Cost Effective Optimal Placement and Sizing of Active Power Filter Using Grey Wolf Optimization in Radial Distribution System

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***Abstract*—Now-a-days the active power filter (APF) plays significant role for harmonics mitigation. The optimal placement and sizing of APF (OPSAPF) in a radial distribution system (RDS) is a constrained nonlinear problem. OPSAPF using grey wolf optimization (GWO) algorithm along with cost effectiveness is presented in this paper. The GWO is a nature emboldened algorithm. The optimization characteristics exploration and exploitation, are balanced in it. Three inequality constraints (a) total harmonic distortion in voltage (THDV), (b) individual harmonic distortion in voltage (IHDV), and (c) maximum size of APF are considered. The GWO is incorporated with harmonic load flow and implemented on the 33-bus system. The simulation is run for 30 independent runs. Simulation results confirm the efficacy and steadiness of GWO algorithm.**

Keywords—active power filter, grey wolf optimizer, total harmonic distortion

I. Introduction

These days, usage of power electronics appliances is increased due to their advantages. Although many advantages of them, they produce harmonics. Various power quality related problems are occurred due to these harmonics. The losses in machines, over heating of transformer, poor power factor, over heating of power cables, mal-operation of protective devices, resonance etc. Overall, the performance of distribution system is degraded. Therefore, it is mandatory to control the harmonics. The level of the harmonic distortion is limited by IEEE standards [1, 2]. For a radial distribution system (RDS), the total harmonic distortion in voltage (THDV) should not more than 5% and individual harmonics distortion of voltages (IHDV) at a bus should not go beyond 3%.

Harmonic filters are used to mitigate the harmonics. Passive filters have advantages of lower cost, simple construction, but they have disadvantages like, bulky size, fixed compensation and resonance. To overwhelmed these disadvantages, active power filters (APFs) are used [3]. But, APF is a very costly device and its cost depends on the current compensated by it. Therefore, to decide the placement and size of APF in a RDS to limit the harmonics up to standard limits is not an easy task. It is a constraint nonlinear optimization problem. Therefore, an optimization technique is needed for placement and sizing of APF to ensure the lower cost.

Many algorithms have been used for the optimal placement and sizing of APFs (OPSAPF), such as conventional optimization approaches [4], genetic algorithm (GA) [5], particle swarm optimization (PSO) with its modified versions, modified discrete PSO (MDPSO) [6], harmony search (HS) for APF [7], dynamic discrete firefly algorithm (DDFA) [8] and trade-off / risk analysis method [9].

The performance of optimization algorithm depends upon the type of the problem. The optimization problems are linear, nonlinear, constraint, un constraint etc. its behavior is not same for all optimization problems which is stated by the no free lunch theorem (NFL) [10]. It motivates the usage of different algorithms for the solution of optimization problem. A newly researched and widely used grey wolf optimizer (GWO) [11] algorithm is used for the OPSAPF.

The behavior of grey wolf during hunting is mapped in the GWO. In the social hierarchy, alpha wolf is the leader of grey wolf family. Others wolves are known as beta, delta and omega. They follow the instruction of alpha and give support during hunting. There are four stages in the GWO- a) encircling the prey. b) hunting mechanism. c) attacking the prey (exploitation). d) exploration phase. The alpha is the nearest wolf to prey. It set its optimal condition. The other wolves- beta, delta and omega are not near as alpha. In optimization problem the solution found by alpha is the optimal solution. It is a derivation free algorithm. It is flexible and simple. The exploration and exploitation characteristics is balanced in search space. Moreover, it also requires less algorithmic specific tuning parameters compared other algorithms like PSO, GA, cuckoo search algorithm, simulate annealing, etc. [11].

The computational tests- best value, average value, worst value and statistical test are carried out to validate the GWO for OPSAPF in RDS. The simulation is run for 30 independent runs and employed on 33-bus RDS including nonlinear loads.

