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A Novel Nature-Inspired Meta-heuristic Algorithm for Solving the Economic and Environmental Dispatch Problems in Power System

Abstract. *In this paper, a novel nature-based meta-heuristic technique, named cheetah optimizer (CO) algorithm is suggested to solve the Optimal Power Flow (OPF) problem in electric power systems. The optimization method is inspired by the hunting behavior of cheetahs in the wild. The investigation process for optimal global solutions is based on three principal prey-hunting strategies, namely search, sit-and-wait, and attack. The presented technique is applied to solve two famous OPF problems, which are Economic and Environmental Dispatch (EED) by reducing total fuel cost and total gas emission level, respectively. The proposed approach was employed in the case of the IEEE 30-bus test system. The effectiveness of the CO method is justified based on a comparison report of its simulation results with those of other optimization algorithms recently developed in the literature.*

Streszczenie. *W artykule zaproponowano nowatorską meta-heurystyczną technikę opartą na naturze, nazwaną algorytmem optymalizatora geparda (CO), do rozwiązywania problemu optymalnego przepływu mocy (OPF) w systemach elektroenergetycznych. Metoda optymalizacji jest inspirowana zachowaniami łowieckimi gepardów na wolności. Proces poszukiwania optymalnych rozwiązań globalnych opiera się na trzech głównych strategiach polowania na ofiary, a mianowicie poszukiwaniu, siedzeniu i czekaniu oraz ataku. Zaprezentowana technika jest stosowana do rozwiązywania dwóch znanych problemów OPF, którymi są dyspozycja ekonomiczna i środowiskowa (EED) poprzez zmniejszenie całkowitego kosztu paliwa i całkowitego poziomu emisji gazów. Proponowane podejście zostało zastosowane w przypadku systemu testowego IEEE 30-bus. Skuteczność metody CO jest uzasadniona na podstawie raportu porównawczego jej wyników symulacji z wynikami innych algorytmów optymalizacyjnych opracowanych ostatnio w literaturze.* (***Nowatorski, inspirowany naturą algorytm metaheurystyczny do rozwiązywania problemów ekonomicznych i środowiskowych w systemie elektroenergetycznym***)

Keywords: Cheetah optimizer algorithm, Prey-hunting strategies, Economic dispatch, Environmental dispatch, Electric power system,
Słowa kluczowe: algorytm optymalizatora Cheetah, dyspozycja ekonomiczna, dyspozycja środowiskowa, system elektroenergetyczny.

Introduction

The optimal power flow (OPF) is considered the most important problem for energy system managers. This is used in many applications as an indispensable and efficient tool for optimal network planning and operation by tuning predetermined control parameters. The principal objective of solving the OPF problem is satisfying at the same time all the network constraints (equality and inequality)[1], [2]with the reduction in a specified non-linear objective function, such as the total cost of electricity generation and the total emission of pollutant gases by the thermal power plant[3]. The OPF problem was first proposed by Carpentier in 1962 and further elaborated by Dommel and Tinny[4], [5]. Several classical methods have been applied to solve the OPF problem, such as nonlinear and quadratic programming (NLP, QP)[6], Newton, linear programming and interior point methods (NM,LP,IPM) [7]. Nevertheless, the majority of these methods can not ensure convergence towards the global optimum and æ often blocked in the local optimality. In order to avoid the disadvantages of traditional techniques, a number of meta-heuristic optimization algorithms have been used effectively applied in the past years to solve the OPF problem. They are inspired by different natural phenomena, physical effects, mathematical laws or animal behavior[8]such as Symbiotic Organisms Search (SOS)[9], Shuffled Frog Leaping Algorithm (SFLA) [10], Sine-Cosine Algorithm (SCA)[11], Slap Swarm Optimization (SSO)[12], Harris Hawks Optimization (HHO)[13], Moth Swarm Algorithm (MSA) [14], Grasshopper Optimization Algorithm (GOA)[15], Firefly Algorithm (FFA)[16], Turbulent Flow of a Water Optimizer (TFWO)[17], Adaptive Gaussian Teaching Learning Based Optimization (AGTLBO) [18], Slime Mould Algorithm(SMA)[19], Novel Bat Algorithm (NBA)[20], Bisection Method (BM)[21] and others. The increase in the diversity of meta-heuristic methods over the past decade is attested by the statement of the no-free-lunch optimization theorem [22], which claims that no one meta-heuristic technique can effectively resolve all optimization problems better than the others. As a result, the experts in this area are always searching for new and better approaches to solve OPF problems.

