Optimal Power Flow using Collective Animal Behavior Algorithm

P.K. Pany[1], S.P. Ghoshal[2] and V. Mukherjee[3]

[1] *Department of Electrical Engineering,Ajay-Binay Institute of Technology, Cuttack, Odisha, India*
[2] *Department of Electrical Engineering, National Institute of Technology, Durgapur, West Bengal, India*
[3] *Department of Electrical Engineering, Indian School of Mines, Dhanbad, Jharkhand, India*

Corresponding Author: P.K. Pany

Abstract:- **This paper proposes collective animal behavior (CAB) algorithm for solving optimal power flow (OPF) problem of power system. The proposed approach is examined and tested on three power system models like IEEE 30-bus, IEEE 57-bus and IEEE 118-bus test systems with different objective functions that reflect either minimization of fuel cost, or that of transmission loss, or improvement of voltage profile. The simulation results of the proposed approach are compared to those reported in the recent literature. The results demonstrate the potential of the proposed approach and show its effectiveness and robustness to solve the OPF problem for the test systems considered.**

Keywords: **Active power loss, collective animal behavior algorithm, fuel cost, optimal power flow, power systems optimization, voltage profile**

I. INTRODUCTION

In optimal power flow (OPF), the values of some or all of the control variables need to be obtained by optimizing (either minimizing or maximizing) a predefined objective function [1]. It is also important that the proper problem definition with clearly stated objectives must be given at the onset. The quality of the solution depends on the accuracy of the model under study. Objective function of OPF may take various forms such as minimization of fuel cost, or that of transmission loss (P_{Loss}), or improvement of voltage profile. Usually, the objective function of interest is the minimization of total production cost of scheduled generating units. This is mostly used as it reflects current economic dispatch practice and, importantly, cost related aspect is always ranked high among operational requirements in power system. OPF aims to optimize the above objective, subject to the network power flow equations, system and equipment operating limits. Many optimization techniques have been emerged so far and these have been applied to solve OPF problem of power system.

Earlier, the basis of the solution of the OPF algorithms was classical mathematics-based programming methods. Gradient method (GM) [1], non-linear programming [2], linear programming (LP) [3, 4], quadratic programming [5], Newton-based method [6, 7] and interior point method (IPM) [8] have been successfully applied to the solution of the OPF problem.

Lately, many population-based optimization techniques have been used to solve complex constrained optimization problems. These techniques have been, increasingly, applied for solving power system optimization problems such as economic dispatch, optimal reactive power flow and OPF in decades. Some of the population-based methods have been proposed for solving the OPF problem successfully, such as genetic algorithm (GA) [9], improved GA (IGA) [10], Tabu search (TS) [11], particle swarm optimization (PSO) [12], differential evolution (DE) algorithm [13], simulated annealing [14], evolutionary programming [15] and so on.

One of the recently introduced heuristic algorithms is collective animal behavior (CAB) algorithm, proposed by Cuevas and Gonza´lez in [16]. It assumes the existence of a set of operations that resemble the interaction rules and models the collective behavior of animals. Sumpter [17] has investigated how animals move and arrive together, how they transfer information, how they make decisions and synchronize their activities and how they build collective structures. In CAB [16], each solution within the search space represents an animal position. The “fitness value” refers to the animal dominance with respect to the group. The complete process mimics the collective behavior of animals. CAB algorithm implements a memory for storing best solutions (animal positions) mimicking the aforementioned biological process.

In this paper, CAB algorithm is applied to solve the OPF problem which is formulated as a nonlinear optimization problem with equality and inequality constraints. The objective functions considered in this article is either minimization of fuel cost, or that of P_{Loss} or that of total voltage deviation (TVD). The performance of the proposed approach is sought and tested on modified IEEE 30-bus, IEEE 57-bus and IEEE 118-bus test systems. Obtained simulation results are compared to those reported in the recent literature. The rest of the paper is organized as follows.

Section 2 deals with the problem formulation of the OPF work. CAB algorithm is described in Section 3. Section 4 focuses on the implementation of the CAB for the solution of the OPF problem. Simulation results are presented and discussed in Section 5. Finally, conclusions of the present paper are drawn in Section 6.

II. PROBLEM FORMULATION OF OPF

The OPF problem is concerned with optimization of steady-state performance of power system with respect to specified objective function, subject to various equality and inequality constraints. Mathematically, OPF problem may be represented as [9-15]

$$\text{Minimize } J(\boldsymbol{x}, \boldsymbol{u}) \quad (1)$$

$$\text{subject to } eq(\boldsymbol{x}, \boldsymbol{u}) = 0 \quad (2)$$

$$\text{and } ieq(\boldsymbol{x}, \boldsymbol{u}) \leq 0 \quad (3)$$

where J is the objective function to be minimized, $\boldsymbol{x}$ and $\boldsymbol{u}$ are the vectors of dependent and control variables, respectively.

The vector of dependent variables $\boldsymbol{x}$ may be represented as

$$x^T = [P_{G-1}, V_{L-1} \ldots\ldots, V_{L-NPQ}, Q_{G-1,} \ldots.., Q_{G-NPV}, S_{l-1} S_{l-NTL}] \quad (4)$$

where P_{G-1} is the slack bus power; V_L is the PQ bus voltages; Q_G indicate the reactive power outputs of the generators; S_l indicate the transmission line flows; NPQ is the number of PQ buses; NPV is the number of voltage controlled buses and NTL is the number of transmission lines.

