One Rank Cuckoo Search Algorithm for Optimal Reactive Power Dispatch

Nguyen Huu Thien An, Vo Ngoc Dieu, Thang Trung Nguyen and Vo Trung Kien

Abstract— *This paper proposes a one rank cuckoo search algorithm (ORCSA) for solving optimal reactive power dispatch (ORPD) problem. The proposed ORCSA can deal with different objectives of the problem such as minimizing the real power losses, improving the voltage profile, and enhancing the voltage stability and properly handle various constraints for reactive power limits of generators and switchable capacitor banks, bus voltage limits, tap changer limits for transformers, and transmission line limits. The ORCSA method is created based on the conventional CSA method so as to improve optimal solution and speed up convergence. In the ORCSA method, new eggs generated via Lévy flights are replaced partially and the newly generated eggs are then evaluated and ranked at once. On the other hand, there is a bound by best solution technique proposed for replacing the invalid dimension in order to improve convergence rate and performance. The proposed method has been tested on the IEEE 30-bus and IEEE 118- bus systems and the obtained results are compared to that from other methods reported in the paper has indicated that the proposed method is very efficient for the optimal reactive power optimization problems.*

Keywords— **Constriction factor, optimal reactive power dispatch, one rank cuckoo search algorithm, voltage deviation, voltage stability index.**

1. INTRODUCTION

Optimal reactive power dispatch (ORPD) is to determine the control variables such as generator voltage magnitudes, switchable VAR compensators, and transformer tap setting so that the objective function of the problem is minimized while satisfying the unit and system constraints [1]. In the ORPD problem, the objective can be total power loss, voltage deviation at load buses for voltage profile improvement [2], or voltage stability index for voltage stability enhancement [3]. ORPD is a complex and large-scale optimization problem with nonlinear objective and constraints. In power system operation, the major role of ORPD is to maintain the load bus voltages within their limits for providing high quality of services to consumers.

The problem has been solved by various techniques ranging from conventional methods to artificial intelligence based methods. Several conventional methods have been applied for solving the problem such as linear programming (LP) [4], [1]mixed integer programming (MIP) [5], interior point method (IPM) [6], dynamic programming (DP) [7], and quadratic programming (QP) [8]. These methods are based on successive linearizations and use gradient as search directions. The conventional optimization methods can properly deal with the optimization problems of deterministic quadratic objective function and differential constraints. However, they can be trapped in local minima of the ORPD problem with multiple minima [9]. Recently, meta-heuristic search methods have become popular for solving the ORPD problem due to their advantages of simple implementation and ability to find near optimum solution for complex optimization problems. Various meta-heuristic methods have been applied for solving the Problem such as evolutionary programming (EP) [9], genetic algorithm (GA) [3], ant colony optimization algorithm (ACOA) [10], differential evolution (DE) [11], harmony search (HS) [12], etc. These methods can improve optimal solutions for the ORPD problem compared to the conventional methods but with relatively slow performance.

In this paper, a One Rank Cuckoo Search Algorithm (ORCSA) [13] is first proposed for the ORPD problem. The ORCSA is developed by Ahmed et al in 2013 by performing two modifications on original Cuckoo Search Algorithm including merging exploration phase and exploitation phase and bound by best solution mechanism.

In this paper, the proposed method has been tested on the IEEE 30-bus and IEEE 118-bus systems and the obtained results are compared to those from Particle Swarm Optimizer (PSO), Self-Organizing Hierarchical Particle Swarm Optimizer - Time Varying Acceleration Coefficients (HPSO-TVAC), Particle Swarm Optimization - Time Varying Acceleration Coefficients (PSO-TVAC), and Firefly Algorithm (FA). The result comparison has shown that the proposed method can obtain total power loss, voltage deviation or voltage stability index less than the others for the considered cases. Therefore, the proposed CRCSA can be a

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favorable method for implementation in the optimal reactive power optimization problems.

2. PROBLEM FORMULATION

The objective of the ORPD problem is to minimize is to optimize the objective functions while satisfying several equality and inequality constraints.

