Artificial Bee Colony Algorithm for Discrete Optimal Reactive Power Dispatch

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Abstract— **In this paper one of the reliable and effective optimization algorithms called "artificial bee colony" algorithm (ABC) for solving the optimal reactive power dispatch (ORPD) problem with the discrete and continuous control variables in an electric power system is presented. In this work ABC algorithm is used to find the settings of control variables such as generator voltages, tap positions of tap changing transformers and the number of capacitors banks to be switched, for optimal reactive power dispatch. The original ABC algorithm designed for the continuous nature of optimization problems, cannot be used for discrete cases; but the real ORPD problem has two different nature types of control variables (discrete and continuous), for this reasons a simple rounding operator is included in the main steps of original ABC algorithm to ensure the discretization process. Then, the feasibility and performance of the proposed algorithm are verified by the serial simulations on the IEEE 14-bus, IEEE 30-bus and IEEE 57-bus power systems. The numerical results are compared to those yielded by the other recently published evolutionary optimization algorithms in the literature. This comparison shows that the ABC algorithm is superior to the other mentioned algorithms and can be efficiently used for solving the discrete ORPD problem.**

Keywords— ***Artificial bee Colony algorithm (ABC); Discrete Optimal Reactive Power Dispatch (ORPD); Power Systems; Optimization.***

I. INTRODUCTION

The Optimal Reactive Power Dispatch (ORPD) is an important issue in power system planning and operation and it's considered as a sub-problem of optimal power flow (OPF). The objective of the ORPD problem is to determine the optimal combination of generator voltages, taps positions of tap changing transformers and the number of capacitors banks must be switched in power system for minimizing the real power transmission losses, while satisfying certain physical and operating constraints at the same time.

The ORPD problem is formulated as a non-linear multi-modal, large-scale, static optimization problem because of the presence of both continuous and discrete control variables such as switching shunt capacitor banks and transformer tap settings are presented as discrete variables.

Over the past quarter of the previous century, a variety of conventional optimization algorithms has been successfully applied for solving the reactive power dispatch problem. For example, Linear Programming (LP), Interior-Point method (IP) and decoupled quadratic programming [1-3] but these algorithms suffer from many drawbacks such as the huge computations and large execution time and the inflexibility with the practical system, and still encounter serious challenges in yielding the optimal solution. Moreover, the inclusion of discrete control variables highly increases the complexity of the ORPD problem. Therefore, it is mandatory to find more accurate and efficient algorithms able to overcome all the above-mentioned drawbacks and such difficulties.

In the past two decades, plenty of heuristic and stochastic optimization algorithms have been developed and applied successfully to deal with optimal reactive power dispatch problem, among them, differential evolution [4], teaching–learning-based optimization algorithm [5], biogeography-based optimization [6], harmony search algorithm [7], and gravitational search algorithm [8]. But, certain of these algorithms have drawbacks such as of trapping into local optima, which forced many researchers to combine between the advantages of the two previous methods in order to provide what is called the hybrid methods that bring the better results, like hybrid particle swarm optimization approach for solving the discrete OPF problem [9], Hybrid shuffled frog leaping and Nelder–Mead [10], and A hybrid artificial bee colony assisted differential evolution algorithm [11].

Recently, a new evolutionary computation algorithm, based on simulating the foraging behavior of honey bee swarm called “artificial bee colony”, has been developed and introduced in 2005 by the scientist Karaboga for real parameter optimization and it has been gaining a popularity in the community of researchers, for its effectiveness in solving some practical problems such as unconstrained numerical optimization constrained numerical optimization [12-13] aircraft attitude control [14], real and reactive power tracing in deregulated power systems [15], and made a series of good experimental results.

like all other evolutionary algorithm, the ABC also suffers in its solution search equation from poor exploitation, contrary to exploration process which is good, [16-18] but, all these/other critics of many researchers about ABC algorithm when comparing it with other modified versions of ABC developed until now, and also some metaheuristic algorithms, are amply commented and clarified by Marjan Mernik et al- in paper titled "*On clarifying misconceptions when comparing variants of the Artificial Bee Colony Algorithm by offering a new implementation*" [19].

In this paper, we aim to prove the efficiency and the ability of original ABC Colony algorithm to solve one of more non-linear multi-modal so-called the discrete optimal reactive power dispatch problem. The main idea behind using the descritezation process is to reflect the real world of the ORPD problem and also for achieving a better solution quality. The algorithm was tested on IEEE 14-bus, IEEE 30-bus and IEEE 57 bus power systems. The numerical results of the proposed ABC algorithm are compared to the results of the many recently published optimization algorithms in the literature.

