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Barnacles Mating Optimizer for Loss Minimization of Optimal Reactive Power Dispatch

Abstract *A recent evolutionary optimization algorithm, Barnacles Mating Optimizer (BMO) algorithm is proposed to solve one of the optimal reactive power dispatch (ORPD) problems viz. loss minimization in power system. The concept of Hardy-Weinberg principle and sperm-cast process of barnacles is adopted in BMO to balance the exploitation and exploration in solving the optimization problem. Optimal reactive power dispatch (ORPD) on the other hand is one of the complex optimization problems in power system operation. BMO is utilized to obtain the optimal combination of control variables such as generator voltages, transformer tap setting and injected MVAR or known as reactive compensation devices to achieve the minimum losses in the power system. To show the effectiveness of proposed BMO, it is tested on IEEE-30 bus system which consists of 25 control variables and also has been tested on the large system of power network viz. IEEE-118 bus system. The obtained results from BMO are compared with other well-known optimization algorithms in the literature. The obtained comparison results indicate that proposed BMO is effective to reach minimum loss for ORPD problem.*

Streszczenie. *Zaproponowano najnowszy ewolucyjny algorytm optymalizacji, algorytm Barnacles Mating Optimizer (BMO), aby rozwiązać jeden z problemów z optymalnym rozprowadzaniem mocy biernej (ORPD), a mianowicie. minimalizacja strat w systemie elektroenergetycznym. Koncepcja zasady Hardy'ego-Weinberga i procesu odlewania nasienia pąkli została przyjęta w BMO w celu zrównoważenia eksploatacji i eksploracji w rozwiązaniu problemu optymalizacji. Natomiast optymalne dysponowanie mocą bierną (ORPD) jest jednym ze złożonych problemów optymalizacji pracy systemu elektroenergetycznego. BMO służy do uzyskania optymalnej kombinacji zmiennych sterujących, takich jak napięcia generatora, ustawienie zaczepów transformatora i wstrzykiwany MVAR lub znane jako urządzenia kompensacji reaktywnej, w celu osiągnięcia minimalnych strat w systemie elektroenergetycznym. Aby pokazać skuteczność proponowanego BMO, został przetestowany na systemie magistrali IEEE-30, który składa się z 25 zmiennych sterujących, a także został przetestowany na dużym systemie sieci energetycznej, a mianowicie. System magistrali IEEE-118. Otrzymane wyniki z BMO są porównywane z innymi znanymi algorytmami optymalizacyjnymi w literaturze. Uzyskane wyniki porównawcze wskazują, że proponowane BMO jest skuteczne w osiąganiu minimalnych strat związanych z problemem ORPD.* (***Optymalizator Barnacles w celu minimalizacji strat optymalnej dystrybucji mocy biernej***)

Keywords: Barnacles mating optimizer, computational intelligence, loss minimization, optimal reactive power dispatch.
Słowa kluczowe: Optymalizator kojarzeń Barnacles, inteligencja obliczeniowa, minimalizacja strat, optymalna dystrybucja mocy biernej.

Introduction

Optimal Reactive Power dispatch (ORPD) is one of the important nonlinear optimization problems in electrical power system operation. It can be categorized as a partial of well-known power system problem namely optimal power flow (OPF) which includes both discrete and continuous control variables to solve the problem formulation of objective function. The objective function is subject to the pre-set of equality and inequality constraints. One of the objective functions of ORPD which get most researchers' attention is the loss minimization. The optimization process for this problem is to achieve the minimum loss by finding the optimal values of control variables that consist of generator bus voltages, transformer tap setting and injected MVAR or known as reactive compensation devices.

To date, there are numerous techniques that have been proposed through literature in solving the loss minimization of ORPD problems especially by using recent computational intelligence (CI) algorithms. CI algorithm basically can be broken down into three main categories: evolutionary algorithms, swarm intelligence (SI) algorithms and physic-based algorithms. For evolutionary algorithms category, the ORPD solution using Genetic Algorithm (GA) [1, 2], Evolutionary Programming (EP) [3] and Differential Evolution (DE) [4] have been proposed in literature.