Similarly, the vector of control variables $\boldsymbol{u}$ may be written as

$$u^T = [P_{G-2} \ldots.., P_{G-NPV}, V_{G-1}, \ldots\ldots, V_{G-PV}, T_1, \ldots\ldots, T_{NT}, Q_{C-1}, \ldots\ldots, Q_{C-NC}] \quad (5)$$

where NT and NC are the number of tap changing transformers and number of shunt VAR compensators, respectively; V_G indicate the terminal voltages at the generator buses; P_G indicate the active power outputs of the generators; T indicate the tap settings of the tap changing transformers and Q_C are the outputs of shunt VAR compensators.

2.1 Constraints

2.1.1 Equality constraints

In (2), eq is the set of equality constraints representing the load flow equations

$$P_{G_i} - P_{D_i} = V_i \sum_{k=1}^{NB} V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik})$$

where i= 1, 2,..., NB (6)

$$Q_{G_i} - Q_{D_i} = V_i \sum_{k=1}^{NB} V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik})$$

where i= 1, 2, ..., NB (7)

where P_{G_i} and Q_{G_i} are the injected active and reactive powers, respectively, at bus i; P_{D_i} and Q_{D_i} are the active and reactive power demands, respectively, at bus i; G_{ik} and B_{ik} are the transfer conductance and susceptance , respectively, between buses i and k; θ_{ik} is the phase angle difference between the voltages at buses i and k and NB is the total number of buses.

2.1.2 Inequality Constraints

In (3), ieq is the set of system inequality constraints presented below.

(i) Generator constraints: For all generator voltages (including slack bus), real and reactive power outputs (including slack bus) must be restricted within their lower and upper limits as stated in (8)-(10).

$$V_{G_i}^{\min} V_{G_i} V_{G_i}^{\max}, i = 1,2,\cdots,NPV$$

(Including slack bus) (8)

$$P_{G_i}^{\min} P_{G_i} P_{G_i}^{\max}, i = 1,2,\cdots,NPV$$

(Including slack bus) (9)

$$Q_{G_i}^{\min} Q_{G_i} Q_{G_i}^{\max}, i = 1,2,\cdots,NPV$$

(Including slack bus) (10)

(ii) Transformer constraints: Transformer tap settings must be within their specified lower and upper limits as presented in (11).

$$T_i^{\min} \leq T_i \leq T_i^{\max}, i = 1,2,\cdots,NT \quad (11)$$

(iii) Shunt VAR compensator constraints: Reactive power outputs of shunt VAR compensators must be restricted within their lower and upper limits as written in (12).

$$Q_{C_i}^{\min} Q_{C_i} Q_{C_i}^{\max}, i = 1,2,\cdots,NC \quad (12)$$

(iv) Security constraints: These include the constraints on voltages at PQ buses and transmission line loadings. Voltage of each PQ bus must be within its lower and upper operating limits. Line flow through each transmission line must be within its capacity limits. Mathematically, these constraints may be expressed as in (13)-(14).

$$V_{L_i}^{\min} V_{L_i} V_{L_i}^{\max}, i = 1,2,\cdots,NPQ \quad (13)$$

$$S_{l_i} \leq S_{L_i}^{\max}, i = 1,2,\cdots,NTL \quad (14)$$

2.2 Objective function

In this paper, three different objective functions are considered to determine the effectiveness of the proposed algorithm. These objective functions are as follows:

(i) *Minimization of fuel cost*: The aim of this type of problem is to minimize the total fuel cost while satisfying all equality and inequality constraints and it is formulated as in (15)

$$Minimize J(FC) \quad (15)$$

where $J(FC)$ is the total fuel cost.

(a) *Cost function without valve point effect*: Total fuel cost of generating units having quadratic cost function without valve point effect is given by (16)

$$J(FC) = (\sum_{i=1}^{NG} FC_i(P_{G_i})) = \sum_{i=1}^{NG} (a_i + b_i P_{G_i} + c_i P_{G_i}^2)$$

(16)

where a_i , b_i and c_i are the cost coefficients of the ith generator and NG is the number of committed generators.

(b) *Cost function with valve point effect*: For more practical and accurate model of the cost function, multiple valve steam turbines are incorporated for flexible operational facilities. Total cost of generating units with valve point loading is given by (17).

$$e_i$$

$$)$$

$$d_i \sin$$

$$)$$

$$+$$

$$(a_i + b_i P_{G_i} + c_i P_{G_i}^2$$

$$) = \sum_{i=1}^{NG}$$

$$J(FC) = FC_i(P_{G_i}) = (\sum_{i=1}^{NG} F_i(P_{G_i})$$

(17)

where d_i and e_i are the coefficients of the ith generator that represent the valve-point loading effect.

(ii) *Minimization of transmission loss*: The aim of this type of problem is to minimize the real power loss in the network while satisfying all equality and inequality constraints and it may be formulated as in (18).

$$Minimize J(P_{Loss}) = \sum_{k=1}^{NTL} g_k (V_{i^2} + V_{j^2} - 2V_i V_j \cos\theta_{ij})$$

(18)

(iii) *Minimization of TVD*: The aim of this type of problem is to minimize the absolute TVD of load bus voltages from their desired values while satisfying all equality and inequality constraints and may be modeled as in (19).

$$Minimize J(TVD) = \sum_{i=1}^{NPQ} \left| V_{G_i} - V_{G_i}^{ref} \right|$$

(19)

III. DESCRIPTION OF CAB ALGORITHM

Fishes travel in schools, birds migrate in flocks, honeybees swarm and ants build trails. How and why do these collective behaviors occur? Exploring how coordinated group patterns emerge from individual interactions, collective animal behavior (CAB) reveals why animals produce group behaviors and examines their evolution across a range of species. Following this biological approach, Couzin in [18] and Couzin and Krauze in [19-20] have proposed a model in which individual animal follows simple rules of thumb viz. (a) keeps the current position (or location) for best individuals, (b) moves from or to nearby neighbors (local attraction or repulsion), (c) moves randomly and (d) competes for the space within a determined distance. Each individual, thus, admits three different movements viz. attraction, repulsion, or random and holds two kinds of states: preserves the position or competes for a determined position. In the model, the movement, which is executed by each individual, is decided randomly (according to an internal motivation). On the other hand, the states follow a fixed criteria set. Thus, it is possible to model complex collective behaviors by using simple individual rules and setting a general memory.