In this paper the details of problem formulation and GWO implementation is presented in Section II. In Section III results are analyzed and discussed. It is concluded in Section IV.

II. PROBLEM FORMULATION

Modeling of RDS and APF is described in this section. The harmonic load flow is coupled with GWO to find the OPSAPF. This problem contains nonlinearity with constraints. Minimization of APF current-cost is as an objective with IEEE limits are as constraints.

A. Distribution System

Fig. 1 shows the distribution line modeling. The impedance of line with harmonics is represented by (1).

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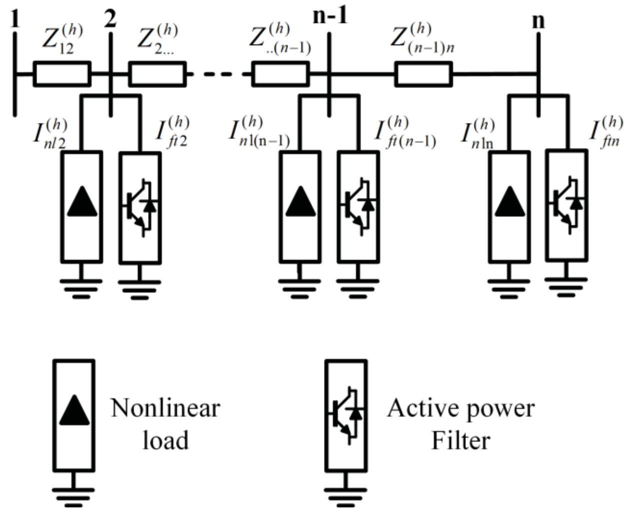

Fig. 1 RDS with nonlinear loads and APFs

The inductive reactance and impedance depend on harmonic order.

$$Z^{(h)} = R + jX_L^{(h)} \tag{1}$$

where R and X_L denote the resistance and inductive reactance of RDS, h is the order of harmonic injected.

B. APF

As given in [6-7], the APF is modelled as nonlinear current source. The APF injects the current as per nonlinear load current at point of common coupling. It has same magnitude with phase opposition.

Model of APF is formulated as

$$I_{ft}^{(h)} = I_{ft,r}^{(h)} + jI_{ft,im}^{(h)} \tag{2}$$

Where $I_{ft}^{(h)}$ denotes APF current with real $I_{ft,r}^{(h)}$ and imaginary $I_{ft,im}^{(h)}$ parts.

C. Harmonic Load Flow

To analyze the load flow with harmonics, backward forward sweep harmonic load flow method is used [12]. It is based on network topology. It consists of two relationship matrices named as the branch-current to the bus-voltage (BCBV) and bus-injection to branch-current (BIBC) matrices.

D. Objective Function

An objective function has a key role in any optimization problem. The main objective is to minimize the APF current such that it fulfills the IEEE standards. To reduce the cost, it is essential for minimization of APF current. Here, three constraints are considered:

1) Constraint-1 total harmonic distortion in voltage *(THDv)*.

2) Constraint-2 individual harmonic distortion in voltage *(IHDv)*,

3) Constraint-3 maximum current of APF $I_{ft,\,MAX}$

THDv and IHDv are controlled by the IEEE standard 519 [2]. The third one is decided by the current of nonlinear load at point of common coupling. In this paper, dynamic penalty method is used. The penalty is given dynamically, when the