SI algorithms have attracted many researchers to implement them into the ORPD problems such as Particle Swarm Optimization (PSO) [5], Improved Pseudo-gradient Search-PSO [6], Grey Wolf Optimizer (GWO) [7], Whale Optimization Algorithm (WOA) [8], Moth-Flame Optimizer (MFO) [9] and many more. For the third category viz. physic-based algorithm, the Harmony Search Algorithm (HSA) with their variants [10], the Gravitational Search Algorithm (GSA) [11] as well as an Adaptive Chaotic Symbiotic Organisms Search Algorithm (A-CSOS) [12] have been proposed to solve ORPD problems. The discussion on the various algorithm invented by Mirjalili such as GWO, MFO, Dragonfly Algorithm (DA), Grasshopper Optimizer (GOA), Sine-Cosine Algorithm (SCA), Ant-lion Optimizer (ALO) and Multiverse Optimizer (MVO) into solving ORPD have been presented in [13].

From the extensive literature review, it is worth to mention that the research on the ORPD problem which use the CI algorithms as a tool for solution are highly active and demanding [14]. Thus, this paper proposes a recent evolutionary algorithm viz. Barnacle Mating Optimizer (BMO) [15, 16] based on the barnacles' mating behavior. BMO can be classified as one of evolutionary algorithms since it produces the new off-springs to achieve the objective that has been set. The rest of the paper is organized as follows: Sections 2 and 3 discuss the loss minimization of ORPD and the development of BMO. In Section 4, the application of BMO into loss minimization of ORPD problems is presented followed by the results and discussion in Section 5. Finally, Section 6 states the conclusion of this paper.

Loss Minimization of Optimal Reactive Power Dispatch

In this paper, the objective function of ORPD problems is to minimize the total power loss in the power system network while meeting all the set constraints. For loss minimization, the basis of formulation can be described as follows:

$$F = \min P_{Loss}(x,u) = \sum_{L=1}^{Nl} P_{Loss} \tag{1}$$

where P_{Loss} is the real power loss calculated in each transmission line in MW, Nl is the total transmission lines in the power system network, x and u are the vector of dependent variables and control variables to be optimized respectively. This expression is subject to the equality, $g(x, u)$ and inequality constraints, $h(x, u)$ that need to be fulfil and expressed as follow:

(2) $$g(x,u) = 0$$

(3) $$h(x,u) \leq 0$$

The equality constraint is the power balanced of load flow which can be expressed in terms of real and reactive power equations, as follow:

(4) $$P_{Gi} - P_{Di} = V_i \sum_{j \in N_i} V_j \left(G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right)$$

(5) $$Q_{Gi} - Q_{Di} = V_i \sum_{j \in N_i} V_j \left(B_{ij} \cos \theta_{ij} - G_{ij} \sin \theta_{ij} \right)$$

where B_{ij} is the susceptance of line *i-j*, G_{ij} is the conductance of line *i-j*, V_i is voltage at bus-*i* and V_j is the voltage at bus-*j*. P_{Gi} and Q_{Gi} on the other hand are the real and reactive power generation, P_{Di} and Q_{Di} are the real and reactive power demand respectively.

For inequality constraints, the elements that cannot be violated are the operating constraints which are expressed as follow:

- Generator constraints: bus voltages, V_{Gi} , real and reactive power generation, (P_{Gi}, Q_{Gi}) and must be operated within their limits:

(6) $$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max} \qquad i = 1,...,N_G$$

(7) $$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \qquad i = 1,...,N_G$$

(8) $$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \qquad i = 1,...,N_G$$

where N_G is the maximum number of generators.

- Reactive compensation elements must be operated within the limits, as follows:

(9) $$Q_{Ci}^{\min} \leq Q_{Ci} \leq Q_{Ci}^{\max} \qquad i = 1,...,N_C$$

where N_C is the number of the reactive elements installed in the system.

- Transformer tap settings must be operated within the limits, as follows:

(10) $$T_i^{\min} \leq T_i \leq T_i^{\max} \qquad i = 1,...,N_T$$

where N_T is the number of transformers.

Barnacles Mating Optimizer (BMO)

Barnacles are classified and recognized as sessile organisms which living deep in the ocean. The development of BMO is based on the mating process of barnacles which occurred by sperm cast and normal copulation. To generate the new off-springs of barnacles, Hardy-Weinberg principle [17] is used for normal mating of barnacles. Basically, in the algorithm development, how the barnacle copulated is not to be considered. Only the effect of the barnacle's penis to find the mating is adopted in this algorithm where the range of the penis will determine whether the new off-springs will be generated using Hardy-Weinberg principle or using sperm-cast mating. It is worth to mention that this paper presented the extension work that using the BMO to solve EELD problems that has been proposed in [18].

