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| Yue xiwen | Formal analysis; Supervision; Visualization |
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Optimal Configuration and Dimension of Active Power Filters in Distribution Networks Based on Improved Beluga Whale Optimization

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**Abstract：**With the widespread use of electric vehicles, the rapid development of power electronics and smart grids making more and more nonlinear devices connected to the grid, the power quality problem is becoming more and more prominent, and active power filters (APFs) are widely used to reduce the harmonic voltage and current in the grid. In this paper, the optimal configuration and dimensions of APFs for distribution networks based on the improved Beluga whale optimization (IBWO) are proposed. The IBWO algorithm proposed in this paper is characterized by fast convergence and high accuracy. The objective of the method proposed in this paper is to reduce the number of APFs used and the investment cost, while making the total voltage harmonic distortion rate (VTHD) and the individual VTHD of the grid meet the requirements. Finally, this paper verifies the effectiveness and feasibility of the proposed method by an example in an IEEE-18 bus test system, and the results show that the proposed method is effective in optimizing the location and capacity of multiple APFs.

Keywords: power quality; active power filters; Beluga whale optimization; voltage harmonic;

# Introduction

With the rapid development of power electronics technology and distributed power grid, the application of modern power electronic devices makes the composition and characteristics of the power grid different from before. The application of non-linear power electronic devices and loads can easily cause distortion of voltage and current on the power supply side and load side, and even resonance in the grid, which not only affects the effective operation of the power system, but also causes huge security risks, so the power quality problem can be managed without delay. The power quality of the power grid includes many aspects, among which the harmonic pollution problem is the most common problem affecting the power quality, and the electronic devices with non-linear characteristics are the main reason for harmonic pollution. In the modern power system harmonic management, APF is most widely used because of its advantages.

Contemporary power electronics-based grids exhibit distributed and complex characteristics; these harmonic sources are scattered in the grid and generate a large amount of harmonic currents flowing into the grid, or a node generates relatively small harmonic currents, but is more susceptible to collective effects by other harmonic sources [1]. It is very difficult and not economical to use APFs of sufficient capacity in industrial grids.Chiang et al [3] proposed a method to increase the compensation capacity of multiple parallel APFs by limiting the capacity of each APF, which reduces the capacity demand and allows the sharing of reactive power and harmonic currents.This modular result of multiple APFs reduces the impact caused by parameter mismatch, reduces the cost , with higher reliability and flexibility.[4] Literature analysis. The literature [5] proposed in 1992 to plan the location of Active Power Line Conditioners (APLCs) to reduce grid voltage distortions, it is worth noting that the authors considered four aspects: THD, the Communication Influence Factor (TIF), the Motor Load Loss Function (MLL), and Single-Bus Sine Wave Correction (SBSWC). The objective function is established according to the desired objective and solving this planning problem leads to the optimal location and capacity of APLCs. The literature [6] determines the optimal allocation and optimal size of APFs based on the adaptive particle swarm algorithm, and the validation is done in 5-bus and 18-bus test systems. Similarly, other evolutionary algorithm solving tools were used to determine the APFs allocation and sizing problem, such as Genetic Algorithm (GA) [7]; Modular Discrete PSO (MPDPSO) [8]; Improved Fuzzy-Improved Accompaniment Search Algorithm (IFAS), Harmony Search Algorithm, (HSA) [9].

Iman Ziari et al. in 2012 proposed the use of PSO to solve the sizing problem of APLCs with the objective of minimizing the investment cost while keeping the total voltage harmonic distortion and individual harmonic distortion as constraints within standard levels. Since the APLC size is a discrete value, the objective function has many local minima. However, the particle swarm algorithm converges slowly and is prone to fall into local optima for problems with multiple local minima. Similarly, the literature [10] proposes a method that aims to minimize the voltage harmonic distortion while satisfying the harmonic criterion level by minimizing the injection of APF current, using a genetic algorithm (GA) as an optimization tool for the solution. All these classical metaheuristic algorithms face the problem of insufficient optimization performance.

In this paper, various costs of active power filters are considered from an economic point of view, a nonlinear integer programming problem is developed, and the developed model is solved using IBWO. The main contributions of this paper are as follows.

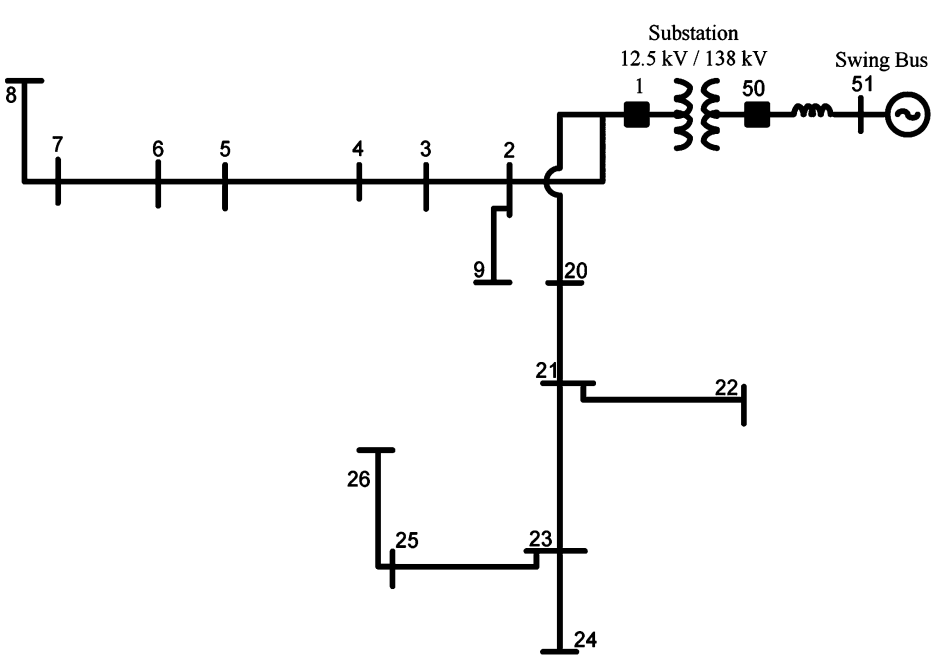
(1) A multi-objective cost model for multiple APF total currents, THD, HTLL, MLLF is established with the cost to establish the objective function with the total voltage harmonic distortion rate of the grid and the total voltage harmonic distortion rate of different nodes as constraints.

(2) For the nonlinear integer programming problem established in this paper, a multi-strategy improved white whale algorithm is proposed in this paper, which effectively solves the problems of slow solution efficiency and low accuracy of the traditional solution algorithm.

(3) The method proposed in this paper is verified in the IEEE-18bus harmonic test system, which has certain feasibility and effectiveness.

# System Modeling

In this paper, harmonics test some systems of the distribution network using the typical test model IEEE 18-bus, this test system is widely used in other studies [11], the operational parameters of the IEEE 18-bus distribution network can be found in these published studies [12]. The system model of IEEE 18-bus is shown in Figure 1 below. The voltage level at 16 buses of this distribution network is 12.5 kV, and the voltage level at the other buses (17 and 18) is 138 kV, for the high voltage side of the substation transformer, and the basic power of the system is 10 MVA.It is worth noting that in Figure 1, the nonlinear loads and APFs are connected at different nodes. APFs are used to compensate harmonic voltages, where the location and size and number of APFs are issues that need to be planned.