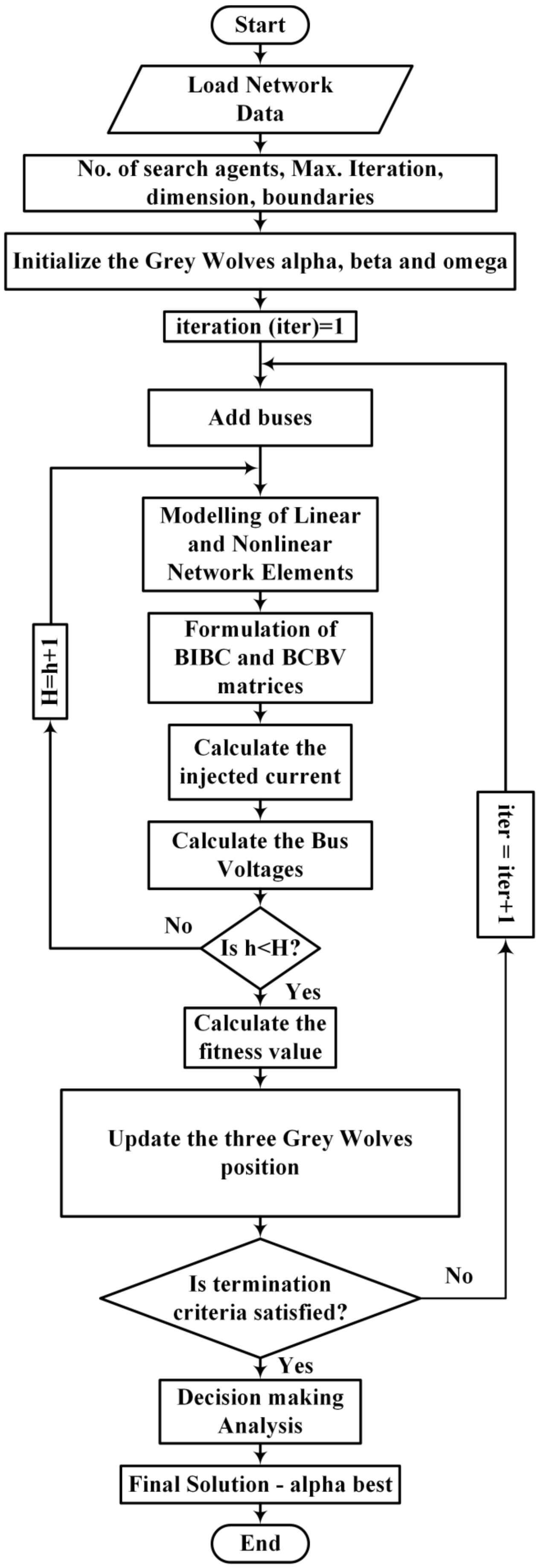

Fig. 2 Flowchart for OPSAPF for RDS optimized by GWO

constraints are not fulfilled.

The objective function is exemplified as,

$$OF_{Ift} = \min \sum_{m=1}^{n} \sqrt{\sum_{h=2}^{H} \left| I_{ft,m}^{h} \right|^2} + DP \tag{3}$$

Where m is the bus number, n is the total number of buses, H is the maximum order of harmonic, and dynamic penalty is denoted by DP.

The constraints are written as:

$$\begin{aligned} &THD_V - 0.05 \le 0 \\ &IHD_V - 0.03 \le 0 \\ &I_{ft} \le I_{ft,MAX} \end{aligned} \tag{4}$$

Fig. 2 shows flowchart for OPSAPF for RDS optimized by GWO

III. RESULT ANALYSIS AND DISCUSSION

In this section simulation results are taken using GWO and analyzed. Fig. 3 shows the 33-bus RDS [13]. Here, it is supposed that four nonlinear loads are connected at 7th ,18th, 25th and 33rd buses. The 18th and 33rd buses are far from supply source The nonlinear loads have harmonic spectrum as shown in Fig. 4. The harmonic order is considered from 5th to 49th.

In Table I, the THDv calculated in the absence of APF is tabulated. Due to nonlinear loads, harmonics are injected into the RDS. Therefore, the THDv at all buses are not less than standard limits. Among the thirty-two buses twenty-two buses have THDv more than 5%. It is extremely harmonics polluted system. The maximum THDv is observed at bus 18 (28.89 %). From Table I, it is noticed that the far end buses of RDS has more THDv compared to the near buses from source of supply.