II. PROBLEM FORMULATION

In general, the aim of a solution of ORPD problem is minimize the real power loss through optimal adjustment power system control parameters while satisfying equality and inequality constraints at the same time [5].

$$Min\,P_{loss}=F_{OBJ}\left(x,\mathrm{u}\right)=\sum_{k=1}^{NTL} g_k\left(V_i^2+V_j^2-2V_iV_j\cos\delta_{ij}\right) \qquad (1)$$

$$\text{Subject to: } g\left(x,\mathrm{u}\right)=0 \qquad (2)$$

$$h\left(x,\mathrm{u}\right)=0 \qquad (3)$$

where $F_{OBJ}\left(x,\mathrm{u}\right)$ is the transmission loss minimization objective function, P_{loss} the total power losses, $g\left(x,\mathrm{u}\right)$: equality constraints; $h\left(x,\mathrm{u}\right)$: inequality constraints, g_k the conductance of k^{th} line connected between i^{th} and j^{th} buses, Vi , V_j the voltage of i^{th} and j^{th} buses respectively, and δ_{ij} is the phase angle between i^{th} and j^{th} bus voltages. *NTL:* depict the number of transmission lines.

x : is the vector of dependent variables consisting of:

Load bus voltages V_L; Reactive powers of generators Q_G and Transmission lines loading S_l.

u : is the vector of independent variables consisting of: continuous and discrete variables.

1. Generator bus voltage (continuous control variable);
2. Transformer taps settings (discrete control variable);
3. Switching shunt capacitor banks (discrete control variable).

Hence, x and u can be expressed as:

$$x^T=\left[V_L..V_{NLB},Q_{G1}..Q_{GNG},S_1..S_{NTL}\right] \qquad (4)$$

$$u^T=\left[\underbrace{V_{G1}...V_{GNG}}^{\text{continuous}},\overbrace{T_1...T_{NT},Q_{C1}......,Q_{C,NC},}^{\text{Discrete}}\right] \qquad (5)$$

NG : is the number of generator in system test; NLB : Number of load buses in the system test; NTL Number of transmission lines in the system test; NT : Number of regulating transformer in the system test; NC Number of capacitor banks in the system test.

A. Constraints

- *Equality constraints*

The equality constraints set typically consists of the load flow equation, which are given below:

$$\begin{cases} P_{Gi}-P_{Li}=\sum_{j=1}^{NB}\left|V_i\right|\left|V_j\right|\left(G_{ij}\cos\delta_{ij}+B_{ij}\sin\delta_{ij}\right) \\ Q_{Gi}-Q_{Li}=\sum_{j=1}^{NB}\left|V_i\right|\left|V_j\right|\left(G_{ij}\sin\delta_{ij}-B_{ij}\cos\delta_{ij}\right) \end{cases} \qquad (6)$$

NB	Number of bus in the system test
V_i,V_j	Voltages of i^{th} and j^{th} respectively in (P.u)
P_{Gi},Q_{Gi}	Active and reactive power of i^{th} generating unit
P_{Li},Q_{Li}	Active and reactive power of i^{th} load bus
$G_{ij},B_{ij},\delta_{ij}$	Conductance, Admittance and phase difference of voltages between i^{th} and j^{th} bus.

- *Inequality constraints*

(i). Generators constraints

$$\begin{cases} V_{Gi}^{\min}\le V_{Gi}\le V_{Gi}^{\max} & i=1,2.....NG \\ Q_{Gi}^{\min}\le Q_{Gi}\le Q_{Gi}^{\max} & i=1,2......,NG \end{cases} \qquad (7)$$

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

(ii). Voltage magnitudes at each bus in the network

$$V_{NB}^{\min}\le V_{NB}\le V_{NB}^{\max} \qquad (8)$$

(iii). The transmission lines loading

$$\left|S_{NTL}\right|\le S_{NTL}^{\max} \qquad (9)$$

(iv). The discrete transformer tap setting

$$T_{NT}^{\min}\le T_{NT}\le T_{NT}^{\max} \qquad (10)$$

(v). The discrete reactive power is supplying by shunt capacitor banks also ought to be limited as:

$$Q_{ci}^{\min}\le Q_{ci}\le Q_{ci}^{\max} \quad i=1,2,........,NC \qquad (11)$$

In the present work, the overall objective function is written in generalized form as:

$$Min\,P_{loss}=F_{OBJ}\left(x,\mathrm{u}\right)+\lambda_V\sum_{i=1}^{NBl}\left(V_i-V_i^{\lim}\right)^2+\lambda_Q\sum_{i=1}^{NG}\left(Q_{Gi}-Q_{Gi}^{\lim}\right)^2$$

where λ_V and λ_Q are the penalty factors; NBl :is the index of PQ busses; $X_i^{\lim}$; are the limit value of dependent variable.

III. ARTIFICIAL BEE COLONY ALGORITHM

Artificial bee colony algorithm (ABC) algorithm is among of newest simulated evolutionary algorithms. It's proposed by Turkish scholar Karaboga [12]. The colony of artificial bee consists of three groups of bees: employed bees, onlooker and scout bees. The number of employed bees or the onlooker bees is equal to the number of food source (solutions) in the ruche and there is exactly one employed bee for each food source [22]. In ABC algorithm, each food source (position) presents a solution to the problem, and the quality of the food source (nectar amounts) is called fitness value for the associated position.

The ABC algorithm has three main steps which are explained in detail below:

Initialization: In the initialization step, a set of food source positions are randomly selected by the bees utilizing the equation (12)

$$x_{ij} = x_{\min j} + \text{rand }[0,1].\left(x_{\max j} - x_{\min j}\right) \tag{12}$$

where $J \in \{1,2........,D\}$ (D is the number of parameters to be optimized).

