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Optimal Placement and Sizing of Multiple Active Power Filters for Radial Distribution System Using Grey Wolf Optimizer

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***Abstract*—This paper presents, grey wolf optimizer (GWO) algorithm to solve a constrained nonlinear optimization problem of optimal placement and sizing of multiple active power filters (OPSMAPFs) for radial distribution system (RDS). It is a nature inspired stochastic algorithm. It has balanced exploration and exploitation characteristics. Minimization of the current of APF is taken as an object with three inequality constraints. To evaluate the performance of GWO algorithm, the simulation is performed on 33-bus RDS for twenty independent runs and compared with recently developed dragonfly algorithm (DA) and whale optimization algorithm (WOA). Simulation results demonstrate the effectiveness and stability of GWO algorithm.**

Keywords—active power filter, dragonfly algorithm, grey wolf optimizer, total harmonic distortion, whale optimization algorithm.

I. Introduction

Nowadays, use of the power electronics devices such as converters, inverters, dimmers variable speed drives, compact fluorescent lamps, light emitting diodes, uninterrupted power supplies, mobile handsets and personal computers are raising due to their daily life necessity and importance. These devices have a nonlinear characteristic which increases harmonic pollution. Hence, issues related to the harmonics in power quality are gaining a significant attention to the both, the user and the supplier. These harmonics degrades the performance of distribution system [1, 2]. The techniques to mitigate harmonics have been presented in [2]. Active power filters (APFs) are used to mitigate the harmonics by injecting the nonlinear current in the radial distribution system (RDS) at the point of common coupling. The current rating of APF is highly dependent on its location. The cost of APF is based on its injected current. Therefore, to minimize the cost of APF, proper placement and size of APF are required. The fulfillment of constraints (total harmonic distortion in voltage (THDv) and individual harmonic distortion in voltage (IHDv) are also essential. Due to that, various optimization techniques have been proposed such as, generalized benders decomposition theory (GBDT) [3], genetic algorithm (GA) [4], particle swarm optimization (PSO) [5], harmony search (HS) algorithm [6], firefly algorithm (FA) [7, 8], and cuckoo search algorithm [9] etc..

According to the no free lunch theorem (NFL) [10], no algorithm can give optimum results for all types of optimization problems. The performance of each algorithm may vary with the type of problem, which motivates the researchers to use new algorithms. With that, a recently developed grey wolf optimizer (GWO) [11] algorithm is used in this paper to find the optimal placement and sizing of multiple APFs (OPSMAPFs) and compared with whale optimization algorithm (WOA) [12] and dragonfly algorithm (DA) [13].

GWO is based on the hunting behavior the grey wolves. It is a simple, flexible and derivation-free algorithm. Also, it has less burden of tuning of algorithmic specific parameters compared to PSO, GA, etc. It has a very good balance between exploration and exploitation phases in search space [11].

WOA is a bio-inspired algorithm. It mimics the behavior of humpback whale for finding the food by bubble net feeding method. The process in the method of searching is done by creating bubbles by encircling or through '9'-shaped path [12, 14].

DA is also a nature-inspired algorithm. It is based on the behavior of a dragonfly. They form swarms for hunting and migration. In that, the dragonfly swarms for the hunting are known as static swarm behavior and the swarms for the migration are known as dynamic swarm behavior. The static and dynamic swarm behavior forms the exploration phase and exploitation phase of optimization process respectively [13].

The performance of GWO is assessed based on computational tests along with the best value and standard deviation value of fitness function and compared with DA and WOA. The 33-bus test system is employed and simulated for twenty independent runs for GWO, DA, and WOA.

The structure of this paper is as follows: the problem formulation is given in Section II, Section III comprises of result analysis and discussion and then followed by the conclusion in Section IV.