Here, APF is used to mitigate the harmonics up to 5%. At first sight the simplest solution is, connect four APFs at all buses which has nonlinear load, with the equal ratings of nonlinear loads. But, this solution is very costly.

The cost of APF depends on its current. If current rating of APF is high, overall cost is high and for low current rating cost is low. Consequently, optimization is needed to find the suitable buses for the placement and proper sizing of APF at these buses.

Here the GWO is used for OPSAPF. The GWO is coupled with harmonic load flow and run for the 100 iterations and 30 runs. The computational tests- best value, average value, worst value and statistical tests are performed

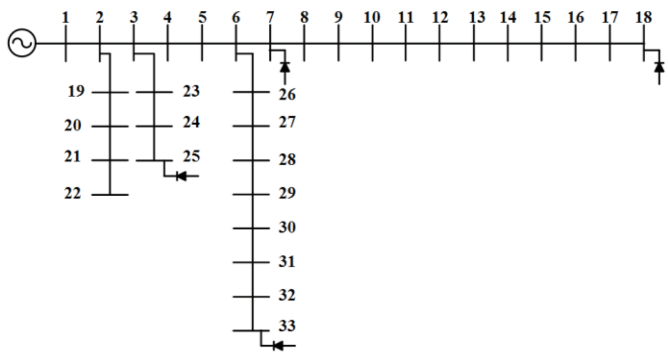

Fig. 3 33-bus RDS with nonlinear loads

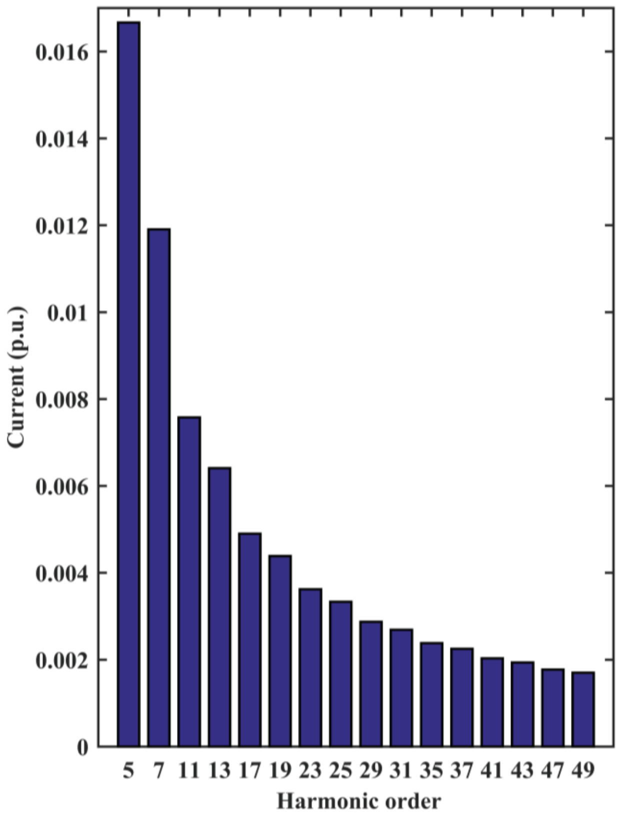

Fig. 4 Harmonic spectrum of nonlinear load

to find the optimal solution and behavior of GWO.

Simulation is performed for the different combinations of APF/APFs at nonlinear load buses as provided in Table II, one, two, three and four APFs. Total combinations are fifteen. In this, the 'Yes' indicates the presence of APF, while "No' indicates the absence of APF.

The GWO used to find the size of APFs at these combinations.