CAB algorithm [16] is an iterative process that starts with initializing the population randomly (generated random solutions or animal positions).

The flow chart of the CAB algorithm is depicted in Fig. 1. The computational procedure for the algorithm can be summarized as follows:

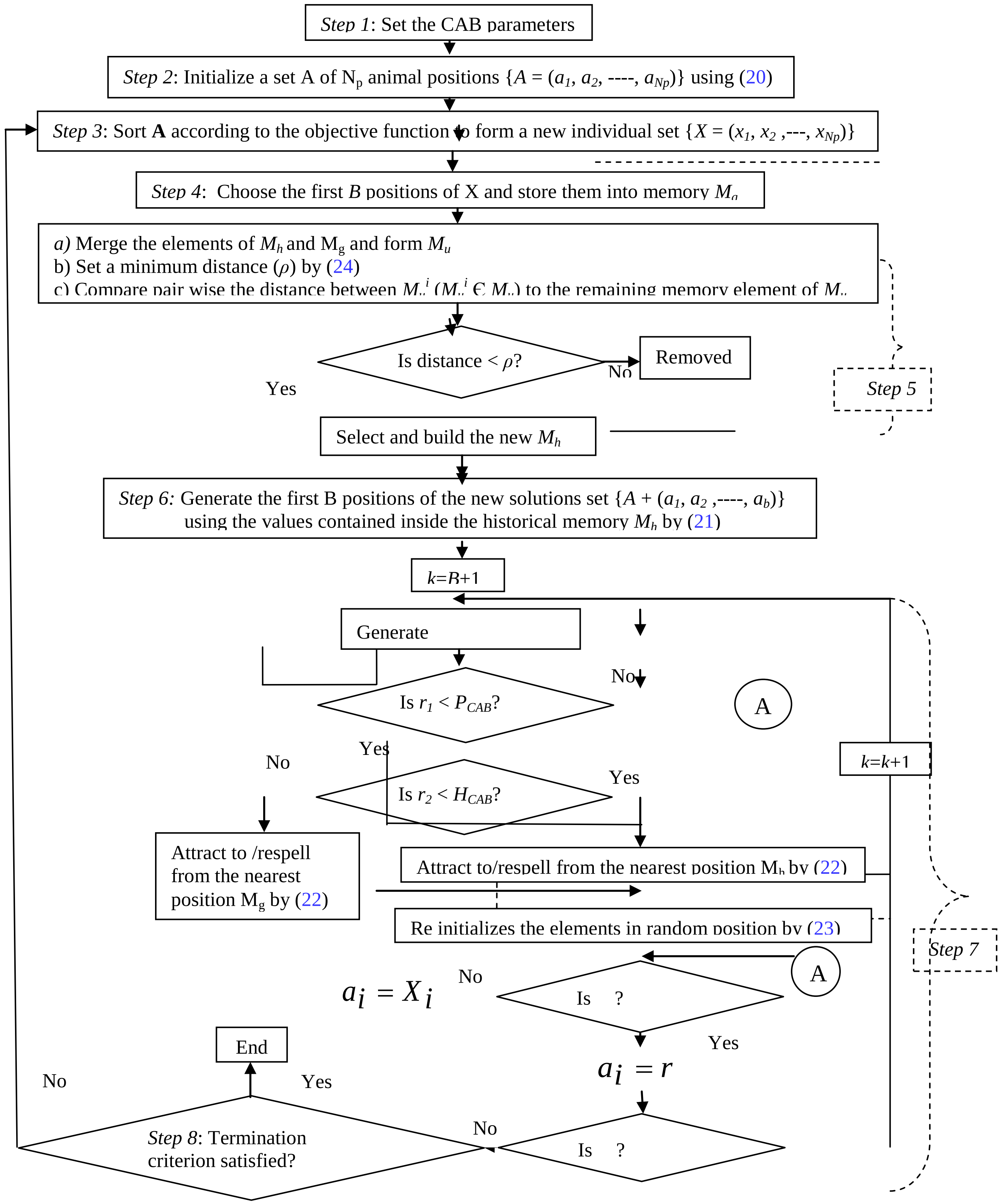

Fig. 1 Flowchart of the CAB algorithm, compatible with the computational procedure shown in Section 3.6.

Computational procedure for CAB algorithm

Step 1 Set the parameters N_p (population size), *B*, CAB parameters (H_{CAB} , P_{CAB}) and $NFFE_{max}$.

Step 2 Generate randomly the position set $A = \{a_1, a_2, ..., a_{N_p}\}$.

Step 3 Sort **A** according to the objective function (dominance) to build $X = \{X_1, X_2, ..., X_{N_p}\}$.

Step 4 Choose the first *B* positions of **X** and store them into the memory M_g .

Step 5 Update M_h .

Step 6 Generate the first *B* positions of the new solution set $A = \{a_1, a_2, ..., a_B\}$. Such positions correspond to the elements of M_h making a slight random perturbation around them. $a_l = m_k^l + v$; being v a random vector of a small enough length.

Step 7 Generate the rest of the **A** elements using the attraction, repulsion and random movements.