Employed Bees Step: In the first step, each bee visits one successively to a food source. Each bee did searches in the proximity of the reference position for finding a new and best position (v_{ij}), using equation (13) and evaluate them by the artificial bee. The formula of search equation is:

$$v_{ij} = x_{ij} + \varphi_{ij}\left(x_{ij} - x_{kj}\right) \qquad i \neq k \tag{13}$$

where $k \in \{1,........,N\}$ and $J \in \{1,2........,D\}$ are randomly chosen indexes, and k is determined randomly, it has to be different from *i,* φ_{ij} is a random number between range [-1,1]. x_{ij} : is the position of i^{th} reference food source and x_{ij} : is the randomly selected food source in dimension j . Once the updating process is over, the new solution (v_{ij}) is compared with that of the reference (x_{ij}). If the new solution (v_{ij}) has an equal or better quality than the reference source (x_{ij}), the reference source is replaced by the new solution. Otherwise, the reference solution is retained. This is called the greedy selection process.

Onlooker Bees Step: In the second step the onlooker bees go to visit the position of food sources depending from all information's shared by employing bees, and choose a food sources with a probability value related to its quality. The same principle applies to the onlooker bees. Each bee searches in the proximity of an old position to produce a new solution and then the artificial bee evaluated the performance of the new solutions by comparing it with that of the old one; afterward, the greedy selection process is applied. The probability value which a food source will be selected is calculated by the following expression:

$$P_i = \frac{fit_i}{\sum_{k=1}^{SN} fit_k} \tag{14}$$

where fit_i is the fitness value of the solution i which is proportional to the nectar amount of source the i^{th} food source. SN : is the number of food sources. For minimization problem, fit_i can be calculated using the following expression:

$$fit_i = \begin{cases} \dfrac{1}{1+F_i} & \text{if } F_i \geq 0 \\ 1+|F_i| & \text{if } F_i < 0 \end{cases} \tag{15}$$

where F_i is the value of objective function.

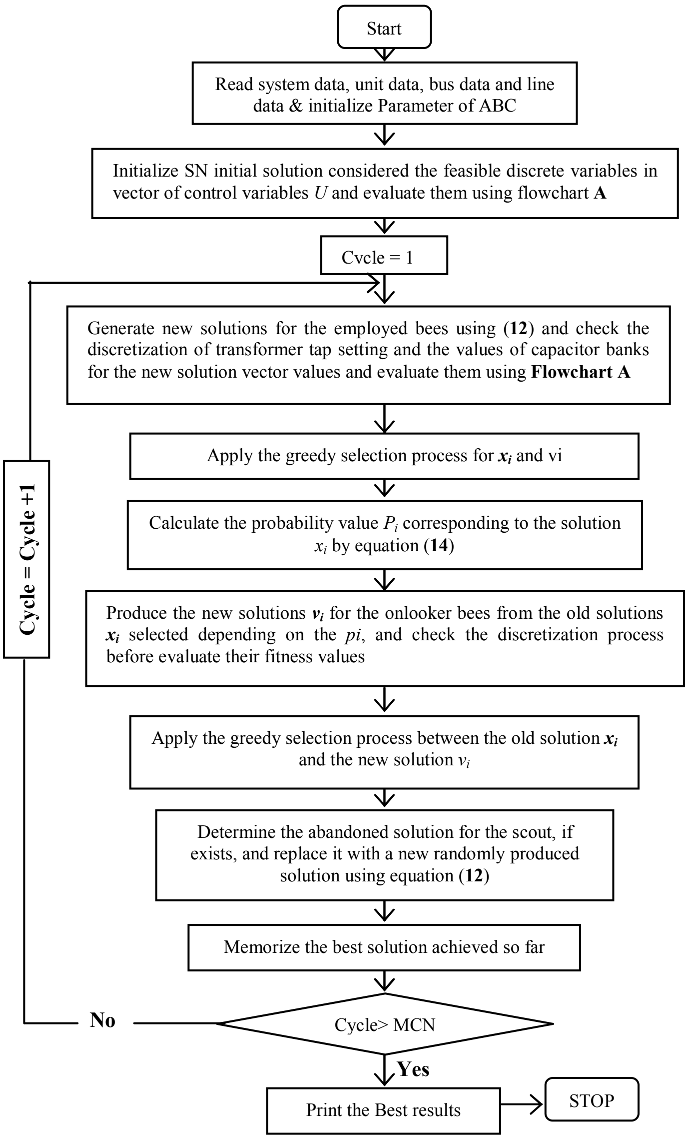
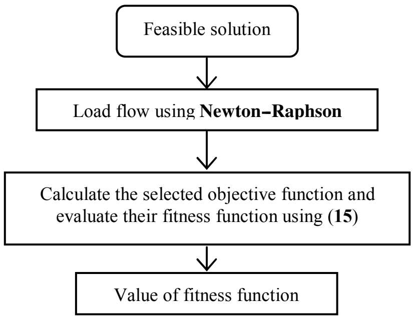


Fig. 1. Flowchart ABC algorithm



Flowchart A

Scout bees step: In the third step, if onlookers and employed bees cannot be improved the position of food source during a predetermined number of cycles, then this food source is assumed to be abandoned and the corresponding employed bees become scout bees. This scouts bees randomly try to find a new food source for replacing the abandoned ones using the equation (12). "*Limit*" is a value of a predetermined number of cycles, that plays an important role, basing on the dimension of the problem to be solved and half of the size colony (or the number of employed or onlooker bees (*SN*)).

