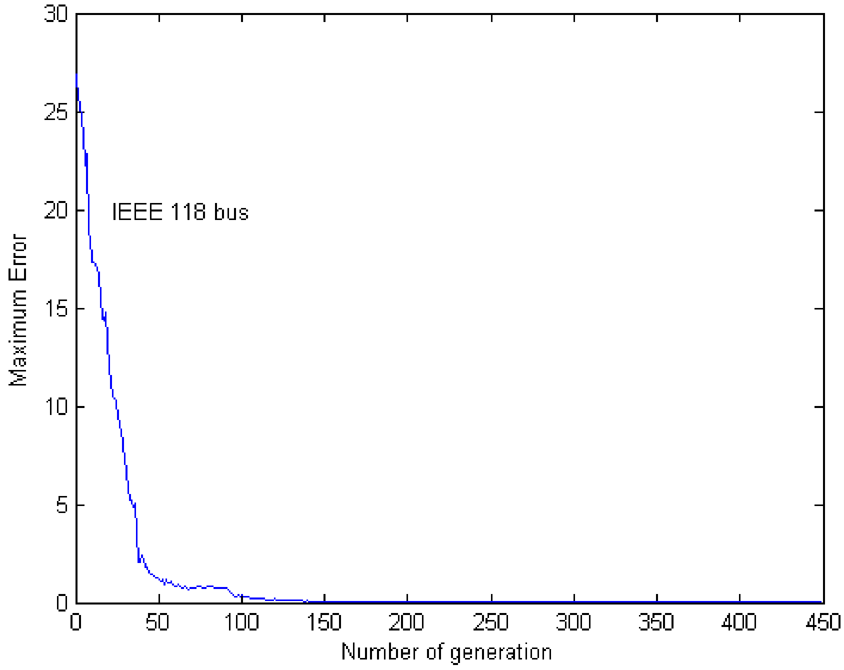

Fig. 4.20: Variation of the maximum error with the number of generation of IEEE 118 bus test system for PSO based coupled algorithm

4.5. IMPROVEMENT SCHEMES

Two improvement schemes, local search and linear perturbation, have been used with the proposed algorithm like the PSO based decoupled algorithm. Both the schemes showed enhancement in the solution-speed in getting the normal solution for all the test cases. The speed of the coupled algorithm has been enhanced as magically as the decoupled algorithm when the perturbation based load flows are used along with the coupled algorithm. The improvement scheme not only enhances the convergence speed of the proposed algorithm but also helps to find multiple load flow solutions. As in case of the decoupled algorithm, the schemes have been applied on the pbest solution of the coupled algorithm. With the improvement of the pbest solution, the performance of the algorithm improves automatically according to the characteristic of the swarm optimization technique. Test results with the improvement schemes are produced in Table 4.2 and 4.3.

Table 4.2

Test results of the PSO based coupled algorithm with Local Search

Test System →	5 bus	11 bus	IEEE 14 bus	IEEE 30 bus	IEEE 57 bus	IEEE 118 bus	Population Size ↓
Number of Generations	07	18	14	22	31	42	100
	09	25	17	28	39	53	40
	18	36	33	51	69	84	20
	42	67	58	92	132	198	12

Table 4.3

Test results of the PSO based coupled algorithm with Linear Perturbation

Test System →	5 bus	11 bus	IEEE 14 bus	IEEE 30 bus	IEEE 57 bus	IEEE 118 bus	Population Size ↓
Number of Generations	16	30	28	38	44	63	100
	16	31	30	39	46	67	40
	22	44	42	70	81	111	20
	48	72	63	108	155	214	10

With the linear perturbations, the required number of generations for desired convergence is more than that of the local search. But with lower population size, the performance of the linear perturbation is almost similar to that of the local search technique.

4.6. CHARACTERISTICS OF THE ALGORITHM WITH IMPROVEMENT SCHEMES

If local search technique is incorporated in the PSO based coupled algorithm, the number of generation for the convergence reduces significantly. The variations of the maximum values of the c1 & c2 are shown in Fig. 4.21 and 4.22 for the population size of 100. the nature of the variations of the learning factors, however, remain almost similar to that of the coupled algorithm without the improvement schemes. At the beginning of c1 & c2 assume large values. But as the convergence is approached, their values decrease drastically. The rate of decrease of the values is faster since the algorithm also is now faster.

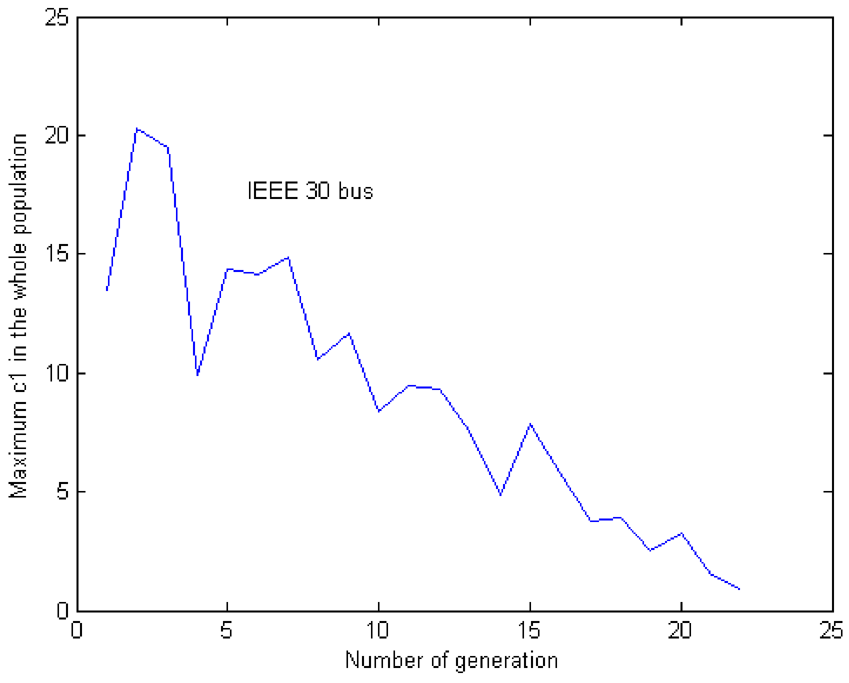

Fig. 4.21: Variation of the maximum value of c1 in the whole population for normal solution using PSO based coupled algorithm with Local search

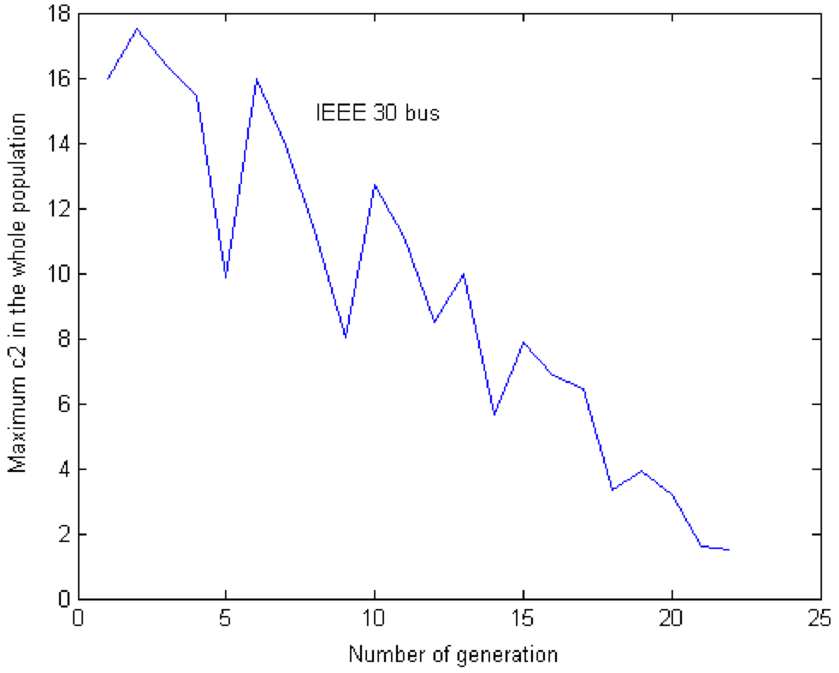

Fig. 4.22: Variation of the maximum value of c2 in the whole population for normal solution using PSO based coupled algorithm with Local search

Fig. 4.23 and Fig. 4.24 show the change of the average value of the c1 and c2 for PSO based coupled algorithm with local search with 100-population size.

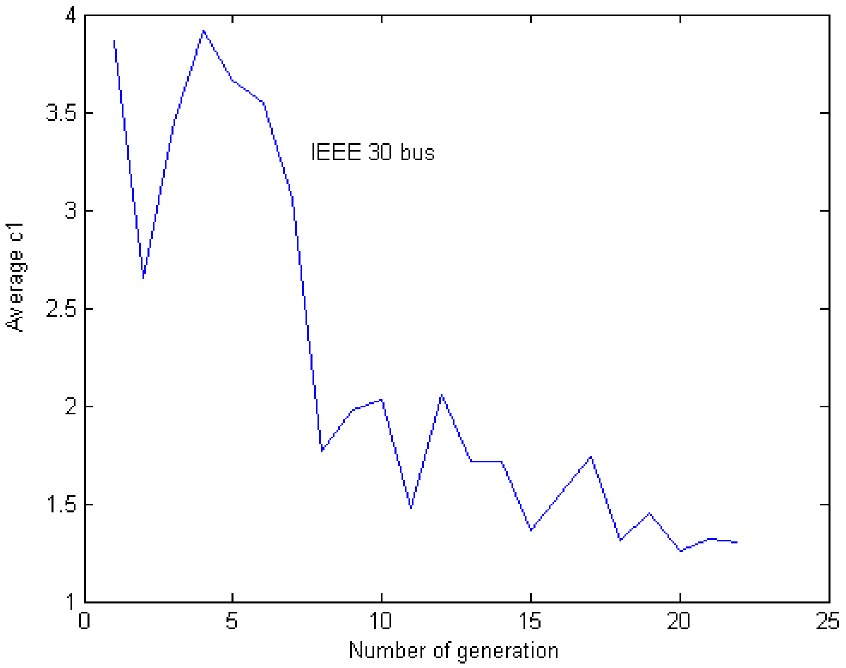

Fig. 4.23: Variation of the average value of c1 for normal solution using PSO based coupled algorithm with local search

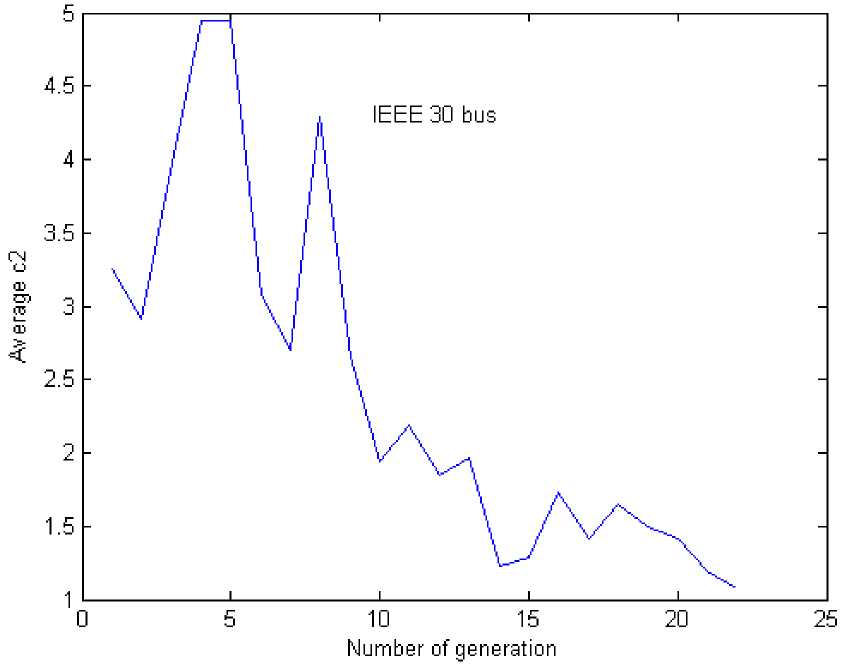

Fig. 4.24: Variation of the average value of c2 for normal solution using PSO based coupled algorithm with local search

The local search techniques have been applied on the pbest solution such that both the sum square error and maximum error are reduced. As the pbest solution is improved, automatically the *g*best solution and other solution-population are updated. So rapid convergence is obtained for the combined global and local search technique. The variation of the sum square error with the number of generation for the different test systems are shown through Fig.4.25 to Fig.4.30.