% r , r_1 and r_2 : Uniformly generated random number within[0, 1]

for *i* = (*B*+1): N_p
  if $(r_1 < P_{CAB})$ then
    % Attraction and repulsion movement
    if $(r_2 < H)$ then

$$a_i = X_i \pm r \times (m_h^{nearest} - X_i)$$

      else

$$a_i = X_i \pm r \times (m_g^{nearest} - X_i)$$

    end if
  else
    % random movement
      if $(r < P_{CAB})$ then
        $a_i = r$
      else
        $a_i = X_i$
      end if
  end if
end for

Step 8 If $NFFE_{max}$ is completed, the process is finished; otherwise go back to Step 3. The best value in M_h represents the global solution for the optimization problem.

IV. IMPLEMENTATION OF CAB FOR THE SOLUTION OF OPF PROBLEM

The fitness value of each animal/agent/vector is calculated by using the objective function of the problem. The real-value position of the animal consists of four parts viz. generators' real power outputs, generators' voltages, transformer taps and VARS of shunt capacitors/inductors. The real-value positions of the agents are changed into mixed-variable vectors which are used to calculate the objective function values of the problem based on Newton–Raphson power flow analysis [20]. The procedure of the OPF task, based on CAB, may be described as follows.

CAB algorithm for the solution of OPF problem

Step 1 Read the parameters of power system (line data, bus data, fuel cost co-efficient, load flow parameters etc) and those of CAB (N_p ,B, H_{CAB} , P_{CAB} and $NFFE_{max}$ etc) and specify the lower and upper limits of each parameter (like lower and upper limits of (a) active power generation, (b) generator bus voltage, (c) load bus voltage, (d) reactive power generation, (e) tap changing transformers, (f) shunt compensating devices, (g) line flow through each transmission line etc).

Step 2 Initialize all the individual animal vectors in N_p population, each having the set of optimizing/ control variables (as mentioned in Section 2) randomly within lower and upper limits of each variable.

Step 3 Keep the positions of the best individuals.

Step 4 Move from or to nearby neighbors (local attraction and repulsion).

Step 5 Move randomly.

Step 6 Compete for the space within a determined distance (update the memory)

Step 7 Fitness evaluations of the animals using the objective function of the problem based on the results of Newton–Raphson power flow analysis [20].

Step 8 Update M_h .

Step 9 Check for the constraints of the problem.

Step 10 Go to **Step 3** until a stopping criterion is satisfied.

Step 11 Output: Control variables (like active power generation, generator bus voltage, tap changing transformer and shunt compensating device), fuel cost, P_{Loss} , TVD, CPU time etc.

V. TEST SYSTEMS VIS-À-VIS SIMULATION RESULTS AND DISCUSSIONS

In the present work, CAB is applied to solve the OPF problem for modified IEEE 30-bus, IEEE 57-bus and IEEE 118-bus test power systems. The software is written in MATLAB 2008a computing environment and applied on a 2.63 GHz Pentium IV personal computer with 3 GB RAM. The value of the maximum number of $NFFE_{max}$ is set to 500 for all the test cases. Discussions on simulation results of the present work are presented below. Results of interest are **bold faced** in the respective tables to indicate the optimization capability of the CAB algorithm. In this study, 30 test runs are performed for all the test cases to solve the OPF problem and the best results are presented and discussed below.

5.1 Test system 1: Modified IEEE 30-bus power system

Modified IEEE 30-bus power system is chosen as test system 1. The line data, bus data and the minimum and maximum limits on control variables are adopted from [12]. This system has six generators at buses 1, 2, 5, 8, 11 and 13 and four transformers with off nominal tap ratios in lines 6-9, 6-10, 4-12 and 28-27. In addition, shunt VAR compensating devices are assumed to have been connected at buses 10, 12, 15, 17, 20, 21, 23, 24 and 29 for reactive power control [12]. The voltages of all load buses are constrained within the limits of 0.95 p.u. - 1.05 p.u.

5.1.1 Fuel cost minimization of modified IEEE 30-bus test system without valve point effect

The optimum control parameter settings yielded by GM [21], MDE [22], IGA [23], PSO [12], DE [24], BBO [25], GSA [26] and the proposed CAB algorithm are provided in Table 1. The fuel cost obtained from the CAB algorithm for this test case is **796.9343** $/h with a percentage reduction of 0.218% as compared to the GSA based best fuel cost of 798.675143 $/h reported in [26]. A statistical comparison of the methods like GM [21], MDE [22], EGA [27], IGA [23], PSO [12], EADDE [28], EADHDE [28], DE [24], BBO [25] and GSA [26] is carried out and presented in Table 1. Fig. 2 shows the convergence for minimum fuel cost ($/h) offered by the proposed CAB method for this objective function of the test system.

Table 1 Best control variable settings for fuel cost minimization objective of modified IEEE 30-bus test system for different techniques without valve point effect, obtained by different techniques

