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Optimal Reactive Power Dispatch Using Chaotic Bat Algorithm

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ABSTRACT In this paper, the chaotic bat algorithm (CBA) is applied to solve the optimal reactive power dispatch (ORPD) problem taking into account small-scale, medium-scale and large-scale power systems. ORPD plays a key role in the power system operation and control. The ORPD problem is formulated as a mixed integer nonlinear programming problem, comprising both continuous and discrete control variables. The most outstanding benefit of the bat algorithm (BA) is its good convergence for optimal solutions. The BA, however, together with other metaheuristics, often gets stuck into local optima and in order to cope with this shortcoming, the use of the CBA is proposed in this paper. The CBA results from introducing the chaotic sequences into the standard BA to enhance its global search ability. The CBA is utilized to find the optimal settings of generator bus voltages, tap setting transformers and shunt reactive power sources. Three objective functions such as minimization of active power loss, total voltage deviations and voltage stability index are considered in this study. The effectiveness of the CBA technique is demonstrated for standard IEEE 14-bus, IEEE 39 New England bus, IEEE 57-bus, IEEE 118-bus and IEEE 300-bus test systems. The results yielded by the CBA are compared with other algorithms available in the literature. Simulation results reveal the effectiveness and robustness of the CBA for solving the ORPD problem.

INDEX TERMS Chaotic bat algorithm, optimal reactive power dispatch, chaotic sequences.

I. INTRODUCTION

In 1962, Carpentier introduced for the first time the optimal power flow (OPF) problem [1] and later on it was developed by Dommel and Tinney [2]. Henceforth, the OPF has aroused widespread interests among researchers in power system operation and planning [3]. The ORPD problem is a special case of the OPF problem and has an ever-increasing impact on the reliability, security as well as economic operation of power system [4].

From the mathematical optimization point of view, the ORPD problem is regarded as a mixed integer nonlinear programming problem which combines discrete control variables such as tap setting transformers and reactive compensators; and continuous variables such as generator bus voltages [5], [6].

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It is worth pointing out that the ORPD problem is addressed in an attempt to minimize either total active power transmission losses (P_{Loss}), or total voltage deviation (TVD), or enhance voltage stability index (VSI) while satisfying specific operating and physical constraints [3].

Over the last decades, extensive efforts have been undertaken to solve the ORPD problem using many classical optimization techniques including quadratic programming [7]–[10], mixed integer programming [11], interior point method [12]–[14], Newton-based method [15], linear programming [16], [17], non-linear programming [18], dynamic programming [19], gradient-based algorithm [20], decomposition approach [21] etc. Despite their excellent convergence characteristics, these classical optimization techniques fail to find the global solution due to their non-convexity characteristics. Furthermore, they are unable to handle the problems with discontinuous and non-differentiable objective functions, as well as discrete variables. Hence they are inappropriate to address the ORPD problem [3], [22].

The metaheuristic algorithms are typically inspired from physical phenomena such as gravitational force, electromagnetic force, inertia force, ray casting; animals' behavior such as schools of fish, flocks of birds, herds of land animals, ants, bees; or evolutionary concepts. The metaheuristics have become outstandingly popular owing to their simplicity, flexibility, derivation-free mechanism, and local optima avoidance [23]. Therefore, the metaheuristic algorithms overcome the shortcomings associated with the classical optimization algorithms [22], [24], [25]. Renowned metaheuristics include, among others, genetic algorithm (GA) [26], differential evolution (DE) [27], particle swarm optimization (PSO) [28], bat algorithm (BA) [29], firefly algorithm (FA) [30], flower pollination algorithm (FFA) [31], harmony search algorithm (HAS) [32], simulated anneal (SA) [33], gravitational search algorithm (GSA) [34], ant colony optimization (ACO) [35], wolf search algorithm (WSA) [36], grey wolf optimizer (GWO) [23], whale optimization algorithm (WOA) [37], elephant search algorithm (ESA) [38], ant lion optimizer (ALO) [39], salp swarm algorithm (SSA) [40], dragonfly algorithm (DA) [41], moth-flame optimization (MFO) [42], harris hawks optimization (HHO) [43], grasshopper optimization algorithm (GOA) [44], multi-verse optimization (MVO) [45], sine cosine Algorithm (SCA) [46], etc.

In recent times, some of metaheuristics including genetic algorithm (GA) [47]–[49], particle swarm optimization (PSO) [50], [51], differential evolution (DE) [52], seeker optimization algorithm (SOA) [53], gravitational search algorithm (GSA) [24], [54], [55], harmony search algorithm (HSA) [56], biogeography-based optimization (BBO) [57], teaching-learning-based optimization (TLBO) [58], krill herd algorithm (KHI) [59], bacteria foraging algorithm (BFA) [60], gray wolf optimizer (GWO) [61], ant-lion optimizer (ALO) [62], exchange market algorithm (EMA) [3], moth-flame algorithm (MFA) [4], imperialist competitive algorithm (ICA) [6], invasive weed optimization (IWO) [63], bat algorithm (BA) [64], cuckoo search algorithm (CSA) [65], etc, have been successfully employed to address the ORPD problem.

The BA is a novel metaheuristic optimization algorithm, introduced by Xin-She Yang in 2010, inspired by the echolocation of micro-bats [66]. The BA has recently been applied in numerous areas of research, including engineering optimization problems [67]–[69], economic load dispatch problems [70], microelectronic applications [71], scheduling problems [72], biological systems [73], image processing [74], classification, clustering and data mining [75]–[82], etc.

In an attempt to ameliorate its performance, various variants of BA have been proposed in the literature such as K-Means bat algorithm (KMBA) [75], fuzzy logic bat algorithm (FLBA) [77], multi-objective bat algorithm (MOBA) [69], binary bat algorithm (BBA) [82], bat algorithm with differential operator and Lévy flights (DLBA) [83], improved bat algorithm (IBA) [84], quantum-behaved bat algorithm [85]–[87], etc.

Thus far, chaos theory has been widely utilized to a broad-spectrum of applications and to numerous metaheuristics in an effort to further improve their performance such as providing better convergence speed and avoiding entrapment into local optima [88]. In addition, the use of chaotic sequences has proved to outperform the use random numbers in terms of enhancing the performance of the metaheuristics (by tuning certain parameters) [89], [90]. In literature, examples of meta-heuristics which employ chaos include genetic algorithm (GA) [91], harmony search algorithm (HSA) [92], differential evolution (DE) [93], particle swarm optimization (PSO) [94], imperialist competitive algorithm (ICA) [95], krill herd algorithm (KHA) [96], gravitational search algorithm (GSA) [97], bat algorithm (BA) [98], firefly algorithm (FA) [99], cuckoo search algorithm (CSA) [100], butterfly optimization algorithm (BOA) [101], whale optimization algorithm (WOA) [88], grey wolf optimization (GWO) [102], moth-flame optimization (MFO) [103], salp swarm algorithm (SSA) [104]–[106], etc.

Some chaos-based metaheuristics have been efficiently applied to solve the ORPD problem [59], [107], [108] as well as economic load dispatch (ELD) problem [90], [109], [110], [111].

In the present work, the chaotic bat algorithm is implemented on the standard IEEE 14-bus, IEEE 39 New England, IEEE 57-bus, IEEE 118-bus and IEEE 300-bus test power systems with the aim to demonstrate its performance in solving the ORPD problem. The objective functions considered in this paper are the minimization of the active power loss, minimization of the total voltage deviation and minimization of the voltage stability index. The simulation results approve that the CBA is more potential and effective than the compared metaheuristic algorithms reported in the literature.

The rest of the paper is organized as follows: Section II presents the mathematical formulation of the ORPD problem, the CBA algorithm is described in Section III, the implementation of the CBA algorithm on the ORPD problem is described in Section IV, Section V presents the simulation results along with the discussions, and Section VI draws the conclusion of this paper.

II. PROBLEM FORMULATION

In this paper, three different objective functions are considered and described as follows:

A. OBJECTIVE FUNCTIONS

The purpose of the ORPD problem is to minimize either the active power loss (P_{Loss}) or total voltage deviation (TVD) or voltage stability index (VSI) while simultaneously fulfilling various equality and inequality constraints.

The mathematical formulation of the ORPD problem in general form is expressed as follows [3], [112], [113]:

$$\text{Minimize } J(x,u) \quad (1)$$
$$\text{Subject to}$$
$$g(x,u) = 0 \quad (2)$$
$$h(x,u) \le 0 \quad (3)$$

where $J(x,u)$ is the objective function to be minimized, $g(x,u) = 0$ represents the equality constraints, $h(x,u) \le 0$ represents the inequality constraints.

x is the vector of dependent variables (state vector) including:

- Load bus voltage V_L.
- Generator reactive power output Q_G.
- Transmission line loading S_l.

Hence, the vector x can be expressed as:

$$x^T = [V_{L1} \ldots V_{LNPQ}, Q_{G1} \ldots Q_{GNG}, S_{l1} \ldots S_{lNTL}] \quad (4)$$

where NG depicts the number of generators; NPQ is the number of PQ buses and NTL is the number of transmission lines.

u is the vector of independent variables (control variables) including:

- Generator bus voltages V_G (continuous control variable).
- Transformer tap settings T (discrete control variable).
- Shunt VAR compensation Q_C (discrete control variable).

Therefore, u can be illustrated as follows:

$$u^T = [V_{G1} \ldots, V_{GNG}, Q_{C1} \ldots Q_{CNC}, T_1 \ldots T_{NT}] \quad (5)$$

where NT and NC define the number of tap regulating transformers and number of shunt VAR compensators, respectively.

1) MINIMIZATION OF ACTIVE POWER LOSS

The mathematical formulation of the ORPD problem for the minimization of the active power loss (P_{Loss}) is expressed as follows [113]:

$$\text{Minimize } J_1(x_1,u_1) = \text{minimize } P_{Loss} = \sum_{k=0}^{NTL} g_k \left(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij}\right) \quad (6)$$

where $J_1(x_1,u_1)$ denotes the active power loss minimization function of the transmission network, g_k is the conductance of the branch k, V_i and V_j are the voltages of i th and jth bus, respectively, NTL is the number of transmission lines, δ_{ij} is the phase difference of voltages between bus i and j.

2) MINIMIZATION OF TOTAL VOLTAGE DEVIATIONS

The voltage deviations at load buses are minimized in an effort to enhance the voltage profile as well as the security of the electric power network. Mathematically, the total voltage deviations (TVD) at load buses are expressed as [3]:

$$\text{Minimize } J_2(x_2,u_2) = \text{minimize } TVD = \sum_{i=1}^{NPQ} \left|V_i - V_i^{ref}\right| \quad (7)$$

where $J_2(x_2,u_2)$ is the total voltage deviation minimization function, i is the element of NPQ, V_i^{ref} is the reference voltage magnitude at i th load bus which is taken as $1p.u.$

3) IMPROVEMENT OF VOLTAGE STABILITY INDEX

The $L-$ index/stability index is an index which plays a significant role in voltage stability of the power system. Its values range from 0 to 1. In fact, the closer the $L-$ index is to 0, the more stable is the voltage stability; the closer the $L-$ index is to 1, the more unstable is the voltage stability [3].

The voltage stability index (VSI) or $L_{\max}$ can be mathematically expressed as [3]:

$$\text{Minimize } J_3(x_3,u_3) = \text{minimize} L_{\max} = \min\lfloor\max(L_j)\rfloor, \quad j = 1,2,3,\ldots,NPQ \quad (8)$$

where L_j is the voltage stability indicator ($L-$ index) of j th node.

The value of L_j is given by

$$L_j = \left|1 - \sum_{i=1}^{NPV} F_{ij}\frac{V_i}{V_j}\right| \quad (9)$$
$$F_{ij} = -[Y_1]^{-1}[Y_2] \quad (10)$$

where i and j represent the elements of PV (Generator) and PQ (Load) buses, respectively. $[Y_1]$ and $[Y_2]$ denote the sub-matrices of the system Y bus which result from the separation of PV and PQ buses as given in the following equation:

$$\begin{bmatrix} I_{PQ} \\ I_{PV} \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \begin{bmatrix} V_{PQ} \\ V_{PV} \end{bmatrix} \quad (11)$$

B. CONSTRAINTS

1) EQUALITY CONSTRAINTS

In (2), g is the set of equality constraints illustrating the load flow equations as follows:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{NB} V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) = 0 \quad (12)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{NB} V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) = 0 \quad (13)$$

where NB is the number of buses, P_{Gi} and Q_{Gi} are active and reactive power generation at the i th bus, P_{Di} and Q_{Di} are active and reactive power demands at the i th bus, G_{ij} and B_{ij} are the transfer conductance and susceptance between the i th and the jth buses respectively.

C. INEQUALITY CONSTRAINTS

In (3), h is the set of inequality constraints that consists of:

1) GENERATOR CONSTRAINTS

The generation bus voltages including slack bus and reactive power outputs including slack bus must be restricted within their lower and upper limits as follows:

$$V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max}, \quad i = 1, 2, \ldots, NG \tag{14}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, \quad i = 1, 2, \ldots, NG \tag{15}$$

where $V_{Gi}^{\min}$ and $V_{Gi}^{\max}$ are the minimum and maximum generator voltage of i th generating unit, $Q_{Gi}^{\min}$ and $Q_{Gi}^{\max}$ are the minimum and maximum reactive power output of i th generating unit.

2) TRANSFORMER CONSTRAINTS

Transformer tap settings are constrained within their lower and upper limits as below:

$$T_i^{\min} \le T_i \le T_i^{\max}, \quad i = 1, 2, \ldots, NT \tag{16}$$

where $T_i^{\min}$ and $T_i^{\max}$ depict the minimum and maximum tap setting limits of i th transformer.

3) SHUNT VAR COMPENSATOR CONSTRAINTS

The lower and upper limits of the shunt VAR compensators are given as:

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, \quad i = 1, 2, \ldots, NC \tag{17}$$

where $Q_{Ci}^{\min}$ and $Q_{Ci}^{\max}$ are the minimum and maximum VAR injection limits of i th shunt compensator.

4) SECURITY CONSTRAINTS

These includes the constraints on voltages at load buses and transmission line loadings as

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max}, \quad i = 1, 2, \ldots, NPQ \tag{18}$$

$$S_{li} \le S_{li}^{\max}, \quad i = 1, 2, \ldots, NTL \tag{19}$$

where $V_{Li}^{\min}$ and $V_{Li}^{\max}$ are the minimum and maximum load voltages of i th unit. S_{li} denotes apparent power flow of i th branch and $S_{li}^{\max}$ denotes maximum apparent power flow limit of i th branch.

D. CONSTRAINT HANDLING

The independent variables of the ORPD problem are self-constrained whereas the dependent variables are constrained by means of the penalty functions. Hence, the equation (1) becomes [3]:

Minimize

$$F = F_{obj} + \lambda_V \sum_{i=1}^{NPQ} \left(V_{Li} - V_{Li}^{\lim}\right)^2 + \lambda_Q \sum_{i=1}^{NG} \left(Q_{Gi} - Q_{Gi}^{\lim}\right)^2 + \lambda_S \sum_{i=1}^{NTL} \left(S_{li} - S_{li}^{\lim}\right)^2 \tag{20}$$

where F_{obj} denotes the objective function under consideration i.e. $J_1(x_1, u_1)$ or $J_2(x_2, u_2)$ or $J_3(x_3, u_3)$. λ_V, λ_G and λ_S are the penalty factors related to load bus voltage limit violation, generation reactive power limit violation and line flow violation, respectively. $V_{Li}^{\lim}$, $Q_{Gi}^{\lim}$ and $S_{li}^{\lim}$ are defined as the limit values associated with load bus voltage, real generation reactive power, and line flow, respectively. They are expressed as follows

$$V_{Li}^{\lim} = \begin{cases} V_{Li}^{\max} & if \quad V_{Li} > V_{Li}^{\max} \\ V_{Li}^{\min} & if \quad V_{Li} < V_{Li}^{\min} \\ V_{Li} & if \quad V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max} \end{cases} \tag{21}$$

$$Q_{Gi}^{\lim} = \begin{cases} Q_{Gi}^{\max} & if \quad Q_{Gi} > Q_{Gi}^{\max} \\ Q_{Gi}^{\min} & if \quad Q_{Gi} < Q_{Gi}^{\min} \\ Q_{Gi} & if \quad Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \end{cases} \tag{22}$$

$$S_{li}^{\lim} = \begin{cases} S_{li}^{\max} & if \quad S_{li} > S_{li}^{\max} \\ S_{li}^{\min} & if \quad S_{li} < S_{li}^{\min} \\ S_{li} & if \quad S_{li}^{\min} \le S_{li} \le S_{li}^{\max} \end{cases} \tag{23}$$

III. CHAOTIC BAT ALGORITHM

A. BRIEF REVIEW OF THE BASIC BAT ALGORITHM

The BA mimics the echolocation behavior of the microbats while searching for prey and avoiding obstacles [66].

Three rules have been suggested in [66] in order to idealize the echolocation characteristics of microbats:

1) Each microbat utilizes echolocation to estimate the distance between prey and surroundings.
2) Bats fly randomly with velocity V^i at position X^i with a fixed frequency $f^{\min}$, varying wavelength λ and loudness A^0 to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission $r_1 \in [0, 1]$,depending on the proximity of their target.
3) It is assumed that the loudness varies from a large (positive) A^0 to a minimum constant value $A^{\min}$.