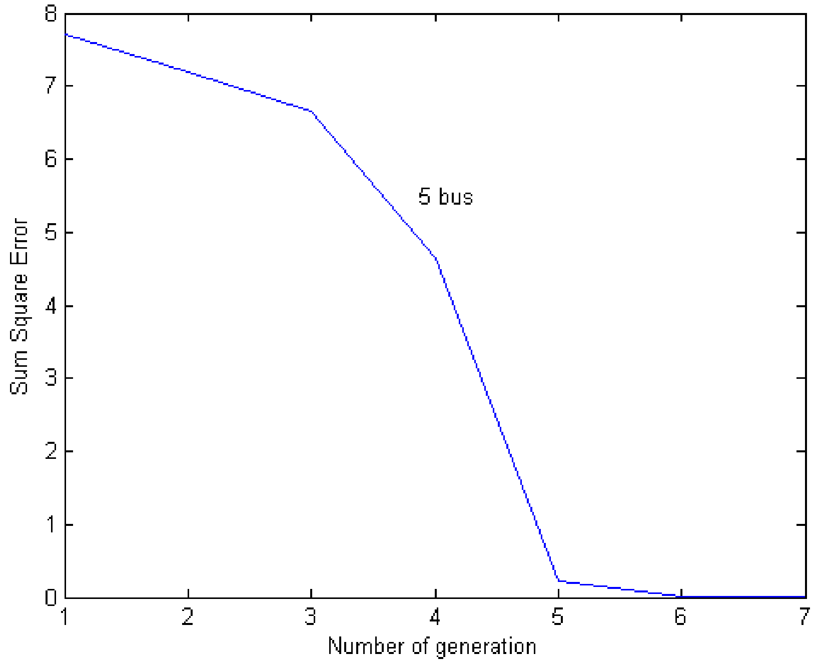

Fig. 4.25: Convergence characteristics of 5-bus test system for PSO based coupled algorithm with local search with 100-population size

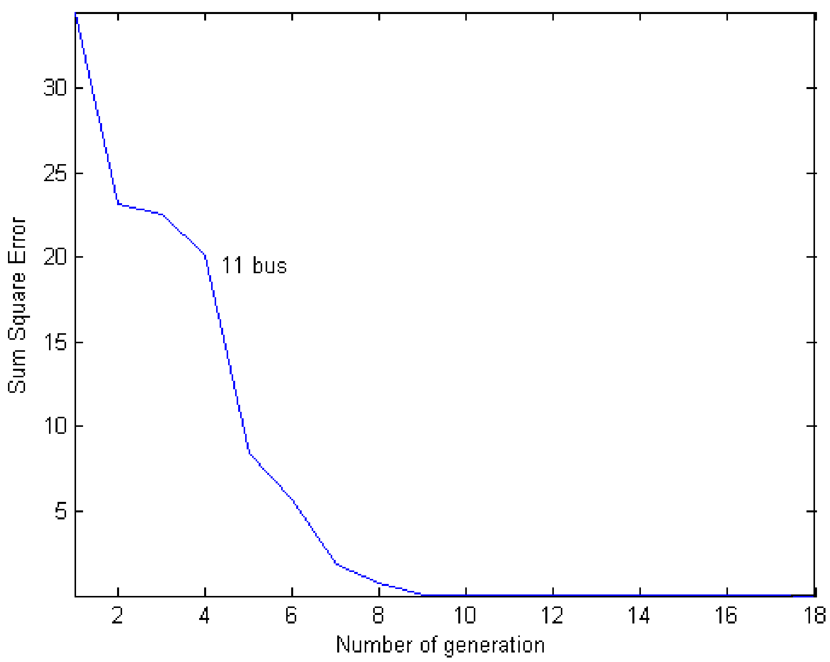

Fig. 4.26: Convergence characteristics of 11-bus test system for PSO based coupled algorithm with local search with 100-population size

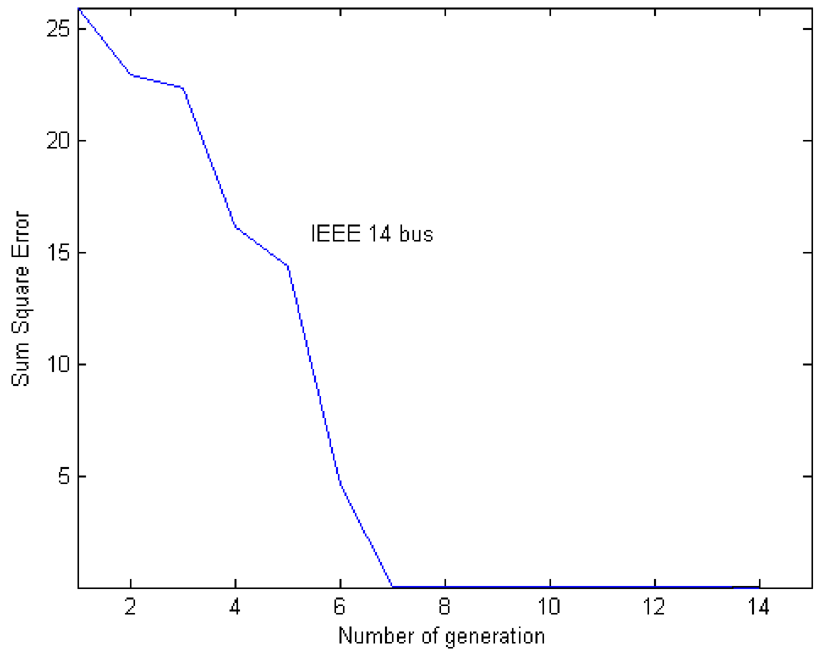

Fig. 4.27: Convergence characteristics of IEEE 14 bus test system for PSO based coupled algorithm with local search with 100-population size

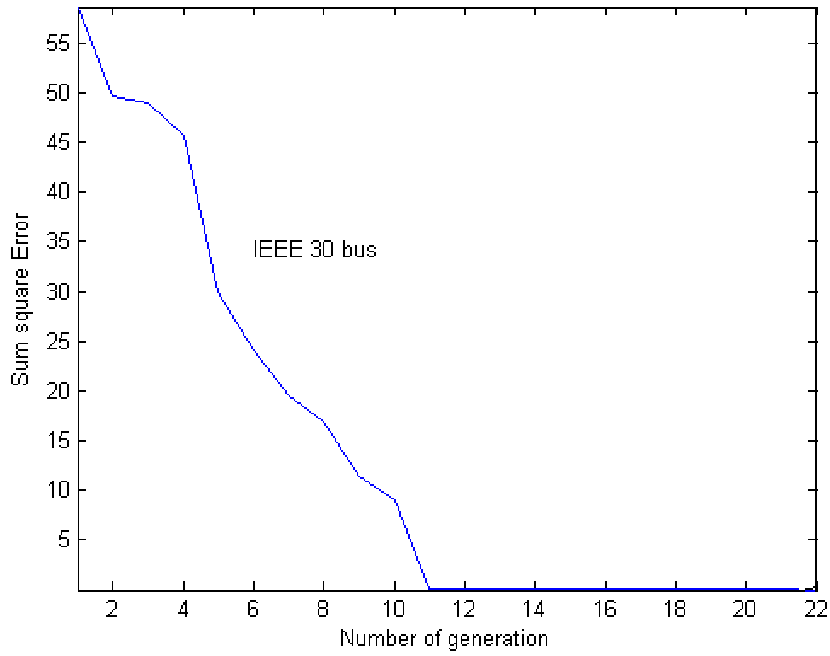

Fig. 4.28: Convergence characteristics of IEEE 30 bus test system for PSO based coupled algorithm with local search with 100-population size

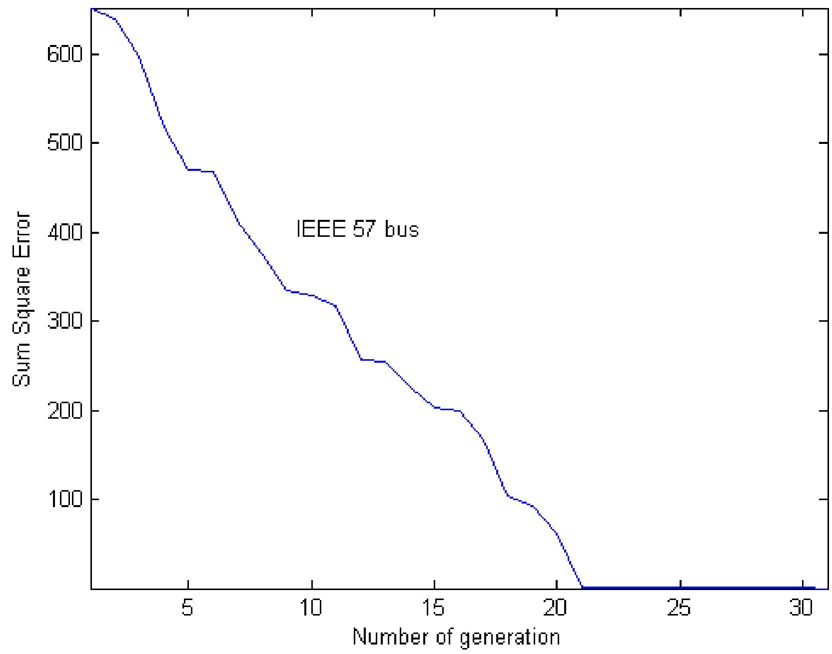

Fig. 4.29: Convergence characteristics of IEEE 57 bus test system for PSO based coupled algorithm with local search with 100-population size

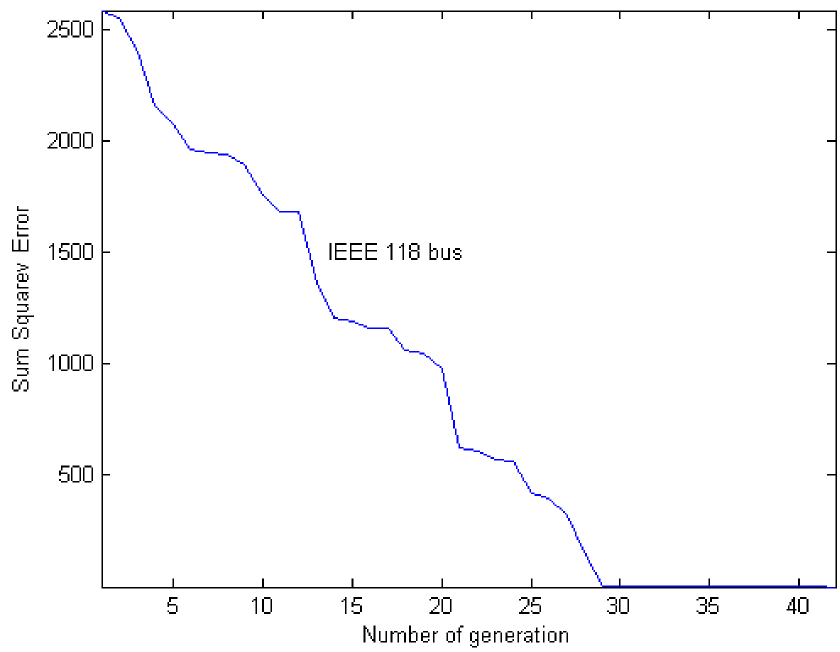

Fig. 4.30: Convergence characteristics of IEEE 118 bus test system for PSO based coupled algorithm with local search with 100-population size

Variations of the maximum bus power mismatches corresponding to the gbest solutions for different test systems are shown in Fig. 4.31 through 4.36. It may be noted that the application of the local search removes all ups and downs in the convergence characteristics. On some occasions, the mismatch values remained same for a few iterations. But it never went up.