Control variables	GM [21]	MDE [22]	IGA [23]	PSO [12]	DE [24]	BBO [25]	GSA [26]	CAB
P_{G-1} (p.u.)	1.87219	1.75974	1.77594	1.7696	1.762592	1.770177	1.75749826	1.70021
P_{G-2} (p.u.	0.53781	0.48884	0.48722	0.4898	0.485602	0.486410	0.48165537	0.49810
P_{G-5} (p.u.)	0.16955	0.21510	0.21454	0.2130	0.213402	0.212390	0.21381724	0.212010
P_{G-8} (p.u.)	0.11288	0.22240	0.20954	0.2119	0.220553	0.211360	0.21561405	0.24561
P_{G-11} (p.u.)	0.11287	0.12251	0.11768	0.1197	0.117785	0.119440	0.12417360	0.12860
P_{G-13} (p.u.)	0.1335	0.12000	0.12052	0.12005	0.120217	0.120540	0.12510199	0.127001
V_1 (p.u.)	1.10	1.0500	1.081	1.0855	1.0999	1.1000	1.086235	0.9902
V_2 (p.u.)	1.08	1.0382	1.063	1.0653	1.0890	1.0876	1.046685	0.9812
V_5 (p.u.)	1.03	1.0113	1.034	1.0333	1.0659	1.0614	1.035570	0.9926
V_8 (p.u.)	1.04	1.0191	1.038	1.0386	1.0697	1.0695	1.076962	1.007
V_{11} (p.u.)	1.08	1.0951	1.10	1.0848	1.0965	1.0982	1.077452	0.9787
V_{13} (p.u.)	1.08	1.0837	1.055	1.0512	1.0996	1.0998	1.099999	1.0472
T_{6-9} (p.u.)	1.072	0.9866	1.0	1.0233	1.0429	1.05	0.939297	0.9800
T_{6-10} (p.u.)	1.070	0.9714	0.975	0.9557	0.9179	0.90	1.006593	0.9900
T_{4-12} (p.u.)	1.032	0.9972	0.975	0.9724	1.0190	0.99	0.907372	1.0300
T_{28-27} (p.u.)	1.068	0.9413	1.0	0.9728	0.9836	0.97	0.921855	1.0300
Q_{C-10} (p.u.)	0.00692	NR*	0.001	0.0335	0.045453	0.05	0.02190333	0.0200
Q_{C-12} (p.u.)	0.00046	NR*	0.007	0.0220	0.044158	0.05	0.05000000	0.0200
Q_{C-15} (p.u.)	0.00285	NR*	0.019	0.0198	0.041734	0.05	0.00000000	0.00
Q_{C-17} (p.u.)	0.00287	NR*	0.024	0.0315	0.025171	0.05	0.02715239	0.0300
Q_{C-20} (p.u.)	0.00208	NR*	0.015	0.0454	0.020916	0.05	0.00000672	0.0600
Q_{C-21} (p.u.)	0.0	NR*	0.022	0.0381	0.041990	0.05	0.00000000	0.0400
Q_{C-23} (p.u.)	0.0033	NR*	0.047	0.0398	0.025527	0.04	0.00000593	0.0200
Q_{C-24} (p.u.)	0.00938	NR*	0.047	0.0500	0.043812	0.05	0.00000000	0.0600
Q_{C-29} (p.u.)	0.00269	NR*	0.024	0.02510	0.027503	0.03	0.00000000	0.0500
Fuel cost ($/hr)	804.853	802.376	800.805	800.41	799.2891	799.1116	798.675143	**796.9343**
P_{Loss} (MW)	10.486	9.459	NR*	NR*	8.6150	8.63	8.386049	7.7540
TVD (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.872862	0.7756
CPU time (s)	NR*	NR*	NR*	NR*	NR*	NR*	NR*	10.5132

NR* means not reported

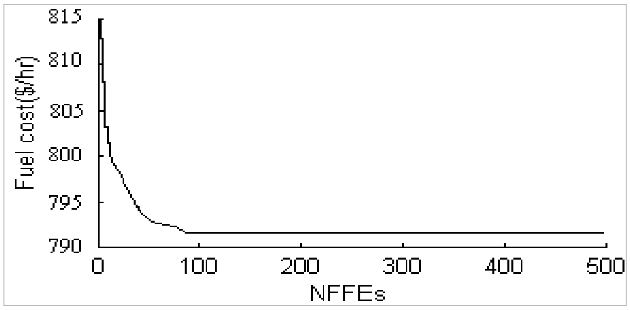

Fig. 2 Convergence profile of fuel cost for fuel cost minimization objective of modified IEEE 30-bus test system without valve point effect.

5.1.2 Minimization of system real power loss of modified IEEE 30-bus power system without valve point effect

Considering minimization of active power loss as one of the objective function for this test power network, obtained optimal values of the control variables, as yielded by the proposed CAB method, are presented in Table 2 along with those reported in base case [30], PSO [30], and EGA-DQLF [30]. Minimum real power loss obtained by the proposed CAB approach is found to be **3.2000 MW**. The value of P_{Loss} (MW) yielded by CAB is **0.0008 MW** (i.e. 0.025**%**) less than the EGA-DQLF based best result of 3.2008 MW reported in [30]. The convergence profile of the P_{Loss} (MW) for this test power system is presented in Fig. 3.

Table 2 Statistical analysis of the simulation results for P_{Loss} minimization objective of modified IEEE 30-bus test system without valve point effect, obtained by different techniques

	Base-case [30]	PSO [30]	EGA–DQLF [30]	CAB
Fuel cost ($/hr)	902.9	956.45	967.86	967.8053
P_{Loss} (MW)	6.1678	3.6294	3.2008	**3.2000**
TVD (p.u.)	NR*	NR*	NR*	0.7828
CPU time (s)	NR*	NR*	NR*	9.3294

NR* means not reported

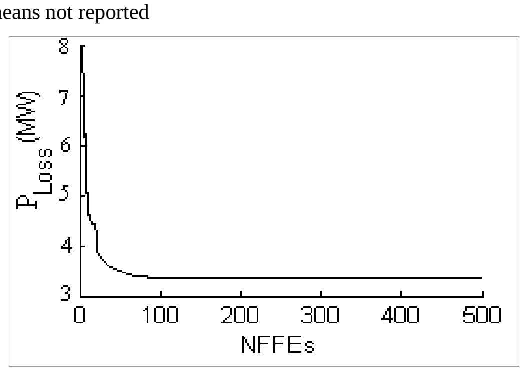

Fig. 3 Convergence profile of P_{Loss} for P_{Loss} minimization objective of modified IEEE 30-bus test system without valve point effect

5.1.3 Minimization of system TVD of modified IEEE 30-bus power system without valve point effect

The proposed CAB approach is applied for the minimization of TVD of this test power network. The results yielded by the proposed CAB are presented in Table 3 along with those reported in the literature like DE [22], BBO [25] and GSA [26]. From this table, **1.15%** improvement in TVD may be recorded by using the proposed CAB based algorithm (**0.0922 p.u.**) as compared to GSA counterpart (0.093269 p.u.) as reported in [26]. CAB based convergence profile of TVD (p.u.) for this power system is presented in Fig. 4.