A. Control variables treatment

In our formulation two types of problem optimization variables are considered: continuous and discrete as shown in equation (4) that requires special initialization. The continuous variables are initialized with uniformly distributed pseudo-random numbers in a given range as follows, e.g: $P_{Gi} = \text{random}\left[P_{Gi}^{\min}, P_{Gi}^{\max}\right]$ and $U_{Gi} = \text{random}\left[U_{Gi}^{\min}, U_{Gi}^{\max}\right]$. But, in the case of the discrete variables, all the values including, transformer tap setting and the discrete reactive shunt capacitor banks are rounded to its nearest decimal values; this operation is achieved by the introduction of rounding operator that ensures each discrete value is rounded to their nearest decimal integer value. Mathematically, the rounding operator can be expressed as follows: $\text{round}\left(\text{random}\left[T_i^{\min}, T_i^{\max}\right], 0.01\right)$; $\text{round}\left(\text{random}\left[Q_{Ci}^{\min}, Q_{Ci}^{\max}\right], 1\right)$.
After the initialization phase, the solution vector is subject to update (modification on the position food source (solution)) in order to find a new vicinity solution vector using the motion equation (eq 13), yielding a vector uniformly distributed random due to the addition two different types of vectors. Once the rounding process is over, all solution elements go through a feasibility check. This simple rounding technique guarantees that power flow calculations and fitness function are obtained only when all problem variable are correctly assigned to their corresponding types.

IV. NUMERICAL RESULTS AND DISCUSSION

A. IEEE 14-bus power system

The proposed algorithm was implemented in MATLAB Platform and the simulation conducted on a personal computer "Core (TM) i3-3217U CPU 1.80 GHz - 4 Go RAM". The first test power system is IEEE 14-bus that includes five generators at the buses 1, 2, 3, 6 and 8; 20 branches, 17 of which are transmission lines and 3 are tap changing transformers. In addition two capacitors banks installed at bus 9 and 14. Detailed description of the system data are taken from [22-23]. The line and minimum and maximum limits of real power generations are presented in [22][11]; The number of control variables and real power loss in initial condition are respectively listed in Table I and the limit on control variables and dependent variables for all systems test are given in Table II.

TABLE I. VARIABLES LIMITS FOR ALL IEEE *X*-BUS POWER SYSTEM.

	14-bus	**30-bus**	**57-bus**
No of control.Var	10	12 or **19**	25
No of Taps	3	4	15
No of PV bus	5	6	7
No of Q_{shunt}	2	2 or **9**	3
P_{Loss}^{0} (MW)	13.49	5.66 or **5.81**	28.462

TABLE II. CONTROL VARIABLE SETTINGS FOR THE ALL TEST SYSTEMS. TABLE STYLES

Test System	**Variables**	**Minimum**	**Maximum**	**Step**
14-bus [23][11-24]	V_G	0.9	1.1	
	V_{PQ}	0.9	1.1	
	T	0.9	1.1	0.01
	Q_{shunt} (9-14)	0	0.18	1
30-bus Case 1 [26]	V_G	0.95	1.1	
	V_{PQ}	0.95	1.1	
	T	0.9	1.1	0.01
	Q_{shunt} (10 , 24)	0	0.3	1
Case 2 [25]	Q_{shunt} (n= 9)	0	0.05	1
57-bus [5][10] [11]	V_G	0.95	1.1	
	V_{PQ}	0.95	1.1	
	T	0.9	1.1	0.01
	$Q_{\text{shunt 18}}$	0	0.20	1
	$Q_{\text{shunt 25}}$	0	0.18	1
	$Q_{\text{shunt 53}}$	0	0.18	1

In order to verify the quality and robustness of the proposed algorithm, 30 independent runs for each reviewed test systems were performed to reaching the optimal solution.

The optimal solution control variables of ORPD problem obtained by ABC algorithm and some existing algorithms are listed in Table III. Table IV, tabulated the full comparison in term minimum real power loss, average, maximum, standard deviation and average computation time between ABC and recent results reported in the literature. Fig 1, shows the convergence curve of the ABC for Test System I.

From the simulation results of problem ORPD, it is clear that ABC algorithm is superior to all other algorithms. Also, we can see that an 9.22% reduction in power loss is accomplished by the proposed algorithm, which is better than that obtained by presented algorithms.