The generation of new off-springs is guided by the principle of Hardy-Weinberg concept. The definition is as in (11) and (12):

(11) $$x_i^{N\_new} = p x_{barnacle\_m}^N + q x_{barnacle\_d}^N \quad for \quad k \leq pl$$

(12) $$x_i^{N\_new} = rand() \times x_{barnacle\_m}^N \quad for \quad k > pl$$

where *k* = |*barnacle_m-barncle_d*|, *p* is the normally distributed pseudo random number, *q* = (1-*p*), $x^N_{barnacle\_m}$ and $x^N_{barnacle\_d}$ are the randomly chosen variables for barnacle's parents (Mum and Dad) respectively. Meanwhile, *rand*() denotes the random number range between zero to one (0~1). By referring to these equations, *p* and *q* represent the inheritance percentage from the respective barnacles' parents. For example, let say *p* is generated to 0.80. It indicates that the new off-spring inherits 80% of the Mum's feature or behavior and 20% (100%-80%) of Dad's feature. Eqn. (11) basically can be treated as the exploitation process of optimization while eqn. (12) can be treated as the exploration process of developed BMO. It is also worth to mention here that the exploration process (sperm-cast) is associated with Mum's barnacle only since the Mum's barnacle received the sperm released from the other barnacles elsewhere. Pseudo code of BMO is exhibited in Fig. 1.

```
Initialize the population of barnacles X_i
Calculate the fitness of each barnacle
Sorting to locate the best result at the top of the population (T=the best solution)
while (l < Maximum iterations)
    Set the value of pl
    Selection using the following equations:
    barnacle_d = randperm(n)
    barnacle_m = randperm(n)

    if selection of Dad and Mum = pl
        for each variable
            Off spring generation using equation (11):
            x_i^N_new = p x^N_barnacle_d + q x^N_barnacle_m  for  k <= pl
        end for
    else if selection of Dad and Mum > pl
        for each variable
            Off spring generation using equation (12):
            x_i^N_new = rand() × x^N_barnacle_m  for  k > pl
        end for
    end if
    Bring the current barnacle back if it goes outside the boundaries
    Calculate the fitness of each barnacles
    Sorting and update T if there is a better solution
    l=l+1
end while
Return T
```

Fig.1. Pseudo code of BMO

BMO for ORPD Solution

It is important to emphasize that in this paper, the total transmission loss is obtained using the load flow program namely MATPOWER [19] in order to assist the analysis as well as to ensure there are no violations of the equality and inequality constrains. The evaluation process is started by mapping the control variables into the respective location or components in the load flow data following the execution of load flow program to calculate the total transmission loss. Basically, in the load flow program, the loss is calculated using the $I_{line}^2 Z_{line}$, where the I_{line} is the current flow at each transmission line and Z_{line} represents the impedance at each line. The current of each line is obtained by solving the load flow solution, normally using the Newton-Raphson technique. The MATPOWER program is used in the calculation of obtaining the loss as expressed in Eqn. (1) and the load flow program can ensure there are not violation of equality and inequality constraints expressed in Eqns. (2)-(10). The detail application of BMO to solve loss minimization of ORPD is shown in Fig. 2.