Table 3 Statistical analysis of the simulation results for TVD minimization objective of modified IEEE 30-bus test system without valve point effect, obtained by different techniques

Control variables	DE [22]	BBO [25]	GSA [26]	CAB
Fuel cost ($/hr)	805.2619	804.9982	804.314844	861.0913
P_{Loss} (MW)	10.4412	9.95	9.765939	7.7870
TVD (p.u.)	0.1357	0.1020	0.093269	**0.0922**
CPU time (s)	NR*	NR*	NR*	10.2219

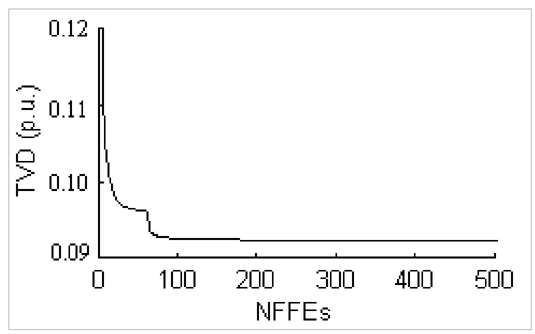

Fig. 4 Convergence profile of TVD for TVD minimization objective of modified IEEE 30-bus test system without valve point effects.

5.1.4 Fuel cost minimization of modified IEEE 30-bus power system with valve point effect

In this case, the objective function may be represented as [31]

$$J(FC)=\left(\sum_{i=1}^{2}\left(a_i+b_iP_{Gi}+c_iP_{Gi}^2+\left|d_i\times \text{sinsin}\left\{e_i\times(P_{Gi}^{\min}-P_{Gi})\right\}\right|\right)\right)+\left(\sum_{i=3}^{NG}a_i+b_iP_{Gi}+c_iP_{Gi}^2\right) \quad (20)$$

Fuel cost is minimized after satisfying constraints as mentioned in Section 2. The results obtained from the CAB method for this test system are presented in Table 4 and are compared to MDE [22], GA [23], PSO [12], FPSO [31], FGA [31], BBO [25] methods. The total fuel cost as obtained using CAB is **916.5917 $/h**, which is less than the previously published best result of 919.7647 $/h of BBO [25] by **0.345%**.

Table 4 Best control variable settings for fuel cost minimization objective of modified IEEE 30-bus test system with valve point effect, obtained by different techniques

Control variables	MDE [22]	GA [23]	PSO [12]	FPSO [31]	FGA [31]	BBO [25]	CAB
P_{G-1} (MW)	197.426	200	199.7800	199.78	199.7800	1.99.99	200
P_{G-2} (MW)	52.037	20.11	20.1100	20	20.2300	37.812	21.9544
P_{G-5} (MW)	15.000	27.42	27.4200	25.42	21.6500	20.251	15.3924
P_{G-8} (MW)	10.000	15.65	15.6500	22.43	19.8100	14.375	15.962
P_{G-11} (MW)	10.001	17.74	17.7400	13.37	14.1200	10.035	23.6581
P_{G-13} (MW)	12.000	12.9	12.9000	12.94	18.1000	12.001	12.0671
V_1 (p.u.)	1.0371	NR*	NR*	NR*	NR*	1.0500	1.0464
V_2 (p.u.)	1.0130	NR*	NR*	NR*	NR*	1.0358	1.0175
V_5 (p.u.)	0.9648	NR*	NR*	NR*	NR*	1.0086	0.9595
V_8 (p.u.)	1.0320	NR*	NR*	NR*	NR*	1.0137	1.0362
V_{11} (p.u.)	1.0982	NR*	NR*	NR*	NR*	1.0958	1.0322
V_{13} (p.u.)	1.0890	NR*	NR*	NR*	NR*	1.0814	0.9994
T_{6-9} (p.u.)	1.0969	NR*	NR*	NR*	NR*	1.0308	1.0400
T_{6-10} (p.u.)	1.0909	NR*	NR*	NR*	NR*	0.91443	0.9500
T_{4-12} (p.u.)	1.0991	NR*	NR*	NR*	NR*	0.99142	0.9600
T_{28-27} (p.u.)	1.0021	NR*	NR*	NR*	NR*	0.93864	1.0700
Q_{C-10} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.0100
Q_{C-12} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.0100
Q_{C-15} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.0100
Q_{C-17} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.00
Q_{C-20} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.0200
Q_{C-21} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.0200
Q_{C-23} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.0100
Q_{C-24} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.0100
Q_{C-29} (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.0800
Fuel cost ($/hr)	930.793	926.2754	925.0018	923.4718	922.9916	919.7647	**916.5917**
P_{Loss} (MW)	13.064	NR*	NR*	NR*	NR*	12.18	5.634
TVD (p.u.)	NR*	NR*	NR*	NR*	NR*	NR*	0.7896
CPU time (s)	NR*	NR*	NR*	NR*	NR*	NR*	12.3241

NR* means not reported

5.2 Test system 2: IEEE 57-bus power system

IEEE 57-bus test system is considered as test system 2. This test system has 80 transmission lines, 7 generators (at the buses 1, 2, 3, 6, 8, 9, 12) and 17 branches under load tap setting transformer branches (in the lines 4-18, 4-18, 21-20, 24-25, 24-25, 24-26, 7-29, 34-32, 11-41, 15-45, 14-46, 10-51, 13-49, 11-43, 40-56, 39-57 and 9-55). Three reactive power sources are considered at buses 18, 25 and 53. Line data, bus data, variable limits and the initial values of the control variables are given in [32, 33].