Each bat i has a position X^i, a velocity V^i, a frequency f^i in a $d-$ dimensional space, and they should be updated iteratively towards the current best position as follows

$$f^i = f^{\min} + r_1 \left(f^{\max} - f^{\min}\right) \tag{24}$$

$$V^i(t+1) = V^i(t) + f^i \left(X^i(t) - X^{best}(t)\right) \tag{25}$$

$$X^i(t+1) = X^i(t) + V^i(t+1) \tag{26}$$

where r_1 is a uniformly distributed random number in the range $[0, 1]$; $f^{\min}$ and $f^{\max}$ are the minimum and maximum allowable frequencies while f^i is the frequency for the i th bat. For the present ORPD problem, the values of $f^{\min}$ and $f^{\max}$ are set to 0 and 100, respectively as given in [66] and in [90], t is the current iteration number, X^{best} is the location (solution), that has the best fitness in the current population. At initialization, V^i is assumed to be 0.

A new solution for each bat can be generated locally through random walk as follows

$$X^{i,new}(t) = \begin{cases} X^{best}(t) + r_3 A^i(t) & if \quad r_2 > R^i(t) \\ X^r(t) + r_3 A^i(t) & else \end{cases} \tag{27}$$

where $R^i(t)$ is the pulse emission rate, $A^i(t)$ is the loudness, $r_2 \in [0,1]$, $r_3 \in [-1,1]$, $r \in [1,2,\ldots,N_b]$, $r \neq i$ is a randomly chosen integer, N_b is the number of bats or solutions, $X^r(t)$ is a randomly chosen solution in the current iteration, and different from the i th iteration.

The fitter solution is given by

$$X^i(t) = X^{i,new}(t), \quad if\, f\left(X^{i,new}(t)\right) < f\left(X^i(t)\right), \text{ and}$$
$$r_4 < A^i(t)\,\forall i, \quad i \in [1,2,\ldots,N_b] \tag{28}$$

where $r_4 \in [0,1]$ is a uniformly distributed random number.

Once the bat has found its prey, the loudness keeps on decreasing whereas the pulse rate emission keeps on increasing. The loudness A^i and the pulse emission rate R^i are iteratively updated as follows

$$A^i(t+1) = \alpha A^i(t) \tag{29}$$
$$R^i(t+1) = R^i(0)\left[1 - \exp(-\gamma t)\right] \tag{30}$$

where $A^i(0) \in [1,2]$ and $R^i(0) \in [0,1]$ are randomly generated within their respective limits. For the sake of simplicity, we set $\alpha = \gamma = 0.9$, as in [66] and in [90].

B. CHAOTIC BAT ALGORITHM

In standard BA algorithm, the loudness and pulse emission rate are two parameters that can be adjusted to control exploration and exploitation of the BA algorithm and hence to improve its performance. Furthermore, the replacement of randomness by chaotic maps in adjusting the aforementioned parameters has proved to be more effective [98].

In this paper, two variants of CBA are going to be considered:

1) CBA-III

In this CBA variant, the sinusoidal map has been used to adjust the loudness as follows [90], [98]:

$$A^i(t+1) = a\left\{A^i(t)\right\}^2 \sin\left(\pi A^i(t)\right) \tag{31}$$
$$\text{where } a = 2.3,$$
$$A^i(0) \in [0,1], \text{ and is randomly generated.}$$

2) CBA-IV

In this CBA variant, the sinusoidal map has been used to adjust the pulse rate emission as follows [98]:

$$R^i(t+1) = a\left\{R^i(t)\right\}^2 \sin\left(\pi R^i(t)\right) \tag{32}$$
$$\text{where } a = 2.3,$$
$$R^i(0) \in [0,1], \text{ and is randomly generated.}$$

IV. IMPLEMENTATION OF CBA TO ORPD PROBLEM

This section discusses the procedure of applying CBA to solve the ORPD problem.

A. CBA-III

Step 1: The initial position (bat solution)X^i and its velocity V^i of each bat are randomly generated within the specified limits. The bat solution X^i is a vector of the control variables of the ORPD problem such as generator voltages, tap setting transformers and shunt compensators.

For each i th bat, define pulse frequency f^i at X^i.

Initialize the pulse rate emission R^i and loudness A^i and specify their lower and upper limit values.

Step 2: Evaluate the fitness values of all the bats using the objective function of the problem defined in (6) or (7) or (8) in accordance with the results of New-Raphson power flow analysis [114].

Step 3: For each bat i, adjust the frequency f^i using (24).

Step 4: Update the velocity and position of each bat in accordance with (25) and (26) respectively.

Step 5: Generate a new solution by randomly walk based on (27).

Step 6: Select the best among the old and new solutions, with a probability $A^i(t)$, by using (28).

Step 7: Update the values of R^i and A^i in accordance with (30) and (31), respectively.

Step 8: Check for the equality constraints of the problem (12)-(13) and the inequality constraints (14)-(19) of the problem.

Step 9: Go to step 2 until stopping criteria is met.

B. CBA-IV

Step 1: The initial position (bat solution)X^i and its velocity V^i of each bat are randomly generated within the specified limits. The bat solution X^i is a vector of the control variables of the ORPD problem such as generator voltages, tap setting transformers and shunt compensators.

For each i th bat, define pulse frequency f^i at X^i.

Initialize the pulse rate emission R^i and loudness A^i and specify their lower and upper limit values.

Step 2: Evaluate the fitness values of all the bats using the objective function of the problem defined in (6) or (7) or (8) in accordance with the results of New-Raphson power flow analysis [114].

Step 3: For each bat i, adjust the frequency f^i using (24).

Step 4: Update the velocity and position of each bat in accordance with (25) and (26) respectively.

Step 5: Generate a new solution by randomly walk based on (27)

Step 6: Select the best among the old and new solutions, with a probability $A^i(t)$, by using (28).

Step 7: Update the values of A^i and R^i in accordance with (29) and (32), respectively.

Step 8: Check for the equality constraints of the problem (12)-(13) and the inequality constraints (14)-(19) of the problem.

Step 9: Go to step 2 until stopping criteria is met.

V. RESULTS AND DISCUSSION

In order to verify the performance and effectiveness of the CBA algorithm for ORPD problem, the standard BA and two different variants of CBA namely CBA-III and CBA-IV have been tested on standard IEEE 14-bus, IEEE 39 New England bus, IEEE 57-bus, IEEE 118-bus and IEEE 300-bus test systems for the minimization of the active power loss, total voltage deviations and voltage stability index objective functions. All these algorithms were implemented in MATLAB 2014a incorporated with MATPOWER 6.0 [115] and run on PC i.e Lenovo Ideapad 100-15IKB, 2.1 GHz Intel Pentium with 4GB RAM.

The population size is set to 120 ($N_b = 120$). The iteration numbers are set to 100 for IEEE 14-bus test system; 200 for IEEE 39 New England bus and IEEE 57-bus test systems; and 300 for IEEE 118-bus and IEEE 300-bus test systems. In this simulation, 30 independent test trial runs were carried out for all the test cases.

The performance capability of the CBA-IV for each objective function is indicated by bold faced results.

A. IEEE 14-BUS TEST SYSTEM

The IEEE 14-bus test system constists of five generators at bus 1, 2, 3, 6, and 8; 20 branches 17 branches are transmission lines and 3 branches are tap changing transformers; and 2 shunt VAR compensators installed at buses 9 and 14. In total, this system contains 10 control variables including five generators, three tap changing transformers and two shunt capacitors. Further details are found in [52], [58], [116].

The total demand of the system are

$P_{load} = 259MW$ (active power demand),

$Q_{load} = 73.5MVAR$ (reactive power demand).

The initial total generations and power losses are given by

$\sum PG = 272.39MW$ (active power of generators),

$\sum QG = 82.44MVAR$ (reactive power of generators),

$P_{LOSS} = 13.49MW$ (active power losses),

$Q_{LOSS} = -54.54MVAR$ (reactive power losses).

The control variable limits are listed in Table 1 in p.u. [58], [116].

TABLE 1. Control variable limits for IEEE 14-bus test systems [58], [116].

V_G^{max}	V_G^{min}	V_{PQ}^{max}	V_{PQ}^{min}	T_k^{max}	T_k^{min}	Q_C^{max}	Q_C^{min}
1.1	0.95	1.05	0.95	1.1	0.9	0.3	0

1) CASE 1: MINIMIZATION OF ACTIVE POWER LOSS

The standard BA, CBA-III and CBA-IV algorithms are implemented on the IEEE 14-bus test system for the minimization of the active power loss defined in (6) taking into account the penalty terms defined in (20).

Table 2 illustrates the best results yielded by the standard BA, CBA-III, CBA-IV and those yielded by other algorithms reported in the literature including DE [52], MTLA-DDE [116], MGBTLBO [58], SARGA [49], etc.

According to simulation results from Table 2, the best (minimum) power loss P_{Loss} offered by the CBA-IV algorithm is **12.2923 MW** which is also better than that obtained by the other algorithms compared with it.

Table 3 provides the comparison of statistical results such as the best active power loss (Best), the worst active power loss (Worst), the mean power loss (Mean), the standard deviation (Std) and **t**he percent of power loss reduction (% P save); yielded by different algorithms available in the literature for IEEE 14- bus system. From Table 3, it is seen that the CBA-IV algorithm outperforms other algorithms as it can achieve a power loss reduction of **8.88**% (from the initial power loss) compared with 8.75% by CBA-III, 8.74% by MGBTLBO [58], 8.7% by BA, 8.68% by JAYA [117], 8.3% by DE-ABC [118], 8.1% by IGSA-CSS [24], 8% by CSSP4 [119], 7.72% by DE [120], 7.717% by DEEP [121],7.05% by GSAPSO [54], 4.39% by MTLA-DDE [116], 3.86% by PSO [122], 2.03% by SARGA [49], 1.87% by PSO-AM [123], 1.86 by DE [52] and 1.68% by PSO-CM [123].

The outperformance of the CBA-IV over CBA-III and the standard BA is due to the sinusoidal map that has been employed to adjust the pulse rate emission as discussed in (32).

The convergence characteristics of active power loss (over 100 iterations) yielded by (the best solutions of) the standard BA, CBA-III and CBA-IV algorithms for IEEE 14-bus are shown in Fig.1. From this figure, it observed that the CBA-IV

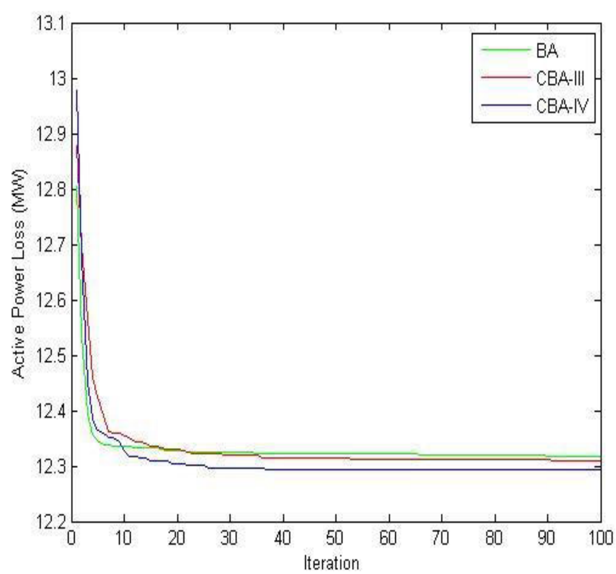

FIGURE 1. The convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 14-bus test power system with the minimization of P_{Loss} objective function.

TABLE 2. Optimal settings of control variables for IEEE 14-bus test systems with the minimization of P_{Loss}. Objective function.

Variable	Base Case (Initial)	MTLA-DDE [116]	MGB-TLBO [58]	DE [52]
Generator voltage (p.u)				
V_{G1}	1.06	1.07531	1.1	1.06
V_{G2}	1.045	1.05734	1.0791	1.0449
V_{G3}	1.01	1.02847	1.0485	1.0416
V_{G6}	1.07	0.05057	1.0552	1.1
V_{G8}	1.09	1.03535	1.0326	1.1
Transformer tap ratio (p.u)				
T_{4-7}	0.9467	1.08	1.01	1.06
T_{4-9}	0.9524	0.91	1.01	1.04
T_{5-6}	0.9091	1.01	1.03	1.1
Capacitor banks (p.u)				
Q_{C9}	0.18	0.3	0.3	0.18
Q_{C14}	0.18	0.08	0.07	0.06
P_{Loss} (MW)	13.49	12.8978	12.3106	13.239
TVD (p.u)	-	-	-	-
$L-$index (p.u)	-	-	-	-
Variable	**PSO [122]**	**GSAPSO [54]**	**IGSA-CSS [24]**	**JAYA [117]**
Generator voltage (p.u)				
V_{G1}	1.0917	1.1	1.1	1.10
V_{G2}	1.0862	1.076853	1.076578	1.086
V_{G3}	1.0876	1.046118	1.046787	1.057
V_{G6}	1.0577	1.025647	1.062305	1.10
V_{G8}	1.0278	1.096356	1.097861	1.092
Transformer tap ratio (p.u)				
T_{4-7}	1.0039	0.96	1.02	1.045
T_{4-9}	1.0324	1.1	0.94	0.90
T_{5-6}	1.0083	1.04	1.00	1.003
Capacitor banks (p.u)				
Q_{C9}	0.0513	0.045	0.050	0.18
Q_{C14}	0.1920	-	-	0.18
P_{Loss} (MW)	12.9691	12.44901	12.39706	12.3192
TVD (p.u)	-	-	-	-
$L-$index (p.u)	-	-	-	-

TABLE 2. *(Continued.)* Optimal settings of control variables for IEEE 14-bus test systems with the minimization of P_{Loss}. Objective function.

Variable	Base Case (Initial)	BA	CBA-III	CBA-IV
Generator voltage (p.u)				
V_{G1}	1.06	1.0990	1.0981	1.0921
V_{G2}	1.045	1.0325	1.0832	1.0884
V_{G3}	1.01	1.0123	1.0587	1.0558
V_{G6}	1.07	1.0631	1.0527	1.0325
V_{G8}	1.09	1.0368	1.0991	1.0951
Transformer tap ratio (p.u)				
T_{4-7}	0.9467	0.9562	1.0055	0.9746
T_{4-9}	0.9524	1.0251	1.0059	1.0676
T_{5-6}	0.9091	0.9730	1.0679	1.0599
Capacitor banks (p.u)				
Q_{C9}	0.18	0.0863	0.1597	0.2208
Q_{C14}	0.18	0.6490	0.0827	0.0786
P_{Loss} (MW)	13.49	12.3171	12.3092	**12.2923**
TVD (p.u)	-	0.06108	0.05489	0.05308
$L-$index (p.u)	-	0.03769	0.03678	0.03642

gives better convergence characteristics than CBA-III and BA algorithms.

2) CASE 2: MINIMIZATION OF TOTAL VOLTAGE DEVIATION

For the present case, the minimization of the Total Voltage Deviations (TVD) discussed in (7) is considered as the objective function together with the penalty factors defined in (20).

The best results yielded by the CBA algorithm are tabulated in Table 4 together with the results of the CBA-III, BA and IGSA-CSS [24]. According to Table 4, it can be observed that the CBA-IV yielded a TVD value of **0.0330** compared with the results 0.0332, 0.0336 and 0.0339 achieved by CBA-III, CBA and IGSA-CSS [24] respectively. It is also recognized from Table 5 that an improvement of **31.10%** in TVD has been achieved by using CBA-IV in comparison to 30.69% with CBA-III, 29.85% with BA and 29.22% with IGSA-CSS [24]. The Fig.2 illustrates the comparison of the convergence characteristics of TVD for IEEE 14-bus system. From this figure, it is clear that the convergence characteristics of TVD for the CBA-IV outperforms those from the compared algorithms.

TABLE 3. Statistical results for IEEE 14-bus test system with the minimization of P_{Loss}. Objective function.

Algorithm	Best (MW)	Worst (MW)	Mean (MW)	Std	% Psave
DE [52]	13.239	13.275	13.25	0.000161	1.86
MTLA-DDE [116]	12.8978	12.8986	12.8982	0.000006486	4.39
MGB-TLBO [58]	12.3106	12.3111	12.3106	0.0000086	8.74
GSAPSO [54]	12.44901	-	-	-	7.05
IGSA-CSS [24]	12.39706	12.90281	12.46443	0.094	8.1
SARGA [49]	13.21643	13.23891	13.22317	0.000024	2.03
DE-ABC [118]	12.3712	12.3712	12.3712	7.29E-08	8.3
JAYA [117]	12.3192	-	-	-	8.68
PSO-CM [123]	13.2634	13.3142	13.2671	0.00009	1.68
PSO-AM [123]	13.2371	13.2550	13.2395	0.00006	1.87
DEEP [121]	12.4489	12.4507	12.4494	0.0005	7.717
CSSP4 [119]	12.4087	12.4974	12.4393	0.228	8
DE [120]	12.4486	12.4496	12.4486	0.0018	7.72
PSO [122]	12.9691	-	-	-	3.86
CBA	12.3171	12.3456	12.3230	0.0099	8.7
CBA-III	12.3092	12.3212	12.3161	0.0034	8.75
CBA-IV	**12.2923**	12.3098	12.3042	0.0046	**8.88**

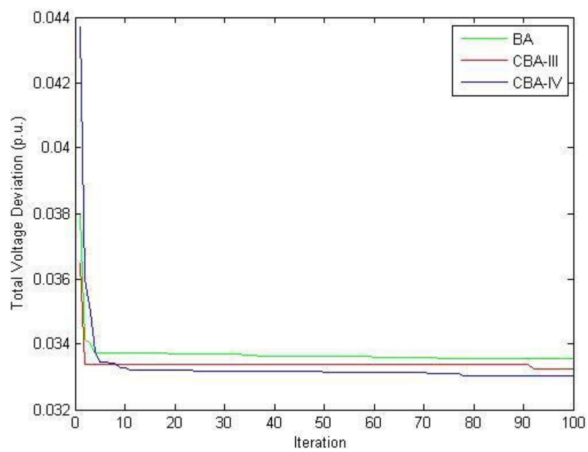

FIGURE 2. The convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 14-bus test power system with the minimization of TVD bjective function.