**Fig.1 IEEE 18-bus harmonic test model.**

**2.1 APF Model**

In this paper, the APF is considered as a current source injecting harmonic currents into the grid, and in order to represent the magnitude and phase angle of the injected currents, the injected currents are modeled using vectors.

|  |  |
| --- | --- |
|  | (1) |

Among them:

|  |  |
| --- | --- |
| *h* | *h*th harmonic |
| *F* | Output current of APF |
| *m* | The *m*th bus |
| *r* | Real part of APF output current |
| *i* | Imaginary part of APF output current |
|  | APF current at bus for harmonic order *h* |
|  | real part of APF current at bus for harmonic order *h* |
|  | imaginary part of APF current at bus for harmonic order *h* |

The root mean square (RMS) current of each APF is also obtained according to Equation (2).

|  |  |
| --- | --- |
|  | (2) |

**2.2 Objective function**

In this paper, the primary issue of the main research objectives is the need to determine the optimal economy under which APFs are allocated and sized. In view of this, we will consider: minimization of harmonic voltage across the network, with voltage as the minimization objective; lowest cost of APF allocation across the network; and minimization of the number and capacity of APFs. In this paper, the harmonics generated by the APF access and the control effect are considered, with the cost minimization as the target, and the voltage distortion rate constraint, line loss, and maintenance cost to meet IEEE-519 standard are also considered.

In fact, the determination of the location and of the APF, which is a multi-objective planning problem with harmonic distortion kept within the standard level, so that the objective function can be designed as in equation (3).

|  |  |
| --- | --- |
|  | (3) |

Where

|  |  |
| --- | --- |
| *k*1 | weight coefficient for *F*APF |
| *k*2 | weight coefficient for *F*HTLL |
| *k*3 | weight coefficient for *F*M |
| *k*4 | weight coefficient for *F*THD |
| *F*APF | Installation cost of all APFs |
| *F*HTLL | Line loss of harmonic transmission |
| *F*M | Maintenance cost of APF |
| *F*THD | Total harmonic distortion rate of voltage |

**2.2.1 Installation cost of APF**

The total installed cost of the APF is shown in equation (4). The objective function aims to minimize the size of the APF and therefore considers the maximum current injected by the APF, whose output current is proportional to its cost.

|  |  |
| --- | --- |
|  | (4) |

*Iapf* is the output current of each APF installed, as shown in equation (5).

|  |  |
| --- | --- |
|  | (5) |

**2.2.2 Line loss of harmonic transmission**

Harmonics can cause the transmission capacity of the power system to be occupied and the losses to increase. In this paper, the line loss equation (6) is considered, where *R* is the line impedance, *Z* is the impedance between the buses, and *h* is the harmonic order.

|  |  |
| --- | --- |
|  | (6) |

**2.2.3 Maintenance cost of APF**

After accessing the APF, consider the maintenance cost of the APF, as shown in equation (7).

|  |  |
| --- | --- |
|  | (7) |

where n is the *n*th APF installed and *cn* is the daily maintenance cost of the *n*th APF.

**2.2.4 Maintenance cost of APF**

In this paper, the total harmonic distortion rate is used as one of the cost functions, as shown in equation (8)

|  |  |
| --- | --- |
|  | (8) |

Among them

|  |  |
| --- | --- |
|  | (9) |

After giving some consideration to the total voltage THD, the voltage distortion rate is summed for each bus. In fact, some constraints of the grid and APF cannot be neglected when considering the above conditions. These constraints are:

|  |  |
| --- | --- |
|  | (10) |

The harmonic voltage at the bus *m* of harmonic order *h*. *Vh m*, can be obtained after installing the APF at different locations, as shown in equation (11-12).

|  |  |
| --- | --- |
|  | (11) |

|  |  |
| --- | --- |
|  | (12) |

The voltage at bus *b* for harmonic of order h depends on the impedance matrix, the injection current of the h-order harmonic APF, and the voltage at bus *b* before the APF is installed. Based on, the impedance matrix and the voltage at bus *b* before installation of the APF of harmonic order *h* are assumed to be defined as follows. In this problem, the APF injection current of harmonic order h is also assumed as a decision variable. The real and imaginary parts of the voltage of harmonic order *h* at bus b can be calculated according to the equation. where Z is the impedance matrix with known parameters, which can be found in the appendix.

|  |  |
| --- | --- |
|  | (13) |
|  | (14) |

# Improving Moby Dick optimization algorithm based on multi-strategy approach

Beluga whale optimization (BWO) is a new swarm-based metaheuristic algorithm proposed in 2022 [10]. It is inspired by the behavior of beluga whales, including swimming, feeding, and whale falling behavior in the sea.

The beluga whale optimization algorithm contains exploration phase, development phase and whale fall phase in the mathematical model of the optimization problem, where the global search capability in the design space is ensured by the random selection of beluga whales in the exploration phase, and the local search capability in the design space is controlled in the development phase, and the Levy flight function is used to improve the convergence capability of the algorithm. Since the BWO algorithm is based on a population-based mechanism, the belugas are considered as search agents, and each beluga is treated as a candidate solution, thus updated during the optimization process, the search agent position matrix is as follows:

|  |  |
| --- | --- |
|  | (15) |

where *n* is the population size of beluga whales and d is the dimensionality of the design variable. The corresponding beluga whale fitness values are as follows

|  |  |
| --- | --- |
|  | (16) |

Introducing the balancing factor *Bf* , which shifts the beluga from the exploration phase to the development phase, is calculated as follows:

|  |  |
| --- | --- |
|  | (17) |

where *t* is the current number of iterations, *T* is the maximum number of iterations, and *B0* is a random variation between (0,1) in each iteration. When the equilibrium factor *Bf* > 0.5, the exploration phase starts, and when *Bf* ≤ 0.5, it goes to the exploitation phase. The fluctuation range of the equilibrium factor decreases from (0,1) to (0,0.5) as the number of iterations increases. the probability of moving from the exploration phase to the exploitation phase increases with the number of iterations.

During the exploration phase, the location of the search strip agents is determined by the pairwise swimming of belugas, which is updated by the following equation

|  |  |
| --- | --- |
|  | (18) |

where *T* is the current number of iterations, denotes the position of the *i*th beluga in dimension *Pj*, *Pj* (j =1,2,...,*d*) denotes the random number selected from dimension *d*, *r*1 and *r*2 are random operators, which are random numbers in the range of (0,1), denotes the updated position of the *i*th beluga in dimension *j*, denotes the current position of the random beluga *r*, sin(2 π*r*2), cos(2π*r*2) represents the orientation of the mirror beluga's fins relative to the water surface, and *n* is an integer. The number of dimensions is chosen by odd-even numbers, and the updated position responds to the mirroring behavior of the beluga whale while diving or swimming.



The development phase of the beluga optimization algorithm was inspired by beluga whale feeding behavior, where belugas can move and collaborate to feed based on the location of nearby belugas, thus belugas select the best feeding belugas by sharing their location with each other. The Levy flight strategy was introduced in the development phase, which serves to enhance the convergence of the algorithm, at which point the position of the beluga whales is updated as follows:

|  |  |
| --- | --- |
|  | (19) |

where *T* is the current number of iterations, and is the current position of the *i*th beluga and the random beluga *r*, is the updated position of the *i*th beluga, *r*3, *r*4 are random numbers in the range (0,1), denotes the best beluga position in the beluga population, *C*1 is the random jump intensity in Levy's flight, which is used to measure the flight intensity, and the expression is:



|  |  |
| --- | --- |
|  | (20) |

The Levy flight function is *LF* with the following expression

|  |  |
| --- | --- |
|  | (21) |

|  |  |
| --- | --- |
|  | (22) |

where m and n are normally distributed random numbers and *b* =1.5.