TABLE III. COMPARISON OF SIMULATION RESULTS FOR IEEE 14-BUS TEST POWER SYSTEM

Variable (p.u)	Active Power Loss (p.u.)				
	Base Case	**MGBTLBO algorithm[5]**	**EP [27]**	**SARGA [27]**	**ABC**
V_{G1}	1.06	1.1	-	-	1.1
V_{G2}	1.045	1.0791	1.029	1.096	1.0834
V_{G3}	1.01	1.0485	1.016	1.036	1.0495
V_{G6}	1.07	1.0552	1.097	1.099	1.1
V_{G8}	1.09	1.0326	1.053	1.078	1.1
$T_{4\text{-}7}$	0.9467	1.01	1.04	0.95	1.01
$T_{4\text{-}9}$	0.9524	1.01	0.94	0.95	0.92
$T_{5\text{-}6}$	0.9091	1.03	1.03	0.96	0.98
Q_{C9}	0.18	0.3	0.18	0.18	0.18
Q_{C14}	0.18	0.07	0.06	0.06	0.08
Power losses(MW)	13.49	12.3106	13.3462	13.216	12.2459

TABLE IV. STATISTICS OF TRIAL RESULTS OF ABC ALGORITHM AND OTHERS ALGORITHMS; IEEE 14- BUS POWER SYSTEM.

Algorithm	P_{Loss}^{max}	P_{Loss}^{aver}	P_{Loss}^{min}	***Std .Devi***	**CPU (s)**
DE [11]	12.6364	12.3892	12.3713	0.035123	30.3782
PSO [24]	13.402	13.352	13.250	0.0640	9.283
DE [24]	13.275	13.250	13.239	0.0161	8.172
CSSP3[32]	12.5644	12.4648	12.3868	0.0478	NA
TLBO [5]	13.1251	12.9973	12.9882	NA	7.68
SARGA [27]	13.2389	13.22317	13.21643	0.000178	54
EP [27]	13.3986	13.37124	13.34620	0.000024	72
ABC	13.0672	12.4744	12.2459	0.1991	14.146

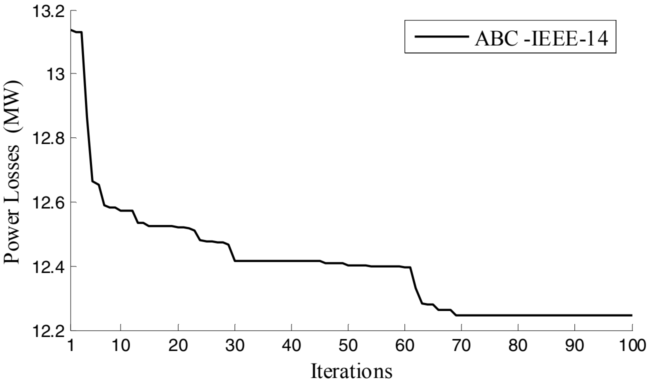


Fig. 2. Convergence characteristic of IEEE-14 test System

B. *IEEE 30-bus system*

The second test system is IEEE 30-bus that includes six generators at buses 1, 2, 5, 8, 11 and 13. Four branches 6-9, 6-10, 4-12, and 27-28 have tap setting transformers. In addition, two capacitors banks installed at bus 10 and 24 for case 1. However, in second case of IEEE 30 bus to the original system, these capacitor banks are not considered rather the new emplacement of capacitor banks are provided at buses 10, 12, 15, 17, 20, 21, 23, 24 and 29 as given in [25].

Case 1: IEEE-30bus test system used in [24, 27-29].
Case 2: IEEE-30bus test system used in [27-28, 4,and 25].

The optimal solution control variables of ORPD problem obtained by ABC algorithm and some existing algorithms are listed in Table V. Table VI, depicts the full comparison in term minimum real power loss, average, maximum, and average computation time between ABC and recent results reported in the literature.

TABLE V. COMPARISON OF SIMULATION RESULTS FOR IEEE 30-BUS TEST POWER SYSTEM - **CASE 1**

Variable	**GPAC [26]**	**BBO [27]**	**DE [24]**	**MICA-IWO [29]**	**PSO-TS [28]**	**ABC**
V_{G1}	1.02942	1.1000	1.05	1.07	1.0992	1.1
V_{G2}	1.00645	1.0943	1.0446	1.06136	1.0948	1.0925
V_{G5}	1.01692	1.0804	1.0247	1.04406	1.0766	1.0749
V_{G8}	1.03952	1.0939	1.0265	1.04595	1.0977	1.0764
V_{G11}	1.03952	1.1	1.1	1.1	1.0837	1.1
V_{G13}	1.04870	1.1	1.1	1.1	1.0754	1.1
$T_{6\text{-}9}$	1.04225	1.1	1.0	1.0	0.9257	1.02
$T_{6\text{-}10}$	0.99417	0.9058	1.1	0.91	1.0291	1.01
$T_{4\text{-}12}$	1.00218	0.9521	1.0888	1.0	0.9265	0.99
$T_{28\text{-}27}$	1.00751	0.9638	0.9200	0.95	0.9422	0.97
Q_{C10}	0.17267	0.2891	0.2600	0.06	0.2864	0.30
Q_{C24}	0.06539	0.1007	0.1000	0.05	0.1363	0.12
P-Losses (MW)	5.09226	4.9650	5.011	4.9178	4.6304	4.6248
CPU(s)	3.434	3.5680	13.64	66.92	NA	73.79
% P_{save}	10.03	12.27	11.46	13.11	18.19	18.28
$\sum P_G$(p.u)	NA	NA	NA	2.8832	NA	2.8802
$\sum Q_G$(p.u)	NA	NA	NA	1.2097	NA	0.6628