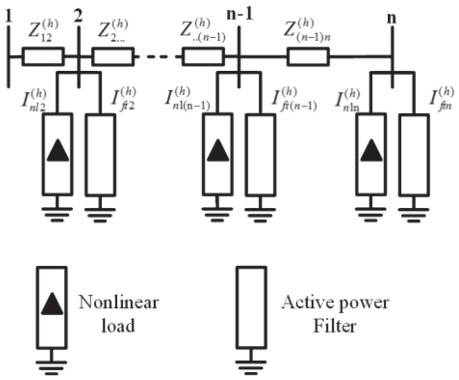

Fig. 1 RDS with nonlinear load and APF

II. Problem Formulation

This section deals with modeling of the distribution system, APF, and harmonic load flow. The objective function with constraints is formulated to solve the OPSMAPFs using the GWO.

A. *Distribution system*

The impedance Z of the distribution line can be represented by Fig. 1. The inductive reactance of the distribution line depends upon the order of harmonic frequency.

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

where R and X_L are the resistance and inductive reactance of the distribution line and h is the order of harmonic content.

B. APF

The APF is modeled as a nonlinear current source [15-17], which injects the current equal to the nonlinear load current (it is equal in magnitude but opposite in phase). The phasor model of APF can be written as

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

Where $I_{ft}^{(h)}$ is APF current, $I_{ft,r}^{(h)}$ is the real part and $I_{ft,im}^{(h)}$ is the imaginary part of APF current.

C. Harmonic Load Flow

The network topology based backward forward sweep harmonic load flow method is used for the analysis of harmonics [18]. This method is based on the formulation of two relationship matrices named as bus-injection to branch-current (BIBC) matrix and the branch-current to the bus-voltage (BCBV) matrix.

D. Objective Function

The objective function is an essential part of the optimization process. The OPSMAPFs is a constrained nonlinear problem. Here, the decision variable is the current of APF. The objective function is formed in the form of rms value of the current of APF. It is very important to minimize the current of APF because the cost of APF increases with the increase in its current rating.

Here, three constraints have been considered to solve the OPSMAPFs problem. First, the total harmonic distortion in voltage (*THDv*). Second, the individual harmonic distortion in voltage (*IHDv*), and the third one being a maximum current of APF ($I_{ft,MAX}$). The IEEE standard 519 [19] dictates the first two constraints and third constraint based on the nonlinear load current. The dynamic penalty factor method is used as a penalty method.
The objective function is illustrated 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 highest order of harmonic, and DP is dynamic penalty factor.
The objective function is subjected to following constraints:

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

E. *Mathematical modeling*

The formulation of the mathematical model of group hunting behavior of grey wolves is described in this section. It comprises of social hierarchy, encircling the prey, hunting, exploitation, and exploration [11].

a) Social hierarchy:

As per the social hierarchy as shown in Fig. 2, the alpha is considered as the fittest solution. While beta and delta are the second and third best solutions respectively. The remaining solutions are called omega.

b) Encircling the prey:

The following equations have been used to model the encircling behavior of grey wolves. The distance between prey and the grey wolf is given by following equations:

$$\vec{D}_t = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}_g(t)| \tag{5}$$

$$\vec{X}_g(t+1) = \vec{X}_p(t) - \vec{K} \cdot \vec{D}_t \tag{6}$$

Where t indicates the current iteration; $\vec{X}_g$ and $\vec{X}_p$ are the position vectors of grey wolf and prey respectively; and $\vec{K}$ and $\vec{C}$ are the coefficient vectors. The calculation of $\vec{K}$ and $\vec{C}$ is done with the help of following equations:

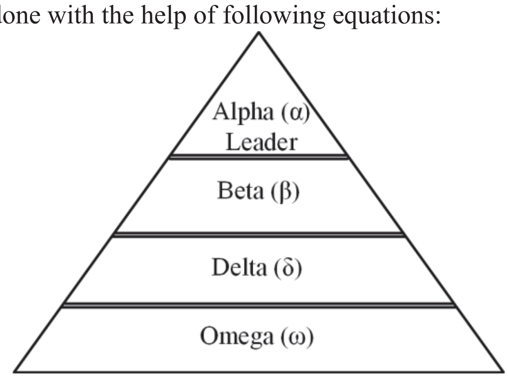

Fig. 2 Social hierarchy of grey wolves

$$\vec{K} = 2\vec{k}\cdot\vec{r}_1 - \vec{k} \tag{7}$$

$$\vec{C} = 2\cdot\vec{r}_2 \tag{8}$$

Where, $\vec{r}_1$ and $\vec{r}_2$ are random vectors in [0, 1] and the elements of $\vec{k}$ are linearly decreased from [2, 0] over the course of iterations. By using (7) and (8) grey wolf can update their position according to the position of prey by adjusting the values of $\vec{K}$ and $\vec{C}$. Here, random variation of $\vec{r}_1$ and $\vec{r}_2$ permit grey wolf to reach any position. Therefore, the grey wolf can update its position around the prey in any random location.

c) Hunting

The alpha leads the pack for hunting. Therefore, alpha is considered as the best solution. The beta and delta are considered as better solutions because they have better information about the probable location of the prey. Among the all obtained solutions, three best solutions are considered as alpha, beta, delta, and others have to update their position according to the position of best search agents.

The hunting mechanism can be formulated by following equations:

$$\vec{D}_{t\alpha} = |\vec{C}_1\cdot\vec{X}_\alpha - \vec{X}_g| \tag{9}$$

$$\vec{D}_{t\beta} = |\vec{C}_2\cdot\vec{X}_\beta - \vec{X}_g| \tag{10}$$

$$\vec{D}_{t\delta} = |\vec{C}_3\cdot\vec{X}_\delta - \vec{X}_g| \tag{11}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{K}_1\cdot(\vec{D}_{t\alpha}) \tag{12}$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{K}_2\cdot(\vec{D}_{t\beta}) \tag{13}$$

$$\vec{X}_3 = \vec{X}_\delta - \vec{K}_3\cdot(\vec{D}_{t\delta}) \tag{14}$$

$$\vec{X}_g(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{15}$$

By using above equations alpha, beta and delta guess the location of prey. The other wolves update their locations randomly nearby the prey.

d) Attacking the prey (Exploitation):

When the prey stops moving, the grey wolves attacking it and finish the hunt. Here, k is decreased from 2 to 0 over the course of iteration, as mentioned above. According to (7) the fluctuation in $\vec{K}$ also depends on $\vec{k}$. Therefore when $|\vec{K}| < 1$ the wolves attack towards the prey and vice versa for $|\vec{K}| > 1$. To escape from local minima stagnation more operators are emphasizing for exploration in the GWO.

e) Exploration:

In the GWO, $\vec{K}$ and $\vec{C}$ have random values. For $|\vec{K}| > 1$, search agents diverge from the prey, which provides good exploration. And for $|\vec{K}| < 1$, search agents move towards the prey. Therefore, the problem of local minima is avoided. For $\vec{C}$ component, it provides random weights in defining the distance. Therefore, it helps a more random behavior during optimization process for good exploration. The flowchart for OPSMAPFs for RDS using GWO is shown in Fig. 3.