To keep the population size constant, it is assumed that beluga whales either migrate to other places or are shot down and fall into the deep sea, so the location of beluga whales and the step of whale fall are used to update the location of beluga whales, and the expressions are as follows:

|  |  |
| --- | --- |
|  | (23) |

where *r*5, *r*6, *r*7 are random numbers in the range of (0,1), *Xstep* is the step size of the whale fall, and the expression is as follows:

|  |  |
| --- | --- |
|  | (24) |

where *ub* and *lb* are the upper and lower bounds of the variables, and *C*2 denotes the step factor related to whale population size and whale fall probability, calculated as follows

|  |  |
| --- | --- |
|  | (25) |

It can be seen that the step size of whale fall is influenced by the upper and lower bounds of the design variables, the number of iterations and the maximum number of iterations. Where *Wf* denotes the probability of whale fall and is calculated as follows

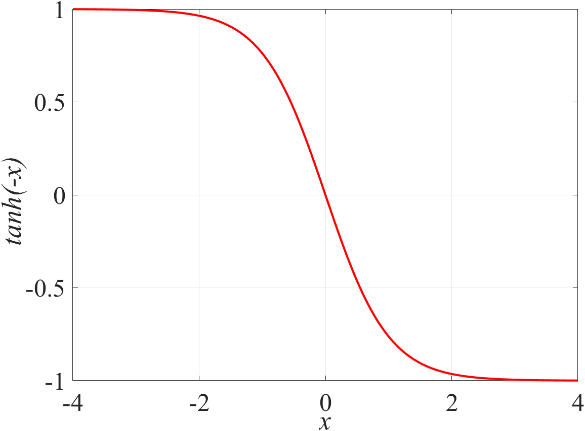
|  |  |
| --- | --- |
|  | (26) |

# Multi-strategy improvement method

**4.1 nonlinear equilibrium factor *Bf* based on tanh function**

Analyzing the balance factor *Bf* of the white whale algorithm, when the balance factor Bf > 0.5, the exploration phase starts, and when *Bf* ≤ 0.5, it enters into the exploitation phase. However, Bf decreases linearly, which cannot control the optimization-seeking strategy of BWO better, so this paper proposes a nonlinear balance factor based on the Tanh function. And because the Tanh function is a monotonically increasing function, so this paper takes Tanh(-*x*) and turns the function into a monotonically decreasing function, whose formula and function image are as follows.

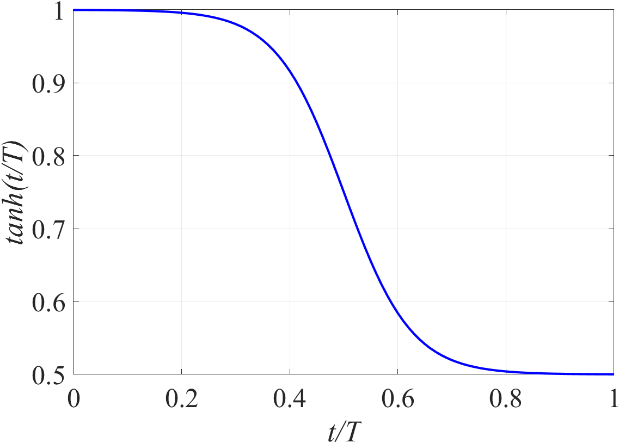
|  |  |
| --- | --- |
|  | (27) |



**Fig.2 Tanh function**

Figure 2, for the purpose of the BWO search strategy, transforms tanh(-*x*) again, with the following equations and function images Fig.3.

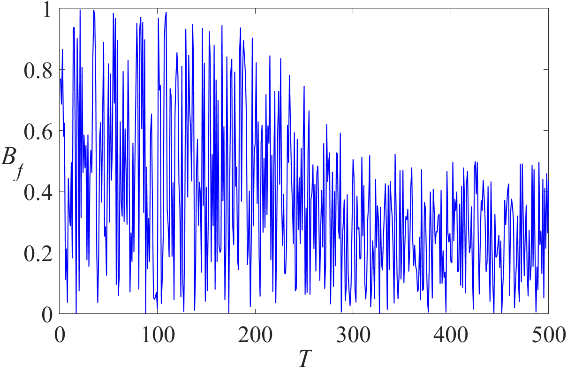
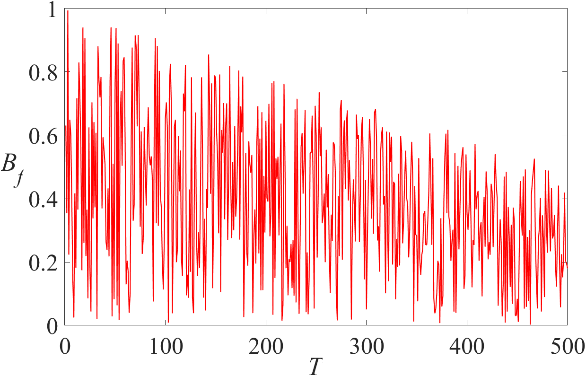
|  |  |
| --- | --- |
|  | (28) |



**Fig.3 Tanh function**

Then the improved equilibrium factor *Bf* is as follows:

|  |  |
| --- | --- |
|  | (28) |

****

(a) Original balance factor (b) Improved balance factor

**Fig.4 Iteration Curve**

Figure 4 gives the iteration curve of the balance factor *Bf* for 500 iterations, and it can be seen that compared with the original balance factor Bf, the improved balance factor *Bf*, after 200 generations, has converged, and the probability of the balance factor *Bf* < 0.5 is greater, so the improved balance factor *Bf*can ensure that BWO performs sufficient global optimization search on the basis of fine local optimization as well, in order to improve The efficiency and accuracy of the optimization search.

**4.2 Elite Reverse Learning Formula**

Opposition - based Learning (OBL) is a new algorithm proposed by Tizhoosh in 2005.The basic idea of OBL is to find the corresponding inverse solution based on the current solution, and then evaluate and compare them to save the better solution, and its basic formula is as follows.

|  |  |
| --- | --- |
|  | (29) |

Elite opposition-based learning (EOBL) constructs a reverse population based on the elite individuals in the current population to increase the population diversity, and selects the best individuals in the new population for the next iteration. Assuming that the extreme value point of individuals in the population is the elite individual, the elite inverse solution can be expressed as:

|  |  |
| --- | --- |
|  | (30) |

where *K*∈(0,1) is the dynamic coefficient; (*aj*, *bj*) is the dynamic boundary of the *j*th dimensional space; *xei,j* is the elite individual. The dynamic boundary solves the drawback that the fixed boundary cannot preserve the search experience, and makes the inverse solution located in the gradually shrinking search space, which improves the convergence speed and the global search ability. If the inverse solution jumps out of the dynamic boundary, it is reset using the random generation method with the following equation.

|  |  |
| --- | --- |
|  | (31) |

The variation is also determined by the given learning probability *S*. If the condition is met, the original position update formula is replaced using the elite reverse learning formula, whose expression is

|  |  |
| --- | --- |
|  | (32) |

where *r* is a random number between (0,1) and elite reverse learning is performed if *S*=1, and no learning is performed if *S*=0.