3) CASE STUDY 3: IMPROVEMENT OF VOLTAGE STABILITY INDEX

In this case, the CBA algorithm is employed to minimize the Voltage Stability Index (VSI) discussed in (8) as the objective function together with the penalty terms defined in (20).

TABLE 4. Optimal settings of control variables for IEEE 14-bus test systems with the minimization of TVD objective function.

Variable	IGSA-CSS [24]	BA	CBA-III	CBA-IV
Generator voltage (p.u)				
V_{G1}	1.060879	0.9993	0.9998	0.9958
V_{G2}	1.040856	1.0004	0.9969	1.0189
V_{G3}	1.011222	1.0006	0.9972	1.0008
V_{G6}	1.016776	0.9999	0.9945	1.0102
V_{G8}	1.035129	0.9993	1.0015	1.0501
Transformer tap ratio (p.u)				
T_{4-7}	1.04	1.0307	1.0581	1.0121
T_{4-9}	0.9	1.0455	0.9085	1.0975
T_{5-6}	0.92	0.9966	0.9457	1.0370
Capacitor banks (p.u)				
Q_{C9}	0.050	0.2308	0.1542	0.0903
Q_{C14}	-	0.2168	0.1458	0.0637
P_{Loss} (MW)	-	16.2499	16.0172	15.9506
TVD **(p.u)**	0.03390	0.0336	0.0332	**0.0330**
$L-$ index (p.u)	-	0.0435	0.0425	0.0414

TABLE 5. Statistical results for IEEE 14-bus test system with the minimization of TVD objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std	% TVD Improve
IGSA-CSS [24]	0.03390	0.09056	0.04583	0.017	29.22
BA	0.0336	0.0515	0.0410	0.0058	29.85
CBA-III	0.0332	0.0489	0.0399	0.0054	30.69
CBA-IV	**0.0330**	0.0425	0.0368	0.0029	31.10

The table 6 shows the best results obtained using the CBA-IV alongside with the CBA-III and the BA. From this table, it can be seen that an $L-$ index value of **0.0170** is obtained by the CBA-IV compared to 0.0174 with the CBA-III and 0.0179 with the BA. The statistical results for the present case are summarized in Table 7. According to Table 7, it is found that the CBA-IV also provides the smallest Best, Mean and Std values than the CBA-III and the BA. The comparison of convergence characteristics of VSI for IEEE 14-bus system is depicted in Fig.3. According to this figure, it can be recognized that the convergence

TABLE 6. Optimal settings of control variables for IEEE 14-bus test systems with the minimization of VSI objective function.

Variable	BA	CBA-III	CBA-IV
Generator voltage (p.u)			
V_{G1}	1.0400	0.9895	1.100
V_{G2}	1.0292	0.9600	1.0964
V_{G3}	0.9779	1.0092	0.9270
V_{G6}	1.0344	1.0212	1.0187
V_{G8}	1.0337	1.0249	1.0003
Transformer tap ratio (p.u)			
T_{4-7}	0.9649	0.9639	0.9975
T_{4-9}	1.0151	1.0576	1.0413
T_{5-6}	0.9836	0.9399	0.9495
Capacitor banks (p.u)			
Q_{C9}	0.1416	0.0156	0.0572
Q_{C14}	0.2630	0.2665	0.0903
P_{Loss} (MW)	18.3607	17.9569	17.6910
TVD (p.u)	0.07563	0.07348	0.07159
$L-$index **(p.u)**	0.0179	0.0174	**0.0170**

TABLE 7. Statistical results for IEEE 14-bus test system with the minimization of VSI objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std
BA	0.0179	0.0204	0.0189	7.8736×10^{-4}
CBA-III	0.0174	0.0187	0.0179	3.8850×10^{-4}
CBA-IV	**0.0170**	0.0182	0.0175	3.6334×10^{-4}

characteristics from the CBA-IV outperforms the convergence characteristics from the CBA-III and the BA.

B. IEEE 39 NEW ENGLAND BUS TEST SYSTEM

The IEEE 39 New England bus test system comprises 10 generators at the buses 30, 31, 32, 33, 34, 35, 36, 37, 38 and 39; 46 lines; 5 tap changing transformers at lines 12-11, 10-32, 22-35, 2-30 and 19-20; and 6 shunt VAR compensators installed at buses 1, 5, 10, 14, 22 and 27. Totally, the IEEE 39-bus test system contains 21 control variables including ten generators, five tap changing transformers and six shunt capacitors. See [124] and [125] for further details.

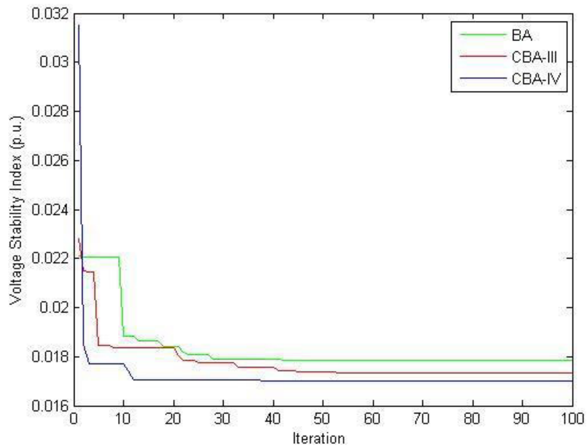

FIGURE 3. The convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 14-bus test power system with the minimization of VSI objective function.

TABLE 8. Control variable limits for IEEE 39-bus test systems [124].

V_G^{max}	V_G^{min}	V_{PQ}^{max}	V_{PQ}^{min}	T_k^{max}	T_k^{min}	Q_C^{max}	Q_C^{min}
1.1	0.9	1.1	0.9	1.07	0.93	0.25	0

The control variable limits are listed in Table 8 in p.u. [124].

1) CASE 1: MINIMIZATION OF ACTIVE POWER LOSS

Table 9 presents the best results yielded by different algorithms for the minimization of the active power loss of the IEEE 39-bus test system. It can be observed that the CBA-IV gives the best active power loss which is **35.9971 MW**. The comparative statistical results are illustrated in Table 10. It can be seen from Table 6 that a **17.44 %** decrease (from the initial power loss of 43.6 MW) in active power loss is achieved with the CBA-IV algorithm, which performs better than other algorithms compared with it. The comparative convergence characteristics of active power loss over 200 iterations yielded by the standard BA, CBA-III and CBA-IV are presented in Fig.4. It can be observed from Fig.4 that the CBA-IV gives better convergence characteristics than the CBA-III and BA algorithms.

2) CASE 2: MINIMIZATION OF TOTAL VOLTAGE DEVIATION

Table 11 presents the solution of the ORPD problem obtained by using the CBA-IV algorithm in order to minimize the TVD of the IEEE 39-bus system. It is seen that the CBA-IV out-performs other algorithms compared with because the CBA-IV provides a TVD value of **0.0739** against 0.0796 with the CBA-III and 0.0825 with the BA. The statistical analysis of the present case is illustrated in Table 12. It is observed that the CBA-IV offers the minimum Best, Mean and Std values in comparison to the CBA-III and the BA. In addition, Fig.5 depicts the comparison of the convergence characteristics for TVD obtained by CBA-IV with the other approaches.

TABLE 9. Optimal settings of control variables for IEEE 39-bus test systems with the minimization of P_{Loss}. Objective function.

Variable	Base Case (Initial)	PSO [122]	BA	CBA-III	CBA-IV
Generator voltage (p.u)					
V_{G30}	1.027	1.0496	1.0906	1.0668	1.0810
V_{G31}	1.023	1.0888	1.0999	1.0968	1.0999
V_{G32}	1.033	1.0931	1.0998	1.0989	1.1000
V_{G33}	1.046	1.0431	1.0943	1.0857	1.0952
V_{G34}	1.026	1.0944	1.0956	1.0941	1.0999
V_{G35}	1.068	1.0268	1.1000	1.0976	1.1000
V_{G36}	1.090	1.0856	1.0989	1.1000	1.0992
V_{G37}	1.031	1.0925	1.1000	1.1000	1.1000
V_{G38}	1.065	0.9767	1.0992	1.0988	1.0996
V_{G39}	1.005	1.0435	1.1000	1.1000	1.1000
Transformer tap ratio (p.u)					
T_{12-11}	0	0.9917	1.0250	1.0461	1.0337
T_{10-32}	0	1.0394	1.0700	1.0656	1.0703
T_{22-35}	0	1.0304	1.0034	0.9792	1.0072
T_{2-30}	0	1.0039	1.0478	1.0591	1.0485
T_{19-20}	0	0.9857	1.0700	1.0645	1.0701
Capacitor banks (p.u)					
Q_{C1}	1.000	0.1710	0.1985	0.2392	0.2092
Q_{C5}	1.000	0.1428	0.1266	0.0729	0.1188
Q_{C11}	1.000	0.1248	0.1985	0.2392	0.2092
Q_{C14}	1.000	0.1094	0.1266	0.0729	0.1188
Q_{C22}	1.000	0.0841	0.1985	0.2392	0.2092
Q_{C27}	1.000	0.1449	0.1985	0.2392	0.2092/
P_{Loss} **(MW)**	43.6	41.8892	36.7317	36.3125	**35.9971**
TVD (p.u)	-	-	0.275	0.271	0.269
$L-$ index (p.u)	-	-	0.0829	0.0824	0.0821

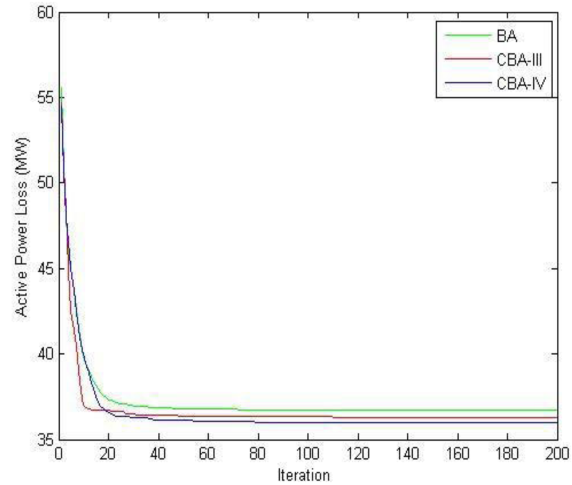

FIGURE 4. The convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 39-bus test power system with the minimization of P_{Loss} objective function.

TABLE 10. Statistical results for IEEE 39-bus test system with the minimization of P_{Loss}. Objective function.

Algorithm	Best (MW)	Worst (MW)	Mean (MW)	Std	% Psave
PSO [122]	41.8892	-	-	-	3.92
CBA	36.7317	38.2621	36.8847	0.3309	15.75
CBA-III	36.3125	37.7435	36.4527	0.3272	16.71
CBA-IV	35.9971	36.6986	36.1028	0.2122	**17.44**

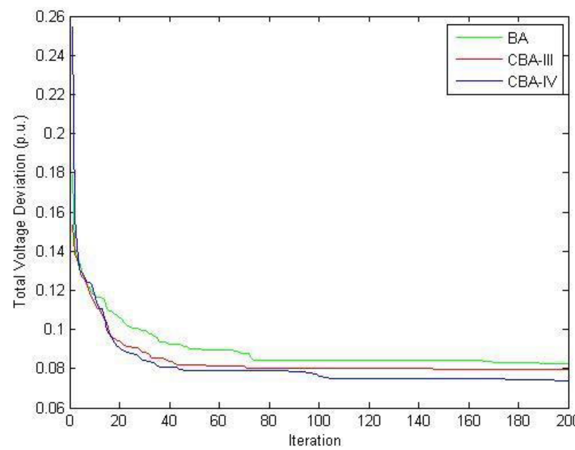

FIGURE 5. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 39-bus test power system with the minimization of TVD objective function.

3) CASE STUDY 3: IMPROVEMENT OF VOLTAGE STABILITY INDEX

The solution of the ORPD problem for minimizing the VSI of the IEEE 39-bus system by using the CBA-IV algorithm is shown in Table 13. It is observed that the CBA-IV out-performs other algorithms compared with it because the CBA-IV offers an $L-$ index value of **0.0113** against 0.0130 with the CBA-III and 0.0136 with the BA. Table 14 shows the statistical results for this case. Furthermore,

TABLE 11. Optimal settings of control variables for IEEE 39-bus test systems with the minimization of TVD objective function.

Variable	Base Case (Initial)	BA	CBA-III	CBA-IV
Generator voltage (p.u)				
V_{G30}	1.027	0.9395	1.0286	0.9423
V_{G31}	1.023	1.0999	1.0723	0.9124
V_{G32}	1.033	0.9995	0.9782	1.0483
V_{G33}	1.046	1.0690	1.0084	0.9723
V_{G34}	1.026	0.9474	0.9797	0.9983
V_{G35}	1.068	0.9151	1.0668	0.9011
V_{G36}	1.090	0.9740	0.9279	0.9866
V_{G37}	1.031	0.9001	0.9512	0.9588
V_{G38}	1.065	0.9468	0.9362	1.0161
V_{G39}	1.005	1.0995	1.0077	0.9772
Transformer tap ratio (p.u)				
T_{12-11}	0	0.9833	0.9731	0.9318
T_{10-32}	0	1.0559	0.9972	0.9017
T_{22-35}	0	0.9989	0.9457	0.9061
T_{2-30}	0	0.9563	1.0325	1.0105
T_{19-20}	0	0.9124	0.9636	0.9193
Capacitor banks (p.u)				
Q_{C1}	1.000	0.0533	0.2198	0.1234
Q_{C5}	1.000	0.1485	0.0554	0.2607
Q_{C11}	1.000	0.0533	0.2198	0.1234
Q_{C14}	1.000	0.1485	0.0554	0.2607
Q_{C22}	1.000	0.0533	0.2198	0.1234
Q_{C27}	1.000	0.0533	0.2198	0.1234
P_{Loss} (MW)	43.6	53.74922	53.4682	51.6495
TVD **(p.u)**	-	0.0825	0.0796	**0.0739**
$L-$ index (p.u)	-	0.0880	0.0874	0.0868

Fig.6 illustrates the comparison of the convergence characteristics for VSI obtained by CBA-IV with the other methods.

TABLE 12. Statistical results for IEEE 39-bus test system with the minimization of TVD objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std
CBA	0.0825	0.0967	0.0864	0.0038
CBA-III	0.0796	0.0921	0.0846	0.0034
CBA-IV	**0.0739**	0.0864	0.0763	0.0027

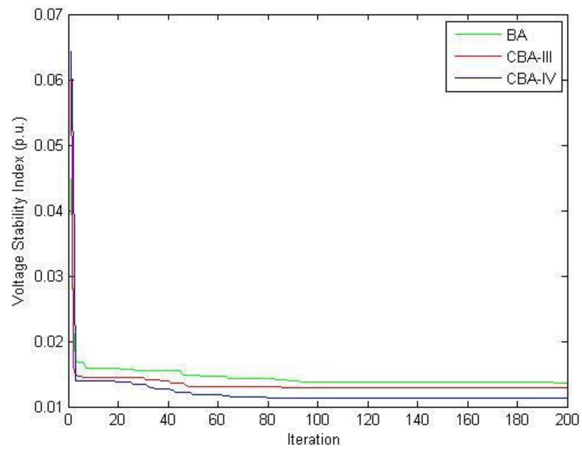

FIGURE 6. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 39-bus test power system with the minimization of VSI objective function.

C. IEEE 57 BUS TEST SYSTEM

The IEEE 57 bus test system comprises 7 generators at the buses 1,2,3,6,8,9 and 12; 80 transmission lines; 15 tap changing transformers and 3 shunt VAR compensators installed at buses 18, 25 and 53. Totally, the IEEE 57-bus test system contains 25 control variables including 7 generators, 15 tap changing transformers and 3 shunt capacitors.

Refer to [53], [63] and [118] for further details.

The total demand of the system are

$P_{load} = 1250.8MW$ (active power demand),

$Q_{load} = 336.4MVAR$ (reactive power demand).

The initial total generations and power losses are given by

$\sum PG = 1279.26MW$ (active power of generators),

$\sum QG = 345.45MVAR$ (reactive power of generators),

$P_{LOSS} = 28.462MW$ (active power losses),

$Q_{LOSS} = -124.27MVAR$ (reactive power losses).

The control variable limits are listed in Table 15 in p.u. [118].

1) CASE 1: MINIMIZATION OF ACTIVE POWER LOSS

Table 16 illustrates the best results obtained by different algorithms to minimize the active power loss of the IEEE 57-bus test system. From Table 16, the CBA-IV algorithm leads to **21.9627 MW** active power loss which is better than the active power losses obtained by the other compared algorithms. The comparative statistical results are illustrated

TABLE 13. Optimal settings of control variables for IEEE 39-bus test systems with the minimization of VSI objective function.