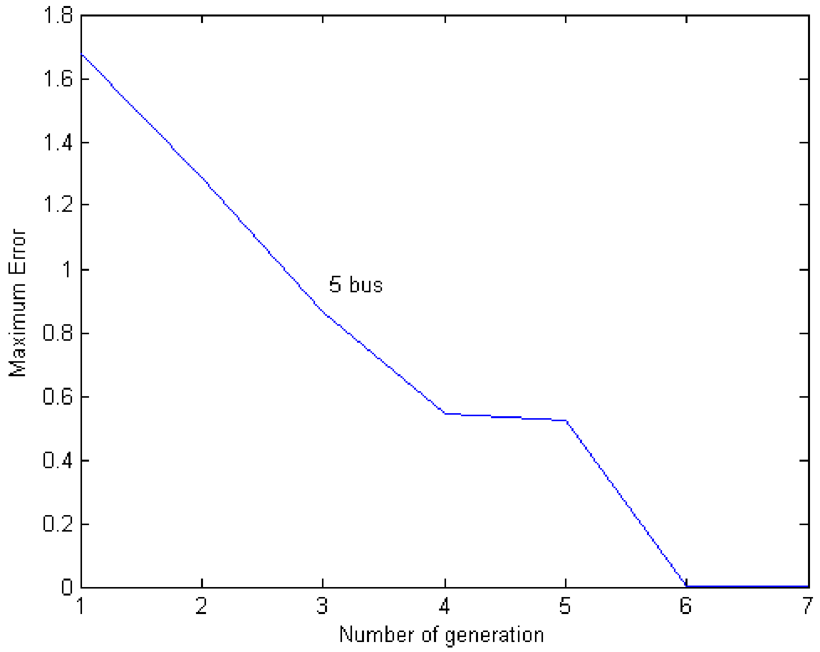

Fig. 4.31: Variation of the maximum error with the number of generation of 5-bus test system for PSO based coupled algorithm with local search

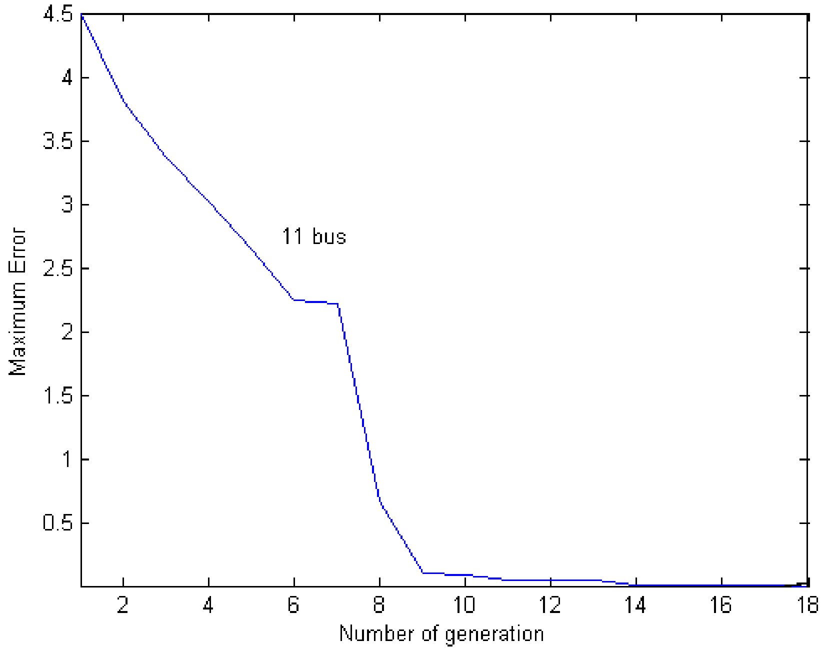

Fig. 4.32: Variation of the maximum error with the number of generation of 11-bus test system for PSO based coupled algorithm with local search

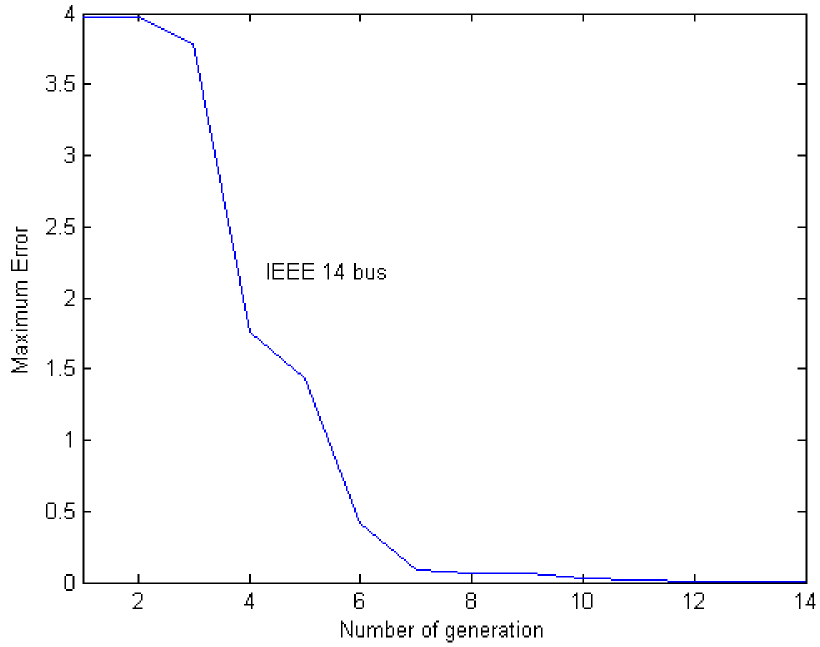

Fig. 4.33: Variation of the maximum error with the number of generation of IEEE 14 bus test system for PSO based coupled algorithm with local search

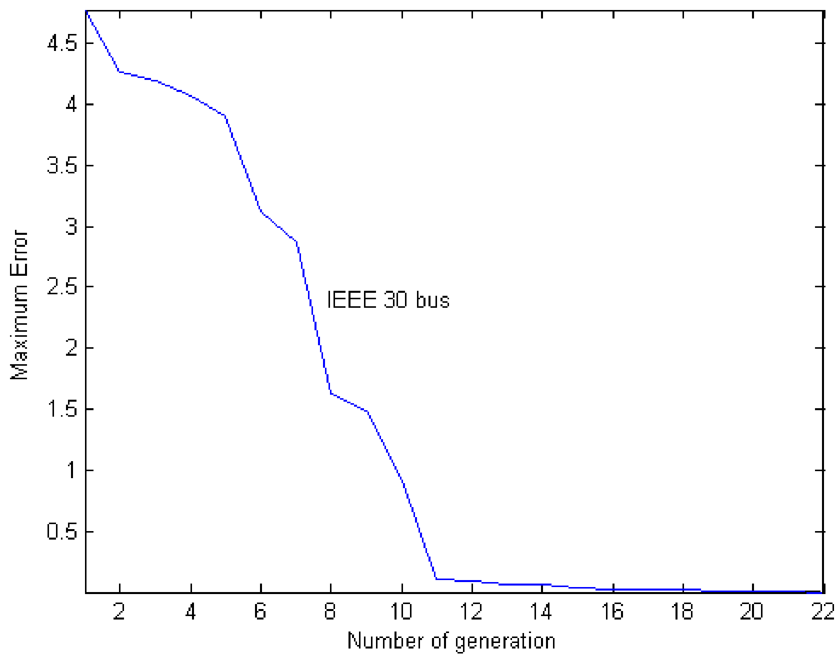

Fig. 4.34: Variation of the maximum error with the number of generation of IEEE 30 bus test system for PSO based coupled algorithm with local search

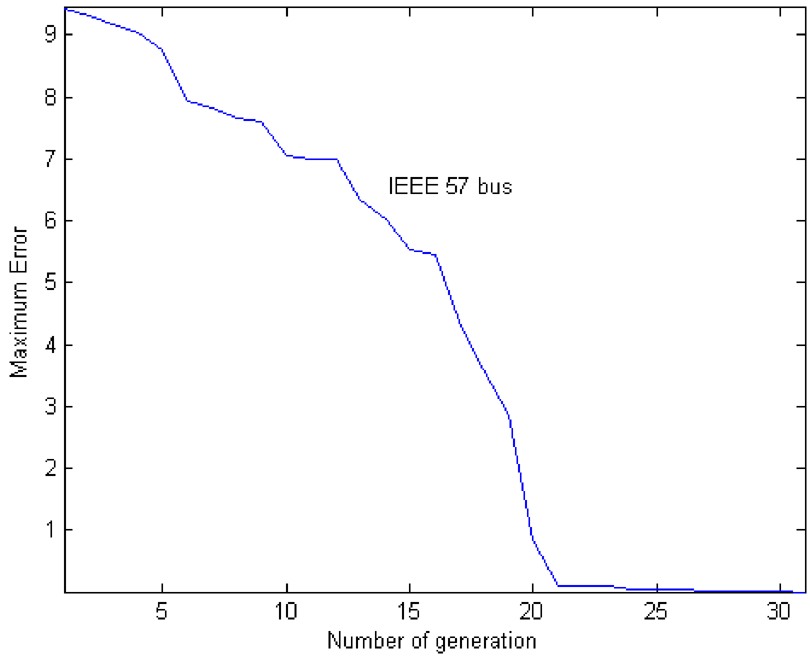

Fig. 4.35: Variation of the maximum error with the number of generation of IEEE 57 bus test system for PSO based coupled algorithm with local search

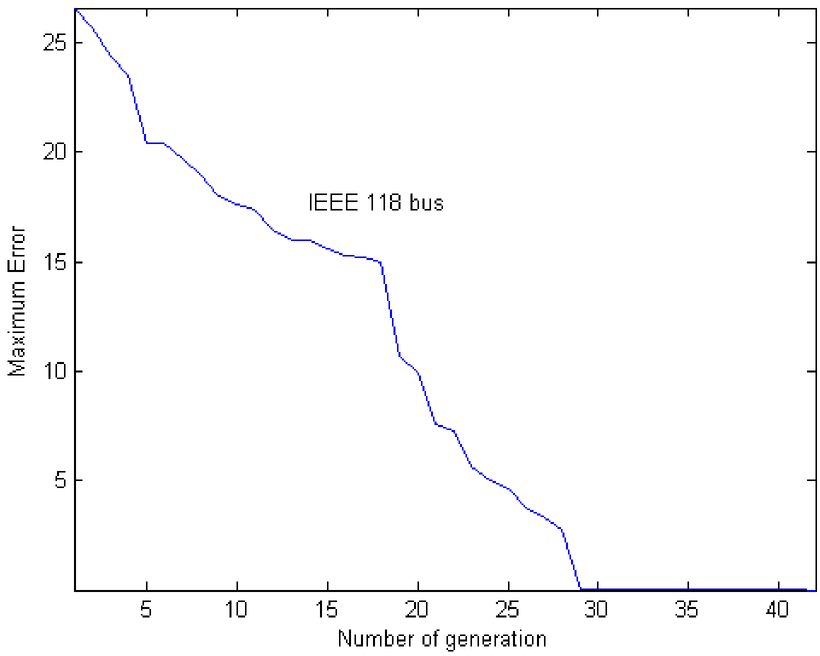

Fig. 4.36: Variation of the maximum error with the number of generation of IEEE 118 bus test system for PSO based coupled algorithm with local search

As the maximum error has decreased smoothly without any spikes, the number of generation for the convergence for all type of test systems is reduced significantly. The characteristics of the proposed method with linear perturbation are almost the same as that of the local search.