TABLE VI. STATISTICS OF TRIAL RESULTS OF ABC ALGORITHM AND OTHERS ALGORITHMS; IEEE 30- BUS. **CASE 1**

Algorithms[28]	***min***	***average***	***max***	P_{save} %	***CPU (S)***
DE	5.0110	5.013	5.022	11.46	13.647
PSO	5.116	5.1254	5.218	9.61	16.42
RGA	4.951	4.969	4.953	12.52	18.42
CMAES	4.945	4.95	4.946	12.45	19.582
SF-DE	4.9458	4.947	4.954	12.61	85.03
SP-DE	4.9466	4.9667	5.0762	12.60	85.03
EC-DE	4.9457	4.9467	4.9495	12.62	85.48
SR-DE	4.9461	4.9481	4.9529	12.61	86.54
ECHT-DE	4.9471	4.9499	4.9563	12.59	90.01
HSA	5.0070	-	-	11.53	-
ICA	4.9444	4.9735	5.1186	12.64	66.45
IWO	4.9995	5.2016	5.4894	11.66	69.27
MICA-IWO	4.9178	4.9197	4.9202	13.11	66.92
Proposed	4.6248	4.77629	5.0613	18.28	73.79

From these tables, it is seen that ABC is able to reduce the real power loss, with respect to the base case, by 18.28 % [26] whereas MICA-IWO [29] has reduced it by 13.11%. The average simulation time of ABC is less than of some other algorithms. From Table VI, when makes a statistical analysis to all sides, i.e., minimum solution, average, maximum solution, average saving percent of the real power loss and average computation time, it appears that the proposed algorithm is better of all presented algorithms. Hence, it affirms that ABC is statistically more robust in global searching ability and computational efficiency.

- *Case 2: IEEE 30 bus (19 control variables).*

Detailed description of the system data are taken from Refs [21-25]. The limit of control and dependent variables are given in Table II. The set of optimal solutions of control variables from the proposed algorithm, particle swarm optimization, biogeography-based optimization, and gravitational search algorithm are summarize in Table VII. Fig.2. shows the convergence curve of the ABC for case 2 of IEEE 30 bus system. From Fig.2 and Table VII, it can be seen that ABC algorithm converges in 65 iterations achieving the least real power loss of 4.5463 MW in less time than all the other tabulated algorithms. As a partial conclusion, according to all the numerical results until now, appears the ability of the ABC algorithm to find the optimal or the near optimal solution and handling optimization problems.

TABLE VII. COMPARISON O F SIMULATION RESULTS FOR IEEE 30-BUS TEST POWER SYSTEM - **CASE 2**

Variable	**PSO [28]**	**CLPSO [27]**	**BBO [27]**	**OGSA [30]**	**ABC**
Generator Voltage					
V_{G1}	1.1000	1.1000	1.1000	1.071652	1.1000
V_{G2}	1.1000	1.1000	1.0944	1.022199	1.0924
V_{G5}	1.0832	1.0795	1.0749	1.040094	1.0731
V_{G8}	1.1000	1.1000	1.0768	1.050721	1.0765
V_{G11}	0.9500	1.1000	1.0999	0.977122	1.1000
V_{G13}	1.1000	1.1000	1.0999	0.967650	1.1000
Transformer tap ratio					
$T_{6\text{-}9}$	1.1000	0.9154	1.0435	1.098450	1.040
$T_{6\text{-}10}$	1.0953	0.9000	0.90117	0.982481	0.90
$T_{4\text{-}12}$	0.9000	0.9000	0.98244	1.095909	0.98
$T_{28\text{-}27}$	1.0137	0.9397	0.96918	1.059339	0.97
Capacitor banks					
Q_{C10}	5.0000	4.9265	4.9998	1.653790	5
Q_{C12}	5.0000	5.0000	4.987	4.372261	5
Q_{C15}	0.0000	5.0000	4.9906	0.119957	5
Q_{C17}	5.0000	5.0000	4.997	2.087617	5
Q_{C20}	5.0000	5.0000	4.9901	0.357729	5
Q_{C21}	5.0000	5.0000	4.9946	0.260254	5
Q_{C23}	5.0000	5.0000	3.8753	0.000000	4
Q_{C24}	5.0000	5.0000	4.9867	1.383953	5
Q_{C29}	5.0000	5.0000	2.9098	0.000317	3
P-Losses (MW)	4.6862	4.5615	4.5511	4.514310	4.5463
CPU(s)	NA	138	NA	94.6938	91.76
% P_{save}	19.37	21.51583	21.694	22.327	21.777
$\sum P_G$(p.u)	NA	2.879615	2.879511	NA	2.879463