Variable	Base Case (Initial)	BA	CBA-III	CBA-IV
Generator voltage (p.u)				
V_{G30}	1.027	0.9445	1.0346	0.9418
V_{G31}	1.023	1.0350	0.9322	1.0642
V_{G32}	1.033	1.0062	1.0853	1.0396
V_{G33}	1.046	0.9684	0.9507	1.0288
V_{G34}	1.026	0.9898	1.0492	1.0595
V_{G35}	1.068	1.0183	1.0566	0.9294
V_{G36}	1.090	0.9685	1.0177	1.0481
V_{G37}	1.031	1.0649	1.0512	0.9604
V_{G38}	1.065	1.0839	1.0534	0.9323
V_{G39}	1.005	1.0428	1.0981	1.0565
Transformer tap ratio (p.u)				
T_{12-11}	0	0.9863	1.0483	0.9484
T_{10-32}	0	1.0249	0.9787	1.0282
T_{22-35}	0	1.0569	1.0299	0.9397
T_{2-30}	0	0.9817	1.0213	0.9326
T_{19-20}	0	0.9496	0.9689	0.9570
Capacitor banks (p.u)				
Q_{C1}	1.000	0.1522	0.2214	0.0093
Q_{C5}	1.000	0.0773	0.0577	0.2351
Q_{C11}	1.000	0.1522	0.2214	0.0093
Q_{C14}	1.000	0.0773	0.0577	0.2351
Q_{C22}	1.000	0.1522	0.2214	0.0093
Q_{C27}	1.000	0.1522	0.2214	0.0093
P_{Loss} (MW)	43.6	56.2912	55.5923	55.1812
TVD (p.u)	-	0.2842	0.2809	0.2776
$L-$ index **(p.u)**	-	0.0136	0.0130	**0.0113**

in Table 17. It can be seen from Table 17 that a **22.84 %** reduction (from the initial loss of 28.462 MW) in active power loss is achieved with the CBA-IV algorithm, which performs better than other algorithms. The comparative con-vergence characteristics of active power loss over 200 iterations yielded by the standard BA, CBA-III and CBA-IV are presented in Fig.7. It can be observed from Fig. 7 that the CBA-IV gives better convergence characteristics than the CBA-III and BA algorithms.

TABLE 14. Statistical results for IEEE 39-bus test system with the minimization of VSI objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std
CBA	0.0136	0.0161	0.0147	7.3272×10^{-4}
CBA-III	0.0130	0.0156	0.0140	7.1840×10^{-4}
CBA-IV	**0.0113**	0.0142	0.0124	7.8366×10^{-4}

TABLE 15. Control variable limits for IEEE 57-bus test systems [118].

V_G^{max}	V_G^{min}	V_{PQ}^{max}	V_{PQ}^{min}	T_k^{max}	T_k^{min}	Q_C^{max}	Q_C^{min}
1.1	0.9	1.1	0.9	1.1	0.9	0.2	0

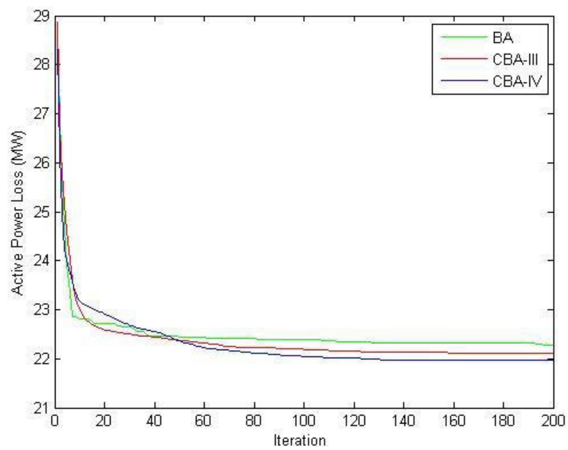

FIGURE 7. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 57-bus test power system with the minimization of P_{Loss} objective function.

2) CASE 2: MINIMIZATION OF TOTAL VOLTAGE DEVIATION

The best results of TVD minimization for IEEE 57-bus system achieved by the CBA-IV, CBA-III and CBA algorithms are tabulated in Table 18. According to this table, it can be seen that the CBA-IV outperforms other algorithms compared with it as the CBA-IV gives a TVD value of **0.6399** against 0.6413 with CBA-III, 0.6434 with BA, 0.6501 with NGBWCA [127], 0.6634 with ALC-PSO [130] and 0.6982 with OGSA [128]. The statistical results obtained by different methods are presented in Table 19. According to this table, it can be seen that the CBA-IV is able to enhance the TVD value by **48.13%** with respect to initial TVD value, in comparison to 48.01% with CBA-III, 47.84% with BA,

TABLE 16. Optimal settings of control variables for IEEE 57-bus test systems with the minimization of P_{Loss}. Objective function.

Variable	CBA-IV	CBA-III	BA	ABC [126]
Generator voltage (p.u)				
V_{G1}	1.0964	1.0919	1.0989	1.0808
V_{G2}	1.0999	1.0905	1.0960	1.0637
V_{G3}	1.0906	1.0903	1.0927	1.0467
V_{G6}	1.0838	1.0841	1.0863	1.0337
V_{G8}	1.1000	1.0902	1.0933	1.0464
V_{G9}	1.0869	1.0886	1.0873	1.0253
V_{G12}	1.0822	1.0825	1.0839	1.0526
Transformer tap ratio (p.u)				
T_{4-18}	0.9002	1.0249	0.9071	0.97
T_{4-18}	0.9005	0.9006	0.9067	0.94
T_{21-20}	0.9958	1.0481	0.9776	0.97
T_{24-25}	1.0086	0.9849	1.0257	0.97
T_{7-29}	0.9061	0.9997	0.9703	0.94
T_{34-32}	0.9990	1.0160	1.0192	0.93
T_{11-41}	0.9087	0.9001	0.9620	0.90
T_{15-45}	0.9003	0.9017	0.9101	0.99
T_{14-46}	0.9002	0.9030	0.9135	0.96
T_{10-51}	0.9123	0.9175	0.9454	0.98
T_{13-49}	0.9002	0.9995	0.9007	0.93
T_{11-43}	0.9000	0.9738	0.9026	0.92
T_{40-56}	1.0267	1.0549	1.0240	0.96
T_{39-57}	0.9729	1.0119	0.9742	0.94
T_{9-55}	0.9220	0.9035	0.9853	0.94
Capacitor banks (p.u)				
Q_{C18}	0.1827	0.0826	0.1053	0.15
Q_{C25}	0.1335	0.0529	0.0573	0.17
Q_{C53}	0.0858	0.1806	0.0853	0.13
P_{Loss} (MW)	**21.9627**	22.0162	22.2716	23.9666
TVD (p.u)	1.1661	1.1668	1.1674	-
$L-$ index (p.u)	0.3508	0.3639	0.3817	-

TABLE 16. *(Continued.)* Optimal settings of control variables for IEEE 57-bus test systems with the minimization of P_{Loss}. Objective function.

Variable	NGBWCA [127]	MICA-IWO [63]	CKHA [59]	PSO-ICA [6]
Generator voltage (p.u)				
V_{G1}	1.0600	1.06	1.0600	1.0395
V_{G2}	1.0591	1.05841	1.0590	1.0259
V_{G3}	1.0492	1.04568	1.0487	1.077
V_{G6}	1.0399	1.03969	1.0431	0.9982
V_{G8}	1.0586	1.06	1.0600	1.0158
V_{G9}	1.0461	1.02737	1.0447	0.985
V_{G12}	1.0413	1.03499	1.0410	0.9966
Transformer tap ratio (p.u)				
T_{4-18}	0.9712	1.01	0.9179	0.9265
T_{4-18}	0.9243	0.95	1.0256	0.9532
T_{21-20}	0.9123	1.02	0.9000	1.0165
T_{24-26}	0.9001	1.01	0.9020	1.0071
T_{7-29}	0.9112	0.96	0.9104	0.9414
T_{34-32}	0.9004	0.98	0.9005	0.9555
T_{11-41}	0.9128	0.9	0.9000	0.9032
T_{15-45}	0.9000	0.95	0.9000	0.9356
T_{14-46}	1.0218	0.94	1.0797	0.9172
T_{10-51}	0.9902	0.95	0.9887	0.9337
T_{13-49}	0.9568	0.91	0.9914	0.9
T_{11-43}	0.9000	0.95	0.9000	0.9206
T_{40-56}	0.9000	0.1	0.9002	1.0042
T_{39-57}	1.0118	0.97	1.0173	1.0297
T_{9-55}	1.0000	0.96	1.0023	0.9294
Capacitor banks (p.u)0.1				
Q_{C18}	0.0914	0.1	0.0994	0.099846
Q_{C25}	0.0587	0.059	0.0590	0.10
Q_{C53}	0.0634	0.063	0.0630	0.10
P_{Loss} (MW)	23.27	24.25684	23.38	25.5856
TVD (p.u)	-	-	-	-
$L-$ index (p.u)	-	-	-	-

TABLE 16. *(Continued.)* **Optimal settings of control variables for IEEE 57-bus test systems with the minimization of P_{Loss}. Objective function.**

Variable	SOA [53]	BBO [57]	OGSA [128]	GSA [129]
Generator voltage (p.u)				
V_{G1}	1.06	1’06	1.06	1.060000
V_{G2}	1.0580	1.0504	1.0594	1.060000
V_{G3}	1.0437	1.0440	1.0492	1.060000
V_{G6}	1.0352	1.0376	1.0433	1.008102
V_{G8}	1.0548	1.0550	1.0600	1.054955
V_{G9}	1.0369	1.0229	1.0450	1.009801
V_{G12}	1.0336	1.0323	1.0407	1.018591
Transformer tap ratio (p.u)				
T_{4-18}	1.00	0.96693	0.9000	1.100000
T_{4-18}	0.96	0.99022	0.9947	1.082634
T_{21-20}	1.01	1.0120	0.9000	0.921987
T_{24-26}	1.01	1.0087	0.9001	1.016731
T_{7-29}	0.97	0.97074	0.9111	0.996262
T_{34-32}	0.97	0.96869	09000	1.100000
T_{11-41}	0.90	0.90082	09000	1.074625
T_{15-45}	0.97	0.96602	09000	0.954340
T_{14-46}	0.95	0.95079	1.0464	0.937722
T_{10-51}	0.96	0.96414	0.9875	1.016790
T_{13-49}	0.92	0.92462	0.9638	1.052572
T_{11-43}	0.96	0.95022	09000	1.100000
T_{40-56}	1.00	0.99666	09000	0.979992
T_{39-57}	0.96	0.96289	1.0148	1.024653
T_{9-55}	0.97	0.96001	0.9830	1.037316
Capacitor banks (p.u)				
Q_{C18}	0.09984	0.09782	0.0682	0.078254
Q_{C25}	0.05808	0.05904	0.0590	0.005869
Q_{C53}	0.06288	0.06288	0.0630	0.046872
P_{Loss} (MW)	24.26548	24.544	23.43	23.461194
TVD (p.u)	-	-	1.1907	-
$L-$ index (p.u)	-	-	0.4120	-

TABLE 16. *(Continued.)* **Optimal settings of control variables for IEEE 57-bus test systems with the minimization of P_{Loss}. Objective function.**

Variable	MFO [4]	ALC-PSO [130]	MGBICA [131]	CPVEIHBMO [132]
Generator voltage (p.u)				
V_{G1}	1.06000	1.0600	1.06	1.076
V_{G2}	1.05870	1.0593	1.0492	1.054
V_{G3}	1.04690	1.0491	1.0388	1.035
V_{G6}	1.04210	1.0432	1.0353	1.013
V_{G8}	1.06000	1.0600	1.0558	1.044
V_{G9}	1.04230	1.0451	1.0212	1.093
V_{G12}	1.03730	1.0411	1.0295	0.989
Transformer tap ratio (p.u)				
T_{4-18}	0.95011	0.9611	0.95	1.029
T_{4-18}	1.00760	0.9109	1	1.034
T_{21-20}	1.00630	0.9000	1.01	0.989
T_{24-26}	1.00760	0.9004	1.02	1.016
T_{7-29}	0.97523	0.9106	0.99	0.994
T_{34-32}	0.97218	0.9000	0.93	1.100
T_{11-41}	0.90000	0.9000	0.91	1.072
T_{15-45}	0.97186	0.9000	0.97	1.000
T_{14-46}	0.95355	1.0275	0.96	0.987
T_{10-51}	0.96736	0.9876	0.96	0.933
T_{13-49}	0.92788	0.9756	0.92	1.029
T_{11-43}	0.96406	0.9000	095	1.0923
T_{40-56}	0.99980	0.9000	1.03	0.996
T_{39-57}	0.96060	1.0121	0.98	1.0645
T_{9-55}	0.97899	0.9944	0.99	0.9847
Capacitor banks (p.u)				
Q_{C18}	0.099968	0.0994	0.04	0.0653
Q_{C25}	0.059000	0.0590	0.06	0.0084
Q_{C53}	0.063000	0.0630	0.03	0.0763
P_{Loss} (MW)	24.25293	23.39	24.8863	22.78
TVD (p.u)	-	1.2697	1.0283	-
$L-$ index (p.u)	-	-	-	-

TABLE 17. Statistical results for IEEE 57-bus test system with the minimization of P_{Loss}. Objective function.

Algorithm	Best (MW)	Worst (MW)	Mean (MW)	Std	% Psave
SOA [53]	24.26548	24.28046	24.27078	4.2081E-005	14.7443
MICA-IWO [63]	24.25684	24.28364	24.27561	2.3361E-004	14.7746
ALC-PSO [130]	23.39	23.44	23.41	82×10^{-5}	17.82
SR-DE [133]	23.3550	24.1656	23.4392	0.1458	17.94
BA	22.030	23.2109	22.6017	0.3482	22.6
CBA-III	22.0162	22.9062	22.4721	0.2735	22.65
CBA-IV	21.9627	22.7961	22.0853	0.2241	**22.84**

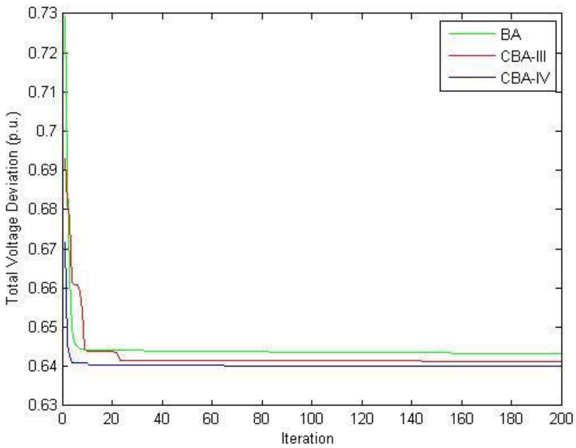

FIGURE 8. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 57-bus test power system with the minimization of TVD objective function.

47.29% with NGBWCA [127], 46.22% with ALC-PSO [130] and 43.40% with OGSA [128].

Moreover, the comparison of the convergence characteristics for TVD obtained by CBA-IV with the other methods is shown in Fig.8.

3) CASE STUDY 3: IMPROVEMENT OF VOLTAGE STABILITY INDEX

Table 20 presents the best results of minimization of the VSI for IEEE 57-bus system by using the CBA-IV algorithm. It is seen that the CBA-IV outperforms other algorithms compared with it, because the CBA-IV provides an $L-$ index value of **0.1608** against 0.1789 with CBA-III, 0.19001 with OGSA [128], 0.190709 with SOA [53] and 0.1917 with BA. Table 21 sums up the statistical results performed by different algorithms for the present case.

Besides, the comparison of the convergence characteristics for VSI yielded by CBA-IV with the other approaches is illustrated in Fig.9. According to this figure, it can be recognized that the CBA-IV convergence characteristic outperforms the CBA-III as well as the BA convergence characteristics.

TABLE 18. Optimal settings of control variables for IEEE 57-bus test systems with the minimization of TVD Objective function.

Variable	CBA-IV	CBA-III	BA	OGSA [128]	NGBWCA [127]
Generator voltage (p.u)					
V_{G1}	1.0014	0.9966	1.0013	1.0138	1.0151
V_{G2}	1.0010	0.9983	0.9995	0.9608	0.9810
V_{G3}	1.0002	0.9948	1.0008	1.0173	1.0002
V_{G6}	0.9995	0.9998	0.9996	0.9898	1.0039
V_{G8}	0.9998	1.0026	1.0006	1.0362	1.0198
V_{G9}	1.0003	0.9991	0.9997	1.0241	1.0254
V_{G12}	0.9994	1.0001	0.9991	1.0136	1.0081
Transformer tap ratio (p.u)					
T_{4-18}	0.9638	0.9443	0.9524	0.9833	1.0185
T_{4-18}	0.9172	1.0247	1.0919	0.9503	0.9601
T_{21-20}	0.9997	0.9874	0.9145	0.9523	0.9458
T_{24-25}	0.9418	1.0211	0.9848	1.0036	0.9919
T_{7-29}	1.0699	0.9584	0.9439	0.9778	0.9951
T_{34-32}	0.9352	1.0910	1.0324	0.9146	0.9000
T_{11-41}	1.0632	1.0773	0.9868	0.9454	0.9622
T_{15-45}	1.0644	1.0919	1.0874	0.9265	0.9058
T_{14-46}	0.9109	1.0915	1.0031	0.9960	0.9764
T_{10-51}	0.9224	0.9388	0.9938	1.0386	1.0600
T_{13-49}	1.0108	0.9777	0.9899	0.9060	0.9100
T_{11-43}	0.9982	1.0160	1.0118	0.9234	0.9302
T_{40-56}	1.0809	1.0518	1.0523	0.9871	0.9770
T_{39-57}	1.0111	0.9294	1.0352	1.0132	1.0271
T_{9-55}	0.9112	1.0521	0.9454	0.9372	0.9000
Capacitor banks (p.u)					
Q_{C18}	0.0992	0.219	0.1491	0.0463	0.0550
Q_{C25}	0.1393	0.998	0.0203	0.0590	0.0590
Q_{C53}	0.0191	0.0865	0.1910	0.0628	0.0381
P_{Loss} (MW)	27.0982	28.1872	28.8669	32.34	29.20
TVD (p.u)	**0.6399**	0.6413	0.6434	0.6982	0.6501
$L-$ index (p.u)	0.4246	0.4369	0.4472	0.5123	-

TABLE 18. ***(Continued.)*** **Optimal settings of control variables for IEEE 57-bus test systems with the minimization of TVD Objective function.**