A new meta-heuristic optimization technique called the Cheetah Optimizer (CO), proposed in 2022 by Mohammad Amin Akbari et al[8], was inspired by the hunting behaviour of cheetahs in nature. This algorithm (CO) is based on three principal prey- hunting strategies, searching, sitting-and-waiting, and attacking. The possibility of leaving the prey and returning home during the chase is included in the hunting process. The approach has been verified with a series of optimization experiments on 14 benchmark functions and complex engineering problems [8]. In this paper, we present a new population-based meta-heuristic algorithm, called the Cheetah Optimizer (CO) algorithm, inspired by the hunting behavior of cheetahs in nature, proposed to solve the Economic and Environmental Dispatch (EED) problems. The performance of the CO algorithm avoids any local optima in the OPF solution and ensures a balance between the exploration and exploitation phases. Based on the results obtained from simulations using the IEEE 30-bus test system, demonstrate the efficiency of the CO algorithm compared to other optimization techniques described in the literature. The rest of this work is arranged as follows: Section II describes the mathematical formulation of the OPF problem, while Section III explains the CO method. In Section IV, the simulation results are discussed and compared with other existing techniques in the literature. Finally, Section V ends with a conclusion.

Optimal Power Flow Problem

Formulation Problem

The goal of solving the OPF problem is to obtain the optimal values of decision parameters that provide the minimum value objective function while satisfying all operating constraints[23].The basic formulation of the OPF problem is given as:

$$\begin{cases} \text{Minimise} : & f(x,u) \\ \text{Subject to} : & g_j(x,u) = 0 \quad j = 1, \dots, r \\ & h_j(x,u) \leq 0 \quad j = 1, \dots, z \end{cases} \quad \begin{matrix}(1)\\(2)\\(3)\end{matrix}$$

Where, $f(x, u)$, $g_j(x, u)$, and $h_j(x, u)$ are respectively, the objective function to be minimized, Equality constraints and Inequality constraints.

State and Control Variables

The vectors of the state and control variables (x,u) of the electrical system can be defined as:

$$\mathbf{x} = \left[P_{G_1}, V_{L_1}, \dots, V_{L_{N_L}}, Q_{G_1}, \dots, Q_{G_{N_G}}, S_{l_1}, \dots, S_{l_{nl}}\right]' \quad (4)$$

\

The variables P_{G1}, V_{Li}, Q_{Gi} and S_{li} represent the active power generated by the slack bus, the voltage magnitude of the load buses, the reactive power produced by the generators and the apparent power flow in the transmission lines. N_L, N_G and nl denote the number of load buses, generator buses and transmission lines, respectively.

$$\mathbf{u} = \left[P_{G_2} \dots P_{G_{N_G}}, V_{G_1} \dots V_{G_{N_G}}, Q_{C_1}, \dots Q_{C_{NC}}, T_1, \dots T_{N_T}\right]' \quad (5)$$

Where P_{Gi}, V_{Gi}, Q_{Ci} and T_i are generated active power from generators, Voltage magnitude in i-th generator bus, the power injected via the i-th VAR shunt compensator and transformer tap settings. N_C and N_T denote the number of shunt compensators and regulating transformers, respectively.

Optimal power flow constraints

Equality Constraints

These constraints are formulated by power flow equations to reflect the balance between generation and load powers (for both active and reactive powers) as given below[9], [18]:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N_B} V_j \left[G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}\right] = 0 \quad (6)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N_B} V_j \left[G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij}\right] = 0 \quad (7)$$

Here, N_B, G_{ij} and B_{ij} represent the number of buses, the conductance and the susceptibility of the transmission line between buses (i) and (j). P_{Di}, Q_{Di} and V_i are the active, reactive power demands and the voltage magnitudes of the i-th bus, respectively.

Inequality Constraints

The OPF inequalities represent the operating limits of power system devices as shown below[1]:

- Generation constraints:

$$V_{Gi,min} \leq V_{Gi} \leq V_{Gi,max}, \quad i = 1,2, \dots, N_G \quad (8)$$

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max}, \quad i = 1,2, \dots, N_G \quad (9)$$

$$Q_{Gi,min} \leq Q_{Gi} \leq Q_{Gi,max}, \quad i = 1,2, \dots, N_G \quad (10)$$

- Transformer constraints :

$$T_{i,min} \leq T_i \leq T_{i,max}, \quad i = 1,2, \dots, N_T \quad (11)$$

$$P_{Si,min} \leq P_{Si} \leq P_{Si,max}, i = 1,2, \dots, N_{phase} \quad (12)$$

Where P_{Si} represents a phase shifter.