Mathematically, the problem is formulated as follows:

$$MinF(x,u) \quad (1)$$

where the objective function $F(x,u)$ can be expressed in one of the forms as follows:

- Real power loss:

$$F(x,u) = P_{loss} = \sum_{i=1}^{N_l} g_l \begin{bmatrix} V_i^2 + V_j^2 \\ -2V_i V_j \cos(\delta_i - \delta_j) \end{bmatrix} \quad (2)$$

- Voltage deviation at load buses for voltage profile improvement [2]:

$$F(x,u) = VD = \sum_{i=1}^{N_d} \left| V_i - V_i^{sp} \right| \quad (3)$$

where V_i^{sp} is the pre-specified reference value at load bus i, which is usually set to 1.0 pu.

- Voltage stability index for voltage stability enhancement [3], [18]:

$$F(x,u) = L_{\max} = \max\{L_i\}; i = 1,..., N_d \quad (4)$$

For all the considered objective functions, the vector of dependent variables x represented by:

$$x = [Q_{gl},...,Q_{gN_g}, V_{l1},...,V_{lN_d}, S_1,...,S_{N_l}]^T \quad (5)$$

and the vector of control variables u represented by:

$$u = [V_{gl},...,V_{gN_g}, T_1,...,T_{N_t}, Q_{c1},...,Q_{cN_c}]^T \quad (6)$$

The problem includes the equality and inequality constraints as follows:

a) Real and reactive power flow equations at each bus:

$$P_{gi} - P_{di} = V_i \sum_{j=1}^{N_b} V_j \left[G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right] \quad (7)$$

$$i = 1,..., N_b$$

$$Q_{gi} - Q_{di} = V_i \sum_{j=1}^{N_b} V_j \left[G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right] \quad (8)$$

$$i = 1,..., N_b$$

b) Voltage and reactive power limits at generation buses:

$$V_{gi,\min} \le V_{gi} \le V_{gi,\max}; i = 1,..., N_g \quad (9)$$

$$Q_{gi,\min} \le Q_{gi} \le Q_{gi,\max}; i = 1,..., N_g \quad (10)$$

c) Capacity limits for switchable shunt capacitor banks:

$$Q_{ci,\min} \le Q_{ci} \le Q_{ci,\max}; i = 1,..., N_c \quad (11)$$

d) Transformer tap settings constraint:

$$T_{k,\min} \le T_k \le T_{k,\max}; k = 1,..., N_t \quad (12)$$

e) Security constraints for voltages at load buses and transmission lines:

$$V_{li,\min} \le V_{li} \le V_{li,\max}; i = 1,..., N_d \quad (13)$$

$$S_l \le S_{l,\max}; l = 1,..., N_l \quad (14)$$

where the S_l is the maximum power flow between bus i and bus j determined as follows:

$$S_l = \max\{ |S_{ij}|, |S_{ji}| \} \quad (15)$$

3. ONE RANK CUCKOO SEARCH ALGORITHM (ORCSA)

3.1. One Rank Cuckoo Search Algorithm (ORCSA):

The cuckoo search algorithm (CSA), a new meta-heuristic algorithm, is inspired from the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of other host birds of other species for solving optimization problems. The CSA was first developed by was first developed by Yang and Deb in 2009. The CSA is summarized in the three main principal rules as follows [15]:

1. A cuckoo bird lays an egg and chooses a nest among the predetermined number of available host nests to dump its egg.

2. The best nests with high quality of egg (better solution) will be carried over to the next generation.

3. The number of available host nests is fixed, and the egg laid by a cuckoo is discovered by the host bird with a probability probability pa∈ [0, 1]. For the fraction of eggs, the host bird can either throw them away, or abandon them and build a new nest.

There is one more parameter is introduced in the proposed method in order to decide if the computational process merges exploration phase and exploitation phase together, called one rank ratio ror. The task of selection of the ratio is easy. It is initially set to 1 to allow merging new eggs from exploration phase and exploitation phase together. The ratio is still fixed at 1 until a better nest cannot be found at a current iteration. For the situation, the ratio is reduced as in the following equation (16).

$$r_{or}^{Iter+1} = r_{or}^{Iter} - 0.5/D \quad (16)$$

where Iter is the current iteration and D is the number of objective function dimension.