**4.3 DE-based population preference strategy**

BWO will update the position of the next generation population directly after the iteration, and does not compare the latest population position with the previous generation population position, so the case of inferior evolution. In this paper, the updated beluga population is selected again based on the selection strategy of differential evolution algorithm (DE) with the following equation.

|  |  |
| --- | --- |
|  | (33) |

where *fit*(*Xi*) is the fitness value corresponding to beluga whale position *Xi*. By comparing the fitness value before and after individual beluga whale update, the optimal position is selected for update to ensure that each beluga whale update is beneficial to the whole population, so as to increase the optimization-seeking ability of the beluga whale population in the enhancement iteration cycle.

**4.3 Analysis of improvement effect**

In order to improve the performance of BWO search, three improvement methods based on tanh function nonlinear balance factor, elite reverse learning formula, and population preference strategy proposed in Section 4.3 will be used to improve BWO research, which are analyzed as follows.

1) The nonlinear balancing factor based on tanh function fully considers balancing the exploitation and exploration behaviors of beluga whales, avoiding beluga whales to carry out too much global optimization search, so that beluga whales have more time to carry out local effective optimization search, so as to improve the efficiency and accuracy of beluga whale population's optimization search.

2) The elite reverse learning strategy is used to update the foraging beluga population again. According to the learning probability S, the elite reverse learning is performed on the updated position of beluga whale individuals, which can improve the performance of the whole population to a greater extent and solve the situation that the beluga whale population is prone to fall into the local optimization in the process of foraging.

(3) The population preference strategy is used to compare the fitness values of beluga individuals before and after the update, so as to select the optimal position for the update, thus ensuring that each update of beluga is beneficial to the whole population, and increasing the merit-seeking ability of the beluga population in the iteration cycle.

The TEDIBWO merit search process is as follows in Algorithm and the optimization process is shown in Figure. 5:

|  |  |
| --- | --- |
| **Algorithm 1: IBWO algorithm pseudo-code** | |
| **Input**: Algorithm parameters (number of populations, maximum number of iterations) | |
| **Output**: Optimal solution | |
| 1： | Initialize the population and evaluate the adaptation values to get the best solution. |
| 2： | **While** *T* ≤ *Tmax* **Do** |
| 3： | The probability of whale fall *Wf* is obtained by equation (18), the equilibrium factor Bf based on tanh function is obtained by equation (28) |
| 4： | **For** *Xi* **Do** |
| 5： | **If** *Bf* (i) > 0.5 |
| 6： | //During the exploration phase |
| 7： | Randomly generated from dimension *pj*(j=1, 2, …, d) |
| 8： | Randomly select a white whale *Xr* |
| 9： | Update the new position of the *i*th beluga whale |
| 10： | **Else** If *Bf* (i) ≤ 0.5 |
| 11： | // During the development phase |
| 12： | Update random jump intensity *C*1 and calculate Levy flight function |
| 13： | Update the new position of the ith beluga whale |
| 14： | **End If** |
| 15： | Check the boundaries, calculate and rank the fitness values, compare with the previous generation and select. |
| 16： | **End For** |
| 17： | **For** *Xi* **Do** |
| 18： | // Whale Drop Stage |
| 19： | **If** *Bf* (*i*) ≤ *Wf* |
| 20： | Update the new position of the *i*th beluga whale |
| 21： | Check the boundaries, calculate and rank the fitness values. |
| 22： | **End If** |
| 23： | **End For** |
| 24： | **Elite reverse learning for the beluga with the lowest fitness value based on learning improvement S** |
| 25： | Check the boundaries, calculate and rank the fitness values, compare with the previous generation and select. |
| 26： | Find the current optimal solution |
| 27： | *T*= *T*+1 |
| 28： | **End While** |
| 29： | Output the optimal solution |



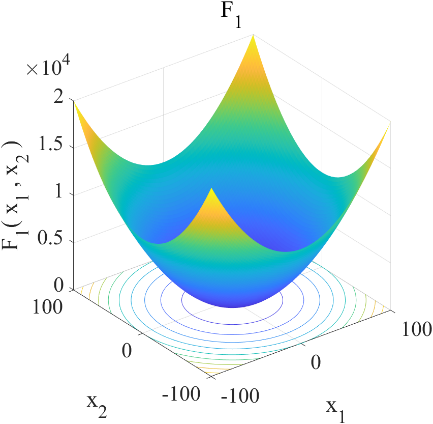
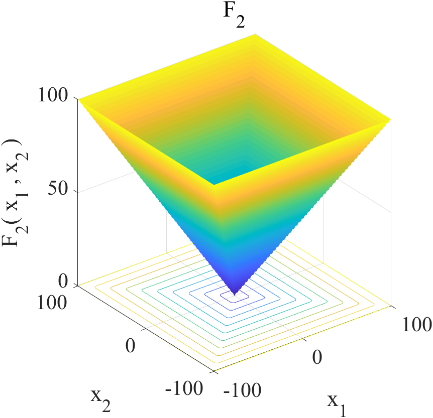
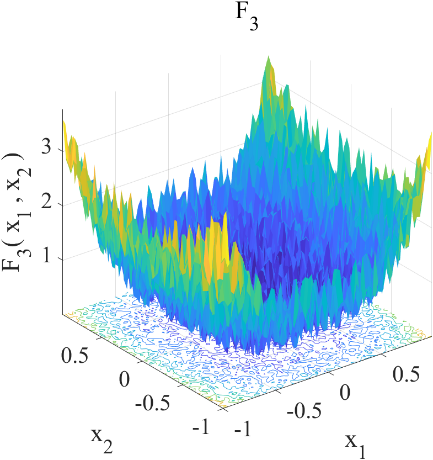
**Fig. 5 The method proposed in this paper**

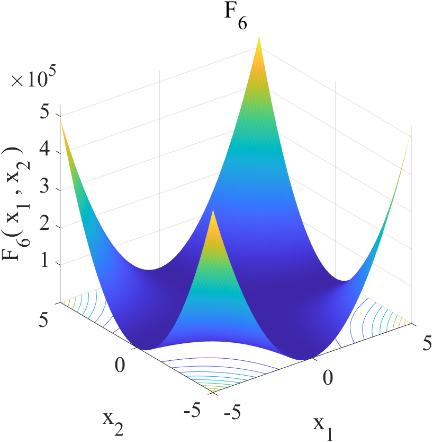
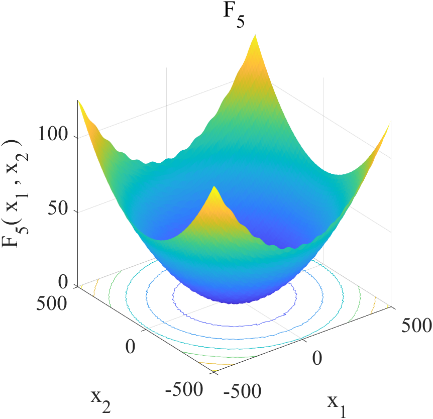
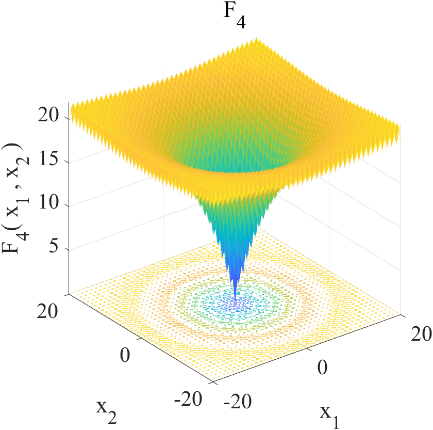
**4.3 TEDIBWO Advantage Seeking Performance Test**

In this paper, three single-peak benchmark test functions, two multi-peak benchmark test functions and one fixed-dimensional multi-peak benchmark test function are selected to test the performance of TEDIBWO and compare the test results with PSO, GWO, SFO and SOA. All the algorithms are tested 30 times, and the best (Best), mean (Mean) and standard deviation (Std) of the test results are taken as the evaluation indexes, and to verify the significance of the proposed algorithms, the Wilcoxon rank sum test was used to analyze the test results. The six test function formulas are shown in Table 1, and their function image plots are shown in Figure 6.