- VAR sources constraints :

$$Q_{Ci,min} \leq \mathbf{Q_{Ci}} \leq Q_{Ci,max}, \quad i = 1,2, \dots, N_C \quad (13)$$

- Security constraints :

$$V_{Li,min} \leq \mathbf{V_{Li}} \leq V_{Li,max}, \quad i = 1,2, \dots, N_L \quad (14)$$

$$S_{li,min} \leq \mathbf{S_{li}} \leq S_{li,max}, \quad i = 1,2, \dots, n_l \quad (15)$$

Objective function of EED Problem

Quadratic total fuel cost function

The total fuel cost quadratic function for each power plant can be expressed as follows [20], [21]:

$$\mathbf{F_C} = \sum_{i=1}^{N_G} a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (16)$$

Total gas emission function

The Kyoto Protocol is an international agreement signed in 1997 to reduce greenhouse gas emissions [25]. The types of gases are defined by emission function as follows[3], [13]:

$$\mathbf{F_{Em}} = \sum_{i=1}^{N_G} \alpha_i + \beta_i P_{Gi} + \lambda_i P_{Gi}^2 + \xi_i e^{(\theta_i P_{Gi})} \quad (17)$$

Cheetah Optimizer Algorithm

This section presents the principles of the CO optimization technique for solving complex optimization problems, described in the following subsections:

Source of inspiration

The cheetah (Acinonyx jubatus) is one of the most recognizable cats in the world, native to Africa and central Iran. It is known for its speed due to its streamlined and very flexible body and its long legs. It is the land animal capable of running at speeds of up to 120 km per hour. The cheetah starts its hunt from a high place where it can observe the environment or settles in the grassland without being seen. It moves slowly towards its prey (gazelles, zebras, lemmings..., etc.) keeping a minimum distance (60-70 meters). The chase takes about half a minute with an average distance of 173 m. In this way, the cheetah trips its prey and bites its throat. But if the chase lasts too long, the cheetah gives up, as its failure rate is high. Thus, biological studies show that the cheetah's flexibility allows it to turn immediately from one side to the other, its long tail acting as a balance or counterweight and the flexibility of its spine permits it to "fly" between jumps when pursuing prey [8], [26]. Figure 1 shows the hunting behaviour of the cheetah.

Fig 1: Cheetah hunting behavior

Mathematical model of CO

The CO algorithm is based on an intelligent exploitation of hunting strategies, as shown in Figure 2, during the hunting phases (iterations). Each prey is a place of a decision variable corresponding to the best solution, and the cheetah situations constitute a population. The pseudo-code [8] of the CO algorithm for solving the OPF problem is given in Figure 3.

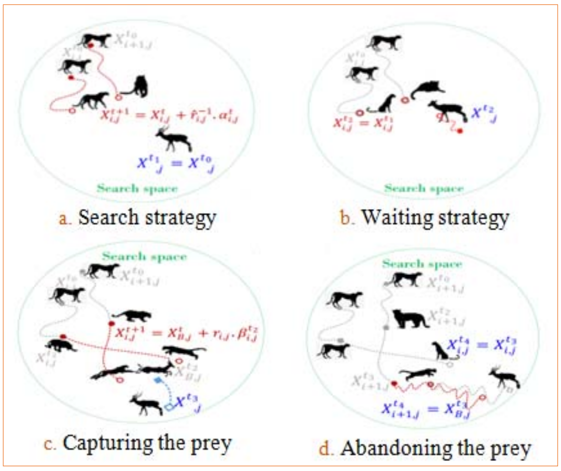


Fig 2: Schematic representation of CO hunting strategies

In this section, we present the mathematical model for each hunting strategy as below:

Search strategy

The cheetah must examine its territory (search area) or environs, looking for its prey; it uses one of two modes: the scanning mode (sitting or standing) is preferred when prey are numerous on the plains, while the active mode is favored when prey are dispersed and active. This strategy is illustrated in Figure 2. The following random search equation to update the new position of cheetah ***i*** based on its current position is proposed, as below:

(18) $$X_{i,j}^{t+1} = X_{i,j}^{t} + \hat{r}_{i,j}^{-1} . \alpha_{i,j}^{t}$$

Where, $\alpha_{i,j}^{t} = 0.001 \times t/T$

Waiting strategy (sit and wait)

After detecting a prey in an unsuitable situation, the cheetah sits and waits for the prey to approach its side; if not, it will choose a better situation. This strategy is illustrated in Figure 2b. This is expressed mathematically as follows:

(19) $$X_{i,j}^{t+1} = X_{i,j}^{t}$$

Attack strategy

The two basic steps of this strategy are:

- Rushing: The cheetah, which decided to attack, accelerates its speed to catch its prey, as shown in Figure 2c
- Capturing : Cheetah attack and capture their prey quickly using both their speed and agility, as shown in Figure 2d.

This mode is defined mathematically as follows:

(20) $$X_{i,j}^{t+1} = X_{B,j}^{t} + \check{r}_{i,j} . \beta_{i,j}^{t}$$

(21) Where, $\check{r}_{i,j} = |r_{i,j}|^{exp\left(r_{i,j}/2\right)} \sin\left(2\pi\, r_{i,j}\right)$

Abandoning the prey

This strategy has two steps:

- Impossibility of hunting prey: If it is unable to hunt a prey for a certain period, the cheetah may move on to the last available prey.
- Unsuccessful hunt for prey: If the hunt is unsuccessful, the cheetah must change location or return home.

Results and simulation

In this research, the novel CO algorithm is implemented in the power system optimization. It has been tried on the standard IEEE 30-bus electrical system as shown in Figure 4 to solve two different cases (fuel cost and gas emission level) of OPF problems. The data for buses and lines of this network are obtained from[27], and the total power demand is 2834 MW + j 1262 MVAR. Table 1 defines the parameters of the CO algorithm. The coefficients representing the gas emission for each generator are found in [15]; while the fuel cost coefficients concerning the quadratic fuel cost function are taken from[24]. Table 2 gives the simulation results for two cases of objective functions with optimal control values obtained by the CO method. Figure 5 illustrates the smooth convergence curves for both objective functions determined by the CO algorithm. The voltage levels for each bus are depicted in Figure 6. The simulation work was performed by my Dell personal computer, characterized by an Intel ® Core(TM) i5 -5200U @2.20 GHZ 2.19 GHZ / RAM=4.00 GB. The proposed work was also executed by MATLAB (2018) software.

Define the problem data, dimension (D), and the initial population size (n)
Generate the initial population of cheetahs $X_i (i = 1, 2, \ldots, n)$ and evaluate the fitness of each cheetah
Initialize the population's home, leader, and prey solutions
$t \leftarrow 0$
$it \leftarrow 1$
$MaxIt$ ←desired maximum number of iterations
$T \leftarrow 60 \times \lceil D/10 \rceil$
while $it \le MaxIt$ **do**
    Select m $(2 \le m \le n)$members of cheetahs randomly
    for each member $i \in m$ **do**
    Define the neighbor agent of member i
        for each arbitrary arrangement $j \in \{1, 2, \ldots, D\}$**do**
            Calculate $\hat{r}, \check{r}, \alpha, \beta$, and H
            r_2, r_3 ← random numbers are chosen uniformly from 0 to 1
            If $r_2 \le r_3$ **then**
                r_4 ← a random number is chosen uniformly from 0 to 3
                if $H \ge r_4$ **then**

```
                Calculate the new position of member i in arrangement j using Equation (1) // Search
            Else
                Calculate the new position of member i in arrangement j using Equation (3) // Attack
            End
        Else
            Calculate the new position of member i in arrangement j using Equation (2) // Sit-and-wait
        End
    End
    Update the solutions of member i and the leader
End
t ← t + 1
if t > rand × T and the leader position doesn't change for a time, then // Leave the prey and go back home
    Implement the leave the prey and go back home strategy and change the leader position
    Substitute the position of member i by the prey position
    t ← 0
End
it ← it + 1
Update the prey (global best) solution
End
```