4.7. MULTIPLE LOAD FLOW SOLUTIONS USING THE COUPLED ALGORITHM

It is known that load flow problem can have multiple solutions. The maximum possible solutions have been estimated to be 2^N-1, where N is the number of buses in the systems. The number of solutions that actually exists, however, depends upon the loading on the system. More solutions exist when the system is lightly loaded. As the loading on the system increases, the number of solutions reduces and when the system reaches its maximum permissible loading condition only one solution, that is the normal solution of the systyem, exist. Finding the multiple power flow solution of a system is thus important as it gives an idea regarding the system's state with respect to its critical loading condition.

Finding the normal solution of a system is rather easier for a power system. As it is known that normal operation of any power system is very close to its rated voltage conditions. Any power flow method thus starts with flat voltage initialization to find the normal solutions. It is, however, very difficult to predict the location of the low voltage solutions. The only thing one can, perhaps, do to find the low voltage solutions is to initialize a load flow method with low voltages. As such initializations rarely can be close to a solution of the power flow equations, Newton based power flows invariably fail to converge to a solution. General-purpose optimization techniques such as PSO may, however, succeed in such a situation.

An attempt to find the low voltage solutions using the developed PSO based power flow method fared very poorly requiring large number of generations and that too in case of the 5 bus system only. The method failed for all other cases. But the coupled algorithm assisted by the local network based load flow can efficiently find multiple solutions. The PSO population however need to be initialized using lower starting values. The range of starting values are 0.06 p.u. to 0.7 p.u. for the voltage magnitudes and 0.01 to -3.0 radian for the phase angles. Determination of multiple low voltage solutions requires greater computing efforts in terms of the number of generations and also the population size. Some of the low voltage solutions determined by the PSO based coupled algorithm for different test systems are given though Table 4.4 to 4.8. Table 4.9 shows the average number of generations required for varied size of population for the proposed method with the local search. Variation of c1 & c2 are very similar to that of the normal solutions.

Table 4.4

Some low Voltage solutions of 5- Bus Test System

Solution Number	Voltage Magnitudes					Phase Angles				
	V1	V2	V3	V4	V5	$\delta 1$	$\delta 2$	$\delta 3$	$\delta 4$	$\delta 5$
1	1.0600	0.5676	0.1329	0.0636	0.2314	0	-5.0274	-36.3000	-72.1101	-38.3108
2	1.0600	0.6911	0.6150	0.5629	0.0850	0	-3.7402	-9.4714	-10.8411	-61.3444
3	1.0600	1.0474	1.0242	1.0236	1.0179	0	-2.8064	-4.9970	-5.3291	-6.1503
4	1.0600	0.8451	0.7947	0.7639	0.4593	0	-1.4600	-4.7945	-5.0739	-2.3516
5	1.0600	0.7308	0.6621	0.6151	0.1563	0	-2.7673	-7.6507	-8.5373	-18.7123
6	1.0600	0.9135	0.0376	0.1638	0.6177	0	-14.2451	-67.1734	-39.6159	-22.7293
7	1.0600	0.7189	0.7236	0.6511	0.0784	0	-4.4497	-11.4435	-12.1953	-63.1949
8	1.0600	0.6135	0.1364	0.0547	0.3154	0	-5.6686	-34.0862	-73.7245	-28.2495
9	1.0600	0.6522	0.1327	0.0450	0.6312	0	-7.8874	-34.1074	-79.2185	-30.8006
10	1.0600	0.4732	0.0991	0.1338	0.8421	0	-26.3512	-71.1800	-97.7929	-116.1348
11	1.0600	0.8103	0.1679	0.0370	0.5421	0	-10.7006	-27.4960	-78.2853	-22.5258
12	1.0600	0.4626	0.5431	0.9329	0.3440	0	-36.1404	-113.4513	-127.4195	-99.7738
13	1.0600	0.7723	0.1600	0.0581	0.3891	0	-22.9006	-39.2713	-90.1506	-157.4634
14	1.0600	0.5723	0.0536	0.1402	0.8445	0	-12.8318	-69.5903	-61.4130	-51.4357
15	1.0600	0.8765	0.3634	0.4384	0.5673	0	-139.1935	-130.9780	-136.9980	-141.8959
16	1.0600	0.9789	0.4320	0.4989	0.4987	0	-137.1120	-126.5111	-132.0886	-136.1188
17	1.0600	0.5676	0.1329	0.0636	0.2314	0	-5.0274	-36.3000	-72.1101	-38.3108
18	1.0600	0.6911	0.6150	0.5629	0.0850	0	-3.7402	-9.4714	-10.8411	-61.3444
19	1.0600	0.7308	0.6621	0.6151	0.1563	0	-2.7673	-7.6507	-8.5373	-18.7123
20	1.0600	0.9432	0.0362	0.1711	0.6424	0	-15.1454	-67.8843	-38.8216	-23.0746
21	1.0600	0.9135	0.0376	0.1638	0.6177	0	-14.2451	-67.1734	-39.6159	-22.7293
22	1.0600	0.3765	0.4530	0.4142	0.2896	0	4.8033	-11.0289	-13.2044	-26.9416
23	1.0600	0.7414	0.5529	0.4739	0.3598	0	-1.0253	-3.6475	-2.6888	-5.9562
24	1.0600	0.6266	0.3559	0.2498	0.1598	0	-2.7132	-9.1448	-8.8803	-32.4683
25	1.0600	0.6100	0.2543	0.0466	0.3177	0	-4.9362	-28.2113	-51.8082	-26.5315
26	1.0600	0.6951	0.0602	0.0878	0.4557	0	-8.3357	-59.2872	-61.8269	-24.7084

Table 4.5 (a)

Some low Voltage solutions of 11 Bus Test System: Solution Set I

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0500	0	1	1.0500	0
2	0.7863	-1.6835	2	0.8641	-12.8148
3	0.6080	-3.0638	3	0.8217	-214372
4	0.6511	-5.7298	4	0.7496	-33.0198
5	1.0500	-8.6596	5	1.0500	-44.3024
6	0.0001	-3.1623	6	0.8177	-35.3356
7	0.8017	-6.7789	7	0.9700	-58.3388
8	0.8970	-6.1175	8	0.9902	-64.7775
9	1.0375	-5.2729	9	1.0375	-73.8140
10	0.9827	-4.2489	10	0.0021	-110.0449
11	0.7597	-4.9984	11	0.5798	-28.7502

Table 4.5 (b)

Some low Voltage solutions of 11 Bus Test System: Solution Set II

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0500	0	1	1.0500	0
2	0.7887	-1.6172	2	0.6311	-1.8541
3	0.7244	-3.5034	3	0.4674	-5.3574
4	0.5451	-6.5663	4	0.3158	-18.0788
5	1.0500	-9.4280	5	1.0500	-23.2296
6	0.7221	-5.7388	6	0.1549	-8.9682
7	0.9883	-7.0467	7	0.8388	-16.3625
8	1.0095	-6.5378	8	0.9190	-14.8294
9	1.0375	-5.7332	9	1.0375	-12.8895
10	0.8541	-4.1270	10	0.8094	-9.6695
11	0.1987	0.2136	11	0.0344	-3.1119

Table 4.5 (c)

Some low Voltage solutions of 11 Bus Test System: Solution Set III

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0500	0	1	1.0500	0
2	0.6555	-1.9534	2	0.7404	-2.4572
3	0.4560	-4.4977	3	0.6633	-5.4055
4	0.0234	-18.0771	4	0.4600	-11.2587
5	1.0500	-33.1041	5	1.0500	-14.4411
6	0.3684	-13.1049	6	0.6580	-9.0746
7	0.8868	-20.0495	7	0.9712	-10.7052
8	0.9471	-17.5077	8	0.9991	-9.9330
9	1.0375	-14.1638	9	1.0375	-8.7705
10	0.8749	-10.6776	10	0.8188	-6.5375
11	0.3183	-10.2593	11	0.0644	-0.9340

Table 4.6 (a)

Some low Voltage solutions of 14 Bus Test System: Solution Set I

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0600	0	1	1.0600	0
2	1.0450	-10.0911	2	1.0450	-9.5574
3	1.0100	-21.6702	3	1.0100	-20.5427
4	0.8682	-19.0999	4	0.9305	-19.0729
5	0.8951	-18.5901	5	0.9433	-17.6669
6	1.0700	-46.6839	6	1.0700	-39.4297
7	0.7044	-30.2874	7	0.8851	-29.1115
8	1.0900	-30.2870	8	1.0900	-29.1114
9	0.3867	-43.8389	9	0.7351	-35.9271
10	0.0163	-78.6315	10	0.7840	-37.0279
11	0.5213	-46.5146	11	0.9198	-38.3743
12	1.0048	-48.0172	12	0.9389	-41.5846
13	0.9485	-47.4044	13	0.8142	-40.0483
14	0.5995	-48.8383	14	0.0357	-81.3755

Table 4.6 (b)

Some low Voltage solutions of 14 Bus Test System: Solution Set II

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0600	0	1	1.0600	0
2	1.0450	-27.7856	2	1.0450	-14.9197
3	1.0100	-68.9457	3	1.0100	-33.6764
4	0.0272	-131.5955	4	0.5580	-28.5830
5	0.2653	-45.6753	5	0.4889	-17.5057
6	1.0700	-105.9993	6	1.0700	-184.7323
7	0.6028	-107.2298	7	0.5759	-82.3182
8	1.0900	-106.9329	8	1.0900	-82.3059
9	0.6020	-107.3261	9	0.4509	-114.8216
10	0.6736	-107.0585	10	0.4629	-137.5143
11	0.8635	-106.2152	11	0.7047	-170.1332
12	1.0237	-107.0240	12	0.9862	-184.7045
13	0.9836	-106.7560	13	0.9226	-182.0747
14	0.7454	-108.5087	14	0.5185	-160.4695

Table 4.6 (c)

Some low Voltage solutions of 14 Bus Test System: Solution Set III

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0600	0	1	1.0600	0
2	1.0450	-14.0134	2	1.0450	-20.2334
3	1.0100	-30.1441	3	1.0100	-40.3235
4	0.6458	-25.2512	4	0.6889	-42.1773
5	0.5613	-22.1614	5	0.6180	-37.8716
6	1.0700	-154.1945	6	1.0700	-136.7891
7	0.5597	-45.6091	7	0.7956	-74.2736
8	1.0900	-45.6088	8	1.0900	-74.2736
9	0.2313	-77.1058	9	0.7430	-89.6422
10	0.0289	-147.0292	10	0.7497	-100.4900
11	0.5292	-153.3718	11	0.8635	-121.4193
12	0.9782	-155.1587	12	0.0106	-177.4730
13	0.8996	-153.3907	13	0.6891	-138.7573
14	0.3934	-142.5434	14	0.6288	-112.5116

Table 4.6 (d)

Some low Voltage solutions of 14 Bus Test System: Solution Set IV

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0600	0	1	1.0600	0
2	1.0450	-128.7299	2	1.0450	-28.9423
3	1.0100	-146.0018	3	1.0100	-67.1182
4	0.5633	-138.7793	4	0.1666	-84.1615
5	0.4252	-137.4999	5	0.0156	-98.9133
6	1.0700	-203.9957	6	1.0700	-205.9055
7	0.4656	-145.9471	7	0.6036	-172.2559
8	1.0900	-145.7571	8	1.0900	-171.5616
9	0.0466	-211.1909	9	0.6204	-182.1033
10	0.1972	-204.8718	10	0.6860	-188.0938
11	0.6201	-203.0418	11	0.8661	-198.1943
12	0.9844	-205.1579	12	1.0253	-205.3095
13	0.8995	-204.3966	13	0.9876	-203.9750
14	0.3784	-208.5802	14	0.7523	-195.0546

Table 4.6 (e)