5.2.1 Minimization of fuel cost function for IEEE 57-bus power system

Table 5 depicts the best control variable settings offered by the algorithms like EADDE [28], GSA [26] and the proposed CAB algorithm for fuel cost minimization objective of this test system. In Table 5, CAB based results are also compared to other optimization techniques like base-case [28], MATPOWER [28], EADDE [28] and GSA [26] methods. From Table 5, it may be observed CAB based results yield minimum fuel cost of **41688.5183** $/h i.e. **0.0176%** less compared to previously reported best result 41695.8717 $/h using GSA [26]. Convergence profile of fuel cost, as yielded by the proposed CAB, is depicted in Fig.5.

Table 5 Best control variable settings for fuel cost minimization objective of IEEE 57-bus test system, obtained by different techniques

Control variables	EADDE [28]	GSA [26]	CAB
P_{G-1} (p.u.)	1.4315	1.42369	1.47245
P_{G-2} (p.u.)	0.9529	0.92630	0.88072
P_{G-3} (p.u.)	0.4532	0.45318	0.4168

$P_{G\text{-}6}$ (p.u.)	0.7360	0.72355	0.72134
$P_{G\text{-}8}$ (p.u.)	4.6485	4.64743	4.66943
$P_{G\text{-}9}$ (p.u.)	0.8344	0.84999	0.86433
$P_{G\text{-}12}$ (p.u.)	3.6124	3.63951	3.63767
V_1 (p.u.)	1.0499	1.05941	0.9926
V_2 (p.u.)	1.0479	1.05759	1.0393
V_3 (p.u.)	1.0408	1.06000	1.0191
V_6 (p.u.)	1.0493	1.06000	0.9668
V_8 (p.u.)	1.0562	1.05999	1.0336
V_9 (p.u.)	1.0342	1.05999	1.0391
V_{12} (p.u.)	1.0408	1.04590	1.033
$T_{4\text{-}18}$ (p.u.)	1.0513	0.90000	1.0500
$T_{4\text{-}18}$ (p.u.)	0.9071	0.90000	1.0200
$T_{21\text{-}20}$ (p.u.)	1.0381	0.90856	1.0300
$T_{24\text{-}25}$ (p.u.)	1.0039	1.05921	0.9600
$T_{24\text{-}25}$ (p.u.)	0.9624	0.99921	1.0400
$T_{24\text{-}26}$ (p.u.)	0.9857	0.92201	0.9900
$T_{7\text{-}29}$ (p.u.)	0.9836	0.93243	1.0500
$T_{34\text{-}32}$ (p.u.)	0.9080	1.08828	0.9400
$T_{11\text{-}41}$ (p.u.)	0.9234	1.03902	0.9500
$T_{15\text{-}45}$ (p.u.)	0.9912	1.04318	0.9200
$T_{14\text{-}46}$ (p.u.)	0.9824	1.02494	0.9700
$T_{10\text{-}51}$ (p.u.)	0.9890	0.95425	1.0400
$T_{13\text{-}49}$ (p.u.)	0.9658	0.92897	1.0300
$T_{11\text{-}43}$ (p.u.)	0.9724	1.09942	0.9500
$T_{40\text{-}56}$ (p.u.)	0.9969	0.96948	1.0300
$T_{39\text{-}57}$ (p.u.)	1.0021	1.06200	0.9900
$T_{9\text{-}55}$ (p.u.)	1.0446	1.09388	0.9500
$Q_{C\text{-}18}$ (p.u.)	0.0903	0.15243	0.0300
$Q_{C\text{-}25}$ (p.u.)	0.0817	0.14403	0.0300
$Q_{C\text{-}53}$ (p.u.)	0.2013	0.15102	0.0400
Fuel cost ($/h)	41713.62	41695.8717	**41688.5183**
P_{Loss} (p.u.)	NR*	NR*	0.15422
TVD (p.u.)	NR*	NR*	3.2437
CPU time (s)	NR*	NR*	22.4569

NR* means not reported

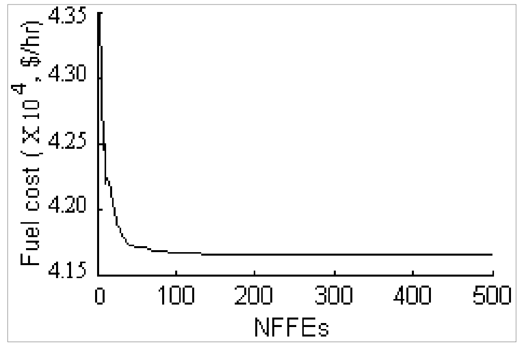

Fig. 5 Convergence profile of fuel cost for fuel cost minimization objective of IEEE 57-bus test system.

5.2.2 Minimization of system TVD for IEEE 57-bus power system

The best OPF solutions as yielded by the proposed CAB along with EADDE [28] for TVD minimization objective for this test system are tabulated in Table 6. In Table 6, CAB based results are compared to other optimization techniques recently reported in the literature like base-case [28], MATPOWER [28], and EADDE [28]. From this table, **4.61%** improvement in TVD may be recorded by using the proposed CAB based algorithm as compared to EADDE counterpart reported in [28].

Table 6 Comparison of simulation results for TVD minimization objective of IEEE 57-bus test system

Methods	TVD (p.u.)
Base-case [28]	1.2334
MATPOWER [28]	NR*
EADDE [28]	0.7882
CAB	**0.7519**

NR* means not reported

5.3 Test system 3: IEEE 118-bus power system

In order to exhibit the effectiveness and robustness of the proposed CAB technique in solving larger power systems, IEEE 118-bus test system is considered as test system 3 [32, 34]. The search space of this case system has 131 dimensions, that is, the 54 generator buses, 64 load buses, 186 transmission lines, 9 transformer taps and 14 reactive power sources. The system line data, bus data, variable limits and the initial values of control variables may be found in [32, 34].