Variable	ALC-PSO [130]	MGBICA [131]	CKHA [59]
Generator voltage (p.u)			
V_{G1}	1.0172	1.0555	1..0236
V_{G2}	0.9819	1.0339	1.0121
V_{G3}	1.0044	1.0086	1.0030
V_{G6}	1.0050	1.0067	1.0052
V_{G8}	1.0208	1.0462	1.0180
V_{G9}	1.0258	1.0067	1.0427
V_{G12}	1.0080	1.0059	1.0030
Transformer tap ratio (p.u)			
T_{4-18}	1.0197	0.93	0.9650
T_{4-18}	0.9609	1.01	0.9877
T_{21-20}	0.9465	0.98	0.9584
T_{24-26}	0.9923	1.07	1.0085
T_{7-29}	0.9960	0.96	1.0112
T_{34-32}	0.9000	0.91	0.9000
T_{11-41}	0.9622	0.9	0.9784
T_{15-45}	0.9059	0.95	0.9000
T_{14-46}	0.9764	0.95	0.9809
T_{10-51}	1.0622	0.98	1.0388
T_{13-49}	0.9106	0.94	0.9041
T_{11-43}	0.9289	0.97	0.9119
T_{40-56}	0.9771	1.04	0.9899
T_{39-57}	1.0281	0.93	1.0213
T_{9-55}	0.9001	0.98	0.9078
Capacitor banks (p.u)			
Q_{C18}	0.0585	0.03	0.0601
Q_{C25}	0.0587	0.06	0.0590
Q_{C53}	0.0381	0.03	0.0630
P_{Loss} (MW)	29.31	26.4618	28.46
TVD **(p.u)**	0.6634	0.77461	0.6484
$L-$ index (p.u)	-	-	0.1899

TABLE 19. **Statistical results for IEEE 57-bus test system with the minimization of TVD objective function.**

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std	% TVD Improve
OGSA [128]	0.6982	-	-	-	43.40
NGBWCA [127]	0.6501	-	-	-	47.29
ALC-PSO [130]	0.6634	0.6689	0.6636	89×10^{-5}	46.22
BA	0.6434	0.6609	0.6499	0.0045	47.84
CBA-III	0.6413	0.6542	0.6440	0.0031	48.01
CBA-IV	**0.6399**	0.6516	0.6424	0.0028	**48.13**

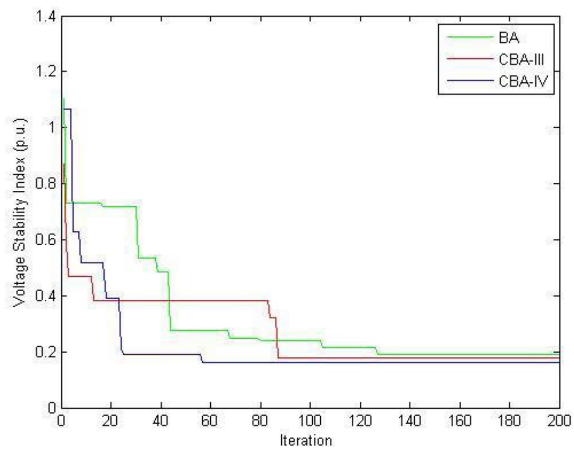

FIGURE 9. **The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 57-bus test power system with the minimization of VSI objective function.**

D. IEEE 118 BUS TEST SYSTEM

The IEEE 118 bus test system comprises 54 generators, 186 transmission lines, 9 tap changing transformers and 14 shunt VAR compensators. Totally, the IEEE 118-bus test system contains 77 control variables. Refer to [53], [63], [115] and [116] for further details.

The total demand of the system are

$P_{load} = 4242MW$ (active power demand),

$Q_{load} = 1438MVAR$ (reactive power demand).

The initial total generations and power losses are given by

$\sum PG = 4375.36MW$ (active power of generators),

$\sum QG = 881.92MVAR$ (reactive power of generators),

$P_{LOSS} = 133.357MW$ (active power losses),

$Q_{LOSS} = -785.11MVAR$ (reactive power losses).

The control variable limits are listed in Table 22 in p.u. [53], [116].

1) CASE 1: MINIMIZATION OF ACTIVE POWER LOSS

The best results achieved by different algorithms for the minimization of the active power loss are tabulated in the Appendix section. The comparative statistical results are

TABLE 20. Optimal settings of control variables for IEEE 57-bus test systems with the minimization of VSI objective function.

Variable	CBA-IV	CBA-III	BA
Generator voltage (p.u)			
V_{G1}	1.0981	1.0887	1.0431
V_{G2}	1.0441	1.0492	0.9996
V_{G3}	1.0859	1.0953	1.0452
V_{G6}	1.0235	1.0219	1.0354
V_{G8}	1.0607	1.0609	0.9327
V_{G9}	0.9399	0.9466	0.9936
V_{G12}	0.9541	0.9444	1.0140
Transformer tap ratio (p.u)			
T_{4-18}	1.0466	1.0442	1.0253
T_{4-18}	1.0263	1.0149	0.9288
T_{21-20}	0.9607	0.9540	0.9683
T_{24-25}	0.9087	0.9103	1.0959
T_{7-29}	0.9013	0.9047	1.0446
T_{34-32}	1.0804	1.0826	0.9646
T_{11-41}	1.0106	1.0156	1.0371
T_{15-45}	0.9982	0.9815	1.0539
T_{14-46}	1.0253	1.0222	1.0908
T_{10-51}	0.9611	0.9615	0.9209
T_{13-49}	1.0233	1.0193	0.9541
T_{11-43}	0.9150	0.9235	1.0356
T_{40-56}	0.9122	0.9041	0.9183
T_{39-57}	0.9790	0.9715	1.0502
T_{9-55}	0.9426	0.9357	0.9616
Capacitor banks (p.u)			
Q_{C18}	0.1784	0.1818	0.1025
Q_{C25}	0.0391	0.0441	0.1912
Q_{C53}	0.1714	0.1704	0.1685
P_{Loss} (MW)	40.3425	40.982	42.4878
TVD **(p.u)**	1.2347	1.2641	1.4414
$L-$ index (p.u)	**0.1608**	0.1789	0.1917

TABLE 21. Statistical results for IEEE 57-bus test system with the minimization of VSI objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std
SOA [53]	0.190709	0.176374	0.187451	2.6388×10^{-3}
OGSA [128]	0.190010	0.175935	0.184112	2.8188×10^{-3}
BA	0.1917	0.2154	0.1991	0.0075
CBA-III	0.1789	0.1898	0.1851	0.0035
CBA-IV	0.1608	0.1712	0.1674	0.0027

TABLE 22. Control variable limits for IEEE 118-bus test systems [53], [116].

V_G^{max}	V_G^{min}	V_{PQ}^{max}	V_{PQ}^{min}	T_k^{max}	T_k^{min}	Q_C^{max}	Q_C^{min}
1.06	0.94	1.1	0.95	1.1	0.9	0.2	0

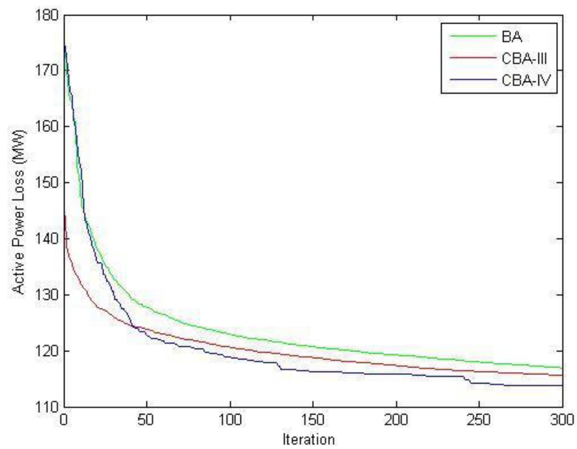

FIGURE 10. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 118-bus test power system with the minimization of P_{Loss} objective function.

presented in Table 23. According to Table 23, the CBA-IV algorithm leads to **113.7040 MW** active power loss which is better than the active power losses obtained by the other algorithms compared with it. In addition, it can also be seen from Table 23 that a **14.74%** reduction (from the initial loss of 133.357 MW) in active power loss is achieved with the CBA-IV algorithm, which performs better than other algorithms compared with it. The comparative convergence characteristics of active power loss over 300 iterations obtained by the standard BA, CBA-III and CBA-IV are shown in Fig.10. It can be observed from Fig.10 that the CBA-IV yields better convergence characteristics than the CBA-III and BA algorithms.

2) CASE 2: MINIMIZATION OF TOTAL VOLTAGE DEVIATION

The best results of TVD minimization for IEEE 118-bus system yielded by the CBA-IV, CBA-III and CBA algorithms

TABLE 23. Statistical results for IEEE 118-bus test system with the minimization of P_{Loss}. Objective function.

Algori-thm	Best (MW)	Worst (MW)	Mean (MW)	Std	% Psave
MICA-IWO [63]	114.04568	114.97562	114.44837	2.4288× 10^{-4}	14.48
MTLA-[116]	113.9814	114.4975	114.0852	2.8755× 10^{-4}	14.53
ALO [62]	119.7792	-	-	-	9.847
OGSA [128]	126.99	131.99	127.14	88 × 10^{-6}	4.4203
GSA [129]	127.7603	-	-	-	4.2
QOTL-BO [134]	112.2789	115.4516	113.7693	0.0244	15.8
FAHCL-PSO [112]	116.2479	-	-	-	12.83
GWO [61]	120.65	-	-	-	9.53
CLPSO [135]	130.96	132.74	131.15	85 × 10^{-6}	1.8
EMA [3]	126.2243	130.98	127.0111	87.2 × 10^{-6}	5.35
ALC-PSO [130]	121.53	132.99	123.14	91 × 10^{-6}	8.245
HFA [22]	134.24	134.8499	134.96	0.008814	-
BA	116.9329	119.2345	117.1409	0.2287	12.32
CBA-III	115.5989	116.3561	115.6542	0.1569	13.32
CBA-IV	**113.7040**	114.1689	114.0108	0.1218	14.74

TABLE 24. Statistical results for IEEE 118-bus test system with the minimization of TVD objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std
ALC-PSO [130]	0.3262	0.3743	0.3281	95 × 10^{-6}
BA	0.3172	0.3206	0.3187	9.7474× 10^{-4}
CBA-III	0.3059	0.3072	0.3062	3.2319 × 10^{-4}
CBA-IV	**0.3032**	0.3041	0.3036	3.0558 × 10^{-4}

are shown in the Appendix section. The statistical results of this case are summarized in Table 24. According this table, it is seen that the CBA-IV outperforms other algorithms compared with it as the CBA-IV gives a TVD value of **0.3032** against 0.3059 with CBA-III, 0.3172 with BA and 0.3262 with ALC-PSO [130]. Futhermore, the CBA provides the smallest Best, Mean and Std values in comparison to CBA-III and BA.

The comparison of the convergence characteristics for TVD obtained by CBA-IV with the other methods is depicted in Fig.11 and shows the robust performance of the CBA-IV for larger dimension systems.

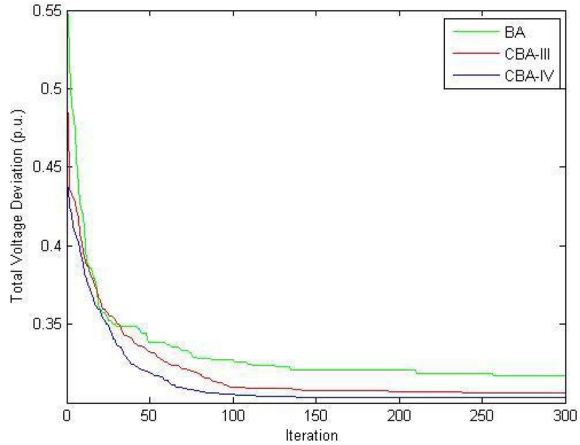

FIGURE 11. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 118-bus test power system with the minimization of TVD objective function.

TABLE 25. Statistical results for IEEE 118-bus test system with the minimization of VSI objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std
QOTLBO [134]	0.0608	0.06311	0.0616	0.0476
BA	0.06126	0.0654	0.0632	0.0010
CBA-III	0.0587	0.0626	0.0607	0.0013
CBA-IV	**0.0570**	0.0609	0.0587	0.0012

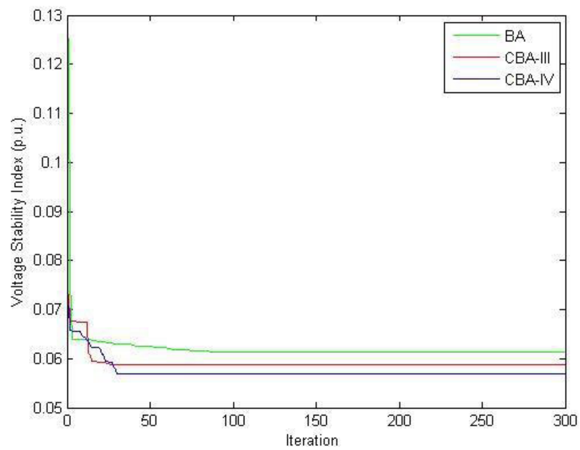

FIGURE 12. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 118-bus test power system with the minimization of VSI objective function.

TABLE 26. Control variable limits for IEEE 300-bus test systems [62], [136].

V_G^{max}	V_G^{min}	V_{PQ}^{max}	V_{PQ}^{min}	T_k^{max}	T_k^{min}	Q_C^{max}	Q_C^{min}
1.1	0.9	1.1	0.9	1.1	0.9	325	0

TABLE 27. Statistical results for IEEE 300-bus test system with the minimization of P_{Loss} objective function.

Algorithm	Best (MW)	Worst (MW)	Mean (MW)	Std
MVMO [137]	385.6284	-	-	-
DEEPSO [137]	394.4343	-	-	-
ALO [62]	384.9224	-	-	-
BA	384.6609	419.145	387.7787	5.0014
CBA-III	379.9265	392.973	385.5485	2.1774
CBA-IV	**373.6675**	380.065	375.5762	1.6047

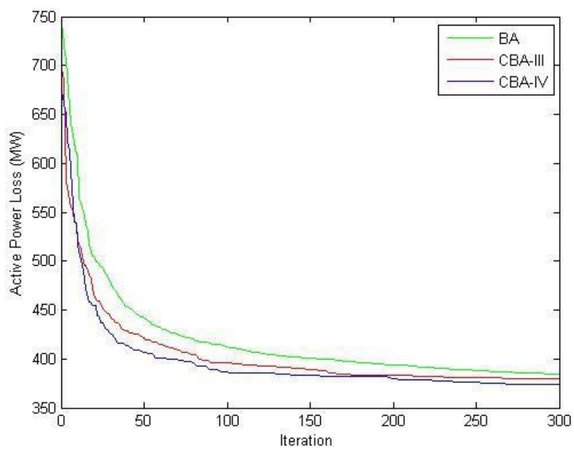

FIGURE 13. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 300-bus test power system with the minimization of P_{Loss} objective function.

TABLE 28. Statistical results for IEEE 300-bus test system with the minimization of TVD objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std
BA	1.1585	1.1712	1.1608	0.0030
CBA-III	1.1462	1.1521	1.1488	9.5050×10^{-4}
CBA-IV	**1.1182**	1.1216	1.1233	7.5829×10^{-4}

3) CASE STUDY 3: IMPROVEMENT OF VOLTAGE STABILITY INDEX

The best results of minimization of the VSI for IEEE i118-bus system achieved by the CBA-IV algorithm are illustrated in the Appendix section. Table 25 provides the comparison in terms of statistical results for this case. It is observed that the CBA-IV outperforms other algorithms compared with it because the CBA-IV provides an $L-$ index value of **0.0570** against 0.0587 with CBA-III, 0.0608 with QOTLBO [134] and 0.06126 with BA.

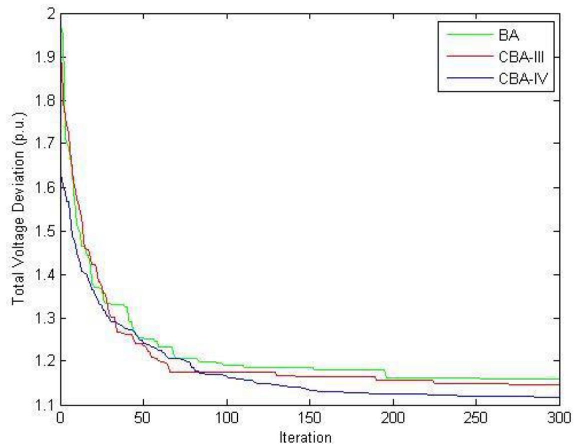

FIGURE 14. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 300-bus test power system with the minimization of TVD objective function.

TABLE 29. Statistical results for IEEE 300-bus test system with the minimization of VSI objective function.

Algorithm	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std
ALO [62]	0.3663	-	-	-
BA	0.3570	0.3611	0.3582	0.0011
CBA-III	0.3556	0.3592	0.3570	9.2311×10^{-4}
CBA-IV	**0.3536**	0.3568	0.3551	9.6273×10^{-4}

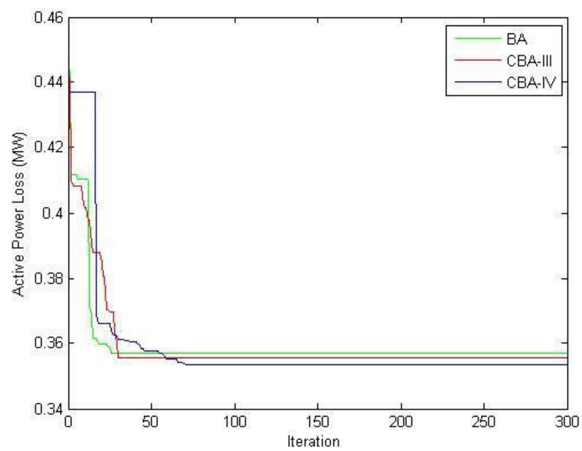

FIGURE 15. The Convergence characteristics of the standard BA, CBA-III and CBA-IV for IEEE 300-bus test power system with the minimization of VSI objective function.