TABLE I THDV AT ALL BUSES IN ABSENCE OF APF

Bus No.	THDv (%)	Bus No.	THDv (%)
2	0.40	**18**	**28.89**
3	2.51	19	0.40
4	3.68	20	0.40
5	4.91	21	0.40
6	**9.33**	22	0.40
7	**11.90**	23	3.15
8	**14.48**	24	4.63
9	**16.03**	**25**	**6.10**
10	**17.57**	**26**	**9.55**
11	**17.71**	**27**	**9.85**
12	**17.97**	**28**	**11.80**
13	**20.39**	**29**	**13.26**
14	**21.87**	**30**	**13.80**
15	**22.97**	**31**	**15.81**
16	**24.11**	**32**	**16.57**
17	**27.69**	**33**	**17.67**

TABLE II COMBINATIONS OF APFS PLACEMENT AT NONLINEAR LOADS

Sr. No.	Nos. of APFs /Bus No.	7	18	25	33
1	One	Yes	No	No	No
2		No	Yes	No	No
3		No	No	Yes	No
4		No	No	No	Yes
5	Two	Yes	Yes	No	No
6		Yes	No	Yes	No
7		Yes	No	No	Yes
8		No	Yes	Yes	No
9		No	Yes	No	Yes
10		No	No	Yes	Yes
11	Three	Yes	Yes	Yes	No
12		Yes	No	Yes	Yes
13		Yes	Yes	No	Yes
14		No	Yes	Yes	Yes
15	Four	Yes	Yes	Yes	Yes

The steps for the simulation procedure are as under:

1) The THDv at all buses without APF is found, using harmonic load flow anlysis.

2) Run the harmonic load flow with APF. By applying GWO catch the optimal size of APF.

3) Compare the results of GWO with unoptimized solution.

To analyze the performance of GWO for different cases, the computational tests are performed. Here, hundred iterations are taken to find the best solution. The best fitness curve shows the performance in terms of best value for the all iterations. The stability is decided by the statistical curve. It is run for thirty runs. The curves are shown in Fig. 5 to Fig. 9 for different number of APFs as well as different placements.

Fig. 5 and Fig. 6 are shown the placement of APF at buses 7 and 18. The value of current found by GWO is very high. It is due to the penalty factor. The constraints are not satisfied, so value of current is very high. It proves that the single APF cannot mitigate the THDv up to standard limit and to solve the problem more than one APFs are required.

A. *Best fitness curve*

In the starting phase of optimization process, due to penalty the GWO has high value of fitness function. It is an exploration phase. After few iterations, it starts exploitation phase and it gives very low value of fitness function. From the curves, it is clear that the GWO converged at fast rate.

B. *Average fitness curve*

Average fitness curve shows the average of the solution found by algorithms. As the number of iterations are increases the average value curve decreases. It shows the improvement in fitness found by GWO.

C. *Worst fitness curve*

This curve shows the relation between worst value and iteration.

D. *Statistical curve*

This curve demonstrates the stability of algorithm during optimization process. The value of standard deviation is low in case of GWO for almost all combinations of APFs, it shows the stability of GWO for different dimensional optimization problems.