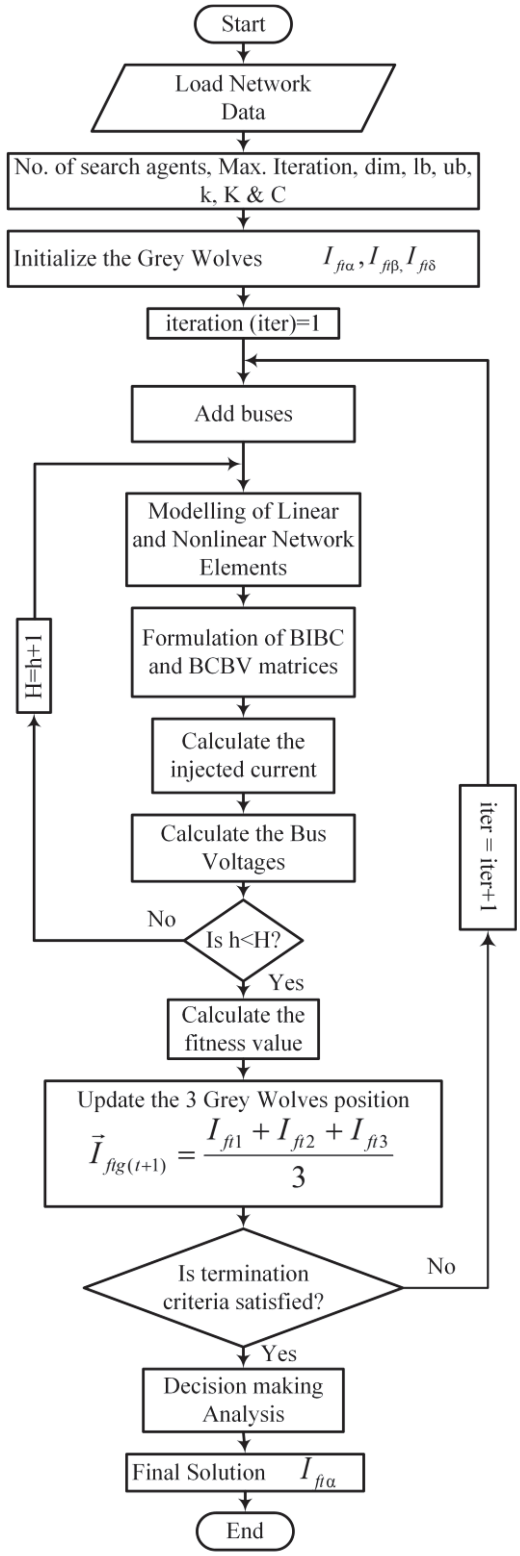

Fig. 3 Flowchart for OPSMAPFs using GWO

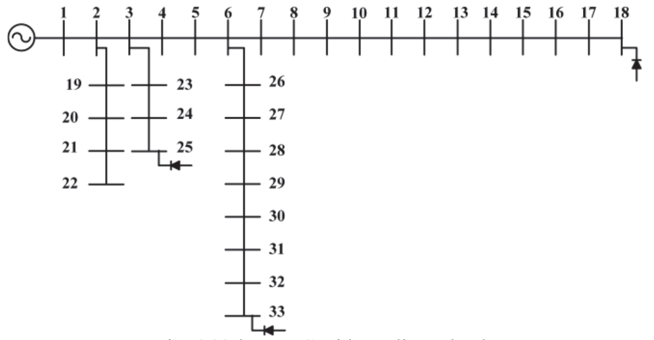

Fig. 4 33-bus RDS with nonlinear loads

III. Result Analysis and Discussion

This section deals with the result analysis and discussion. The 33-bus RDS is shown in Fig. 4. The nonlinear loads with six-pulse converter are placed at 18, 25 and 33 buses. The nonlinear load has a harmonic spectrum as shown in Fig. 5. From 5th to 29th order of harmonics are considered.

The THDv at all buses in absence of APF is tabulated in Table I. Sixteen buses out of thirty-three buses have THDv more than 5%. It shows that it is a highly harmonic distorted distribution system. The highest THDv is at bus 18 (29.82 %) and the minimum THDv is at bus 2 (0.21 %). The nonlinear loads are located at buses 18, 25 and 33. By prima fascia observation, it looks like three APFs will be placed at all nonlinear load buses with nonlinear load ratings. But it is not economical, as the cost of APF is directly proportional to the current compensated by it. Therefore optimization process is required to find the bus/buses is/are most suitable for placement of APF/APFs and size of it. Here, three algorithms (GWO, DA, and WOA) are used to find the OPSMAPFs and compared for best fitness and standard deviation value of fitness function.