Some low Voltage solutions of 14 Bus Test System: Solution Set V

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0600	0	1	1.0600	0
2	1.0450	-42.8770	2	1.0450	-11.6387
3	1.0100	-177.7333	3	1.0100	-24.3090
4	0.2700	-89.9943	4	0.8284	-21.7410
5	0.3219	-66.9520	5	0.8469	-21.9525
6	1.0700	-153.4050	6	1.0700	-62.2746
7	0.0010	-164.6514	7	0.6400	-33.3160
8	1.0900	-179.3431	8	1.0900	-33.3160
9	0.1743	-158.4491	9	0.2742	-52.3488
10	0.3186	-155.1114	10	0.0203	-90.4360
11	0.6848	-152.7060	11	0.5234	-62.1626
12	0.9987	-154.1143	12	0.9411	-64.4817
13	0.9244	-153.5714	13	0.8182	63.0836
14	0.4759	-156.641	14	0.0565	-101.1964

Table 4.6 (f)

Some low Voltage solutions of 14 Bus Test System: Solution Set VI

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0600	0	1	1.0600	0
2	1.0450	-36.8501	2	1.0450	-48.1763
3	1.0100	-181.6095	3	1.0100	-176.6496
4	0.5711	-67.2687	4	0.2055	-143.4557
5	0.6751	-51.8199	5	0.1341	-85.5764
6	1.0700	-67.4918	6	1.0700	-190.3378
7	0.8542	-69.3124	7	0.6798	-175.1070
8	1.0900	-69.3224	8	1.0900	-175.1020
9	0.8494	-70.0353	9	0.6894	-179.9316
10	0.8785	-69.7886	10	0.7448	-182.7703
11	0.9878	-68.6058	11	0.8987	-187.1009
12	1.0400	-68.5193	12	1.0261	-190.9796
13	1.0189	-68.6261	13	0.9950	-190.1893
14	0.9022	-70.6337	14	0.7963	-186.8982

Table 4.7 (a)

Some low Voltage solutions of 30 Bus Test System: Solution Set I

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0500	0	1	1.0500	0
2	1.0338	-6.7081	2	1.0338	-7.21158
3	0.9710	-10.5013	3	0.9632	-11.4632
4	0.9550	-12.8916	4	0.9460	-13.9660
5	1.0058	-15.7845	5	1.0058	-16.5017
6	0.9554	-14.7417	6	0.9730	-16.1053
7	0.9676	-15.7065	7	0.9780	-16.8005
8	1.0230	-16.0639	8	1.0230	-17.0556
9	0.8471	-23.3598	9	0.9404	-24.2991
10	0.6816	-31.6128	10	0.8618	-30.5071
11	1.0913	-21.0475	11	1.0913	-22.2164
12	0.8678	-29.7851	12	0.7214	-38.8335
13	1.0883	-28.3485	13	1.0883	-37.1056
14	0.7736	-32.2388	14	0.0150	-79.4019
15	0.6902	-31.2122	15	0.5571	-43.1913
16	0.7788	-30.8057	16	0.7712	-35.5993
17	0.7029	-31.7373	17	0.8277	-322993
18	0.6681	-32.9666	18	0.6429	-39.1844

19	0.6600	-33.5868	19	0.7003	-36.8606
20	0.6641	-33.2213	20	0.7391	-35.2176
21	0.5484	-33.9819	21	0.8341	-31.4020
22	0.5145	-34.3030	22	0.8308	-31.4502
23	0.3948	-32.7004	23	0.6368	-38.2606
24	0.0249	-54.7363	24	0.7626	-32.6442
25	0.3549	-36.6664	25	0.8528	-28.7703
26	0.4310	-40.1725	26	0.8739	-28.5683
27	0.5209	-34.2685	27	0.8985	-26.7695
28	0.9121	-15.3311	28	0.9668	-17.1563
29	0.4734	-39.3787	29	0.8755	-28.3745
30	0.4463	-43.5342	30	0.8623	-29.5381

Table 4.7 (b)

Some low Voltage solutions of 30 Bus Test System: Solution Set II

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0500	0	1	1.0500	0
2	1.0338	-6.0495	2	1.0338	-3.9579
3	0.9487	-9.2965	3	1.0003	-6.3439
4	0.9274	-11.3159	4	0.9890	-7.6393
5	1.0058	-14.7615	5	1.0058	-11.1110
6	0.9267	-12.5767	6	0.9881	-8.7363
7	0.9506	-14.0318	7	0.9873	-10.2509
8	1.0230	-14.4112	8	1.0230	-9.3577
9	0.6798	-20.0381	9	0.9125	-11.9544
10	0.3559	-34.9622	10	0.7888	-15.6175
11	1.0913	-17.1579	11	1.0913	-9.8130
12	0.7864	-32.1740	12	0.9120	-16.3713
13	1.0883	-30.5901	13	1.0883	-15.0084
14	0.6979	-35.1293	14	0.8328	-17.3473
15	0.6212	-34.3905	15	0.7708	-15.3399
16	0.5889	-33.3605	16	0.8512	-16.4193
17	0.4124	-35.3390	17	0.8008	-16.1890
18	0.4990	-37.5092	18	0.5780	-12.3497
19	0.4336	-39.1698	19	0.4712	-8.6304
20	0.4120	-38.5056	20	0.5471	-11.5751
21	0.0564	-41.7206	21	0.7448	-15.7179
22	0.1105	-38.2747	22	0.7371	-15.4309
23	0.4474	-36.5774	23	0.6984	-14.0048
24	0.2362	-40.9678	24	0.6154	-10.9226

25	0.3567	-33.5001	25	0.7567	-14.9690
26	0.2941	-37.7020	26	0.7321	-15.7693
27	0.4648	-28.9700	27	0.8587	-16.0894
28	0.8872	-12.9368	28	0.9738	-9.2722
29	0.4067	-35.7047	29	0.8472	-18.3096
30	0.3734	-41.5057	30	0.8476	-20.0381

Table 4.7 (c)

Some low Voltage solutions of 30 Bus Test System: Solution Set III

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0500	0	1	1.0500	0
2	1.0338	-4.2281	2	1.0338	-4.2417
3	0.9998	-6.7252	3	0.9911	-6.7624
4	0.9884	-8.1061	4	0.9780	-8.1562
5	1.0058	-11.5707	5	1.0058	-11.6078
6	0.9923	-9.5103	6	0.9726	-9.0800
7	0.9898	-10.8939	7	0.9781	-10.6635
8	1.0230	-10.0522	8	1.0230	-10.0048
9	0.9862	-13.7607	9	0.8272	-12.0909
10	0.9390	-17.3144	10	0.6218	-16.7348
11	1.0913	-11.7796	11	1.0913	-9.7285
12	0.8779	-16.5618	12	0.9171	-19.0353
13	1.0883	-15.1458	13	1.0883	-17.6790
14	0.5429	-5.4838	14	0.8624	-20.5423
15	0.7730	-17.6364	15	0.8198	-19.9475
16	0.8955	-17.3251	16	0.7824	-18.5528
17	0.9199	-17.6052	17	0.6619	-17.7782
18	0.8163	-18.6234	18	0.7320	-20.4025
19	0.8459	-18.8630	19	0.6844	-20.2941
20	0.8682	-18.5695	20	0.6675	-19.5522
21	0.9156	-18.1730	21	0.4264	-10.6959
22	0.9132	-18.2489	22	0.4704	-12.7741
23	0.7912	-18.2562	23	0.7353	-20.5123
24	0.8266	-18.4367	24	0.6346	-20.7136
25	0.7527	-17.9361	25	0.7287	-19.6183
26	0.7281	-18.7387	26	0.7031	-20.4864
27	0.7191	-17.1766	27	0.7998	-18.4102
28	0.9620	-9.7105	28	0.9559	-9.7328
29	0.4336	-10.5297	29	0.7158	-18.4608
30	0.5150	-19.2317	30	0.7240	-21.0737

Table 4.8 (a)

Some low Voltage solutions of 57 Bus Test System: Solution Set I

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0400	0	1	1.0400	0
2	1.0100	-4.0141	2	1.0100	-3.8999
3	0.9850	-17.6254	3	0.9850	-17.1650
4	0.9706	-21.4650	4	0.9527	-20.8534
5	0.9710	-26.1412	5	0.9655	-25.2762
6	0.9800	-27.7652	6	0.9800	-26.7643
7	0.9100	-29.4198	7	0.9160	-27.8321
8	1.0050	-25.3919	8	1.0050	-23.9680
9	0.9800	-29.8690	9	0.9800	-28.4858
10	0.9478	-30.2087	10	0.9449	-28.9605
11	0.8738	-29.0308	11	0.8667	-27.5254
12	1.0150	-25.4188	12	1.0150	-24.4121
13	0.8874	-25.7039	13	0.8827	-24.4399
14	0.8425	-24.2732	14	0.8362	-23.0004
15	0.9017	-18.5506	15	0.8986	-17.6824
16	0.9958	-19.6941	16	0.9974	-18.9513
17	0.9973	-10.9906	17	0.9992	-10.6097
18	0.9388	-29.3710	18	0.7818	-34.2391
19	0.7046	-35.8504	19	0.1067	-80.1389
20	0.6000	-38.2928	20	0.0847	-107.8215
21	0.5384	-41.4763	21	0.4081	-35.2526
22	0.5306	-39.9255	22	0.4815	-36.4582
23	0.4984	-40.2515	23	0.4513	-36.8207
24	0.0020	-16.0296	24	0.0000	-14.1745
25	0.0920	-135.2867	25	0.0597	-134.0432
26	0.0020	-10.1973	26	0.0726	-11.3982
27	0.4972	-39.3383	27	0.5327	-35.2553
28	0.7022	-37.0006	28	0.7241	-34.1837
29	0.8405	-36.0181	29	0.8523	-33.7066
30	0.1282	-133.3811	30	0.0871	-127.4668
31	0.1695	-132.7645	31	0.1159	-121.0624
32	0.2668	-117.6186	32	0.2151	-99.6712
33	0.2660	-118.7261	33	0.2122	-100.8005

Table 4.8 (a)

Some low Voltage solutions of 57 Bus Test System: Solution Set I

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
34	0.2333	-73.0199	34	0.2593	-56.5766
35	0.2668	-64.3831	35	0.2867	-52.4292
36	0.3256	-56.4179	36	0.3311	-47.6706
37	0.3853	-50.5957	37	0.3808	-44.0334
38	0.5930	-38.7473	38	0.5612	-35.8830
39	0.3712	-51.0382	39	0.3651	-44.1744
40	0.3135	-58.1321	40	0.3151	-48.6112
41	0.6082	-52.2996	41	0.5601	-52.0684
42	0.3666	-65.5575	42	0.2912	-68.1589
43	0.8176	-34.1734	43	0.7991	-32.5774
44	0.6629	-34.5707	44	0.6372	-32.2521
45	0.8424	26.4175	45	0.8281	-25.1277
46	0.8439	-30.7350	46	0.8278	-29.2420
47	0.7351	-35.9929	47	0.7113	-34.1509
48	0.6977	-36.7725	48	0.6719	-34.6743
49	0.7828	-36.5889	49	0.7617	-34.9227
50	0.8310	-36.2860	50	0.8153	-34.7739
51	0.9852	-32.9998	51	0.9791	-31.7551
52	0.8252	-38.4105	52	0.8384	-35.9660
53	0.8294	-38.9391	53	0.8423	-36.5335
54	0.9133	-36.3563	54	0.9214	-34.3039
55	1.0157	-33.0490	55	1.0168	-31.3995
56	0.2354	-77.0547	56	0.1612	-86.7122
57	0.1206	-107.1480	57	0.1045	-127.5531

Table 4.8 (b)