TABLE 30. Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

Variable	MICA-IWO [63]	MTLA-DDE [116]	ALO [62]	OGSA [128]
Generator voltage (p.u)				
V_{G1}	1.04189	1.04307	1.0164	1.0350
V_{G4}	1.06	1.06	1.0299	1.0554
V_{G6}	1.05423	1.05397	1.0355	1.0301
V_{G8}	1.05817	1.05813	1.0247	1.0175
V_{G10}	1.06	1.06	1.0469	1.0250
V_{G12}	1.0511	1.05108	1.0259	1.0410
V_{G15}	1.04978	1.04993	1.0526	0.9973
V_{G18}	1.05246	1.05213	1.0580	1.0047
V_{G19}	1.04898	1.04921	1.0565	0.9899
V_{G24}	1.05276	1.0523	1.0549	1.0287
V_{G25}	1.06	1.06	1.0600	1.0600
V_{G26}	1.06	1.06	1.0457	1.0855
V_{G27}	1.04656	1.0464	1.0583	1.0081
V_{G31}	1.04299	1.04256	1.0573	0.9948
V_{G32}	1.04526	1.04514	1.0455	0.9993
V_{G34}	1.06	1.06	1.0322	0.9958
V_{G36}	1.05838	1.05826	1.0264	0.9835
V_{G40}	1.03842	1.0387	1.0124	0.9981
V_{G42}	1.03979	1.03968	1.0321	1.0068
V_{G46}	1.04695	1.04665	1.0446	1.0355
V_{G49}	1.06	1.06	1.0572	1.0333
V_{G54}	1.03876	1.03948	1.0313	0.9911
V_{G55}	1.038	1.03848	1.0305	0.9914
V_{G56}	1.03816	1.0378	1.0292	0.9920
V_{G59}	1.06	1.06	1.0269	0.9909
V_{G61}	1.06	1.06	1.0373	1.0747
V_{G62}	1.05593	1.05613	1.0217	1.0753
V_{G65}	1.06	1.06	1.0582	0.9814
V_{G66}	1.06	1.06	1.0591	1.0487
V_{G69}	1.06	1.06	1.0600	1.0490
V_{G70}	1.03774	1.03763	1.0577	1.0395
V_{G72}	1.04296	1.0419	1.0592	0.9900
V_{G73}	1.03744	1.03733	1.0348	1.0547
V_{G74}	1.02747	1.02741	1.0533	1.0167
V_{G76}	1.02525	1.02506	1.0382	0.9972
V_{G77}	1.04728	1.0474	1.0395	1.0071
V_{G80}	1.06	1.06	1.0508	1.0066
V_{G85}	1.06	1.06	1.0529	0.9893
V_{G87}	1.06	1.06	1.0510	0.9693
V_{G89}	1.06	1.06	1.0600	1.0527
V_{G90}	1.04449	1.04399	1.0382	1.0290
V_{G91}	1.0496	1.049	1.0223	1.0297
V_{G92}	1.06	1.06	1.0532	1.0353
V_{G99}	1.056	1.05529	1.0447	1.0395
V_{G100}	1.06	1.06	1.0445	1.0275
V_{G103}	1.06	1.05243	1.0385	1.0158
V_{G104}	1.05184	1.04431	1.0218	1.0165
V_{G105}	1.05166	1.04094	1.0376	1.0197
V_{G107}	1.03894	1.02781	1.0285	1.0408
V_{G110}	1.05083	1.03739	1.0458	1.0288
V_{G111}	1.06	1.0452	1.0254	1.0194
V_{G112}	1.03578	1.02184	1.0275	1.0132
V_{G113}	1.05998	1.05891	1.0567	1.0386
V_{G116}	1.06	1.06	1.0577	0.9724
Transformer tap ratio (p.u)				
T_{5-8}	1.0	0.99	1.00	0.9568
T_{25-26}	1.1	1.06	0.99	1.0409

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

T_{17-30}	0.99	0.99	1.00	0.9963
T_{37-38}	0.98	0.98	1.01	0.9775
T_{59-63}	0.98	0.98	1.03	0.9560
T_{61-64}	1.0	1.0	1.02	0.9956
T_{65-66}	0.9	0.9	0.97	0.9882
T_{68-69}	0.95	0.95	0.94	0.9251
T_{80-81}	0.99	0.99	1.00	1.0661
Capacitor banks (p.u)				
Q_{C5}	-0.4	-0.0259	-0.19	-0.3319
Q_{C34}	0.14	0.0	0.06	0.0480
Q_{C37}	0.0	-0.0004	-0.19	-0.2490
Q_{C44}	0.0429	0.0387	0.03	0.0328
Q_{C45}	0.0073	0.0236	0.06	0.0383
Q_{C46}	0.0697	0.0575	0.05	0.0545
Q_{C48}	0.0368	0.0348	0.09	0.0181
Q_{C74}	0.0	0.113	0.07	0.0509
Q_{C79}	0.0	0.0	0.06	0.1104
Q_{C82}	0.0	0.0	0.12	0.0965
Q_{C83}	0.0	0.0001	0.06	0.0263
Q_{C105}	0.0001	0.1043	0.04	0.0442
Q_{C107}	0.0016	0.0004	0.03	0.0085
Q_{C110}	0.0002	0.0	0.03	0.0144
P_{Loss} **(MW)**	114.04568	113.9814	119.7792	126.99
TVD (p.u)	-	-	-	1.1829
$L-$ index (p.u)	-	-	0.0642	0.1400

Variable	GSA [129]	QOTLBO [134]	FAHCLPSO [112]	GWO [61]
Generator voltage (p.u)				
V_{G1}	0.9600	1.0254	1.0120	1.0204
V_{G4}	0.9620	1.0451	1.0523	1.0257
V_{G6}	0.9729	1.0342	1.0666	1.0208
V_{G8}	1.0570	1.0817	1.0597	1.0419
V_{G10}	1.0885	1.0886	1.0725	1.0413
V_{G12}	0.9630	1.0277	1.0333	1.0232
V_{G15}	1.0127	1.0245	1.0012	1.0207
V_{G18}	1.0069	1.0284	1.0058	1.0270
V_{G19}	1.0003	1.0224	1.1000	1.0204
V_{G24}	1.0105	1.0487	1.0971	1.0137
V_{G25}	1.0102	1.0821	1.0899	1.0270
V_{G26}	1.0401	1.0995	1.1000	1.0386
V_{G27}	0.9809	1.0368	1.0654	1.0188
V_{G31}	0.9500	1.0313	1.0318	1.0138
V_{G32}	0.9552	1.0380	1.0322	1.0135
V_{G34}	0.9910	1.0333	0.9999	1.0261
V_{G36}	1.0091	1.0321	0.9998	1.0261
V_{G40}	0.9505	1.0145	1.0501	1.0125
V_{G42}	0.9500	1.0181	1.0231	1.0233
V_{G46}	0.9814	1.0391	1.0005	1.0272
V_{G49}	1.0444	1.0448	0.9897	1.0401
V_{G54}	1.0379	1.0183	0.9998	1.0230
V_{G55}	0.9907	1.0194	1.0222	1.0221
V_{G56}	1.0333	1.0188	1.0008	1.0226
V_{G59}	1.0099	1.0341	1.0731	1.0379
V_{G61}	1.0925	1.0276	1.0258	1.0241
V_{G62}	1.0393	1.0289	1.0059	1.0199
V_{G65}	0.9998	1.0973	1.0630	1.0465
V_{G66}	1.0355	1.0581	1.0312	1.0378
V_{G69}	1.1000	1.0746	1.0636	1.0501
V_{G70}	1.0992	1.0289	1.1000	1.0243

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

V_{G72}	1.0014	1.0345	1.0500	1.0187
V_{G73}	1.0111	1.0297	1.0981	1.0397
V_{G74}	1.0476	1.0225	1.0444	1.0170
V_{G76}	1.0211	1.0290	1.0037	1.0080
V_{G77}	1.0187	1.0520	1.0559	1.0192
V_{G80}	1.0462	1.0630	0.9999	1.0329
V_{G85}	1.0491	1.0903	1.0882	1.0224
V_{G87}	1.0426	1.0949	1.0303	1.0361
V_{G89}	1.0955	1.0995	1.0001	1.0558
V_{G90}	1.0417	1.0695	1.0018	1.029
V_{G91}	1.0032	1.0697	1.0298	1.0127
V_{G92}	1.0927	1.0833	1.1005	1.036
V_{G99}	1.0433	1.0530	1.0498	1.0297
V_{G100}	1.0786	1.0600	1.0565	1.036
V_{G103}	1.0266	1.0422	1.0413	1.0232
V_{G104}	0.9808	1.0234	1.0189	1.018
V_{G105}	1.0163	1.0211	1.1000	1.0176
V_{G107}	0.9987	1.0021	1.0222	1.0201
V_{G110}	1.0218	1.0215	1.0115	1.0207
V_{G111}	0.9852	1.0267	1.1000	1.0261
V_{G112}	0.9500	1.0095	1.0500	1.0066
V_{G113}	0.9764	1.0450	1.0099	1.0251
V_{G116}	1.0372	1.0983	1.0500	1.0342
Transformer tap ratio (p.u)				
T_{5-8}	1.0659	1.0381	1.0214	1.0208
T_{25-26}	0.9534	1.0885	1.0533	1.0279
T_{17-30}	0.9328	1.0202	1.0555	1.0323
T_{37-38}	1.0884	1.0319	0.9995	1.0209
T_{59-63}	1.0579	1.0294	1.0619	1.0091

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

T_{61-64}	0.9493	1.0711	1.0318	1.0366
T_{65-66}	0.9975	0.9139	1.0490	1.0301
T_{68-69}	0.9887	0.9622	0.9660	1.0234
T_{80-81}	0.9801	1.0182	0.9732	1.0211
Capacitor banks (p.u)				
Q_{C5}	0.00	0.0012	0.003500	-0.3976
Q_{C34}	0.0746	0.0690	0.101922	0.1379
Q_{C37}	0.00	0.0130	0.017500	-0.2473
Q_{C44}	0.0607	0.0987	0.044000	0.099571
Q_{C45}	0.0333	0.0976	0.069894	0.098678
Q_{C46}	0.0651	0.0134	0.071289	0.099186
Q_{C48}	0.0447	0.0740	0.066668	0.1489
Q_{C74}	0.0972	0.1154	0.110952	0.11972
Q_{C79}	0.1425	0.1915	0.150000	0.19649
Q_{C82}	0.1749	0.1733	0.105509	0.1989
Q_{C83}	0.0428	0.0907	0.055540	0.099515
Q_{C105}	0.1204	0.1803	0.151895	0.19968
Q_{C107}	0.0226	0.0007	0.044140	0.059136
Q_{C110}	0.0294	0.0366	0.022310	0.058834
P_{Loss} **(MW)**	127.7603	112.2789	116.2479	120.65
TVD (p.u)	-	2.6091	-	-
$L-$ index (p.u)	-	0.0645	-	-
Variable	CLPSO [135]	EMA [3]	NGBWCA [127]	ALC-PSO [130]
Generator voltage (p.u)				
V_{G1}	1.0332	0.97937	1.0215	1.0218
V_{G4}	1.0550	1.020732	1.0431	1.0432
V_{G6}	0.9754	0.981264	1.0312	1.0224
V_{G8}	0.9669	0.959845	1.0539	1.0543

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

V_{G10}	0.9811	0.983124	1.0271	1.0901
V_{G12}	1.0092	0.991302	1.0316	1.0325
V_{G15}	0.9787	0.987832	1.0129	1.0140
V_{G18}	1.0799	0.967977	1.0075	1.0080
V_{G19}	1.0805	1.034628	1.0102	1.0104
V_{G24}	1.0286	1.043718	1.0208	1.0200
V_{G25}	1.0307	1.01929	1.0531	1.0551
V_{G26}	0.9877	1.099976	0.9941	0.9932
V_{G27}	1.0157	1.013128	1.0291	1.0288
V_{G31}	0.9615	0.986824	1.0275	1.0288
V_{G32}	0.9851	1.031214	1.0201	1.0248
V_{G34}	1.0157	1.016642	1.0014	1.0362
V_{G36}	1.0849	1.016492	1.0412	1.0407
V_{G40}	0.9830	1.03021	1.0400	1.0391
V_{G42}	1.0516	1.032577	1.0512	1.0507
V_{G46}	0.9754	0.984638	1.0170	1.0171
V_{G49}	0.9838	0.998811	1.0510	1.0492
V_{G54}	0.9637	1.021781	1.0392	1.0424
V_{G55}	0.9716	0.960354	1.0331	1.0339
V_{G56}	1.0250	1.027817	1.0372	1.0393
V_{G59}	1.0003	1.029155	1.0564	1.0585
V_{G61}	1.0771	1.021323	1.0565	1.0569
V_{G62}	1.0480	1.051103	1.0489	1.0491
V_{G65}	0.9684	1.03287	1.0435	1.0437
V_{G66}	0.9648	1.073126	1.0435	1.0716
V_{G69}	0.9574	1.024818	1.0489	1.0535
V_{G70}	0.9765	1.049563	1.0113	1.0111
V_{G72}	1.0243	1.052822	1.0382	1.0389
V_{G73}	0.9651	1.041061	0.9926	0.9932

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

V_{G74}	1.0733	1.016658	0.9934	0.9912
V_{G76}	1.0302	0.99704	1.0324	1.0335
V_{G77}	1.0275	1.048287	1.0185	1.0191
V_{G80}	0.9857	0.988072	1.0021	1.0247
V_{G85}	0.9836	0.999756	1.0312	1.0324
V_{G87}	1.0882	0.974953	1.0212	1.0243
V_{G89}	0.9895	1.044042	1.0387	1.0393
V_{G90}	0.9905	1.00067	1.0071	1.0072
V_{G91}	1.0288	1.026417	0.9989	0.9997
V_{G92}	0.9760	1.01533	1.0001	1.0012
V_{G99}	1.0880	1.049947	1.0467	1.0481
V_{G100}	0.9617	1.031294	1.0213	1.0332
V_{G103}	0.9611	1.053139	1.0416	1.0422
V_{G104}	1.0125	1.04564	1.0174	1.0183
V_{G105}	1.0684	1.033351	1.0223	1.0226
V_{G107}	0.9769	1.03335	1.0340	1.0344
V_{G110}	1.0414	1.046059	1.0103	1.0349
V_{G111}	0.9790	1.063805	1.0345	1.0425
V_{G112}	0.9764	1.067452	1.0160	1.0162
V_{G113}	0.9721	1.006101	1.0181	1.0188
V_{G116}	1.0330	1.024147	1.0330	1.0331
Transformer tap ratio (p.u)				
T_{5-8}	1.0045	0.941949	1.0051	1.0065
T_{25-26}	1.0609	1.003201	0.9614	0.9617
T_{17-30}	1.0008	0.983478	0.9961	0.9745
T_{37-38}	1.0093	0.923284	0.9523	0.9404
T_{59-63}	0.9922	1.020838	1.0521	1.0531
T_{61-64}	1.0074	0.985547	0.9520	0.9539
T_{65-66}	1.0611	0.980426	0.9812	0.9448

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

V_{G85}	0.9876	1.059387	1.0600	
V_{G87}	1.0213	1.042988	1.0599	
V_{G89}	1.0069	1.087995	1.0600	
V_{G90}	1.0298	1.06497	1.0431	
V_{G91}	0.9839	1.060584	1.0496	
V_{G92}	1.0021	1.077217	1.0600	
V_{G99}	0.9853	1.05034	1.0551	
V_{G100}	1.0281	1.047629	1.0584	
V_{G103}	0.9802	1.039985	1.0442	
V_{G104}	1.0187	1.042173	1.0333	
V_{G105}	1.0209	1.028912	1.0281	
V_{G107}	1.0234	1.009039	1.0161	
V_{G110}	0.9842	1.030944	1.0215	
V_{G111}	1	1.027332	1.0280	
V_{G112}	0.993	0.995456	1.0042	
V_{G113}	1.02	1.029401	1.0350	
V_{G116}	1.0016	1.058149	1.0484	
Transformer tap ratio (p.u)				
T_{5-8}	1.0255	1.018418	1.01360	
T_{25-26}	1.0609	1.003201	0.9614	0.9617
T_{17-30}	1.0008	0.983478	0.9961	0.9745
T_{37-38}	1.0093	0.923284	0.9523	0.9404
T_{59-63}	0.9922	1.020838	1.0521	1.0531
T_{61-64}	1.0074	0.985547	0.9520	0.9539
T_{65-66}	1.0611	0.980426	0.9812	0.9448
T_{68-69}	0.9307	0.921672	0.9510	0.9502
T_{80-81}	0.9578	0.996389	0.9754	0.9747
Capacitor banks (p.u)				
Q_{C5}	0.0000	-0.358498	-0.0723	-0.0750
Q_{C34}	0.117135	0.04370472	0.0483	0.0677

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

Q_{C37}	0.0000	-0.215653	-0.2390	-0.2399
Q_{C44}	0.098932	0.0097	0.0032	0.0038
Q_{C45}	0.094169	0.073217	0.0372	0.0179
Q_{C46}	0.026719	0.06216	0.0624	0.0780
Q_{C48}	0.028546	0.044774	0.0172	0.0789
Q_{C74}	0.005471	0.090848	0.0013	0.0000
Q_{C79}	0.148532	0.12324	0.0621	0.0717
Q_{C82}	0.194270	0.16927	0.0463	0.0589
Q_{C83}	0.069824	0.042665	0.0560	0.0561
Q_{C105}	0.090291	0.20	0.0653	0.0641
Q_{C107}	0.049926	0.047809	0.0072	0.0000
Q_{C110}	0.022086	0.002024	0.0108	0.0110
P_{Loss} **(MW)**	130.96	126.22	121.47	121.53
TVD (p.u)	1.8525	1.798	1.452	1.4651
$L-$ index (p.u)	0.1461	0.162	-	-