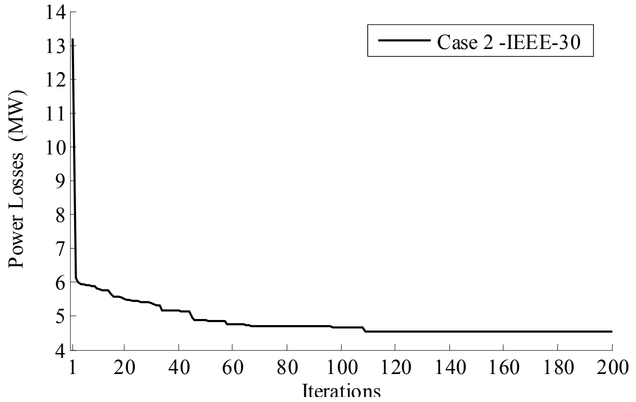


Fig. 3. Convergence characteristic of case 2 to 2nd test System

C. *IEEE 57-bus system*

In order to verify the robustness and efficiency of the proposed algorithm in larger scale power system, a standard IEEE57-bus test system is used. The system consists of eighty transmission lines; 7 generators at buses 1, 2, 3, 6, 8, 9 and 12; and three capacitor banks installed at buses 18, 25 and 53. Line data and bus data are taken from [21]; the minimum and maximum limits on control variables and dependent variables are given in Table II.

The system loads are given as follows:

$$P_{load} = 12.508\ p.u.,\ Q_{load} = 3.364\ p.u$$
$$\sum P_G = 12.7926\ p.u.,\ \sum Q_G = 3.4545\ p.u.,$$
$$P_{Loss} = 0.28462\ p.u$$

The set of optimal solutions of control variables are given in Table IX and compared to those reported in the literature. From Table IX, ABC algorithm still gets better solution than other listed algorithms where the real power loss has reduced by 15.7944 % comparing to that the base case without violating any system constraints. Statistics result of total of real and reactive power generation, real power loss; average saving percent of the real power loss and average computation time are shown in Tables VIII. Fig. 4, shows the convergence curve of real power loss obtained by ABC for IEEE 57 bus power system.

TABLE VIII. STATISTICS OF TRIAL RESULTS OF ABC ALGORITHM AND VARIOUS ALGORITHMS FOR IEEE 57- BUS POWER SYSTEM.

Algorithms	**$\sum P_G$**	**$\sum Q_G$(p.u)**	**P_{loss} (MW)**	**P_{save} %**	***CPU (S)***
CGA [31]	12.7752	3.1744	26.7170	6.1308	353.08
AGA [31]	12.7661	3.0679	25.8072	9.3276	367.31
PSO-W[31]	12.7677	3.1026	25.9729	8.7453	406.42
PSO-cf [31]	12.7559	3.0157	24.7866	12.9132	404.63
CLPSO[31]	12.7660	3.1501	25.7968	9.3642	423.30
SPSO [31]	12.7822	3.1818	27.4210	3.6576	121.98
L-DE [31]	12.7999	3.3656	29.1864	-1.238	426.97
L-SACP-DE [31]	12.7812	3.2085	27.3183	4.0185	427.23
L-SaDE[31]	12.7549	3.0191	24.6712	13.2696	408.97
SOA [31]	12.7543	2.9837	24.6248	13.4820	382.23
DE [11]	NA	NA	25.6228	9.9754	NA
ABC [11]	NA	NA	24.1846	15.0284	NA
DE-ABC[11]	NA	NA	25.5634	10.184	NA
ICA [29]	12.7528	3.0638	24.4799	13.9909	411.32
IWO [29]	12.7539	3.0663	24.5939	13.5904	439.48
MICA-IWO[29]	12.7506	2.9724	24.2568	14.7746	376.25
ABC	12.74766	271.3119	23.9666	15.7943	304.3730

From Fig.4, it can be seen that ABC algorithm converges in 60 iterations achieving the least real power loss of 23.9666 MW in less time than all the other listed algorithms. From Fig. 5, it is observed that all the bus voltages optimized by ABC are within the permissible limits. From all these results and comments until now we can conclude that the proposed algorithm even for larger power system can reach global best solution in less convergence time to ORPD problem. Fig. 6, shows that the reactive power generations are on their security limits.

TABLE IX. COMPARISON OF SIMULATION RESULTS FOR IEEE 57-BUS TEST POWER SYSTEM.