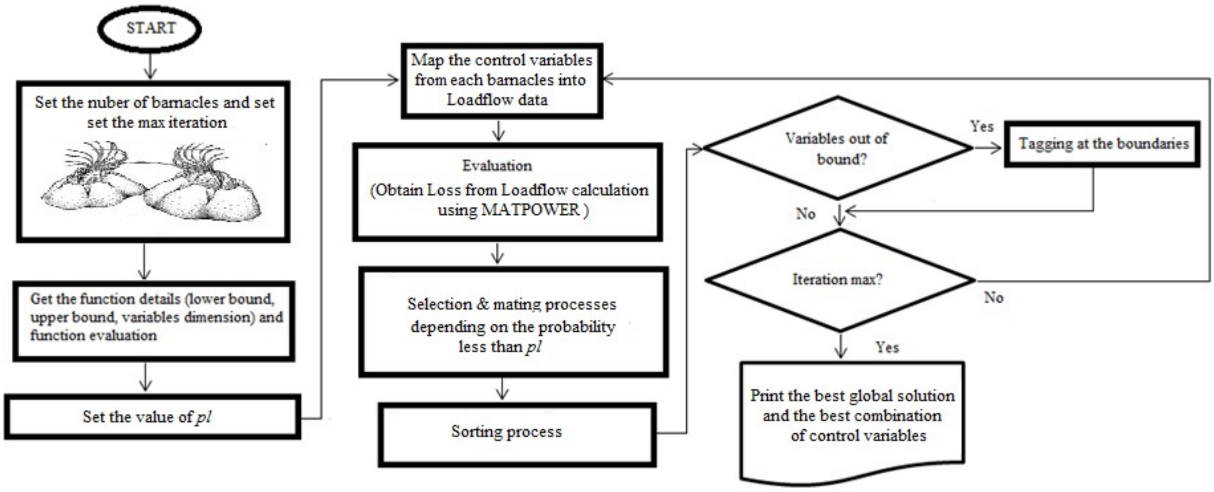

Fig.2. The flow of BMO to obtain minimum loss of ORPD

Results and Discussion

All simulations to calculate the transmission loss minimization using BMO and other selected algorithms are executed in MATLAB. The implementation of BMO has been tested on the IEEE-30 bus and 118 bus systems and the results are compared with various state-of-the-art algorithms available in literature. For IEEE 30-bus system, 25 control variables are adopted in this paper while the IEEE 118-bus system that consist of 77 control variables has been used for large test system to show the effectiveness of proposed BMO in solving the loss minimization in ORPD problem

Case 1: IEEE 30-Bus System with 25 Control Variables

The data to run the simulation are obtained from [20]. The similar real and reactive power demand are set such as in previous case study with the additional control devices need to be optimized by proposed algorithm as well as the different boundary limits of the control devices. Table 1 shows the optimal results of control variables obtained by GWO [7], ABC [20] and the proposed BMO together with the total power loss in MW. It is well depicted that the BMO outperformed ABC and GWO in obtaining the minimum loss and all algorithms obtaining the control variables within the specified limits. Even though the reduction of losses is minimal compared to MFO, it will give big impact in solving the ORPD problem when looking at the bigger point of view such as cost saving annually.

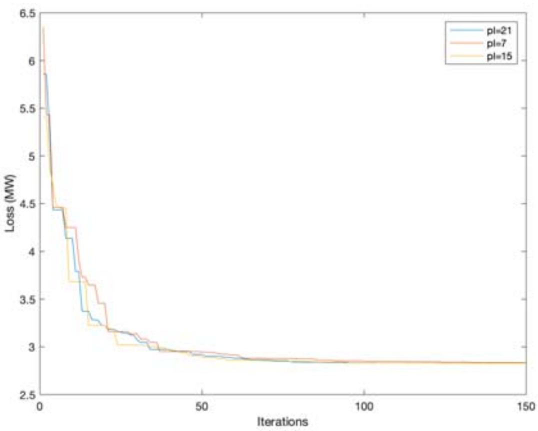

Fig.3. Convergence graph for different setting of *pl* of BMO in solving ORPD problem

It is worth to highlight that the selection of pl is vital in order to obtain good performance of BMO in terms of balancing both exploration and exploitation processes. For this study, the selection is made by experimentally. The performance of in terms of convergence of BMO for different values of pl is exhibited in Fig. 3. Even though the performance of different selection of pl values seems not so much different from this figure, but from the statistically point of view, the value of *pl* =21 gave the best and consistent results throughout 30 runs of simulation as depicted in Fig. 4. The worst result is 2.9632 MW which still better compared to the result obtained by ABC.