Some low Voltage solutions of 57 Bus Test System: Solution Set II

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
1	1.0400	0	1	1.0400	0
2	1.0100	-3.3424	2	1.0100	-4.2441
3	0.9850	-14.9021	3	0.9850	-18.5712
4	0.9605	-17.9457	4	0.9535	-22.8775
5	0.9686	-21.5079	5	0.9652	-28.3634
6	0.9800	-22.6412	6	0.9800	-30.3911
7	0.9488	-23.2149	7	0.8762	-32.5782
8	1.0050	-19.6708	8	1.0050	-28.1701
9	0.9800	-24.5548	9	0.9800	-32.3353
10	0.9507	-25.6494	10	0.9499	-31.2319
11	0.8949	-24.3242	11	0.8809	-30.3738
12	1.0150	-21.7922	12	1.0150	-26.1624
13	0.8983	-21.7814	13	0.8940	-26.4241
14	0.8550	-20.6441	14	0.8522	-24.5826
15	0.9115	-15.8184	15	0.9078	-18.9809
16	1.0014	-17.0419	16	0.9947	-20.2033
17	1.0037	-9.6305	17	0.9960	-11.2478
18	0.8375	-28.3218	18	0.7943	-35.4690
19	0.3059	-33.5497	19	0.1464	-62.6625
20	0.0267	-68.7392	20	0.0557	-115.8613
21	0.4970	-29.6184	21	0.5048	-33.6048
22	0.5769	-32.6630	22	0.5853	-36.2509
23	0.5700	-32.9342	23	0.5779	-36.7953
24	0.5053	-33.5231	24	0.4941	-43.1522
25	0.2661	-97.1143	25	0.2864	-94.6162
26	0.5112	-31.3925	26	0.4943	-42.3401
27	0.7534	-29.7335	27	0.6436	-43.5849
28	0.8571	-28.2927	28	0.7128	-42.3862
29	0.9296	-27.4699	29	0.7635	-41.4928
30	0.2281	-117.4457	30	0.2290	-111.3351
31	0.1949	-143.7076	31	0.1484	-148.1229
32	0.1994	-146.6308	32	0.1223	-158.9421
33	0.1986	-148.0155	33	0.1189	-160.9652

Table 4.8 (b)

Some low Voltage solutions of 57 Bus Test System: Solution Set II

Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree	Bus No.	Voltage magnitude in *p.u.*	Phase angle in degree
34	0.0519	-109.7086	34	0.0001	-33.3643
35	0.0975	-70.4664	35	0.1158	-49.4526
36	0.2305	-52.9040	36	0.2434	-45.3070
37	0.3294	-45.6116	37	0.3393	-42.2386
38	0.6131	-32.6380	38	0.6212	-35.6697
39	0.3254	-47.0548	39	0.3281	-42.5047
40	0.2336	-56.2968	40	0.2376	-47.5309
41	0.7147	-41.1802	41	0.6261	-50.6642
42	0.5322	-47.7387	42	0.3948	-59.8404
43	0.8669	-28.4358	43	0.8305	-34.8402
44	0.6818	-29.4002	44	0.6882	-32.4410
45	0.8547	-22.7550	45	0.8555	-25.8230
46	0.8580	-26.4156	46	0.8585	-30.1261
47	0.7506	-30.9173	47	0.7548	-34.4089
48	0.7144	-31.4235	48	0.7198	-34.8550
49	0.7962	-31.5110	49	0.7982	-35.4896
50	0.8418	-31.2461	50	0.8433	-35.8012
51	0.9893	-28.2659	51	0.9878	-33.6570
52	0.9035	-29.6059	52	0.2848	-49.0692
53	0.9001	-30.3135	53	0.0686	-73.9440
54	0.9543	-28.9021	54	0.4726	-44.4660
55	1.0233	-26.8086	55	0.8969	-39.7727
56	0.4215	-51.2715	56	0.2500	-67.1738
57	0.3436	-59.7147	57	0.1106	-97.9369

Table 4.9

Average number of generation required for obtaining multiple solutions using the PSO based coupled algorithm with the improvement scheme

Test System →	5 bus	11 bus	IEEE 14 bus	IEEE 30 bus	IEEE 57 bus	IEEE 118 bus	Population size ↓
Average Generations	32	64	59	78	112	184	100

4.8. MULTIPLE POWER FLOW SOLUTIONS THROUGH PSO AND OPTIMAL MULTIPLIER BASED NEWTON RAPHSON METHOD

Iwamoto S. and Tamura Y. in [15] have proposed an optimal multiplier based rectangular Newton-Raphson power flow for ill conditioned systems. The proposed method solves a cubic equation to generate multipliers values. The minimum of the three multipliers are used to modify the correction vector at each iteration to ensure convergence of the N-R power flow for ill conditioned system.

This method has been extended in [16] by Iba K., Suzuki H., Egawa M., and Watanabe T. to find a pair of near solutions of the load flow problem. In this case the maximum of the three multipliers are used to generate an estimate of the second solution. Though the multipliers are calculated at each step of N-R algorithm, they are not used to find the first solution. After the first solution is found, the iteration for the second solution starts from the estimated values of the second solution. The normal N-R algorithm runs until the convergence for the second solution is achieved.

It is well known that the Newton method is locally convergent. A good start is essential for the N-R method to converge. Thus, the author feels that N-R method will converge to a low voltage solution provided the algorithm is started at proper initial values. The optimal multipliers that are applicable to find a solution close to the normal solution of the power system may also be applicable for the low voltage solutions. In such a situation a great reduction in computation may be possible. The author, therefore, proposes to use the PSO based algorithm to generate starting values for the N-R algorithm for finding the multiple power flow solutions. The N-R algorithm then will find a pair of low voltage solutions during each run. The procedure can be better understood from the flowchart of fig. 4.37. Here

x_{old} : Solution of the previous iteration

x_{first} : First converged solution by the rectangular N-R method

x_{second} : Starting values for the second solution

μ_3 : Maximum multiplier among the three multipliers

Δx : Correction vectors

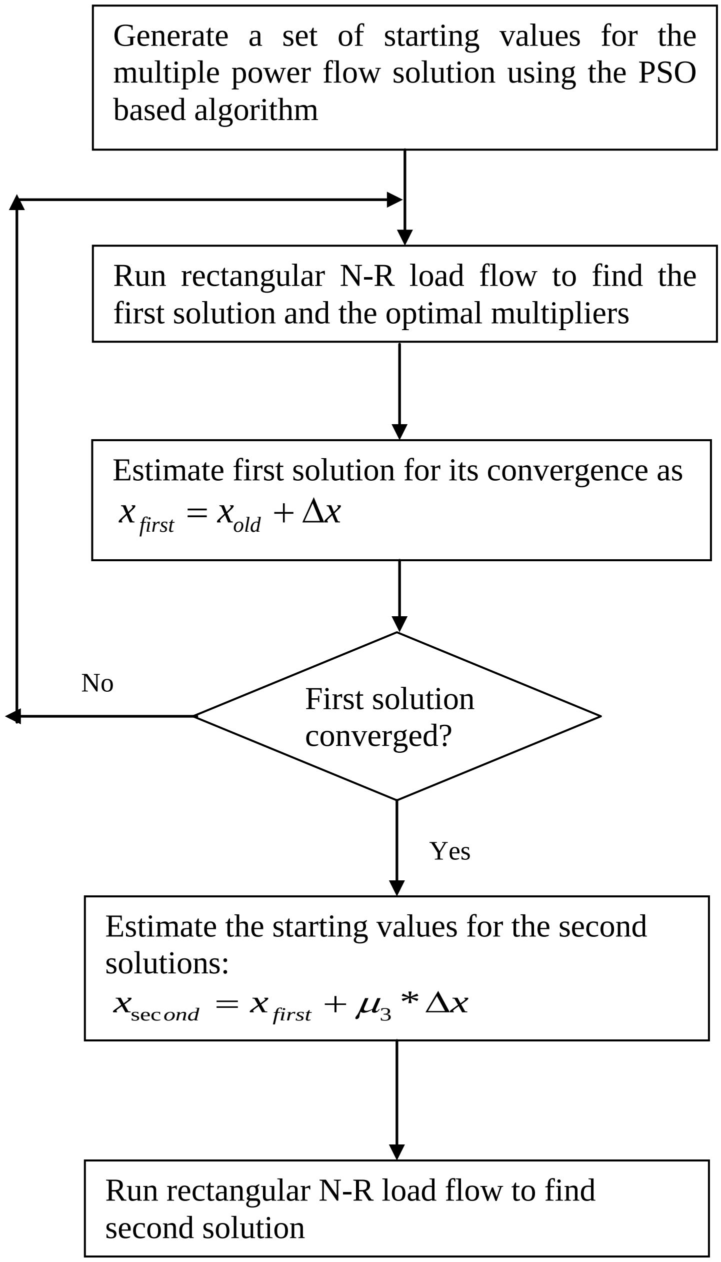

Fig. 4.37: Flowchart of the rectangular N-R load flow to find a pair of low voltage solutions

The proposed algorithm could find the low voltage solution pair for all the test systems studies. The starting values for Optimal Multiplier method, a pair of low voltage solutions, convergence characteristic of the solution pair, the optimal multipliers (μ) and the estimated corrections for the 2nd solution for the Optimal Multiplier method are given through Table 4.10 to Table 4.13 for 14 bus and 5 bus test systems respectively.

Table 4.10 (a)

Starting Solution for the Optimal Multiplier method (obtained by PSO algorithm) for 14 bus test system

Bus No.	Initial Solution	
	Voltage Magnitude	Voltage Magnitude
1	1.0600	0
2	1.0450	-9.2626
3	1.0100	-20.7239
4	0.9376	-18.5366
5	0.9432	-17.5275
6	1.0700	-38.8342
7	0.8880	-28.6324
8	1.0900	-28.6377
9	0.7319	-35.6884
10	0.7808	-37.3411
11	0.9243	-38.3235
12	0.9457	-41.8687
13	0.8116	-39.9469
14	0.0366	-81.0735

Table 4.10 (b)

Pair of Low Voltage Solutions obtained by Optimal Multiplier method for 14 bus test system

Bus No.	Solution 1		Solution 2	
	Voltage Magnitude	Phase angle	Voltage Magnitude	Phase angle
1	1.0600	0	1.0600	0
2	1.0450	-9.2696	1.0450	-13.8408
3	1.0100	-20.3191	1.0100	-29.7026
4	0.9316	-18.3534	0.6035	-22.5662
5	0.9373	-17.8158	0.5837	-24.1410
6	1.0700	-39.2432	1.0700	-124.8068
7	0.8826	-28.7639	0.0990	-68.5267
8	1.0900	-29.8415	1.0900	-137.1314
9	0.7402	-36.0465	0.0844	-175.6647
10	0.7924	-36.5901	0.1941	-142.6391
11	0.9172	-37.8608	0.5907	-127.1065
12	0.9435	-41.4046	0.9093	-127.2617
13	0.8223	-40.5043	0.7924	-126.0738
14	0.0383	-81.2724	0.0816	-169.6470

Table 4.10 (c)

Convergence characteristics for the solution pair for 14 bus test system

No. of iteration	Maximum Mismatch	$\mu 3$	Remarks
1	0.2894	4.9857	
2	0.0040	122.1185	
3	0.0000	3.2659e+005	First solution converged
1	2.2822		Iteration starts for the second solution
2	17.4913		
3	6.6716		
4	2.3090		
5	2.6282		
6	0.9430		
7	0.2066		
8	0.0082		
9	0.0000		Second solution converged

Table 4.10 (d)

The optimum multipliers (μ) during the first solution

No. of iterations	**S**
1	1.0007 4.9857 +61.7366i 4.9857 -61.7366i
2	1.0e+002 * 0.0100 1.2212 + 2.7422i 1.2212 - 2.7422i
3	1.0e+005 * 3.2659 + 0.0000i 0.0000 + 0.0000i 2.4615 - 0.0000i

Table 4.10 (e)

Estimated corrections for the second solution obtained by the optimal multiplier for 14 bus test system