Table. 1 Function formulas

|  |  |  |  |
| --- | --- | --- | --- |
| Function | Dim | Range | *f*min |
|  | 30 | [-100,100] | 0 |
|  | 30 | [-100,100] | 0 |
|  | 30 | [-1.28,1.28] | 0 |
|  | 30 | [-32,32] | 0 |
|  | 30 | [-600,600] | 0 |
|  | 4 | [-5,5] | 0.1484 |

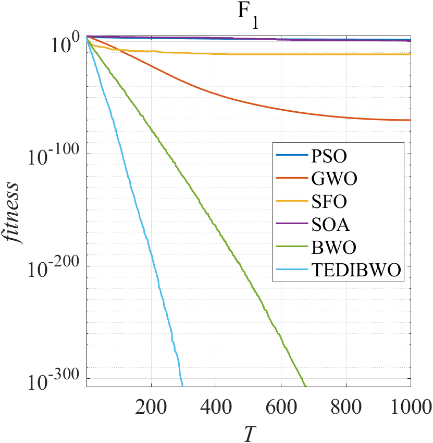
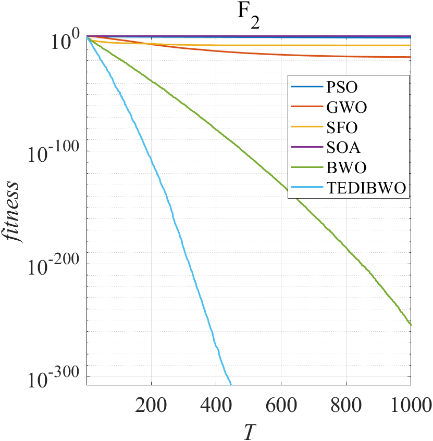
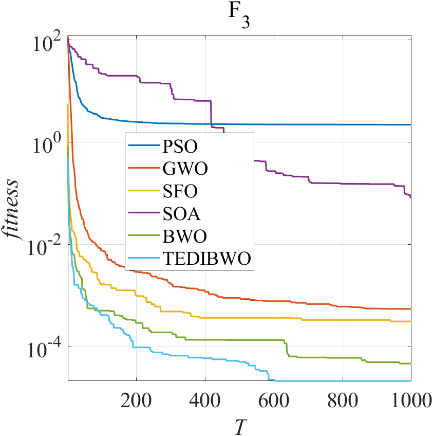
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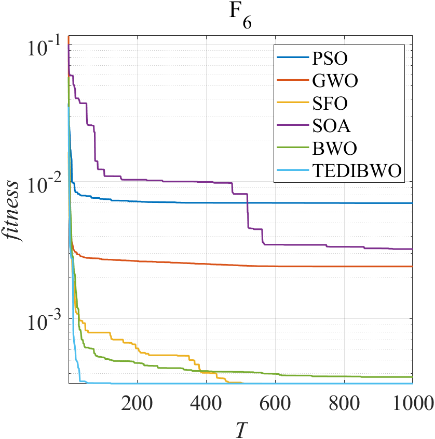
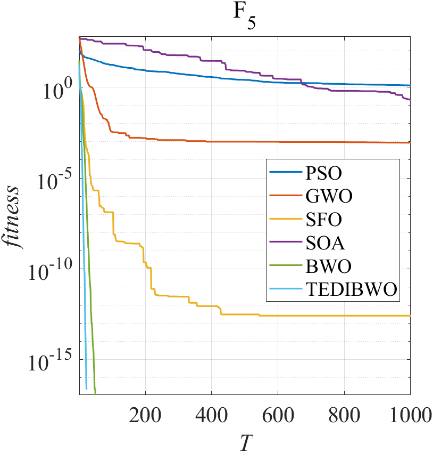
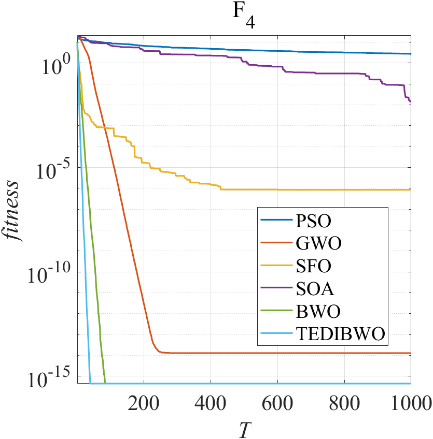
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**Fig.6** Function image

**Table.2 Test results**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Function | Indicator | PSO | GWO | SFO | SOA | BWO | MELBWO |
| F1 | Best | 7.668 | 2.48E-72 | 1.03E-14 | 0.038 | 0 | 0 |
| Aver | 3.189E+01 | 9.97E-71 | 3.70E-12 | 2.685 | 0 | 0 |
| STD | 1.583E+01 | 1.25E-70 | 6.52E-12 | 4.065 | 0 | 0 |
| F2 | Best | 1.041 | 3.48E-19 | 1.39E-08 | 0.0102 | 7.83E-260 | 0 |
| Aver | 2.295 | 1.65E-17 | 3.14E-07 | 60.43 | 8.11E-256 | 0 |
| STD | 1.096 | 1.87E-17 | 1.96E-07 | 32.308 | 0 | 0 |
| F3 | Best | 0.0151 | 1.47E-04 | 4.22E-06 | 0.0037 | 3.20E-06 | 6.05E-07 |
| Aver | 2.193 | 5.46E-04 | 3.11E-04 | 0.081 | 4.64E-05 | 2.12E-05 |
| STD | 6.790 | 2.07E-04 | 2.50E-04 | 0.112 | 3.50E-05 | 1.87E-05 |
| F4 | Best | 1.402 | 7.55E-15 | 2.02E-08 | 1.01E-05 | 4.44E-16 | 4.44E-16 |
| Aver | 2.710 | 1.29E-14 | 8.55E-07 | 0.014 | 4.44E-16 | 4.44E-16 |
| STD | 0.667 | 2.51E-15 | 1.15E-06 | 0.029 | 0 | 0 |
| F5 | Best | 0.982 | 0 | 0 | 4.37E-05 | 0 | 0 |
| Aver | 1.270 | 8.87E-04 | 2.58E-13 | 0.206 | 0 | 0 |
| STD | 0.205 | 2.81E-03 | 4.59E-13 | 0.353 | 0 | 0 |
| F6 | Best | 0.000778 | 3.07E-04 | 3.13E-04 | 1.59E-03 | 3.08E-04 | 3.10E-04 |
| Aver | 0.006969 | 2.40E-03 | 3.37E-04 | 0.003215 | 3.76E-04 | 3.37E-04 |
| STD | 0.009768 | 6.32E-03 | 2.58E-05 | 0.00229 | 1.54E-04 | 2.21E-05 |

****  

****

**Fig.7 Iteration Curve**

Table 2 and Figure 7 show test results of six algorithms, it can be seen that MEDIBWO has the best optimize performance. In table 2, F1, F2, F4, F5, the Indicator of BWO as same as the proposed algorithm. Then, by analyzing Figure 7, we can see that under the same optimization results, the convergence speed of the algorithm proposed in this article is faster. At the same time, in F3 and F6, it can be seen that the convergence speed and optimization accuracy of the algorithm proposed in this article are both optimal. Therefore, it can be proved that the algorithm proposed in this article has certain advantages. In order to further prove the optimization performance of the algorithm proposed in this article, Table 3 provides the significance test results.