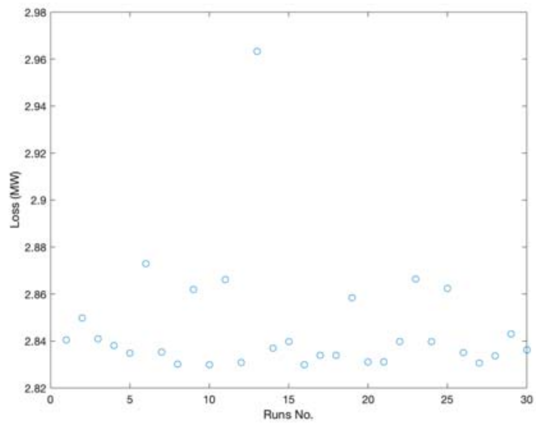

Fig.4. Results of the best objective (loss minimization) obtained by BMO for 30 simulations of 25 variables of IEEE-30 bus system

Table 1. Optimal results obtained by BMO ABC and GWO for 25 control variables of IEEE-30 bus system

Control devices/ variables	Limits		ABC	GWO	BMO
	Lower	Upper			
P_1	0.5	2	0.5462	0.516117	0.5123
P_2	0.2	0.8	0.7863	0.79793	0.8
P_5	0.15	0.5	0.4903	0.5	0.499997
P_8	0.1	0.35	0.3477	0.34933	0.35
P_{11}	0.1	0.3	0.2999	0.3	0.3
P_{13}	0.12	0.4	0.3945	0.4	0.4
V_1	1	1.1	1.0927	1.1	1.1
V_2	1	1.1	1.088	1.0981	1.098
V_5	1	1.1	1.0695	1.0766	1.08
V_8	1	1.1	1.0722	1.087	1.0875
V_{11}	1	1.1	1.086	1.097	1.1
V_{13}	1	1.1	1.0926	1.1	1.1
T_1	0.9	1.1	0.9983	0.9912	1.0609
T_2	0.9	1.1	0.9994	1.0402	0.9
T_3	0.9	1.1	0.9984	1.0332	0.9904
T_4	0.9	1.1	1.0034	0.99125	0.9724

Q_{C10}	0	0.05	0.0155	0.04359	0.05
Q_{C12}	0	0.05	0.0394	0.0103	0.05
Q_{C15}	0	0.05	0.0347	0.02682	0.049891
Q_{C17}	0	0.05	0.0331	0.05	0.05
Q_{C20}	0	0.05	0.0332	0.00058	0.040738
Q_{C21}	0	0.05	0.0395	0.03	0.049994
Q_{C23}	0	0.05	0.013	0.00569	0.019803
Q_{C24}	0	0.05	0.0371	0.04586	0.05
Q_{C29}	0	0.05	0.0399	0.00438	0.021731
Total loss (MW)			3.041	2.9377	**2.829902**

IEEE 118-Bus System With 77 Control Variables

To show the effectiveness of BMO in solving ORPD problems especially for large system, the implementation of BMO into the IEEE 118-bus system has been done. There are 54 generators, 14 reactive compensation elements and 9 transformers which sum out of 77 control variables that need to be optimized. The real and reactive power load demand for this system is set to 4242 MW and 1438 MVAR respectively. The boundaries setting for the control variables are tabulated in Table 2. In this table, slight change has been made compared to [7] for the boundaries of voltages for load and generator bus. Instead of setting to ±10% for the voltage, this paper will enforce only ±6% for the upper and lower limits in order to control the over/under voltage in the system.

Table 2. IEEE 118-bus system data for variables' limit setting

Variables	Upper limit	Lower limit
Voltages for load/ generator bus	1.06 p.u	0.94 p.u
Tap setting	1.1 p.u	0.9 p.u
Q_{C5}	0 MVar	−40 MVar
Q_{C34}	14 MVar	0 MVar
Q_{C37}	0 MVar	−15 MVar
$Q_{C44}, Q_{C45}, Q_{C46}, Q_{C48}, Q_{C74}, Q_{C83}$	10 MVar	0 MVar
$Q_{C79}, Q_{C82}, Q_{C105}$	20 MVar	0 MVar
Q_{C107}, Q_{C110}	6 MVar	0 MVar

Table 3. Total power loss in MW obtained by BMO with other algorithms for IEEE-18 bus system

Algorithms	Power Loss (MW)
PSO	132
CPVEIHBMO	124.1
GSA	127.8
CLPSO	131
GWO	120.7
MFO	116.4
BMO	115.4