5.3.1 Minimization of fuel cost function for IEEE 118-bus power system

CAB based OPF solution for this test system of fuel cost minimization objective is presented in Table 7 along with the best results obtained from the algorithms like PSOIWA [35], PSOCFA [35], RGA [35] and BBO [35]. This table demonstrates that a fuel cost reduction of **0.11%** (from the previous best of 129735.11 $/h (as reported in BBO [35]) to **129592.737 $/h** is accomplished by using the proposed CAB approach. Convergence profile of the fuel cost, as yielded by the proposed CAB algorithm, is depicted in Fig. 6.

Table 7 Statistical analysis of the simulation results for fuel cost minimization objective of IEEE 118-bus test system

	PSOIWA [35]	PSOCFA [35]	RGA [35]	BBO [35]	**CAB**
Fuel cost ($/h)	130033.47	130001.81	129902.90	129735.11	**129592.737**
P_{Loss} (MW)	NR*	NR*	NR*	NR*	71.08
TVD (p.u.)	2.7756	2.7552	3.8688	3.3210	0.0069
CPU time (s)	28.025	28.361	29.058	29.126	24.126

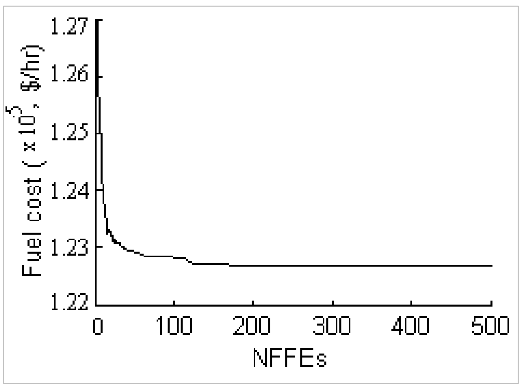

Fig. 6 Convergence profile of fuel cost for fuel cost minimization objective of IEEE 118-bus system.

5.3.2 Minimization of system TVD for IEEE 118-bus power system

The best OPF solutions as yielded by the proposed CAB for TVD minimization objective are tabulated in Table 8. In this table, CAB based results are compared to other optimization techniques recently reported in the literature like PSOIWA [35], PSOCFA [35], RGA [35] and BBO [35]. From this table, considerable improvement in TVD(6.33%) may be recorded by using the proposed CAB based algorithm as compared to BBO as reported in [35]. Convergence profile of the TVD (p.u.) (as yielded by the proposed CAB method) may be observed in Fig. 7.

Table 8 Statistical analysis of the simulation results for TVD minimization objective for IEEE 118-bus test system

Control variables	PSOIWA [35]	PSOCFA [35]	RGA [35]	BBO [35]	CAB
Fuel cost ($/h)	NR*	NR*	NR*	NR*	157646.9181
P_{Loss} (p.u.)	3.7210	1.6108	2.5992	1.6218	1.544
TVD (p.u.)	1.1040	1.0536	0.8839	0.4613	**0.4321**
CPU time (s)	28.325	28.789	29.463	29.716	24.169

NR* means not reported

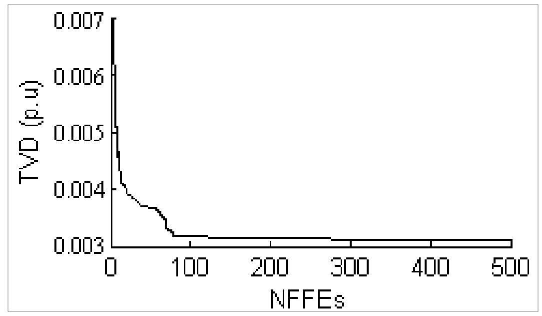

Fig. 7 Convergence profile of TVD for TVD minimization objective of IEEE 118-bus system.

VI. CONCLUSION

In this paper, OPF problem is formulated as a nonlinear optimization problem with equality and inequality constraints of the power network. One recently developed meta-heuristic algorithm like collective animal behavior (CAB) has been, successfully, implemented to solve the OPF problem of power system. The economical (in the form of minimization of fuel cost) as well as technical (in the form of minimization of real power loss or that of TVD) benefits arisen are presented. The proposed CAB is tested on modified IEEE 30-bus IEEE 57-bus and IEEE 118-bus test systems to demonstrate its effectiveness. It is observed that the proposed CAB yields optimal settings of the control variables of these test systems. The simulation results indicate the superiority of the proposed approach consistently to solve the OPF problem. The results obtained from the simulation in the present work obviously demonstrate that the proposed CAB yields better-quality solution in comparison to other results reported in the recent state-of-the art literature. Thus, the proposed CAB may be recommended as a very promising algorithm for solving some more complex engineering optimization problems for the future researchers.

APPENDIX

Generator cost coefficients for the modified IEEE 30-bus system without and with valve point effect are presented in Table A.1 and Table A.2, respectively.

Table A.1 Generator cost coefficients without valve point effect for modified IEEE 30-bus system

Unit	a_i	b_i	c_i
1	0	2	0.00375
2	0	1.75	0.0175
3	0	1	0.0625
4	0	3.25	0.00834
5	0	3	0.025
6	0	3	0.025

Table A.2 Generator cost coefficients with valve point effect for modified IEEE 30-bus system

Unit	a_i	b_i	c_i	d_i	e_i
1	150	2	0.0016	50	0.063
2	25	2.5	0.01	40	0.098
3	0	1	0.0625	0	0
4	0	3.25	0.00834	0	0
5	0	3	0.025	0	0
6	0	3	0.025	0	0

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