On the other hand, there is a bound by best solution technique proposed for replacing the invalid dimension in order to improve convergence rate and performance.

$$r_{bbb} = 1 - 1/\sqrt{D} \quad (17)$$

3.2. ORCSA for the ORPD problem

3.2.1. Initialization

For implementation of the proposed ORCSA to the problem, control variables is defined as follows:

$$x_d = [V_{g1d},...,V_{gN_gd},T_{1d},...,T_{N_td},Q_{c1d},...,Q_{cN_cd}]^T \quad (18)$$
$$d = 1,...,N$$

Initialize input of X_{id} is determined:

$$X_{id} = X_{id}^{\min} + rand(N,FS).*\left(X_{id}^{\max} - X_{id}^{\min}\right) \quad (19)$$

In which

$$X_{id}^{\max} = X_i^{\max} * ones(1,FS) \quad (20)$$

$$X_{id}^{\min} = X_i^{\min} * ones(1,FS) \quad (21)$$

with

$$X_{id}^{\max} = [V_{g1d}^{\max},...,V_{gN_gd}^{\max},T_{1d}^{\max},...,T_{N_td}^{\max},Q_{c1d}^{\max},...,Q_{cN_cd}^{\max}] \quad (22)$$

$$X_{id}^{\min} = [V_{g1d}^{\min},...,V_{gN_gd}^{\min},T_{1d}^{\min},...,T_{N_td}^{\min},Q_{c1d}^{\min},...,Q_{cN_cd}^{\min}] \quad (23)$$

The fitness function to be minimized is based on the problem objective function and dependent variables including reactive power generations, load bus voltages, and power flow in transmission lines. The fitness function is defined as follows:

$$F_T = F(x,u) + K_q\sum_{i=1}^{N_g}(Q_{gi} - Q_{gi}^{lim})^2 + K_v\sum_{i=1}^{Nd}(V_{li} - V_{li}^{lim})^2 + K_s\sum_{l=1}^{N_l}(S_l - S_{lmax})^2 \quad (24)$$

where K_q, K_v and K_s are penalty factor for reactive power generations, load bus voltages, and power flow in transmission lines, respectively.

The limits of the dependent variables in (24) are determined based on their calculated values as follows:

$$x^{\lim} = \begin{cases} x_{\max} & x > x_{\max} \\ x_{\min} & x < x_{\min} \end{cases} \quad (25)$$

whrere x and x^{lim} respectively represent for the calculated value and limits of Q_{gi}, V_{li}, S_{lmax}.

3.2.2. Generation of New Solution via Lévy Flights

The new solution is calculated based on the previous best nests via Lévy flights. In the proposed CSA method, the optimal path for the Lévy flights is calculated by Mantegna's algorithm (Mantegna,1994) [16]. The new solution by each nest is calculated as follows:

$$X_d^{new} = Xbest_d + \alpha \times rand_3 \times \Delta X_d^{new} \quad (26)$$

where $\alpha > 0$ is the updated step size; $rand_3$ is a normally distributed random number in [0, 1] and the increased value ΔX_d^{new} is determined by:

$$\Delta X_d^{new} = v \times \frac{\sigma_x(\beta)}{\sigma_y(\beta)} \times (Xbest_d - Gbest) \quad (27)$$

where

$$v = \frac{rand_x}{\left|rand_y\right|^{1/\beta}} \quad (28)$$

where randx and randy are two normally distributed stochastic variables with standard deviation $\sigma x(\beta)$ and $\sigma y(\beta)$ given by:

$$\sigma_x(\beta) = \left[\frac{\Gamma(1+\beta)\times\sin\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right)\times\beta\times 2^{\left(\frac{\beta-1}{2}\right)}}\right]^{1/\beta} \quad (29)$$

$$\sigma_y(\beta) = 1 \quad (30)$$

where β is the distribution factor ($0.3 \le \beta \le 1.99$) and $\Gamma(.)$ is the gamma distribution function.