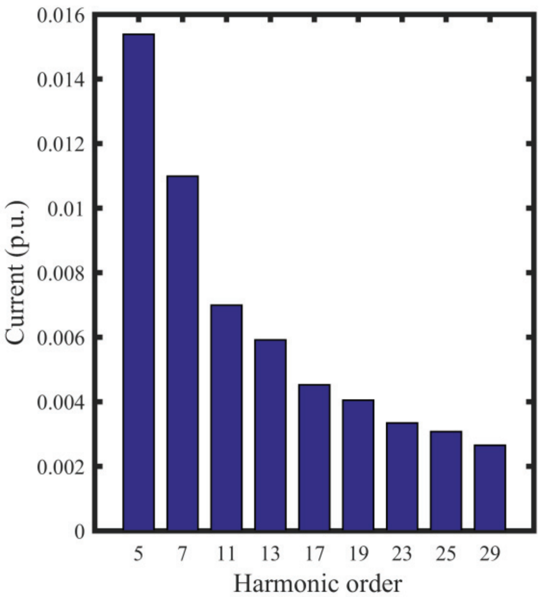

Fig. 5 Harmonic spectrum of nonlinear load

Table I THDv at all buses without APF

Bus No.	THDv (%)	Bus No.	THDv (%)
2	0.21	**18**	**29.82**
3	1.31	19	0.21
4	1.86	20	0.21
5	2.43	21	0.21
6	4.47	22	0.21
7	**5.36**	23	1.76
8	**7.15**	24	2.79
9	**8.23**	25	3.80
10	**9.30**	26	4.62
11	**25.46**	27	4.84
12	**25.58**	**28**	**6.19**
13	**26.42**	**29**	**7.20**
14	**26.93**	**30**	**7.58**
15	**27.36**	**31**	**8.97**
16	**27.82**	**32**	**9.49**
17	**29.27**	**33**	**10.26**

The sequence of step for the simulation are as under:

1) Run the harmonic load flow without APF and find the value of THDv at all buses.

2) Run the harmonic load flow with APF. Using optimization algorithm, find the OPSMAPFs.

3) Compare the results obtained by GWO, DA, and WOA for best and standard deviation values.

To observe and confirm the findings, the best fitness value and standard deviation value curves are shown in Fig. 6 and Fig. 7 respectively. The obtained results are presented in Table II. The best fitness curve shows that how the algorithm performs for the best value for the entire course of the iteration. The statistical curve presents the stability of the algorithm for twenty runs.