Fig 3: Pseudo-code of CO algorithm

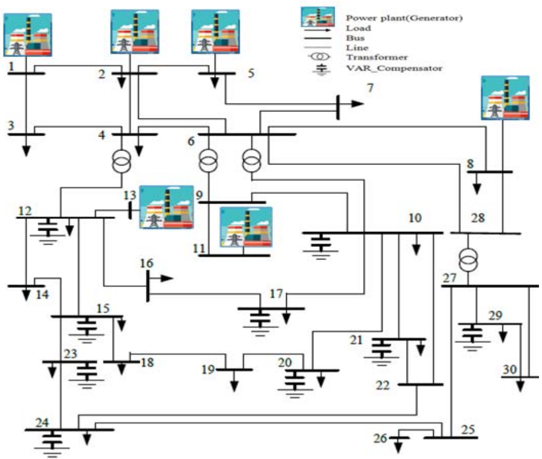
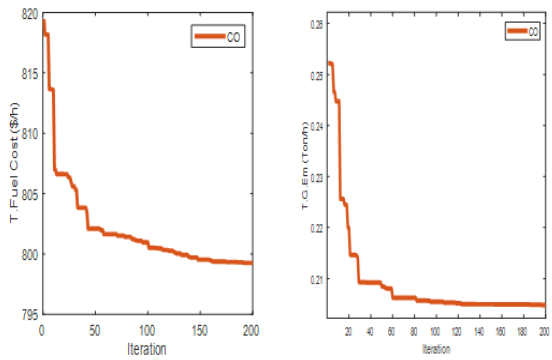


Fig 4: Single-line diagram of the IEEE 30-bus system



a. Convergence curve of case 1 b. Convergence curve of case 2

Fig 5: Convergence curves for the objective function OPF (IEEE 30-bus power system)

Table 1. Characteristics of CO algorithm

Parameters	IEEE 30-Bus Power Systems
Population Size	n = 180
Number of search agents in a group	N = 60
Optimization problem dimension	D=25
Number of iterations	MaxIt = 200
Random numbers r_1 ; r_2 and r_3	[0 1]
Random number r_4	[0 3]
Random value ($H \geq r_4$)	$H = e^{2(1-t/T)}(2_{r1} - 1)$
Runtime	T=1

Table 2. Results of OPF problem using CO algorithm for IEEE 30bus power system

Variables	Min	F_C ($/h)	F_{Em} (Ton/h)	Max
P_{G1} (MW)	50	177.8954	63.5276	200
P_{G2} (MW)	20	48.8346	68.0945	200
P_{G5} (MW)	15	21.4940	49.9810	80
P_{G8} (MW)	10	20.1971	34.9725	35
P_{G11}(MW)	10	11.6197	29.9885	35
P_{G13}(MW)	12	12.0982	39.9886	40
V_{G1} (p.u)	0.95	1.0998	1.0823	1.1
V_{G2} (p.u)	0.95	1.0844	1.0778	1.1
V_{G5} (p.u)	0.95	1.0569	1.0575	1.1
V_{G8} (p.u)	0.95	1.0648	1.0692	1.1
V_{G11}(p.u)	0.95	1.0940	1.0993	1.1
V_{G13}(p.u)	0.95	1.0997	1.0898	1.1
T_{11} (6-9)	0.90	0.9929	1.0154	1.1
T_{12} (6-10)	0.90	1.0144	0.9532	1.1
T_{15} (4-12)	0.90	1.0368	1.0414	1.1
T_{36}(28-27)	0.90	0.9855	0.9803	1.1
Q_{C10}(Mvar)	0	4.6514	2.1927	5
Q_{C12}(Mvar)	0	4.6444	3.0641	5
Q_{C15}(Mvar)	0	2.4769	2.9766	5
Q_{C17}(Mvar)	0	3.5630	3.4805	5
Q_{C20}(Mvar)	0	4.5532	3.0902	5
Q_{C21}(Mvar)	0	4.8564	1.8984	5
Q_{C23}(Mvar)	0	2.7587	4.0793	5
Q_{C24}(Mvar)	0	4.5202	4.9294	5
Q_{C29}(Mvar)	0	2.6850	1.0975	5
F_C ($/h)	-	799.2601	944.8645	-
F_{Em} Ton/h)	-	0.3684	0.2048	-
$F_{Plosses}$(MW)	-	8.7389	3.1527	-
F_{VD} (p.u)	-	1.3308	1.2861	-
F_{Lmax} (p.u)	-	0.1233	0.1260	-

Case 1: Fuel cost reduction

The first case is intended to reduce the total cost of the fuel quadratic function for electricity production, expressed by equation (16). The simulation results, presented in Table 2, demonstrate that the fuel cost obtained by the CO method is equal to **799.2601** ($/h) which is much lower than the other optimization approaches, quoted in Table 3.