3.2.3. Alien Egg Discovery and Randomization

The action of discovery of an alien egg in a nest of a host bird with the probability of pa also creates a new solution for the problem similar to the Lévy flights. The new solution due to this action can be found out in the following way:

$$X_d^{dis} = Xbest_d + K \times \Delta X_d^{dis} \quad (31)$$

where $Xbest_d$ is a solution generated via Lévy flights as in section 3.2.2 and K is the updated coefficient determined based on the probability of a host bird to discover an alien egg in its nest:

$$K = \begin{cases} 1 & \text{if } rand_4 < p_a \\ 0 & \text{otherwise} \end{cases} \quad (32)$$

and the increased value ΔX_d^{dis} is determined by:

$$\Delta X_d^{dis} = rand_5 \times \left[randp_1(Xbest_d) - randp_2(Xbest_d)\right] \quad (33)$$

where $rand_4$ and $rand_5$ are the distributed random numbers in [0, 1] and *randp1(Xbest$_d$)* and *randp2(Xbest$_d$)* are the random perturbation for positions of the nests in $Xbest_d$.

3.2.4. Bound by best solution mechanism

For the newly obtained solution using Matpower toolbox 4.1, its upper and lower limits should be satisfied. As described in the second modification in section 3.1, the bound by best solution mechanism is used to handle the inequality constraint.

3.2.5. Stopping Criteria

The algorithm is stopped when the number of iterations (Iter) reaches the maximum number of iterations (Itermax).

The overall procedure of the proposed ORCSA for solving the ORPD problem is addressed as follows:

Step 1: Select parameters for ORCSA including the number of nest Np, the maximum number of iteration Itermax. Initialize population of host nests as in Section 3.2.1.

Step 2: Calculate value of dependent variables based on power flow solution using Matpower toolbox 4.1.

Step 3: Evaluate fitness function to choose Xbest and Gbest based on the value of their fitness function. Set the iteration counter *Iter* = 1 and one rank ratio $r_{or} = 1$.

Step 4: Set Generate new solutions for abandoned eggs via Lévy flights as in Section 3.2.2

Step 5: Initialize a random number and compare to one rank ratio r_{or}. If the random number is less than r_{or}, go to step 6. Otherwise, go to step 9

Step 6: Discover alien egg and randomize to generate new solution as in Section 3.2.3

Step 7: Perform bound by best solution mechanism to define new solution as in section 3.2.4.

Step 8: Calculate value of dependent variables based on power flow solution using Matpower toolbox 4.1. Calculate fitness function (24), then rank and keep the current best nest. Go to step 14.

Step 9: Perform bound by best solution mechanism to define new solution as in section 3.2.4.

Step 10: Calculate value of dependent variables based on power flow solution using Matpower toolbox 4.1. Calculate fitness function (24), then rank and keep the current best nest.

Step 11: Discover alien egg and randomize to generate new solution as in Section 3.2.3

Step 12: Perform bound by best solution mechanism to define new solution as in section 3.2.4.

Step 13: Calculate value of dependent variables based on power flow solution using Matpower toolbox 4.1. Calculate fitness function (24), then rank and keep the current best nest.

Step 14: Get the best nest Gbest.

Step 15: If the current iteration Iter is equal to the maximum number of predetermined iteration. Stop the iterative procedure. Otherwise, set *Iter* = *Iter* + 1 and go to step 16.

Step 16: If the best nest Gbest at the current iteration is not better than that of the previous iteration. Obtain the one rank ratio using eq. (16) and back to 5.

4. NUMERICAL RESULTS

The proposed ORCSA has been tested on the IEEE 30-bus and 118-bus systems with different objectives including power loss, voltage deviation, and voltage stability index. The data for these systems can be found in [19], [20] . The characteristics and the data for the base case of the test systems are given in Tables 1 and 2, respectively.

The algorithms of the ORCSA methods are coded in Matlab R2009b and run on an Intel Core i3 CPU 2.50 GHz with 2 GB of RAM PC. The parameters of the ORCSA methods for the test systems are summarized in Table 3.