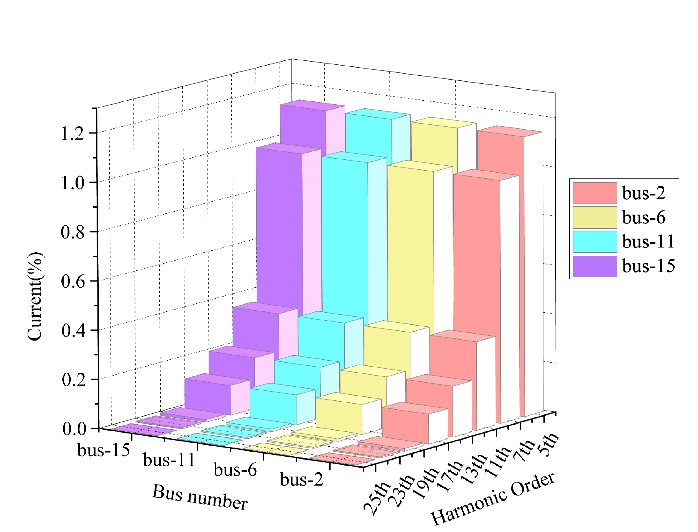
**Tab.3 Wilcoxon rank sum test results**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Algorithm  p-value | PSO | GWO | SFO | SOA | BWO |
| F1 | 6.386E-05 | 6.386e-05 | 6.386e-05 | 6.386e-05 | NaN |
| F2 | 6.386E-05 | 6.386e-05 | 6.386e-05 | 6.386e-05 | 6.386e-05 |
| F3 | 1.827E-04 | 1.827E-04 | 1.314E-03 | 1.827E-04 | 8.897E-02 |
| F4 | 6.386E-05 | 4.768e-05 | 6.386E-05 | 6.386E-05 | NaN |
| F5 | 6.386E-05 | 0.368 | 2.312E-04 | 6.386E-05 | NaN |
| F6 | 1.827E-04 | 2.574E-02 | 0.969 | 1.827E-04 | 0.186 |

The results of the above kind of tests were tested to obtain the *p*-value. That is, whether TEDIBWO is significantly different from the remaining five algorithms at the criterion of *p*=0.05. When *p*>0.05, there is no significant difference between TEDIBWO and algorithm N; when *p*<0.05, there is a significant difference between TEDIBWO and algorithm *N*. From Table 3, it can be seen that in F1 to F6, the p-values calculated by all four algorithms are much less than 0.05, so it can be concluded that TEDIBWO has significant performance in finding the best.

# Model Validation

The system used for verification in this paper is IEEE 18-bus, and this test system is used in numerous published studies [14]. Four nonlinear loads are connected on bus-2, bus-6, bus-11, and bus-15 of the test system. The connected nonlinear loads consist of ideal harmonic sources, which are composed of harmonics of orders 5, 7, 11, 13, 17, 19, 23, and 25 in total, and the composition of the harmonic currents of each order is shown in Figure 8. The composition of the four harmonic sources connected and the magnitude of the harmonic currents of each order are exactly the same. The harmonic data of transmission impedance, voltage amplitude and its angle can be found in the appendix.



**Fig.8 Iteration Curve**

A nonlinear load harmonic source is connected to bus-2, bus-6, bus-11, and bus-15 of the test system, as shown in Figure 9. When the APF is not yet connected, the harmonics propagate with the grid, producing voltage and current distortions at each node. In this test example, the size of the APF is set to a continuous value, determined by the maximum output current.



**Fig.9 Non-linear load access location**

In the test power system without APFs installed, both before optimization when the input matrix of APFs is all-zero matrix, Table 4 shows the simulation results without APFs installed. voltage conditions at different buses in the absence of APFs, the maximum THD is 14.0495%, the minimum is 8.2445%, and the average value is 10.4754%. The THD of each bus is greater than 5%, and the nonlinear harmonic sources make the distribution network has serious distortion and does not comply with IEEE 519 standard.

Table.4 Voltage conditions at different buses in the absence of APFs

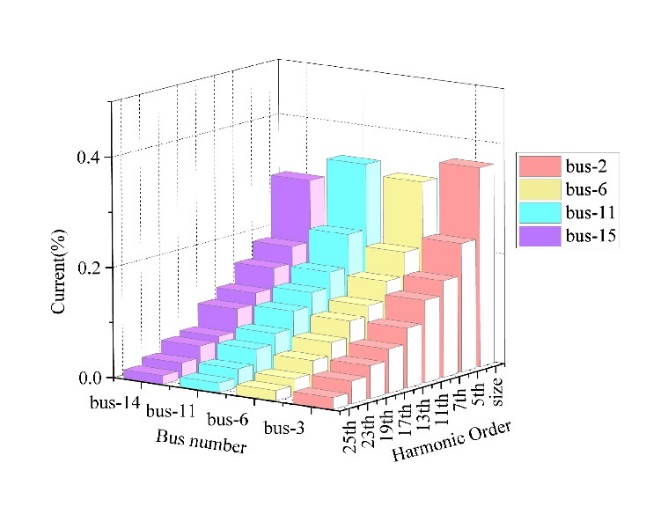
|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Bus Number | THD  (%) | Voltage Distortion for Each Harmonic Order (%) | | | | | | | |
| 5 | 7 | 11 | 13 | 17 | 19 | 23 | 25 |
| 1 | 8.2445 | 7.3694 | 3.0218 | 2.0288 | 1.3713 | 0.7917 | 0.5617 | 0.4366 | 0.2802 |
| 2 | 8.4422 | 7.4792 | 2.8758 | 2.3107 | 1.4814 | 0.7626 | 0.6387 | 0.4749 | 0.2298 |
| 3 | 8.7499 | 7.6860 | 2.8216 | 2.2987 | 1.7968 | 0.8583 | 0.5157 | 0.3097 | 0.1969 |
| 4 | 8.8531 | 7.7637 | 2.7795 | 2.0007 | 1.6137 | 0.8687 | 0.4545 | 0.4543 | 0.2586 |
| 5 | 9.0027 | 7.8670 | 2.9108 | 2.3543 | 2.0496 | 0.7469 | 0.5553 | 0.2732 | 0.1838 |
| 6 | 9.0124 | 7.8627 | 3.0412 | 2.3916 | 2.0267 | 0.6649 | 0.4639 | 0.2276 | 0.2394 |
| 7 | 8.9494 | 7.7846 | 2.8460 | 3.3404 | 1.8444 | 0.7837 | 0.5711 | 0.3314 | 0.1521 |
| 8 | 9.2195 | 7.8592 | 3.3715 | 3.1014 | 1.9710 | 0.8311 | 0.4983 | 0.3154 | 0.2054 |
| 9 | 8.5913 | 7.5228 | 2.8973 | 2.3774 | 1.5418 | 0.8174 | 0.6970 | 0.2112 | 0.1891 |
| 10 | 10.3599 | 9.4416 | 3.1319 | 1.7457 | 1.4106 | 1.0755 | 0.8785 | 0.5725 | 0.2806 |
| 11 | 11.7037 | 10.8146 | 3.8483 | 1.3397 | 1.2236 | 1.0089 | 0.7545 | 0.4324 | 0.2228 |
| 12 | 11.4065 | 10.6224 | 3.3553 | 3.3289 | 1.6937 | 0.9119 | 0.7804 | 0.4133 | 0.1672 |
| 13 | 13.6179 | 12.4920 | 4.8865 | 3.3924 | 1.2129 | 0.8230 | 0.8432 | 0.3595 | 0.1612 |
| 14 | **14.0495** | 12.7082 | **5.0551** | 2.9725 | 1.9705 | 1.6245 | 0.8790 | **0.6430** | 0.2748 |
| 15 | 13.7509 | **12.7607** | 4.8688 | **4.1456** | **2.3801** | 1.3253 | 0.8523 | 0.5427 | **0.2805** |
| 16 | 13.6531 | 12.5831 | 4.6065 | 3.4577 | 2.1847 | **1.8938** | **0.9253** | 0.5797 | 0.2368 |
| Average | 10.4754 | 9.4136 | 3.5199 | 2.6617 | 1.6983 | 0.9493 | 0.6793 | 0.4048 | 0.2224 |