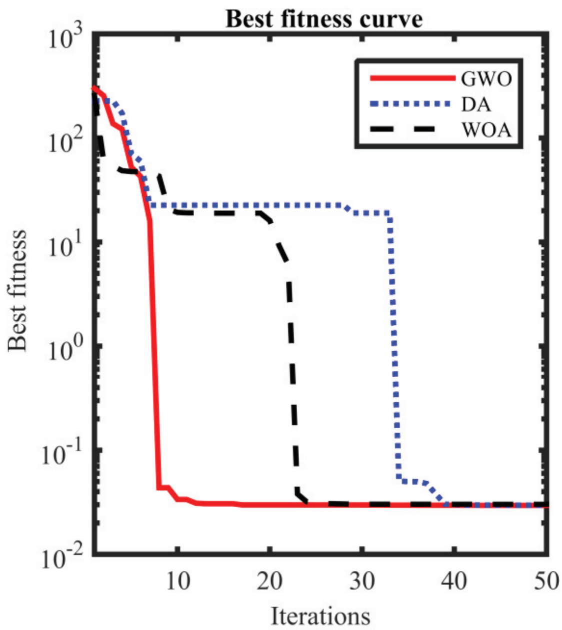

Fig. 6 Best fitness curve

A. Best fitness curve

Fig. 6 shows the best fitness curve for GWO, DA, and WOA. It has been observed that the GWO gives the best value for the given problem compared to DA and WOA. More iterations are required for convergence for DA and WOA compared to GWO. The GWO converges faster than other algorithms, which shows its better performance in terms of exploration and exploitation compared to other considered algorithms. Initially, the value of fitness is very high compared to the best fitness value due to penalty. The dynamic penalty is added due to the unsatisfaction of any constraints. It also shows the exploration phase of algorithms. The best fitness value is found by GWO (0.029524 p.u.) compared to DA (0.029592 p.u.) and the WOA (0.030205 p.u.). If the optimization procedure is not considered and the APFs are placed at all nonlinear load buses with the current capacity of same as nonlinear loads than three APFs are required with a total current capacity of 0.067477 p.u.. The current rating is reduced to 44 % by using GWO. It results in cost saving.

B. Statistical curve

This curve shows the stability of the algorithms during the entire optimization process. Here, the optimization process is done for twenty independent runs. The GWO is more stable algorithm compared to DA and WOA. The standard deviation is the lowest for the GWO, which proves its stability for the entire course of iterations. From the Fig. 7, it has been observed that for all runs, the GWO has almost same best fitness value. Its curve is a straight line. While DA and WOA have not same value of best fitness for all runs. The standard deviation values for GWO, DA, and WOA are 0.000173, 23.488100 and 23.955600 respectively. It proves the stability of GWO for solving the OPSMAPFs problem.

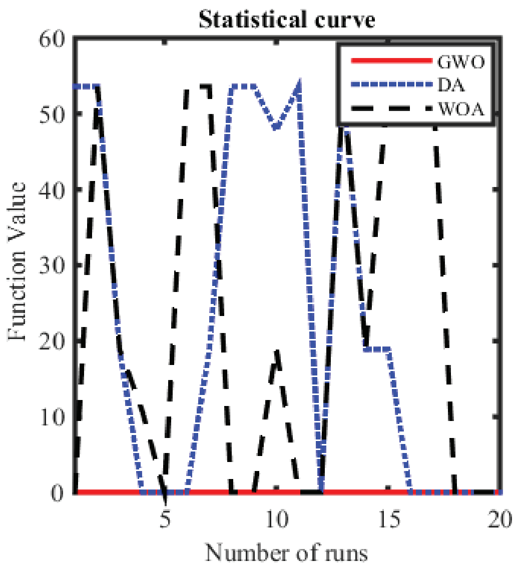

Fig. 7 Statistical curve

Table II Comparative Study of value of objective function

Algorithm	Best Index	Best Value	Standard Deviation Value
GWO	20	0.029524	0.000173
DA	19	0.029592	23.488100
WOA	18	0.030205	23.955600

The Variation of APF current per iteration for each run of GWO, DA, and WOA for APF located at buses 18 and 33 are shown in Fig. 8 - Fig. 10 respectively. Fig. 8 shows the smooth curve for all runs in case of GWO. During initial iterations, the GWO has a high value of fitness function due to penalty. The penalty is due to the unsatisfied constraints. It indicates its exploration phase. After some iterations, it has a very low value of best fitness for all runs. It shows its exploitation phase. After some iterations, the spikes are also shown in the case of DA and WOA. It shows their poor exploration as well as exploitation phase. Both the algorithms are not converged for all runs.

As per the Fig. 11, the THDv at all buses is within allowable limits after OPSMAPFs. The comparison between considered algorithms with unoptimized for the current of APFs is shown in Fig. 12. It has been clearly observed that there is no requirement of APF at bus 25. The obtained total

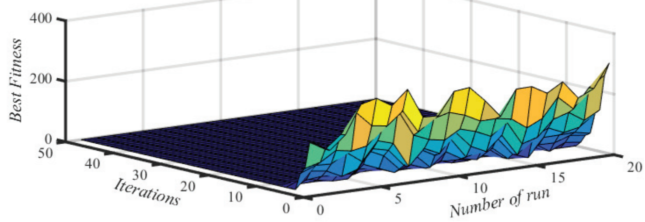

Fig. 8 Variation of APF current per iteration for each run of GWO for APF located at buses 18 and 33