Variable name	$\mu 3 * \Delta X$	Corrections
1	-0.0432	Corrections for Δe
2	-0.1487	
3	-0.3117	
4	-0.3201	
5	-0.9623	
6	-0.3468	
7	-0.3176	
8	-0.4187	
9	-0.5292	
10	-0.6999	
11	-0.7280	
12	-0.7358	
13	-0.0364	
1	-0.1083	Corrections for Δf
2	-0.1904	
3	0.0612	
4	0.0030	
5	-0.2422	
6	0.0245	
7	-0.2536	
8	0.1396	
9	0.1844	
10	0.0127	
11	0.0078	
12	-0.0855	
13	-0.0184	

Table 4.11(a)

Starting Solution for the Optimal Multiplier method (obtained by PSO algorithm) for 14 bus test system

Bus No.	Initial Solution	
	Voltage Magnitude	Voltage Magnitude
1	1.0600	0
2	1.0450	-36.8983
3	1.0100	-181.6871
4	0.5700	-67.2292
5	0.6808	-51.8287
6	1.0700	-67.4227
7	0.8425	-69.3178
8	1.0900	-69.3354
9	0.8523	-69.9799
10	0.8763	-69.7846
11	0.9924	-68.6534
12	1.0507	-68.4918
13	1.0258	-68.5720
14	0.9007	-70.7106

Table 4.11(b)

Pair of Low Voltage Solutions obtained by Optimal Multiplier method for 14 bus test system

Bus No.	Solution 1		Solution 2	
	Voltage Magnitude	Phase angle	Voltage Magnitude	Phase angle
1	1.0600	0	1.0600	0
2	1.0450	-36.8501	1.0450	-48.1973
3	1.0100	-181.6095	1.0100	-176.7293
4	0.5711	-67.2687	0.2060	-143.4847
5	0.6751	-51.8199	0.1346	-85.7171
6	1.0700	-67.4918	1.0700	169.8506
7	0.8542	-69.3124	0.6800	-174.9710
8	1.0900	-69.3224	1.0900	-174.9710
9	0.8494	-70.0353	0.6896	-179.7859
10	0.8785	-69.7886	0.7449	177.3827
11	0.9878	-68.6058	0.8987	173.0701
12	1.0400	-68.5193	1.0261	169.2017
13	1.0189	-68.6261	0.9950	170.0107
14	0.9022	-70.6337	0.7964	173.2611

Table 4.11(c)

Convergence characteristics for the solution pair for 14 bus test system

No. of iteration	Maximum Mismatch	$\mu 3$	Remarks
1 2 3	0.2491 0.0018 0.0000	6.1026 90.8226 2.5967e+005	 First solution converged
1 2 3 4 5 6 7 8	0.3506 34.6450 8.4862 1.8390 0.2456 0.0159 0.0001 0.0000		Iteration starts for the second solution Second solution converged

Table 4.11(d)

The optimum multipliers (μ) during the first solution for 14 bus test system

No. of iteration	**S**
1	1.0012 6.1026 +53.3050i 6.1026 -53.3050i
2	1.0e+002 * 0.0100 0.9082 + 1.9083i 0.9082 - 1.9083i
3	1.0e+005 * 2.5967 + 0.0000i 0.0000 + 0.0000i 2.1550 - 0.0000i

Table 4.11(e)

Estimated corrections for the second solution obtained by the optimal multiplier for 14 bus test system

Variable name	$\mu 3 * \Delta X$	Corrections
1	0.0126	Corrections for Δe
2	0.0504	
3	0.0969	
4	0.1121	
5	0.4829	
6	0.1345	
7	0.1729	
8	0.1455	
9	0.1808	
10	0.3195	
11	-0.0073	
12	0.2722	
13	0.1777	
1	0.0369	Corrections for Δf
2	0.0599	
3	-0.0030	
4	-0.0290	
5	-0.1872	
6	0.0299	
7	0.1096	
8	-0.0052	
9	-0.0250	
10	-0.0964	
11	-0.0131	
12	-0.1467	
13	-0.0815	

Table 4.12(a)

Starting Solution for the Optimal Multiplier method (obtained by PSO algorithm) for 5 bus system

Bus No.	Initial Solution	
	Voltage Magnitude	Voltage Magnitude
1	1.0600	0
2	0.6897	-2.0083
3	0.6288	-9.7977
4	0.5510	-10.7402
5	0.0985	-60.6540

Table 4.12(b)

Pair of Low Voltage Solutions obtained by Optimal Multiplier method for 5 bus test system

Bus No.	Solution 1		Solution 2	
	Voltage Magnitude	Phase angle	Voltage Magnitude	Phase angle
1	1.0600	0	1.0600	0
2	0.6911	-3.7402	0.5676	-5.0274
3	0.6150	-9.4714	0.1329	-36.3000
4	0.5629	-10.8411	0.0636	-72.1101
5	0.0850	-61.3444	0.2314	-38.3108

Table 4.12(c)

Convergence characteristics for the solution pair for 5 bus test system

No. of iteration	Maximum Mismatch	$\mu 3$	Remarks
1	0.6292	0.0001 e+004	
2	0.0162	0.0133 e+004	
3	0.0000	2.5814 e+004	First solution converged
1	0.7188		Iteration starts for the second solution
2	0.0445		
3	0.0107		
4	0.0003		
5	0.0000		Second solution converged

Table 4.12(d)

The optimum multipliers (μ) during the first solution for 5 bus test system

No. of iteration	**S**
1	0.9965 -2.9132 +26.9945i -2.9132 -26.9945i
2	1.0e+002 * 1.3289 - 0.4336i 0.0100 - 0.0000i 1.3289 + 0.4336i
3	1.0e+004 * 2.5814 - 0.0000i 0.0001 - 0.0000i 1.5351 + 0.0000i

Table 4.12(e)

Estimated corrections for the second solution obtained by the optimal multiplier for 5 bus test system

Variable name	$\mu 3 * \Delta X$	Corrections
1	-0.1511	Corrections for Δe
2	-0.4911	
3	-0.4999	
4	0.1690	
1	-0.0038	Corrections for Δf
2	0.0186	
3	0.0252	
4	-0.0690	

Table 4.13(a)

Starting Solution for the Optimal Multiplier method (obtained by PSO algorithm) for 5 bus system

Bus No.	Initial Solution	
	Voltage Magnitude	Voltage Magnitude
1	1.0600	0
2	0.7381	-4.6939
3	0.6754	-8.1341
4	0.6235	-8.5260
5	0.1485	-18.9975

Table 4.13(b)

Pair of Low Voltage Solutions obtained by Optimal Multiplier method for 5 bus test system

Bus No.	Solution 1		Solution 2	
	Voltage Magnitude	Phase angle	Voltage Magnitude	Phase angle
1	1.0600	0	1.0600	0
2	0.7308	-2.7673	0.5933	-4.4492
3	0.6621	-7.6507	0.3619	-15.2075
4	0.6151	-8.5373	0.2502	-15.8910
5	0.1563	-18.7123	0.1085	-93.7612

Table 4.13(c)

Convergence characteristics for the solution pair for 5 bus test system

No. of iterations	Maximum Mismatch	$\mu 3$	Remarks
1	0.7019	1.8358	
2	0.0714	35.8794	
3	0.0015	4.0343e+003	
4	0.0000	1.7520e+007	First solution converged
			Iteration starts for the second solution
1	0.9286		
2	0.2740		
3	0.0129		
4	0.0000		Second solution converged

Table 4.13(d)

The optimum multipliers (μ) during the first solution for 5 bus test system

No. of iterations	**S**
1	0.9650 -1.8358 + 6.8021i -1.8358 - 6.8021i
2	1.0117 35.8794 +27.8978i 35.8794 -27.8978i
3	1.0e+003 * 4.0343 + 0.0000i 0.0010 + 0.0000i 2.8433 - 0.0000i
4	1.0e+007 * 1.7520 - 0.0000i 0.0000 - 0.0000i 1.0502 + 0.0000i

Table 4.13(e)

Estimated corrections for the second solution obtained by the optimal multiplier for 5 bus test system

Variable name	$\mu 3 * \Delta X$	Corrections
1 2 3 4	0.2662 0.2514 0.2942 0.8085	Corrections for Δe
1 2 3 4	0.0014 -0.0163 -0.0316 -0.0284	Corrections for Δf

4.9. PERFORMANCE ANALYSIS

The product of the population size and the number of generation is plotted against the population size in order to have a comparative analysis. Fig. 4.38 shows how the number of generation has varied with the population size for the different test systems. From Fig. 4.38, it has been noticed that the number of generation has decreased with the increase in population size.

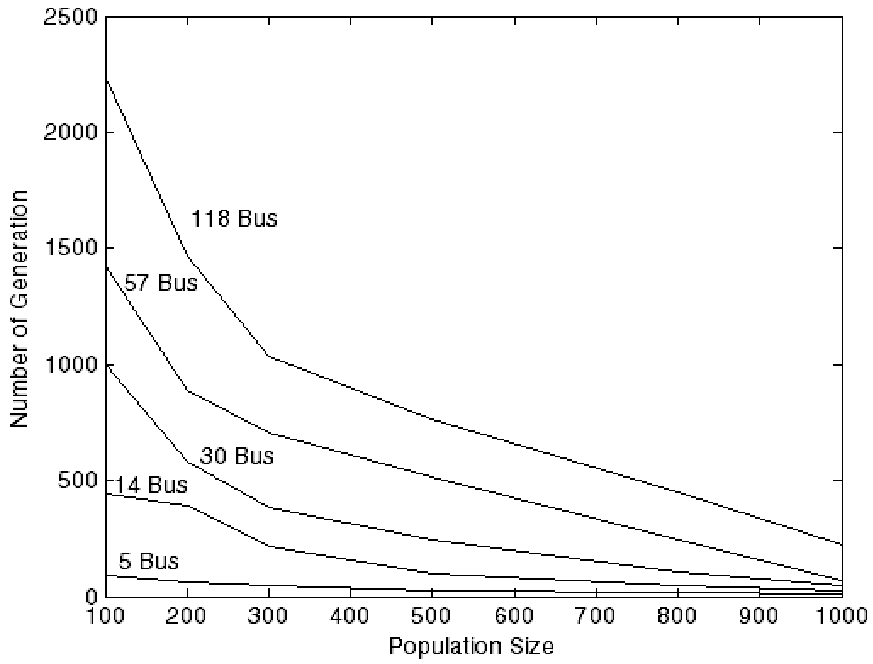

Fig. 4.38: Variation of the number of generation with the population-size for the PSO based coupled power flow

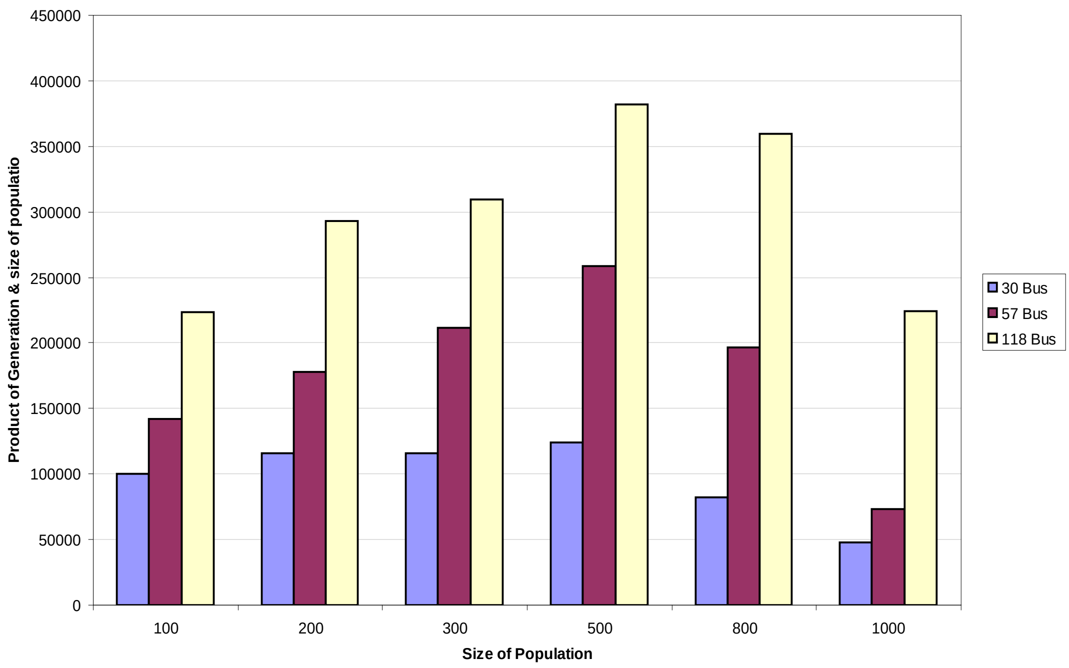

Fig. 4.39: Variation of the product of the number of generation and the population-size with the size of population for the PSO based coupled power flow

Fig. 4.39 shows the performance index for standard test systems for the coupled algorithm. From the performance index it can be seen that the medium population size (200-800) has shown the worst performance. Population size less than 200 has given better results for each test system from the computing point of view. But in simple PSO technique higher population size has produced best performance i.e. best computing time. Usually in simple PSO technique to solve the power flow problem both the required population size and number of generation are more compared to PSO based decoupled algorithm. Hence required computing time in simple PSO based coupled algorithm for the normal solution is obviously more with respect to PSO based decoupled algorithm for all the test systems.