It is worth noting that all the obtained results are rounded to 4 decimal places. By considering harmonic current sources, the results show that the network has a rather impermissible level of harmonic distortion in the sense of the IEEE standard limit of 5%. All buses are considered as candidate buses and the candidate APFs to be accessed are a matrix which consists of 2 × 8 × 16 variables, where 2 is the real and imaginary part of the current to be input, 8 refers to the currents injected by APFs of orders 5th, 7th, 11th, 13th, 17th, 19th, 23rd, and 25th, and 16 are the candidate buses of the APFs to be accessed.

When one APF is assigned on each bus, the result is economically impractical. By the method proposed in this paper, the capacity of the bus to be connected to the APF with the APF is obtained as shown in Table 5 and as shown in Figure 10. By connecting a total of four APFs at different locations in the grid, the distortion voltage in the grid can be almost eliminated. The access locations are shown in the table below, APF1 is connected to bus 5 with a capacity of 0.3621 p.u., APF2 is connected to bus 6 with a capacity of 0.3224 p.u., APF3 is connected to bus 11 with a capacity of 0.3405 p.u., and APF4 is connected to bus 16 with a capacity of 0.297 p.u. It can be seen that the number of APFs is reduced from 16 to 6, the number of APFs is higher around the non-linear loads and they generate the maximum current on these loads. Among them it can be found the higher capacity of the APFs connected to bus-3 and bus-11, which is related to the location of the harmonic sources of the nonlinear loads.

Table.5 Output current per APF

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| No | Capacity | APF input current per order (p.u.) | | | | | | | |
| 5th | 7th | 11th | 13th | 17th | 19th | 23th | 25th |
| 3 | 0.3621 | 0.2337 | 0.1753 | 0.1492 | 0.1082 | 0.0800 | 0.0593 | 0.0414 | 0.0213 |
| 6 | 0.3224 | 0.2036 | 0.1600 | 0.1251 | 0.1064 | 0.0774 | 0.0538 | 0.0305 | 0.0189 |
| 11 | 0.3405 | 0.2215 | 0.1622 | 0.1341 | 0.1096 | 0.0784 | 0.0596 | 0.0331 | 0.0174 |
| 14 | 0.2970 | 0.1848 | 0.1548 | 0.1185 | 0.0989 | 0.0582 | 0.0502 | 0.0290 | 0.0156 |



**Fig.10 Output current per APF**

The distribution network model after installation is shown in Figure 11, with APFs connected at bus-2, bus-6, bus-11, bus-16.

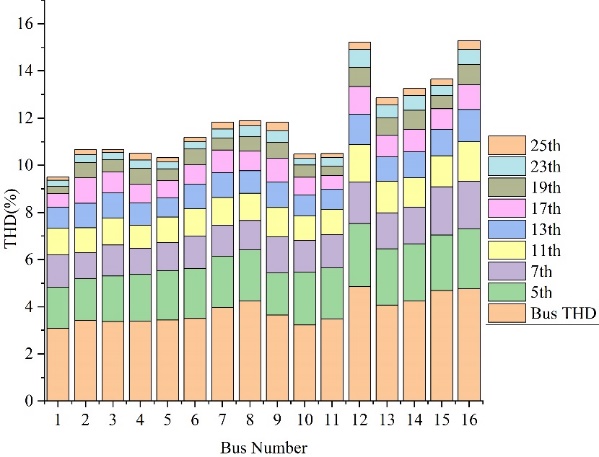
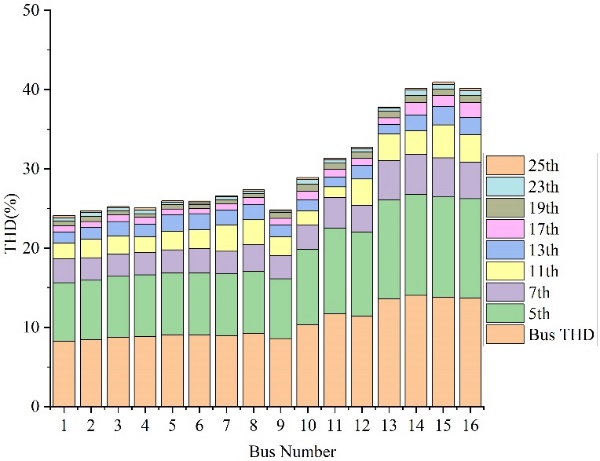


**Fig.11 Location of access to APF**

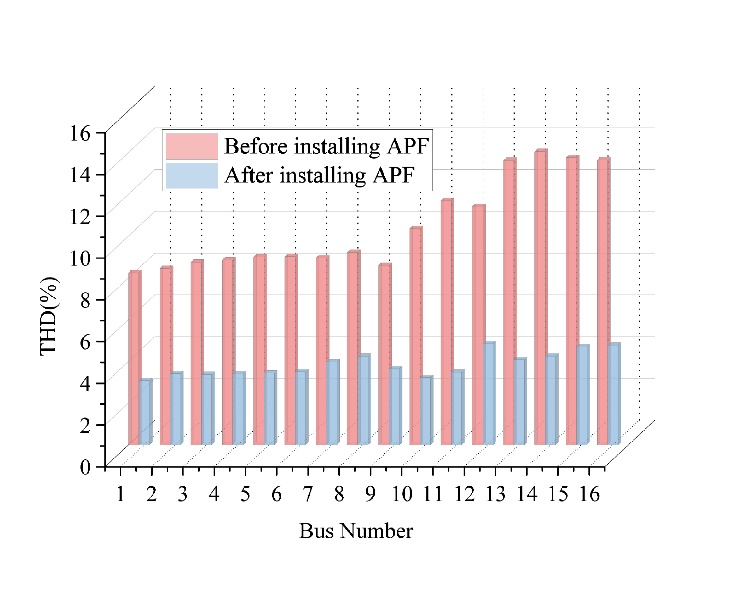
The THD content of each bus after the system is connected to the APF is shown in Figure 11. Under the condition of satisfying the constraint, the THD content of each bus after accessing APF meets the requirement of less than 5%, and the bus near the harmonic sources such as bus-8, bus-22 and bus-25, and bus-26 has higher harmonic content, while it has less influence on the upper bus. The post-installation results demonstrate the reliability of the theoretical approach to APF capacity setting and siting, and the effectiveness of the TEDIBWO algorithm for finding the best solution, as proposed in this chapter. The voltage distortions and THD after installing APFs in Table 6.