4.1 IEEE 30-bus system:

In the test system, the generators are located at buses 1, 2, 5, 8, 11, and 13 and the available transformers are located on lines 6-9, 6-10, 4-12, and 27-28. The switchable capacitor banks will be installed at buses 10, 12, 15, 17, 20, 21, 23, 24, and 29 with the minimum and maximum values of 0 and 5 MVAR, respectively. The limits for control variables are given in [11], generation reactive power in [21], and power flow in transmission lines in [22].

The results obtained by the ORCSA method for the system with different objectives including power loss, voltage deviation for voltage profile improvement, and voltage stability index for voltage enhancement are given in Tables 4, 5, and 6, respectively and the solutions for best results are given in Tables A1, A2, and A3 of Appendix.

The obtained best results from the proposed ORCSA method are compared to Gravitational Search Algorithm (GSA), comprehensive learning particle swarm optimization (CLPSO) [23], Self-Organizing Hierarchical Particle Swarm Optimizer - Time Varying Acceleration Coefficients (HPSO-TVAC), Particle Swarm Optimization - Time Varying Acceleration Coefficients (PSO-TVAC) [24] and Firefly Algorithm (FA) [25] for different objectives as given in Table 7.

The obtained best results from the proposed ORCSA method are compared to those from DE [11], comprehensive learning particle swarm optimization (CLPSO) [23], PSO variants [24], and FA [25] for different objectives as given in Table 7. For the objective of total power loss and voltage deviation, the optimal solutions by the proposed ORCSA are less than those from the others while the best voltage stability index from the ORCSA method is approximate to that from others. For computational time, the ORCSA method obtained its optimal solution for an average of 15 seconds which is similar that from the PSO-CF method. For computational time, the ORCSA method obtained its optimal solution for an average of 15 seconds which is similar that from the other methods.

Table 1. Characteristics of test systems

System	No. of branches	No. of Generatio buses	No. of transformers	No. of capacitor banks	No. of control variables
IEEE 30 bus	41	6	4	9	19
IEEE 118 bus	186	54	9	14	77

Table 2. Base case for test systems

System	$\sum P_{di}$	$\sum Q_{di}$	$\sum P_{gi}$	$\sum Q_{gi}$
IEEE 30 bus	283.4	126.2	287.92	89.2
IEEE 118 bus	4242	1438	4374.86	795.68

Table 3: The parameters of the ORCSA methods

	Number of nest	Pa	Alpha1
ORCS algorithm	10	0.7	0.1

Table 4. Results by ORCSA method and compare to the other methods for the IEEE 30-bus system with power loss objective

Method	PSO-TVAC [24]	HPSO-TVAC [24]	ORCS
Min Ploss (MW)	4.5356	4.5283	4.5134
Avg. Ploss (MW)	4.5912	4.5581	4.5873
Max Ploss (MW)	4.9439	4.6112	5.1346
Std. dev. Ploss (MW)	0.0592	0.0188	0.1181
VD	1.9854	1.9315	2.0460
L_{max}	0.1257	0.1269	0.1256
Avg. CPU time (s)	10.38	10.65	14.719

Table 5. Results by ORCSA method and compare to the other methods for the IEEE 30-bus system with voltage deviation objective

Method	PSO-TVAC [24]	HPSO-TVAC [24]	ORCS
Min VD	0.1210	0.1136	0.0946
Avg. VD	0.1529	0.1340	0.1041
Max VD	0.1871	0.1615	0.1229
Std. dev. VD	0.0153	0.0103	0.0049
Ploss (MW)	5.3829	5.7269	5.6809
Slmax	0.1485	0.1484	0.1478
Avg. CPU time (s)	9.88	9.59	15.622

Table 6. Results by ORCSA method and compare to the other methods for the IEEE 30-bus system with voltage stability index objective

Method	PSO-TVAC [24]	HPSO-TVAC [24]	ORCS
Min Lmax	0.1248	0.1261	0.1249
Avg. Lmax	0.1262	0.1275	0.1258
Max Lmax	0.1293	0.1287	0.1269
Std. dev. Lmax	0.0009	0.0006	0.0004
Ploss (MW)	4.8599	5.2558	4.6584
VD	1.9174	1.6830	1.9975
Avg. CPU time (s)	13.39	13.05	15.150