Variable	CPVEIHBMO [132]	HFA [22]	MFO[4]
Generator voltage (p.u)			
V_{G1}	0.9926	1.026576	1.0173
V_{G4}	1.0108	1.051842	1.0402
V_{G6}	1.0037	1.033094	1.0292
V_{G8}	0.9976	1.037189	1.0600
V_{G10}	1.0215	1.050354	1.0374
V_{G12}	1.0093	1.020722	1.0250
V_{G15}	1.0075	1.059803	1.0268
V_{G18}	1.0259	1.041598	1.0298
V_{G19}	0.9943	1.025998	1.0275
V_{G24}	1.0179	1.067503	1.0483
V_{G25}	1.0177	1.079399	1.0600
V_{G26}	0.999	1.090031	1.0600
V_{G27}	1.0084	1.06328	1.0267

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

V_{G31}	0.9838	1.027676	1.0101
V_{G32}	0.9827	1.042427	1.0226
V_{G34}	1.0065	1.015124	1.0556
V_{G36}	1.019	1.048147	1.0548
V_{G40}	1.0267	1.01646	1.0419
V_{G42}	0.9865	1.018564	1.0429
V_{G46}	1.0084	0.984532	1.0450
V_{G49}	1.0035	1.015655	1.0589
V_{G54}	0.9806	1.022769	1.0284
V_{G55}	0.9969	1.021025	1.0289
V_{G56}	0.9881	1.059781	1.0283
V_{G59}	1.0197	1.061729	1.0512
V_{G61}	0.9956	1.032754	1.0534
V_{G62}	1.0064	1.023555	1.0506
V_{G65}	0.9883	1.052105	1.0596
V_{G66}	1.0101	1.06896	1.0600
V_{G69}	0.9931	1.06172	1.0600
V_{G70}	1.0127	1.034243	1.0600
V_{G72}	1.0145	1.037312	1.0526
V_{G73}	1.0174	1.03344	1.0600
V_{G74}	1.0025	1.036665	1.0600
V_{G76}	0.9842	1.026668	1.0390
V_{G77}	0.9914	1.060286	1.0502
V_{G80}	1.0257	1.035531	1.0600
V_{G85}	0.9876	1.059387	1.0600
V_{G87}	1.0213	1.042988	1.0599
V_{G89}	1.0069	1.087995	1.0600
V_{G90}	1.0298	1.06497	1.0431
V_{G91}	0.9839	1.060584	1.0496
V_{G92}	1.0021	1.077217	1.0600

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

V_{G99}	0.9853	1.05034	1.0551
V_{G100}	1.0281	1.047629	1.0584
V_{G103}	0.9802	1.039985	1.0442
V_{G104}	1.0187	1.042173	1.0333
V_{G105}	1.0209	1.028912	1.0281
V_{G107}	1.0234	1.009039	1.0161
V_{G110}	0.9842	1.030944	1.0215
V_{G111}	1	1.027332	1.0280
V_{G112}	0.993	0.995456	1.0042
V_{G113}	1.02	1.029401	1.0350
V_{G116}	1.0016	1.058149	1.0484
Transformer tap ratio (p.u)			
T_{5-8}	1.0255	1.018418	1.01360
T_{25-26}	0.9891	0.910392	1.10000
T_{17-30}	0.9932	0.991845	1.00380
T_{37-38}	0.9873	0.989105	0.98263
T_{59-63}	0.9868	0.97365	0.98430
T_{61-64}	1.0235	0.984136	1.01390
T_{65-66}	1.009	0.975929	1.10000
T_{68-69}	1.0075	0.918179	1.10000
T_{80-81}	0.9872	0.947921	0.96831
Capacitor banks (p.u)			
Q_{C5}	0	0	0
Q_{C34}	0.060111	0.06780651	0
Q_{C37}	0	0	-0.0003126
Q_{C44}	0.060057	0.0495166	0.10
Q_{C45}	0.030001	0.0478067	0
Q_{C46}	5.9838	0.05927768	0
Q_{C48}	0.03992	0.06336509	0.00000842
Q_{C74}	0.079862	0.03791729	0.00220540

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

Q_{C79}	0.139892	0.07138172	0.020
Q_{C82}	0.17992	0.1097975	0
Q_{C83}	0.040009	0.04017512	0.10
Q_{C105}	0.109825	0.07750165	0
Q_{C107}	0.020251	0.02947845	0.06
Q_{C110}	0.020272	0.01913037	0.06
P_{Loss} **(MW)**	124.0983	134.24	116.4254
TVD (p.u)	-	-	-
$L-$ index (p.u)	-	-	-
Variable	BA	CBA-III	CBA-IV
Generator voltage (p.u)			
V_{G1}	0.9954	1.0080	0.9810
V_{G4}	1.0238	1.0334	1.0286
V_{G6}	1.0097	1.0234	1.0006
V_{G8}	1.0522	1.0679	1.0995
V_{G10}	1.0679	1.0838	1.0826
V_{G12}	1.0086	1.0195	1.0155
V_{G15}	1.0103	1.0155	1.0245
V_{G18}	1.0133	1.0171	1.0217
V_{G19}	1.0110	1.0128	1.0180
V_{G24}	1.0269	1.0276	1.0281
V_{G25}	1.0632	1.0614	1.0823
V_{G26}	1.0561	1.0886	1.0991
V_{G27}	1.0156	1.0195	1.0404
V_{G31}	1.0038	1.0118	1.0182
V_{G32}	1.0124	1.0159	1.0303
V_{G34}	1.0260	1.0241	1.0446
V_{G36}	1.0245	1.0209	1.0411
V_{G40}	1.0030	0.9990	1.0053
V_{G42}	1.0058	1.0033	1.0090
V_{G46}	1.0277	1.0293	1.0414

TABLE 30. *(Continued.)* Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.

V_{G49}	1.0443	1.0459	1.0701
V_{G54}	1.0118	1.0174	1.0462
V_{G55}	1.0108	1.0145	1.0460
V_{G56}	1.0114	1.0151	1.0445
V_{G59}	1.0369	1.0399	1.0740
V_{G61}	1.0372	1.0464	1.0620
V_{G62}	1.0341	1.0439	1.0655
V_{G65}	1.0406	1.0768	1.0744
V_{G66}	1.0593	1.0638	1.0925
V_{G69}	1.0624	1.0613	1.0701
V_{G70}	1.0256	1.0199	1.0246
V_{G72}	1.0195	1.0145	1.0181
V_{G73}	1.0191	1.0103	1.0147
V_{G74}	1.0158	1.0122	1.0184
V_{G76}	1.0138	1.0134	1.0158
V_{G77}	1.0409	1.0393	1.0579
V_{G80}	1.0545	1.0524	1.0753
V_{G85}	1.0628	1.0554	1.0885
V_{G87}	1.0322	1.0051	1.0730
V_{G89}	1.0843	1.0795	1.1051
V_{G90}	1.0523	1.0454	1.0807
V_{G91}	1.0506	1.0436	1.0896
V_{G92}	1.0654	1.0604	1.1031
V_{G99}	1.0394	1.0346	1.0654
V_{G100}	1.0461	1.0443	1.0804
V_{G103}	1.0311	1.0275	1.0632
V_{G104}	1.0196	1.0142	1.0503
V_{G105}	1.0117	1.0090	1.0546
V_{G107}	0.9967	0.9930	1.0229

TABLE 30. *(Continued.)* **Optimal settings of control variables for IEEE 118-bus test systems with the minimization of P_{Loss}. Objective function.**

V_{G110}	0.9996	1.0050	1.0455
V_{G111}	1.0061	1.0095	1.0415
V_{G112}	0.9822	0.9888	1.0052
V_{G113}	1.0219	1.0263	1.0277
V_{G116}	1.0310	1.0679	1.0764
Transformer tap ratio (p.u)			
T_{5-8}	1.0107	1.0145	1.0557
T_{25-26}	0.9661	0.9709	0.9069
T_{17-30}	1.0020	1.0106	0.9964
T_{37-38}	0.9959	1.0416	1.0062
T_{59-63}	0.9465	1.0254	0.9642
T_{61-64}	1.0214	1.0141	1.0350
T_{65-66}	0.9808	1.0361	1.0328
T_{68-69}	0.9541	0.9533	0.9568
T_{80-81}	0.9613	0.9932	0.9515
Capacitor banks (p.u)			
Q_{C5}	0.1394	0.1259	0.1641
Q_{C34}	0.0991	0.0789	0.1155
Q_{C37}	0.1095	0.0955	0.1031
Q_{C44}	0.0288	0.0457	0.0396
Q_{C45}	0.1329	0.1199	0.1811
Q_{C46}	0.1219	0.1305	0.0700
Q_{C48}	0.1866	0.1494	0.1687
Q_{C74}	0.1405	0.0795	0.899
Q_{C79}	0.1733	0.1167	0.0975
Q_{C82}	0.1227	0.0805	0.0569
Q_{C83}	0.0268	0.0418	0.0748
Q_{C105}	0.0959	0.1031	0.0808
Q_{C107}	0.1013	0.0496	0.1885
Q_{C110}	0.0379	0.1106	0.0745
P_{Loss} **(MW)**	116.9329	115.5989	**113.7040**
TVD (p.u)	1.1783	1.17279	1.15726
$L-$ index (p.u)	0.0982	0.0975	0.0969

The comparison of the convergence characteristics for VSI yielded by CBA-IV with the other approaches is illustrated in Fig.12 and reveals that the CBA-IV is able to achieve a good performance for larger dimension systems.

E. IEEE 300 BUS TEST SYSTEM

The IEEE 300-bus test system comprises 69 generators, 411 transmission lines, 107 tap changing transformers and 14 shunt VAR compensators. Totally, the IEEE 300-bus test system contains 190 control variables. See [62] and [136] for further details.

The control variable limits are listed in Table 26 in p.u. [62] and [136].

1) CASE 1: MINIMIZATION OF ACTIVE POWER LOSS

Table 27 illustrates the comparative statistical results obtained by different algorithms in minimizing active power loss for IEEE 300 bus system. From Table 27, the CBA-IV algorithm leads to **373.6675 MW** active power loss which is better than the active power losses obtained by the other algorithms compared with it. The comparative convergence characteristics of active power loss over 300 iterations yielded by the standard BA, CBA-III and CBA-IV are presented in Fig.13. It can be observed from Fig. 13 that the CBA-IV gives better convergence characteristics than the CBA-III and BA algorithms.

2) CASE 2: MINIMIZATION OF TOTAL VOLTAGE DEVIATION

The comparative statistical results of TVD minimization for IEEE 300-bus system achieved by the CBA-IV, CBA-III and CBA algorithms are shown in Table 28. It is observed that the CBA-IV outperforms other algorithms compared with because the CBA-IV provides a TVD value of **1.1182** against 1.1462 with CBA-III, 1.1585 with BA. The comparison of the convergence characteristics for TVD yielded by CBA-IV with the other approaches is given in Fig.14 and reveals that the CBA-IV is able to achieve a good performance for larger dimension systems.

3) CASE STUDY 3: IMPROVEMENT OF VOLTAGE STABILITY INDEX

The comparative statistical results of VSI minimization for IEEE 300-bus system yielded by the CBA-IV, CBA-III and CBA algorithms are tabulated in Table 29. According to this table, it is seen that the CBA-IV outperforms other algorithms compared with it as the CBA-IV gives an $L-$ index value of **0.3536** against 0.3556 with CBA-III and 0.3570 with BA.

The comparison of the convergence characteristics for VSI obtained by CBA-IV with the other methods is presented in Fig.15 and shows the robust performance of the CBA-IV for larger dimension systems.

VI. CONCLUSION

In this paper, two variants of chaotic bat algorithm (CBA), namely CBA III and CBA IV have been successfully applied

TABLE 31. Optimal settings of control variables for IEEE 118-bus test systems with the minimization of TVD objective function.

Variable	OGSA [128]	QOTLBO [134]	FAHCLPSO [112]	CLPSO [135]
Generator voltage (p.u)				
V_{G1}	1.0388	1.0022	1.0310	1.0351
V_{G4}	0.9872	0.9883	1.0429	1.0473
V_{G6}	0.9925	0.9938	1.0181	1.0199
V_{G8}	0.9905	0.9723	1.0731	1.0274
V_{G10}	0.9919	1.0104	1.0912	1.0267
V_{G12}	1.0077	1.0128	1.0443	1.0274
V_{G15}	1.0034	1.0151	1.0198	1.0217
V_{G18}	0.9773	0.9570	1.0550	0.9901
V_{G19}	1.0324	1.0350	1.0905	1.0174
V_{G24}	1.0285	0.9980	1.0798	1.0868
V_{G25}	0.9705	1.0155	1.0636	0.9991
V_{G26}	1.0175	1.0164	1.1000	1.0217
V_{G27}	1.0117	1.0251	1.0218	1.0400
V_{G31}	1.0014	0.9993	1.0789	0.9932
V_{G32}	0.9988	0.9863	1.0505	1.0360
V_{G34}	1.0158	0.9959	1.0420	1.0012
V_{G36}	0.9916	1.0039	1.0099	1.0370
V_{G40}	1.0132	1.0090	1.0834	1.0162
V_{G42}	0.9892	1.0025	1.0917	1.0252
V_{G46}	1.0607	1.0580	0.9999	1.0271
V_{G49}	1.0031	0.9926	1.0088	1.0021
V_{G54}	1.0236	1.0254	1.0009	1.0491
V_{G55}	1.0176	1.0212	1.0414	1.0093
V_{G56}	1.0149	1.0194	1.0055	1.0108
V_{G59}	1.0584	1.0342	1.0639	1.0313
V_{G61}	0.9829	1.0070	1.0193	1.0514
V_{G62}	1.0562	0.9665	1.0123	1.0786
V_{G65}	0.9724	0.9842	1.0719	0.9792
V_{G66}	1.0020	1.0400	1.0818	1.0790
V_{G69}	0.9827	0.9519	1.0450	1.0492
V_{G70}	0.9997	0.9608	1.0890	0.9908
V_{G72}	1.0123	0.9947	1.0500	0.9838
V_{G73}	0.9960	1.0505	1.0360	0.9979
V_{G74}	1.0232	1.0376	1.0128	1.0449
V_{G76}	1.0015	1.0131	1.0085	1.0403
V_{G77}	1.0124	1.0158	1.0888	1.0570
V_{G80}	1.0226	1.0103	1.0111	1.0627
V_{G85}	1.0117	1.0090	0.9789	0.9997
V_{G87}	1.0058	1.0098	0.9955	1.0293
V_{G89}	1.0076	1.0077	1.0452	1.0275
V_{G90}	0.9753	0.9547	1.0215	1.0320
V_{G91}	0.9836	1.0980	1.0719	1.0275
V_{G92}	1.0272	0.9973	1.1000	1.0101
V_{G99}	0.9612	0.9511	1.0465	1.0666
V_{G100}	1.0032	1.0425	1.0333	1.0213
V_{G103}	0.9843	0.9520	1.0458	1.0317
V_{G104}	0.9880	1.0996	1.0127	1.0390
V_{G105}	1.0003	0.9811	-	1.0259
V_{G107}	1.0033	1.0777	-	1.0410
V_{G110}	1.0040	1.0195	1.0121	0.9993
V_{G111}	1.0331	0.9518	1.1000	1.0332
V_{G112}	0.9877	1.0994	1.0497	1.0302
V_{G113}	0.9705	0.9999	1.0111	1.0463
V_{G116}	1.0270	0.9896	1.0418	0.9905
Transformer tap ratio (p.u)				

TABLE 31. *(Continued.)* **Optimal settings of control variables for IEEE 118-bus test systems with the minimization of TVD objective function.**

T_{5-8}	0.9841	0.9311	1.0763	1.0027
T_{25-26}	1.0377	0.9144	1.0339	1.0558
T_{17-30}	0.9573	0.9994	1.0812	1.0114
T_{37-38}	0.9952	0.9975	0.9985	1.0010
T_{59-63}	0.9622	0.9690	1.0435	0.9894
T_{61-64}	1.0320	1.0056	1.0512	1.0236
T_{65-66}	1.0137	1.0834	1.0340	0.9496
T_{68-69}	0.9795	1.0964	0.9797	0.9284
T_{80-81}	0.9985	0.9826	0.9800	0.9661
Capacitor banks (p.u)				
Q_{C5}	-0.2403	-0.3404	-	0
Q_{C34}	0.0371	0.0731	0.128756	0.076593
Q_{C37}	-0.0437	-0.2046	0.043150	0
Q_{C44}	0.0375	0.0983	0.049981	0.027759
Q_{C45}	0.0400	0.0854	0.081112	0.052321
Q_{C46}	0.0749	0.0427	0.100292	0.069942
Q_{C48}	0.0796	0.0084	0.055000	0.063363
Q_{C74}	0.0883	0.0453	0.108156	0.073078
Q_{C79}	0.1218	0.0059	0.150000	0.148257
Q_{C82}	0.0380	0.1982	0.098256	0.133066
Q_{C83}	0.0627	0.0997	0.050000	0.085155
Q_{C105}	0.0830	0.0771	0.181298	0.112338
Q_{C107}	0.0459	0.0210	0.050055	0.022546
Q_{C110}	0.0221	0.0474	0.044497	0.026128
P_{Loss} (MW)	157.72	205.5978	-	132.06
TVD (p.u)	0.3666	0.1910	0.2218	1.6177
$L-$ index (p.u)	0.1562	0.0672	-	0.1210
Variable	NGBWCA [127]	ALC-PSO [130]	HFA [22]	
Generator voltage (p.u)				

TABLE 31. *(Continued.)* **Optimal settings of control variables for IEEE 118-bus test systems with the minimization of TVD objective function.**