Table.6 Voltage distortions and THD after Installing APFs

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Bus Number | THD  (%) | Voltage Distortion for Each Harmonic Order (%) | | | | | | | |
| 5 | 7 | 11 | 13 | 17 | 19 | 23 | 25 |
| 1 | 3.0772 | 1.7382 | 1.3883 | 1.1261 | 0.8938 | 0.5613 | 0.3064 | 0.2680 | 0.1338 |
| 2 | 3.4159 | 1.7646 | 1.1210 | 1.0400 | 1.0437 | 1.0885 | 0.6326 | 0.3360 | 0.2228 |
| 3 | 3.3700 | 1.9267 | 1.3142 | 1.1381 | 1.0707 | 0.8884 | 0.5258 | 0.3135 | 0.1222 |
| 4 | 3.3871 | 1.9780 | 1.1158 | 0.9697 | 0.9455 | 0.8099 | 0.6518 | 0.3575 | 0.2845 |
| 5 | 3.4367 | 2.0938 | 1.1885 | 1.0814 | 0.8123 | 0.7291 | 0.5079 | 0.2992 | 0.1610 |
| 6 | 3.4974 | 2.1219 | 1.3695 | 1.1565 | 1.0421 | 0.8399 | 0.6668 | 0.3084 | 0.1833 |
| 7 | 3.9692 | 2.1635 | 1.3115 | 1.1871 | 1.0471 | 0.9615 | 0.5177 | 0.3721 | 0.2897 |
| 8 | 4.2346 | 2.1842 | 1.2326 | 1.1540 | 0.9532 | 0.8405 | 0.6001 | 0.4657 | 0.2111 |
| 9 | 3.6489 | 1.7749 | 1.5339 | 1.2469 | 1.0862 | 0.9954 | 0.6722 | 0.5067 | 0.3504 |
| 20 | 3.2247 | 2.2286 | 1.3471 | 1.0385 | 0.8886 | 0.7548 | 0.5190 | 0.3040 | 0.1726 |
| 21 | 3.4765 | 2.1661 | 1.4021 | 1.0750 | 0.8582 | 0.5888 | 0.4016 | 0.3492 | 0.1793 |
| 22 | 4.8390 | 2.6906 | 1.7519 | 1.5852 | 1.2853 | 1.1801 | 0.8084 | 0.7603 | 0.3197 |
| 23 | 4.0728 | 2.3831 | 1.5286 | 1.3379 | 1.0210 | 0.9188 | 0.7399 | 0.5471 | 0.3055 |
| 24 | 4.2543 | 2.4145 | 1.5550 | 1.2376 | 1.1041 | 0.9597 | 0.7997 | 0.6253 | 0.3145 |
| 25 | 4.6835 | 2.3576 | 2.0406 | 1.3176 | 1.1235 | 0.8704 | 0.5543 | 0.4443 | 0.2685 |
| 26 | 4.7663 | 2.5412 | 2.0109 | 1.6807 | 1.3603 | 1.0621 | 0.8456 | 0.6487 | 0.3729 |
| Average | 3.8346 | 2.1580 | 1.4507 | 1.2108 | 1.0335 | 0.8781 | 0.6094 | 0.4316 | 0.2432 |



**Fig.12 Harmonic content of each bus when AFP is not connected and connected**



**Fig.13** Comparison of the harmonic content of each bus

The comparison of Fig.12 and 13 shows that the harmonic content of each bus is significantly reduced, all to below 5%. For each bus, a significant reduction in the harmonic components of different orders occurs.

# Conclusion

In order to provide cost-effective APF layouts and dimensions, an overview of different objective functions is presented. Solutions are proposed for their capacity and number of distributions from an economic point of view. Using the proposed hybrid improved Moby Dick algorithm, the established economic model is solved optimally to obtain the optimal capacity and location of APFs. The method saves more cost than the traditional metaheuristic and has faster convergence and accuracy. The method proposed in this paper is important for reducing the harmonics of the power grid, and provides a reference method for the guarantee of power quality and safe operation of the power grid.

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**Appendix A Line Data**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Bus** | | **R** | **X** | **Line** | **Lgth** | **Base** | **Harm** |
| **To** | **From** | % | % | Chg(%) | Mi | Imp(W) | only |
| 1 | 2 | 0.431 | 1.204 | 0.0035 | 0.318 | 15.625 | 0 |
| 2 | 3 | 0.604 | 1.677 | 0.0049 | 0.443 | 15.625 | 0 |
| 3 | 4 | 0.316 | 0.882 | 0.0026 | 0.233 | 15.625 | 0 |
| 4 | 5 | 0.896 | 2.502 | 0.0073 | 0.661 | 15.625 | 0 |
| 5 | 6 | 0.295 | 0.824 | 0.0024 | 0.218 | 15.625 | 0 |
| 6 | 7 | 1.720 | 2.120 | 0.0046 | 0.455 | 15.625 | 0 |
| 7 | 8 | 4.070 | 3.053 | 0.0051 | 0.568 | 15.625 | 0 |
| 2 | 9 | 1.706 | 2.209 | 0.0043 | 0.451 | 15.625 | 0 |
| 1 | 20 | 2.910 | 3.768 | 0.0074 | 0.769 | 15.625 | 0 |
| 20 | 21 | 2.222 | 2.877 | 0.0056 | 0.587 | 15.625 | 0 |
| 21 | 22 | 4.803 | 6.218 | 0.0122 | 1.269 | 15.625 | 0 |
| 21 | 23 | 3.985 | 5.160 | 0.0101 | 1..053 | 15.625 | 0 |
| 23 | 24 | 2.910 | 3.768 | 0.0074 | 0.769 | 15.625 | 0 |
| 23 | 25 | 3.727 | 4.593 | 0.0100 | 0.985 | 15.625 | 0 |
| 25 | 26 | 2.208 | 2.720 | 0.0059 | 0.583 | 15.625 | 0 |
| 25 | 26 | 2.208 | 2.720 | 0.0059 | 0.583 | 15.625 | 0 |
| 50 | 1 | 0.312 | 6.753 | 0.0000 | 0.000 | 0.000 | 0 |
| 50 | 51 | 0.050 | 0.344 | 0.0000 | 0.000 | 0.000 | 0 |
| 51 | 0 | 0.000 | 0.010 | 0.0000 | 0.000 | 0.000 | 0 |