Table 7. Comparison of best results for the IEEE 30-bus system

Method / Function	Power loss (MW)	Voltage deviation (VD)	Stability index (L_{imax})
CLPSO[23]	4.5615	-	-
PSO-TVAC[24]	4.5356	0.1210	0.1248
HPSO-TVAC[24]	4.5283	0.1136	0.1261
HFA [25]	4.529	0.098	-
ORCSA	4.5134	0.0946	0.1247

Table 8. Results by ORCSA method and compare to the other methods for the IEEE 118-bus system with power loss objective

Method	PSO-TVAC [24]	HPSO-TVAC [24]	ORCS
Min Ploss (MW)	124.3335	116.2026	116.9774
Avg. Ploss (MW)	129.7494	117.3553	122.1781
Max Ploss (MW)	134.1254	118.1390	122.1781
Std. dev. Ploss (MW)	2.1560	0.4696	2.4681
VD	1.4332	1.8587	2.0636
Lmax	0.0679	0.0650	0.0632
Avg. CPU time (s)	85.32	85.25	104.062

Table 9. Results by ORCSA methods and compare to the other methods for the IEEE 118-bus system with voltage deviation objective

Method	PSO-TVAC [24]	HPSO-TVAC [24]	ORCS
Min VD	0.3921	0.2074	0.3101
Avg. VD	0.4724	0.2498	0.4345
Max VD	0.5407	0.3012	0.5827
Std. dev. VD	0.0316	0.0215	0.0596
Ploss (MW)	179.7952	146.8104	136.0782
Slmax	0.0667	0.0670	0.0672
Avg. CPU time (s)	78.70	74.90	137.640

Table 10. Results by ORCSA methods and compare to the other methods for the IEEE 118-bus system with stability index objective

Method	PSO-TVAC [24]	HPSO-TVAC [24]	ORCS
Min Lmax	0.0607	0.0607	0.0595
Avg. Lma	0.0609	0.0608	0.0633
Max Lmax	0.0613	0.0612	0.0712
Std. dev. Lmax	0.0001	0.0001	0.0023
Ploss (MW)	184.5627	155.3915	131.9501
VD	1.2103	1.34401	1.3862
Avg. CPU time (s)	119.22	119.16	137.316

Table 11. Comparison of best results for the IEEE 118-bus system

Method / Function	Power loss (MW)	Voltage deviation (VD)	Stability index (L_{imax})
PSO-TVAC[24]	124.3335	0.3921	0.0607
PSO[24]	131.99	2.2359	0.1388
CLPSO[15]	130.96	1.6177	0.0965
FA [25]	135.42	0.378	-
ORCSA	116.9774	0.3101	0.0595

4.2 IEEE 118-bus system

In this system, the position and lower and upper limits for switchable capacitor banks, and lower and upper limits of control variables are given in [23].

The obtained results by the ORCSA methods for the system with different objectives similar to the case of IEEE 30 bus system are given in Tables 8, 9, and 10, respectively and the comparison of best results from methods for different objectives is given in Table 11. It can be seen from the data in Table 11 that the results obtained from the ORCSA method are less than others methods with total power loss, voltage deviation, and voltage stability index. For computational time, the ORCSA method obtained its optimal solution for an average of 137 seconds which is similar that from the other methods.

5. CONCLUSION

In this paper, the ORCSA method has been effectively and efficiently implemented for solving the ORPD problem. The proposed ORCSA has been tested on the

IEEE 30-bus and IEEE 118-bus systems with different objectives including power loss, voltage deviation, and voltage stability index. The test results have shown that proposed method can obtain total power loss, voltage deviation, or voltage stability index less than other methods for test cases. Therefore, the proposed ORCSA could be a useful and powerful method for solving the ORPD problem.

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APPENDIX

The best solutions by ABC methods for the IEEE 30- bus system with different objectives are given in Tables A1, A2, and A3.