The best results of BMO together with other algorithms for IEEE-118 bus system are exhibited in Table 3. From this table, it is proved that BMO performs the best results by producing the lowest value of total power loss in MW. The comparison among BMO with [21] for GSA, PSO, CPVEIHBMO, GWO [7] and MFO [9] gives 7.56%, 10.73%, 14.4%, 13.51%, 4.57% and 0.91% of loss reduction respectively. Fig. 5 shows the convergence graph for the best results obtained for BMO and MFO. It can be seen that the MFO is converged quite early but BMO able to produce the better result of loss minimization compared to MFO. The performance of BMO algorithm with 30 barnacles for 10 simulations is shown in Fig. 6. It is worth to highlight that from this figure; the range of the power loss are lying from 115MW and 120 MW where the best result recorded is 115.3746 MW and the worst result recorded is 120.2858 MW. In terms of voltage profiles for this system, the improvement of BMO, GWO and MFO compared to base case is shown in Fig 7. Overall, all the algorithms produce the voltage for all buses within the specified limits which is ±6% of 1.0 pu.

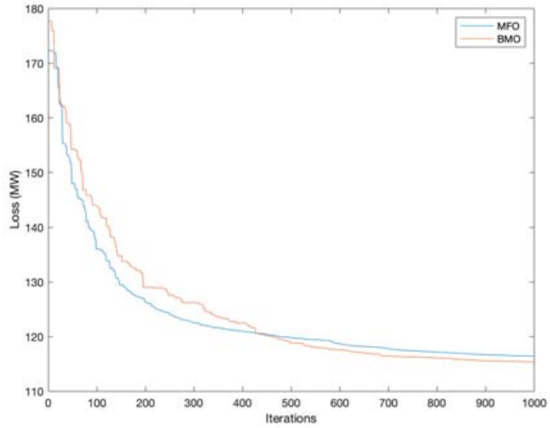

Fig.5. Convergence graph for the best results obtained by MFO vs BMO for IEEE-118 bus system

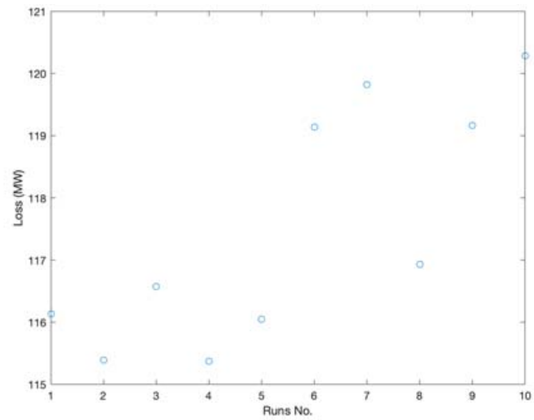

Fig.6. Performance for 30 barnacles for 10 free running of simulations of IEEE-118 bus system

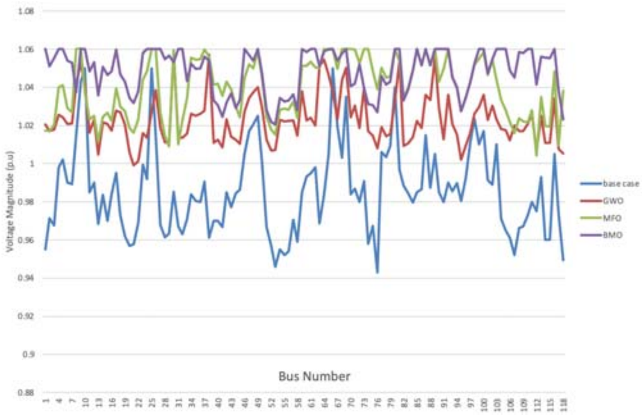

Fig.7. Voltage profiles for IEEE-118 bus system for base case, GWO, MFO and BMO

Conclusion

The application of recent evolutionary optimization algorithm that inspired by barnacles mating behaviour namely BMO in solving the loss minimization of ORPD problem. From the presented simulations, they can be seen that BMO produced very competitive results compared to selected algorithms in obtaining the minimum losses of

ORPD problem through IEEE-30 bus and IEEE-118 bus systems. In addition, BMO only has one parameter to be tuned which is the length of the penis of barnacles, pl apart from number of population and iterations. This is major advantage in solving real application of optimization problems. The implementation of BMO to solve other objectives of ORPD such as voltage deviations and stability index as well as implementation of BMO in other complex engineering problems will be proposed in the near future.

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