V_{G1}	1.0002	1.0011	1.00518
V_{G4}	1.0202	1.0191	0.9991
V_{G6}	0.9936	0.9934	1.01878
V_{G8}	0.9771	0.9762	0.95837
V_{G10}	1.0051	1.0064	0.98375
V_{G12}	1.0120	1.0126	0.99357
V_{G15}	0.9853	0.9865	1.02834
V_{G18}	1.0557	1.0560	1.02191
V_{G19}	1.0190	1.0188	1.00587
V_{G24}	1.0197	1.0202	1.04220
V_{G25}	1.0108	1.0111	1.02798
V_{G26}	0.9954	0.9801	1.01574
V_{G27}	1.0204	1.0231	1.00351
V_{G31}	0.9990	0.9994	1.00564
V_{G32}	0.9877	0.9878	1.02537
V_{G34}	1.0211	1.0214	0.99338
V_{G36}	0.9656	0.9655	0.98535
V_{G40}	1.0031	1.0043	1.00575
V_{G42}	1.0012	1.0138	1.00147
V_{G46}	1.0512	1.0526	1.00842
V_{G49}	1.0001	1.0024	0.95483
V_{G54}	1.0227	1.0234	1.03193
V_{G55}	1.0323	1.0330	1.00171
V_{G56}	1.0139	1.0146	0.99912
V_{G59}	1.0084	1.0090	1.00540
V_{G61}	1.0001	1.0003	0.98207
Variable	BA	CBA-III	CBA-IV
Generator voltage (p.u)			
V_{G1}	1.0039	0.9941	1.0001

TABLE 31. *(Continued.)* **Optimal settings of control variables for IEEE 118-bus test systems with the minimization of TVD objective function.**

V_{G4}	0.9996	1.0022	1.0000
V_{G6}	0.9983	1.0075	0.9999
V_{G8}	1.0053	0.9943	1.0000
V_{G10}	0.9950	1.0015	1.0002
V_{G12}	0.9989	1.0035	1.0000
V_{G15}	1.0032	1.0011	1.0000
V_{G18}	0.9989	0.9999	1.0000
V_{G19}	1.0028	1.0057	0.9999
V_{G24}	1.0048	1.0011	1.0001
V_{G25}	0.9933	0.9946	0.9999
V_{G26}	0.9962	0.9981	1.0001
V_{G27}	1.0028	0.9994	1.0001
V_{G31}	0.9982	0.9943	1.0000
V_{G32}	0.9978	1.0005	0.9998
V_{G34}	1.0048	1.0002	1.0003
V_{G36}	0.9927	0.9974	1.0000
V_{G40}	1.0020	1.0039	1.0000
V_{G42}	1.0040	1.0029	1.0002
V_{G46}	1.0011	0.9985	1.0000
V_{G49}	1.0061	1.0012	0.9999
V_{G54}	1.0016	0.9988	1.0002
V_{G55}	0.9877	0.9969	0.9997
V_{G56}	0.9920	1.0016	1.0001
V_{G59}	0.9986	0.9932	0.9999
V_{G61}	1.0023	1.0038	1.0000
V_{G62}	1.0014	1.0048	0.9999
V_{G65}	1.0059	1.0310	0.9838
V_{G66}	0.9688	0.9923	1.0368
V_{G69}	1.0047	0.9988	0.9659

TABLE 31. *(Continued.)* **Optimal settings of control variables for IEEE 118-bus test systems with the minimization of TVD objective function.**

V_{G70}	1.0099	1.0848	1.0055
V_{G72}	0.9709	1.0253	1.0143
V_{G73}	1.0139	1.0894	0.9803
V_{G74}	1.0458	1.0299	1.0076
V_{G76}	1.0072	0.9647	1.0152
V_{G77}	0.9602	0.9707	0.9929
V_{G80}	0.9904	0.9878	1.0108
V_{G85}	1.0010	0.9717	0.9918
V_{G87}	0.9604	1.0024	1.0292
V_{G89}	1.0467	0.9703	1.0435
V_{G90}	0.9876	1.0288	1.0148
V_{G91}	1.0248	0.9998	1.0357
V_{G92}	0.9779	1.0111	0.9963
V_{G99}	0.9802	0.9549	1.0097
V_{G100}	1.0475	0.9754	0.9835
V_{G103}	1.0316	1.0358	0.9771
V_{G104}	0.9577	0.9827	1.0016
V_{G105}	0.9573	1.0707	1.0226
V_{G107}	1.0038	1.0561	1.0270
V_{G110}	1.0566	1.0306	0.9864
V_{G111}	0.9962	1.0504	0.9744
V_{G112}	1.0129	0.9506	0.9861
V_{G113}	1.0042	1.0631	1.0189
V_{G116}	1.0220	0.9654	1.0289
Transformer tap ratio (p.u)			
T_{5-8}	1.0512	0.9007	1.0441
T_{25-26}	1.0302	1.0953	0.9630
T_{17-30}	1.0855	1.0024	1.0094
T_{37-38}	0.9501	0.9140	1.0776

TABLE 31. *(Continued.)* **Optimal settings of control variables for IEEE 118-bus test systems with the minimization of TVD objective function.**

T_{59-63}	1.0085	1.0978	0.9270
T_{61-64}	1.0220	0.9969	1.0492
T_{65-66}	1.0703	0.9990	1.0400
T_{68-69}	0.9932	1.0299	0.9521
T_{80-81}	1.0385	1.0034	0.9729
Capacitor banks (p.u)			
Q_{C5}	0.1296	0.0320	0.0730
Q_{C34}	0.1271	0.0910	0.1303
Q_{C37}	0.0704	0.1889	0.1174
Q_{C44}	0.1642	0.1814	0.0902
Q_{C45}	0.1692	0.0583	0.1228
Q_{C46}	0.0652	0.0808	0.1283
Q_{C48}	0.1521	0.1373	0.1448
Q_{C74}	0.0397	0.1258	0.0810
Q_{C79}	0.0144	0.1636	0.1032
Q_{C82}	0.0989	0.1230	0.0709
Q_{C83}	0.0163	0.0645	0.0520
Q_{C105}	0.0717	0.1712	0.1013
Q_{C107}	0.0681	0.0382	0.1642
Q_{C110}	0.1969	0.1554	0.0719
P_{Loss} (MW)	156.2585	154.3767	142.1661
TVD **(p.u)**	0.3172	0.3059	**0.3032**
$L-$ index (p.u)	0.1419	0.1209	0.1189

to solve the ORPD problem. Their performance as well as their effectiveness were evaluated on standard IEEE 14-bus, IEEE 39 New England bus, standard IEEE 57-bus, standard IEEE 118-bus and standard IEEE 300-bus test systems. The results yielded by CBA variants were compared to those available in the literature along with those of the standard version of BA. The simulation results approve that the CBA-IV outperforms other compared algorithms in terms of effectiveness and robustness for solving the ORPD problem.

TABLE 32. **Optimal Settings of control variables for IEEE 118-bus test systems with the minimization of VSI objective function.**

Variable	OGSA [128]	QOTLBO [134]	CLPSO [135]	EMA [3]
Generator voltage (p.u)				
V_{G1}	0.9881	0.9889	1.0414	0.95
V_{G4}	0.9924	0.9926	1.0596	1.1
V_{G6}	0.9873	0.9876	1.0940	0.95
V_{G8}	0.9984	0.9989	1.0833	1.1
V_{G10}	1.0138	1.0130	1.0912	0.95
V_{G12}	0.9855	0.9850	1.0691	0.95
V_{G15}	1.0314	1.0311	0.9959	0.95
V_{G18}	1.0373	1.0376	0.9513	1.1
V_{G19}	1.0211	1.0219	0.9607	1.1
V_{G24}	1.0294	1.0296	0.9651	1.1
V_{G25}	1.0515	1.0519	0.9750	1.1
V_{G26}	1.0260	1.0261	1.1000	0.95
V_{G27}	1.0306	1.0377	0.9578	1.1
V_{G31}	1.0307	1.0334	0.9585	0.96542
V_{G32}	1.0601	1.0613	1.0501	1.1
V_{G34}	1.0587	1.0543	1.0858	1.1
V_{G36}	1.0211	1.0209	1.0938	1.1
V_{G40}	1.0356	1.0377	1.1000	0.9601
V_{G42}	1.0734	1.0763	0.9500	1.1
V_{G46}	1.0989	1.0988	0.9906	1.1
V_{G49}	1.0442	1.0402	1.0827	1.09734
V_{G54}	1.0827	1.0877	0.9649	0.95
V_{G55}	1.0943	1.0953	0.9500	1.1
V_{G56}	0.9575	0.9584	1.0221	1.1
V_{G59}	0.9519	0.9510	1.0510	1.1

TABLE 32. *(Continued.)* **Optimal Settings of control variables for IEEE 118-bus test systems with the minimization of VSI objective function.**

V_{G61}	0.9569	0.9587	0.9882	0.95
V_{G62}	1.0869	1.0851	1.0212	0.95
V_{G65}	1.0194	1.0196	1.0987	1.1
V_{G66}	0.9525	0.9505	1.0732	1.1
V_{G69}	0.9553	0.9554	0.9500	1.1
V_{G70}	0.9818	0.9808	0.9672	0.95009
V_{G72}	1.0314	1.0309	0.9966	0.95
V_{G73}	1.0161	1.0142	1.0117	0.95
V_{G74}	1.0002	1.0023	1.0946	1.1
V_{G76}	1.0100	1.0135	0.9652	1.1
V_{G77}	1.0057	1.0047	0.9539	0.95
V_{G80}	0.9844	0.9846	1.0628	1.1
V_{G85}	1.0006	1.0016	1.0020	1.1
V_{G87}	0.9520	0.9524	0.9669	0.95
V_{G89}	1.0661	1.0665	0.9570	1.1
V_{G90}	1.0152	1.0158	1.0767	0.95
V_{G91}	0.9565	0.9569	1.0681	0.95
V_{G92}	1.0172	1.0173	0.9731	1.1
V_{G99}	0.9802	0.9804	1.0391	1.1
V_{G100}	1.0461	1.0460	1.0824	1.1
V_{G103}	1.0864	1.0869	1.0860	0.95
V_{G104}	0.9825	0.9815	1.0799	1.1
V_{G105}	1.0158	1.0138	0.9607	1.1
V_{G107}	1.0087	1.0067	0.9575	1.1
V_{G110}	1.0538	1.0518	1.0852	1.1
V_{G111}	1.0403	1.0413	0.9746	1.1
V_{G112}	0.9941	0.9929	1.0770	1.1
V_{G113}	1.0455	1.0489	1.0852	1.1
V_{G116}	1.0751	1.0775	0.9510	1.1
Transformer tap ratio (p.u)				

TABLE 32. *(Continued.)* **Optimal Settings of control variables for IEEE 118-bus test systems with the minimization of VSI objective function.**

T_{5-8}	0.9621	0.9633	1.0014	0.9
T_{25-26}	1.0749	1.0765	1.0770	1.1
T_{17-30}	1.0149	1.0125	1.0022	1.1
T_{37-38}	0.9910	0.9921	0.9995	0.9
T_{59-63}	1.0871	1.0847	0.9863	0.9
T_{61-64}	0.9121	0.9172	1.0349	1.1
T_{65-66}	1.0637	1.0638	1.1000	0.9
T_{68-69}	0.9049	0.9069	0.9819	0.9
T_{80-81}	0.9848	0.9898	0.9438	0.9
Capacitor banks (p.u)				
Q_{C5}	−0.3071	-0.3080	0	0
Q_{C34}	0.0165	0.0164	0.131777	0
Q_{C37}	−0.1891	-0.1899	0	0.001262
Q_{C44}	0.0814	0.0808	0.098018	0.10
Q_{C45}	0.0777	0.0778	0.046021	0.10
Q_{C46}	0.0454	0.0460	0.049648	0.047775
Q_{C48}	0.0042	0.0038	0.044910	0
Q_{C74}	0.1078	0.1027	0.064931	0
Q_{C79}	0.1361	0.1336	0.167886	0.20
Q_{C82}	0.1391	0.1390	0.159579	0
Q_{C83}	0.0434	0.0438	0.100000	0
Q_{C105}	0.0991	0.0996	0.182425	0
Q_{C107}	0.0520	0.0521	0.043269	0
Q_{C110}	0.0164	0.0165	0.054901	0.046343
P_{Loss} (MW)	295.1122	295.8979	132.08	-
TVD (p.u)	1.4804	1.4820	2.8863	-
$L-$ index **(p.u)**	0.0600	0.0608	0.0965	0.04841

TABLE 32. *(Continued.)* Optimal Settings of control variables for IEEE 118-bus test systems with the minimization of VSI objective function.

Variable	BA	CBA-III	CBA-IV
Generator voltage (p.u)			
V_{G1}	1.0346	1.0636	1.0307
V_{G4}	1.0061	0.9695	1.0197
V_{G6}	0.9874	1.0193	1.0018
V_{G8}	1.0351	1.0277	1.0379
V_{G10}	0.9926	1.0477	0.9986
V_{G12}	1.0009	0.9525	1.0097
V_{G15}	1.0012	1.0217	1.0074
V_{G18}	0.9582	1.0549	0.9739
V_{G19}	0.9776	1.0540	0.9679
V_{G24}	1.0271	0.9639	1.0131
V_{G25}	0.9967	0.9696	1.0157
V_{G26}	1.0333	1.0025	1.0337
V_{G27}	1.0079	0.9790	1.0021
V_{G31}	1.0544	0.9735	1.0539
V_{G32}	0.9690	0.9611	0.9627
V_{G34}	0.9595	0.9691	0.9711
V_{G36}	1.0234	0.9847	1.0185
V_{G40}	1.0420	09473	1.0371
V_{G42}	1.0052	0.9996	1.0017
V_{G46}	0.9516	0.9690	0.9504
V_{G49}	1.0169	1.0425	0.9996
V_{G54}	1.0360	1.0658	1.0300
V_{G55}	0.9821	0.9798	0.9785
V_{G56}	1.0432	0.9736	1.0294
V_{G59}	1.0030	1.0282	0.9918
V_{G61}	1.0176	1.0360	0.9987
V_{G62}	0.9864	1.0094	0.9787

TABLE 32. *(Continued.)* Optimal Settings of control variables for IEEE 118-bus test systems with the minimization of VSI objective function.

V_{G65}	0.9995	1.0267	1.0009
V_{G66}	0.9912	1.0364	1.0045
V_{G69}	1.0059	0.9751	0.9753
V_{G70}	1.0381	0.9957	1.0415
V_{G72}	0.9606	0.9541	0.9646
V_{G73}	0.9990	1.0645	1.0118
V_{G74}	1.0321	0.9758	1.0159
V_{G76}	0.9744	0.9957	0.9907
V_{G77}	0.9580	1.0089	0.9541
V_{G80}	0.9577	1.0054	0.9640
V_{G85}	0.9649	1.0273	0.9645
V_{G87}	1.0111	1.0259	0.9907
V_{G89}	1.0026	0.9537	1.0053
V_{G90}	1.0028	0.9496	0.9952
V_{G91}	0.9624	1.0101	0.9560
V_{G92}	1.0030	0.9599	1.0031
V_{G99}	1.0008	0.9899	1.0058
V_{G100}	1.0346	0.9544	1.0212
V_{G103}	1.0087	1.0473	1.0221
V_{G104}	1.0076	0.9538	1.0107
V_{G105}	1.0140	0.9989	1.0156
V_{G107}	1.0481	0.9722	1.0488
V_{G110}	1.0409	0.9721	1.0390
V_{G111}	0.9650	1.0010	0.9646
V_{G112}	1.0046	1.0003	0.9859
V_{G113}	1.0157	0.9872	1.0088
V_{G116}	1.0201	1.0024	1.0102
Transformer tap ratio (p.u)			
T_{5-8}	0.9613	0.9712	0.9633
T_{25-26}	0.9645	1.0663	0.9623

TABLE 32. ***(Continued.)*** **Optimal Settings of control variables for IEEE 118-bus test systems with the minimization of VSI objective function.**

T_{17-30}	0.9602	0.9571	0.9839
T_{37-38}	1.0178	0.9769	1.0315
T_{59-63}	0.9689	1.0313	0.9762
T_{61-64}	0.9668	1.0599	0.9681
T_{65-66}	0.9961	0.9244	1.0103
T_{68-69}	0.9618	1.0550	0.9323
T_{80-81}	1.0725	1.0062	1.0543
Capacitor banks (p.u)			
Q_{C5}	0.1299	0.0840	0.1155
Q_{C34}	0.1616	0.1243	0.1551
Q_{C37}	0.1689	0.1458	0.1724
Q_{C44}	0.0713	0.1367	0.0786
Q_{C45}	0.1236	0.0534	0.1032
Q_{C46}	0.1124	0.1325	0.1321
Q_{C48}	0.0963	0.1764	0.1125
Q_{C74}	0.1763	0.0316	0.1706
Q_{C79}	0.0547	0.0774	0.0539
Q_{C82}	0.0493	0.0998	0.0631
Q_{C83}	0.0990	0.1244	0.0723
Q_{C105}	0.1575	0.1243	0.1268
Q_{C107}	0.1553	0.0526	0.1564
Q_{C110}	0.0591	0.1615	0.0573
P_{Loss} (MW)	184.0111	178.7326	169.5624
TVD (p.u)	1.4904	1.4642	1.4538
$L-$ index **(p.u)**	0.06126	0.0587	**0.0570**

For future researches, CBA will be utilized to address some other power system optimization problems such as the ORPD problem considering FACTS devices, optimum capacitor placement, optimum VAR sizing and allocation, design of power system stabilizers, short-term electricity load forecasting, short-term wind power forecasting, etc.

APPENDIX

See Tables 30–32.

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