Table A1. Best solutions by ORCSA methods for the IEEE 30-bus system with power loss objective

Control variables	PSO-TVAC	HPSO-TVAC	HFA	ORCSA
V_{g1}	1.1000	1.1000	1.1	1.1000
V_{g2}	1.0957	1.0941	1.054332	1.0937
V_{g5}	1.0775	1.0745	1.075146	1.0734
V_{g8}	1.0792	1.0762	1.086885	1.0756
V_{g11}	1.1000	1.0996	1.1	1.0997
V_{g13}	1.0970	1.1000	1.1	1.1000
$T_{6\text{-}9}$	1.0199	1.0020	0.980051	1.0374
$T_{6\text{-}10}$	0.9401	0.9498	0.950021	0.9058
$T_{4\text{-}12}$	0.9764	0.9830	0.970171	0.9782
$T_{27\text{-}28}$	0.9643	0.9707	0.970039	0.9648
Q_{c10}	4.5982	2.3238	4.700304	4.9985
Q_{c12}	2.8184	2.8418	4.706143	4.7287
Q_{c15}	2.3724	3.6965	4.700662	4.3016
Q_{c17}	3.6676	4.9993	2.30591	4.8615
Q_{c20}	4.3809	3.1123	4.80352	4.2635
Q_{c21}	4.9146	4.9985	4.902598	4.9711
Q_{c23}	3.6527	3.5215	4.804034	2.9871
Q_{c24}	5.0000	4.9987	4.805296	4.9866
Q_{c29}	2.1226	2.3743	3.398351	2.2062

Table A2. Best solutions by ORCSA methods for the IEEE 30-bus system with voltage deviation objective

Control variables	PSO-TVAC	HPSO-TVAC	HFA	ORCSA
V_{g1}	1.0282	1.0117	1.003458	1.0169
V_{g2}	1.0256	1.0083	1.01638	1.0148
V_{g5}	1.0077	1.0169	1.019451	1.0175
V_{g8}	1.0014	1.0071	1.018221	1.0115
V_{g11}	1.0021	1.0707	0.982272	1.0157
V_{g13}	1.0046	1.0060	1.01546	0.9931
$T_{6\text{-}9}$	1.0125	1.0564	0.99	1.0314
$T_{6\text{-}10}$	0.9118	0.9076	0.9	0.9002
$T_{4\text{-}12}$	0.9617	0.9545	0.98	0.9513
$T_{27\text{-}28}$	0.9663	0.9695	0.96	0.9576
Q_{c10}	5.0000	1.5543	3.2	4.0287
Q_{c12}	1.5065	1.4242	0.5	3.0711
Q_{c15}	3.9931	2.5205	4.9	4.2692
Q_{c17}	3.7785	1.6400	0.1	0.9329
Q_{c20}	3.2593	5.0000	3.8	4.9825
Q_{c21}	4.1425	1.8539	5	2.6228
Q_{c23}	4.9820	3.3035	5	4.9425
Q_{c24}	4.5450	4.5941	3.9	4.7014
Q_{c29}	4.1272	3.5062	1.5	2.3272

Table A3. Best solutions by ORCSA methods for the IEEE 30-bus system with objective of stability index

Thông số biến	PSO-TVAC	HPSO-TVAC	ORCSA
V_{g1}	1.1000	1.0979	1.0996
V_{g2}	1.0934	1.0997	1.0949
V_{g5}	1.0969	1.0500	1.0791
V_{g8}	1.0970	1.0663	1.0723
V_{g11}	1.1000	1.0561	1.0975
V_{g13}	1.1000	1.0886	1.0958
T_{6-9}	1.0935	0.9939	0.9693
T_{6-10}	0.9000	1.0150	0.9068
T_{4-12}	0.9579	0.9121	0.9815
T_{27-28}	0.9651	0.9406	0.9458
Q_{c10}	3.1409	3.7685	3.2972
Q_{c12}	3.0186	4.6323	2.2557
Q_{c15}	1.4347	2.6542	4.6097
Q_{c17}	3.8498	2.6897	0.5020
Q_{c20}	0.0000	2.8806	1.8554
Q_{c21}	5.0000	2.1071	1.1608
Q_{c23}	0.0000	3.1044	0.8344
Q_{c24}	2.1733	2.1797	0.3412
Q_{c29}	2.2708	3.5843	3.9241