Case 2: Gas emission level reduction

For the second case, the objective function defined by equation (17) is applied to reduce the gas emission level. The simulation results detailed in Table 2 indicate that the optimal level of gas emission using the CO algorithm is 0.2048 (ton/h), which achieves a lower level of gas emission compared to the other optimization methods mentioned in Table 4.

Table 3. Comparison of CO algorithm with other methods for Case 1

Algorithms	Ref.	F_C ($/h)	F_E (Ton/h)
DA	[16]	802.3183	-
MODA	[3]	802.3169	-
MSA	[16]	802.2238	0.370
FFA	[16]	802.1309	
MFO	[13]	801.960	1.274
NBA	[20]	801.8442	-
GWO	[13]	801.844	1.280
WOA	[13]	801.840	1.270
HHO	[13]	801.829	1.263
SFLA	[10]	801.8280	-
SOS	[9]	801.57	-
PSO	[12]	801.23	0.369
GOA	[15]	800.9728	0.3614
TLBO	[18]	800.674	0.3668
AGTLBO	[18]	800.4811	0.3662
ISSA	[2]	800.4752	-
ESCA	[11]	800.2198	0.36593
MALO	[1]	799.7031	-
BM	[21]	799.4450	-
SSO	[12]	799.41	0.368
CO	/	**799.2601**	0.3684

Table 4. Comparison of CO algorithm with otherOther methods for Case 2

Algorithms	Ref.	F_C ($/h)	F_E (Ton/h)
EMSA	[14]	833.9779	0.3293
MSA	[14]	834.1532	0.3286
GWO	[13]	951.13	0.296
SSA	[13]	950. 93	0.2950
MF	[13]	950. 93	0.2950
WOA	[13]	950. 82	0.2950
HHO	[13]	950. 98	0.2850
SMA	[19]	936. 116	0.2175
TFWO	[17]	943. 546	0.205
PSO	[12]	948. 47	0.205
SSO	[12]	944. 72	0.205
CO	/	944.8645	**0.2048**

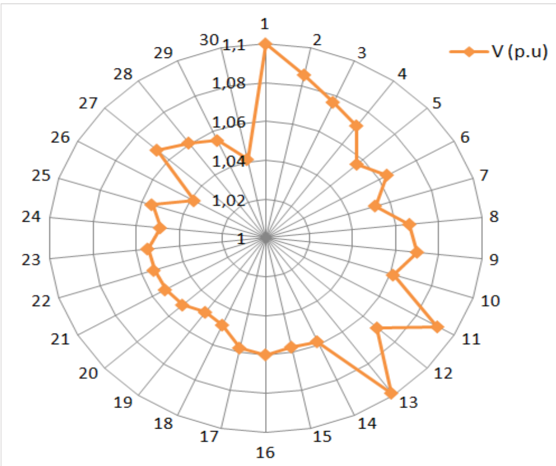


Fig 6**:** Voltage profile values of the IEEE30-bus test system for Case 1

Main advantages of CO method

• The evolution of random solutions in an iterative procedure of the algorithm CO; ensures a good compromise between the exploration (helps the algorithm to perform a global search) and exploitation (helps the algorithm to perform local searches around the region defined by the first phase). Thus, the strategies of the hunting process create a good balance between the exploration and exploitation phases and prevent premature convergence or avoidance of local solutions in the different optimization problems. The comparison report presented in Tables 3 and 4, confirms the CO algorithm's ability to reach the best possible solutions through its smooth convergence curves, as illustrated in Figure 5.

• The values of the control and state variables obtained by the CO method have been verified and are bounded by equality and inequality limits, including safety constraints, which are within their permissible range, as shown in Table 2.

• The voltage profile in Case 1 for each bus (IEEE 30 bus test system) is within acceptable limits as demonstrated in Figure 6.

Conclusion

This paper proposes a new nature-inspired optimization algorithm, Cheetah Optimizer (CO), to solve the OPF problem, considering two different cases of OPF objective function. The performance of the CO algorithm is verified via the IEEE30-bus test system. The simulation results under the MATLAB environment prove the robustness and effectiveness of the proposed CO method in solving the OPF problem more than other well-known meta-heuristic techniques mentioned in the recent literature. It can be clearly stated that the new CO method reduces in two cases the objective function more efficiently than the other methods used in the comparison.

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