When the coupled algorithm is used with the local search, the performance alters significantly. The variation of the number of generation with the population size is given in Fig. 4.40 for PSO based coupled algorithm with local search. It is observed that the number of generation is almost unchanged above 40-population size and below 40-population size the number of generation increase much rapidly.

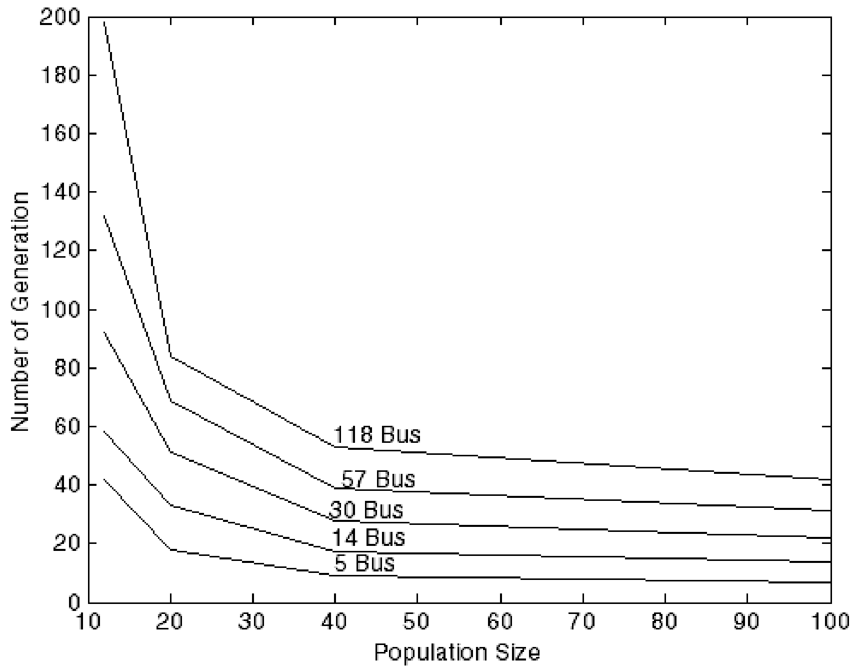

Fig. 4.40: Variation of the number of generation with the population-size for PSO based coupled power flow with local search

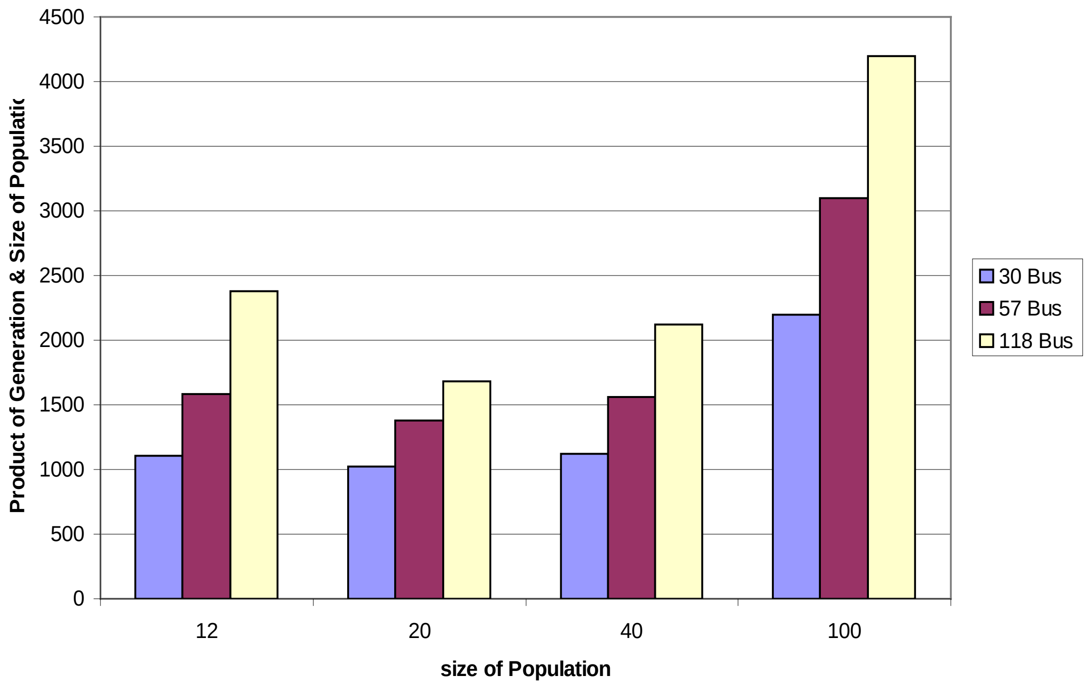

Fig. 4.41: Variation of the product of the number of generation and the population-size with the size of population for PSO based coupled power flow with local search

Variation of the product of the number of generation and the population size with the size of population for the PSO based coupled algorithm with the local search has been shown in Fig. 4.41. From the performance index, it can be noticed that population size more than 40 has been given worst performance. Very low population size (less or equal to 12) is unable to provide better result with respect to computing time. Here population size of 20 has shown the best performance.

The variation of the number of generation with the population size for the algorithm with linear perturbation are given in Fig. 4.42 and the performance is shown in Fig. 4.43. It is observed from Fig. 4.42 that after 20 population size the proposed algorithm with linear perturbation has become insensitive to the size of population. The performance of this improved method has improved with the lower size of population and the best performance has been observed when the size of population is 10 only.

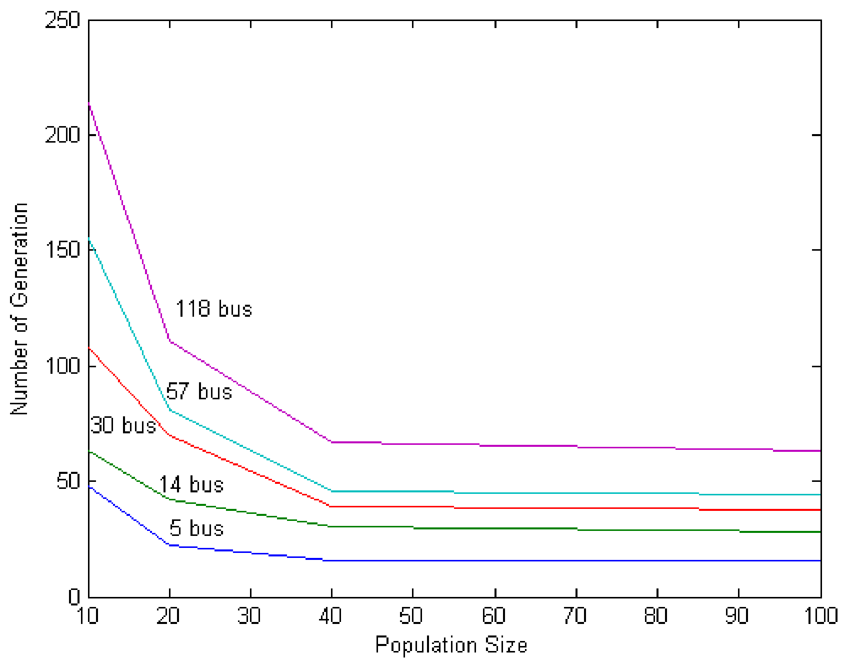

Fig. 4.42: Variation of the number of generation with the population-size for PSO based coupled power flow with linear search

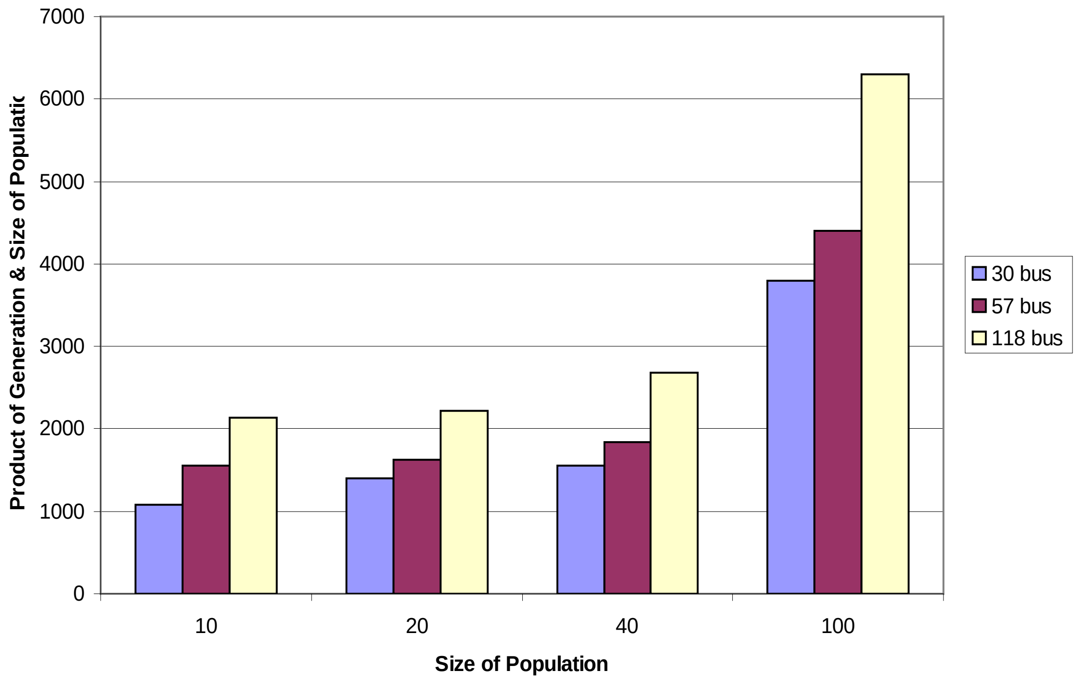

Fig. 4.43: Variation of the product of the number of generation and the population-size with the size of population for PSO based coupled power flow with linear perturbation

4.10. CONCLUSION

A PSO based power flow algorithm that can find both the normal and low voltage multiple solutions has been presented in this chapter. The author has designed a unique formula for the constriction factors which are made to vary adaptively. This method, though simple, requires large number of population and large number of generation for convergence. Hence the computation time is more than the decoupled algorithm. Two improvement schemes, local search & linear perturbation, are used with the algorithm. When the improvement schemes are applied on the pbest solution, the required population size as well as the number of generation reduce drastically. For obtaining the multiple low voltage solutions application of local search along with the PSO, however, is a must.

The developed PSO based power flow has also been used along with the optimal multiplier based N-R method for finding the multiple power flow solutions. The PSO based power flow in this case generates a set of initial values wherefrom the optimal multiplier based N-R method finds a pair of multiple low voltage solutions.

In the next chapter a novel two-stage genetic algorithm based load flow has been reported.