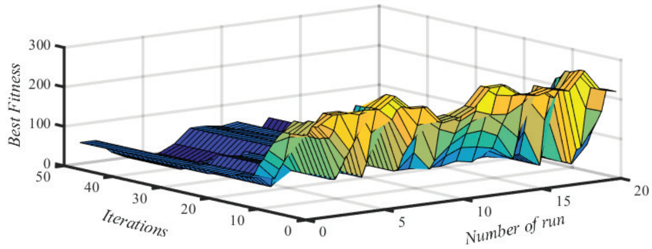

Fig. 9 Variation of APF current per iteration for each run of DA for APF located at buses 18 and 33

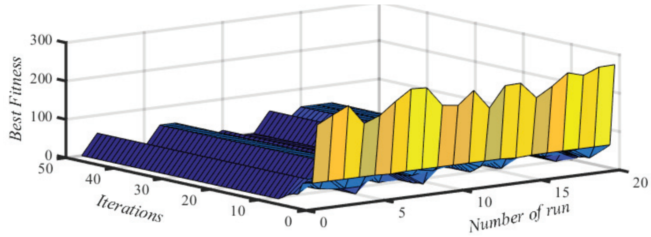

Fig. 10 Variation of APF current per iteration for each run of WOA for APF located at buses 18 and 33

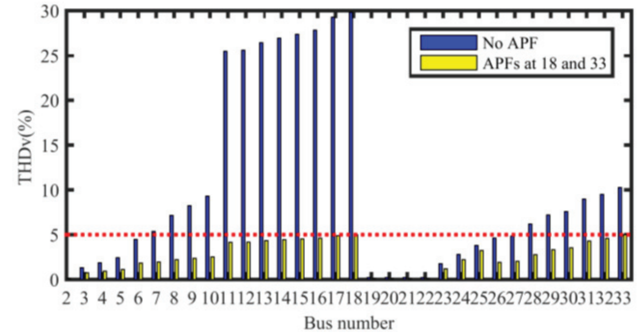

Fig. 11 THDv at all buses after optimal placement and sizing of AFPs

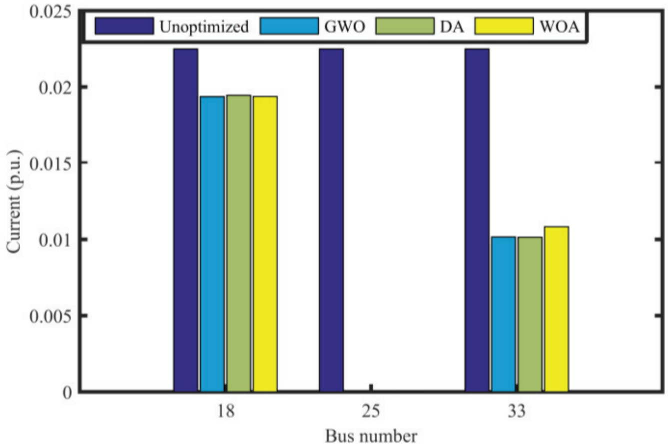

Fig. 12 Comparison of current of APFs without optimization and with different optimization algorithms

current ratings are also less compared to the unoptimized value of APFs current for APFs located at buses 18 and 33. The GWO has the lowest value of APFs current compared to DA and WOA.

IV. Conclusion

The OPSMAPFs for RDS using GWO is presented in this paper. This is a constrained nonlinear optimization problem. To check the efficiency of GWO, it is compared with DA and WOA for best fitness and standard deviation values of fitness function. The best fitness value is found by GWO due to its better performance in terms of exploration and exploitation characteristics and it is 56 % less compared to the unoptimized value of current rating of APFs. The standard deviation value is almost zero in the case of GWO, which shows its good stability. The DA and WOA have higher values of standard deviation compared to GWO. The performance of DA and WOA is poor in both values compared to GWO for this problem. In future, this work can be simulated with multiobjective optimization using GWO.

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