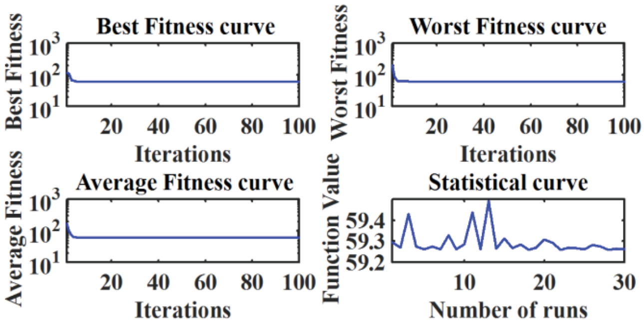

Fig. 5 APF at bus 7

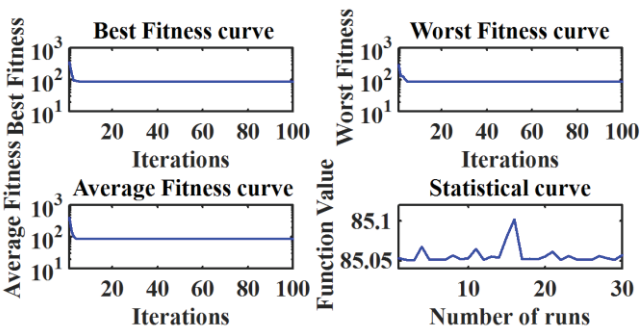

Fig. 6 APF at bus 18

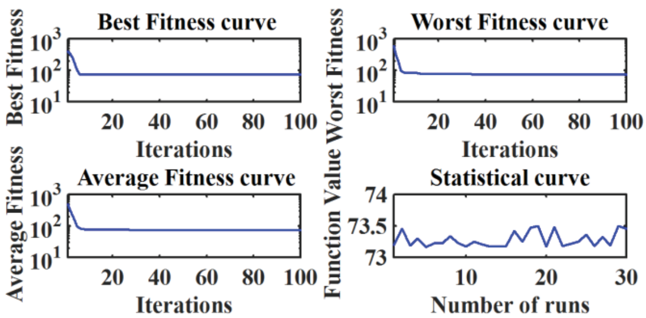

Fig. 7 APFs at buses 18 and 25

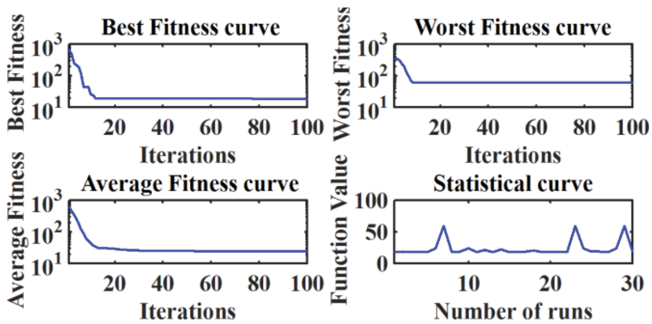

Fig. 8 APFs at buses 7, 18 and 25

TABLE III PERFORMANCE OF GWO

Sr. No.	Nos of APF	Bus No.	Best Value	Average Value	Worst Value	Standard Deviation Value
1	One	7	59.260200	59.293800	59.493400	0.056718
2		18	85.050400	85.056500	85.102400	0.010529
3		25	145.069400	145.075500	145.080900	0.003694
4		33	124.230900	124.237200	124.233100	0.009204
5	Two	7,18	23.901000	25.150000	23.922500	6.348600
6		7,25	59.267600	59.340500	59.623400	0.076520
7		7,33	59.263900	59.358900	59.630300	0.095251
8		18,25	73.164000	73.281500	73.504100	0.116540
9		**18,33**	**0.047783**	**0.047846**	**0.048010**	**0.000056**
10		25,33	115.594100	115.594100	123.602200	1.426400
11	Three	7,18,25	18.128100	23.645500	59.426900	12.074200
12		7,25,33	59.270700	61.318400	115.510400	10.064400
13		**7,18,33**	**0.047805**	**17.409500**	**59.650700**	**25.955200**
14		**18,25,33**	**0.047787**	**10.197900**	**115.710900**	**31.095400**
15	Four	**7,18,25,33**	**0.047988**	**6.035400**	**59.459200**	**15.523600**

TABLE IV COSTING OF APF

Sr. No.	Nos of APF	Bus No.	APF current found by GWO	Fixed cost ($)	Incremental cost ($)	Total cost ($)	% saving compared to unoptimized solution
1	**2**	**18,33**	**0.047783**	**180000**	**34404**	**214404**	**67**
2	3	7,18,33	0.047805	270000	34420	304420	53
3	3	18,25,33	0.047787	270000	34407	304407	53
4	4	7,18,25,33	0.047988	360000	34551	394551	39

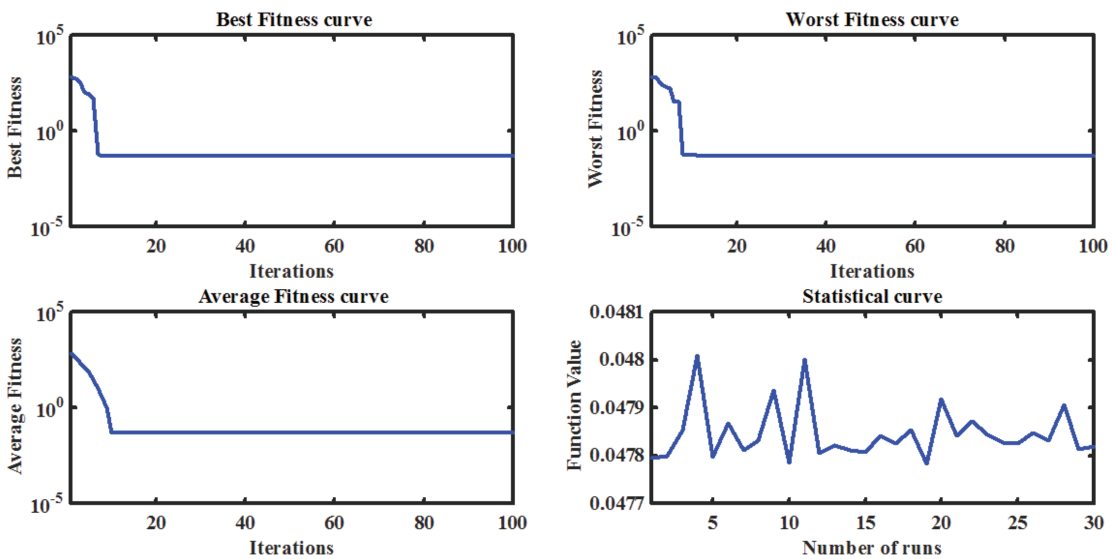

Fig. 9 APFs are at buses 18 and 33

The performance of GWO for different placements of APFs is shown in Fig. 5 to Fig. 9. Among the fifteen combinations only four combinations are feasible and constraints are fulfilled. As discussed earlier, for single APF the solution is not possible. The best value found by GWO is high due to dynamic penalty. The maximum current rating is not capable to satisfy the constraints in case of single APF. With two APFs possible combinations are six. Among them only one solution is feasible. It shows the importance of optimal placement. When APFs are placed at buses 18 and

33 the constraints are fulfilled and total current of APF is 0.047783 p.u.. For three APFs, among four combinations, two combinations (APFs are at buses 7, 18, 33 and 18, 25, 33) are satisfied the constraints and the current values are 0.047805 p.u. and 0.047787 p.u. respectively. When four APFs are used to control the harmonics, total current 0.047988 p.u. is required. This combination (APFs at buses 7,18,25, and 33) is also satisfy the constraints. From above analysis, OPSAPF is- the required APFs are two, optimal placement is at buses 18 and 33, total current is 0.047783 p.u.

The cost calculation is given in Table IV. Here, cost is divided in two parts: Fixed cost and incremental cost. Fixed cost is an installation cost and it is 90000$ per APF. The incremental cost depends on the rating of APF. It is 720000$ per p.u. of APF current [6]. According to Table IV, unoptimized solution is four APFs with current rating of 0.10005097 p.u.. The fixed cost is 360000 $, incremental cost is 288147$. Thus the total cost is 648147 $, which is very high compared to the optimized solution cost 214404 $. Optimal valued found by GWO is very less compared to unoptimized solution. Net saving is 67% in cost.

IV. Conclusion

In this paper, OPSAPF for 33-bus RDS is presented. To solve this nonlinear constrained optimization problem GWO is used. The effectiveness of GWO is judged by computational tests. The best fitness value for different placement combinations is found by GWO with its good exploration and exploitation phases. GWO found the optimal solution with 67% of saving in cost. It has also good stability. This work can be extended with multi-objective optimization using GWO in future.

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