Variables	**BBO[27]**	**SPSO[31]**	**CLPSO[31]**	**DE [11]**	**DE-ABC [11]**	**ABC[11]**	**ABC**
V_{G1}	1.0600	1.0541	1.0596	1.05554	1.05767	1.07087	1.0808
V_{G2}	1.0504	1.0529	1.0580	1.04095	1.04263	1.06601	1.0637
V_{G3}	1.0440	1.0337	1.0488	1.02144	1.01918	1.06068	1.0467
V_{G6}	1.0376	1.0313	1.0362	0.999385	1.00008	1.04931	1.0337
V_{G8}	1.0550	1.0496	1.06	1.01104	1.01477	1.07146	1.0464
V_{G9}	1.0229	1.0302	1.0433	0.987213	0.989268	1.03021	1.0253
V_{G12}	1.0323	1.0342	1.0356	1.00367	1.00134	1.03394	1.0526
$T_{4\text{-}8}$	0.96693	0.99	0.95	1.2	1.1	0.98	0.97
$T_{4\text{-}8}$	0.99022	0.98	0.99	1.06	1.04	1.08	0.94
$T_{21\text{-}20}$	1.0120	0.99	0.99	1.02	1.02	1.04	0.97
$T_{24\text{-}26}$	1.0087	1.01	1.02	0.92	0.98	1.04	0.97
$T_{7\text{-}29}$	0.97074	0.99	0.97	0.92	1.08	1.0	0.94
$T_{34\text{-}32}$	0.96869	0.93	0.96	1.08	1.0	0.92	0.93
$T_{11\text{-}41}$	0.90082	0.91	0.92	0.94	0.9	0.98	0.90
$T_{15\text{-}45}$	0.96602	0.97	0.96	1.08	0.92	1.04	0.99
$T_{14\text{-}46}$	0.95079	0.95	0.95	1.0	1.0	0.98	0.96
$T_{10\text{-}51}$	0.96414	0.98	0.97	1.1	1.04	1.06	0.98
$T_{13\text{-}49}$	0.92462	0.95	0.92	1.08	0.92	1.04	0.93
$T_{11\text{-}43}$	0.95022	0.95	1.00	1.02	0.92	0.94	0.92
$T_{40\text{-}56}$	0.99666	1.00	1.00	1.0	0.98	1.1	0.96
$T_{39\text{-}57}$	0.96289	0.96	0.95	1.0	1.1	1.1	0.94
$T_{9\text{-}55}$	0.96001	0.97	0.98	0.92	1.02	0.98	0.94
$Q_{C\text{-}18}$	9.782	9.888	3.936	5	0	10	15
$Q_{C\text{-}25}$	5.8991	5.424	5.664	18	18	18	17
$Q_{C\text{-}53}$	6.289	6.288	3.552	18	18	18	13
P-Losses (MW)	24544	24.5152	24.43043	25.6228	25.5634	24.1846	23.9666
Pg slack	NA	NA	NA	476.4229	476.3635	474.9847	474.7666

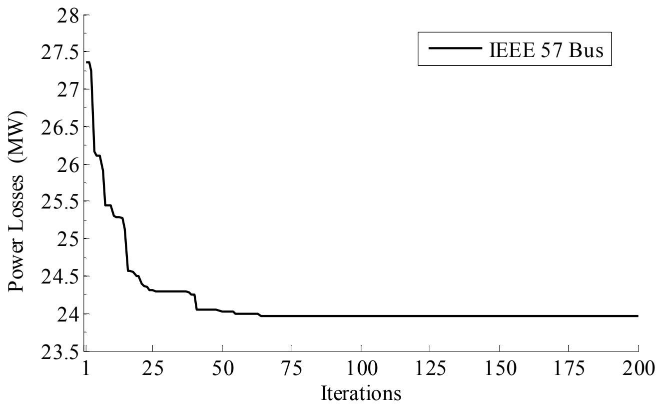


Fig. 4. Convergence characteristic of IEEE-57 test power System

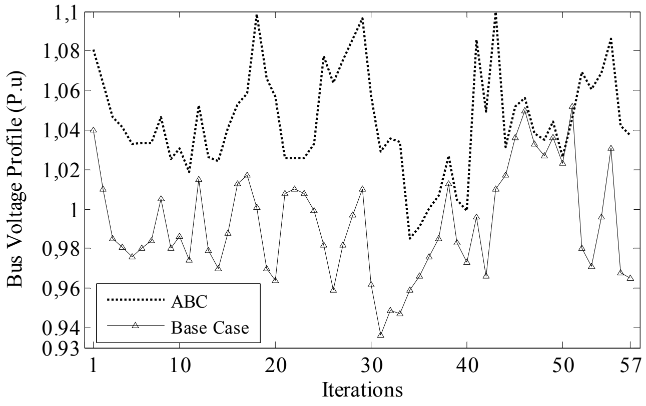


Fig. 5. Bus voltage profile for IEEE-57 Bus test power system

Fig. 7 shows variation of the discrete control variables of tap position. It can be seen that discrete taps transformer also converge to the steady value after 60th iteration.

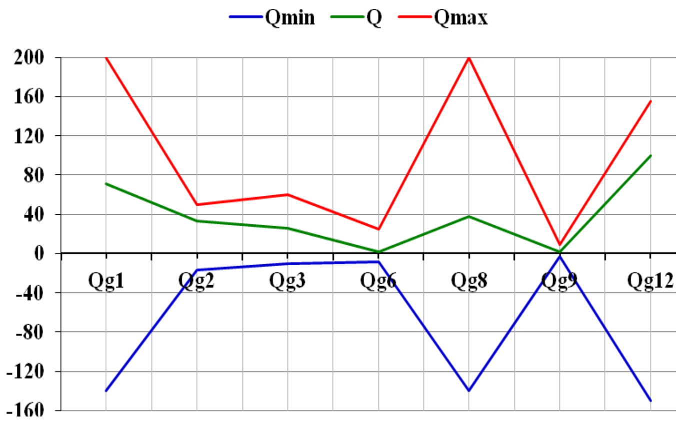


Fig. 6. Reactive power generations for IEEE -57 -bus test power system

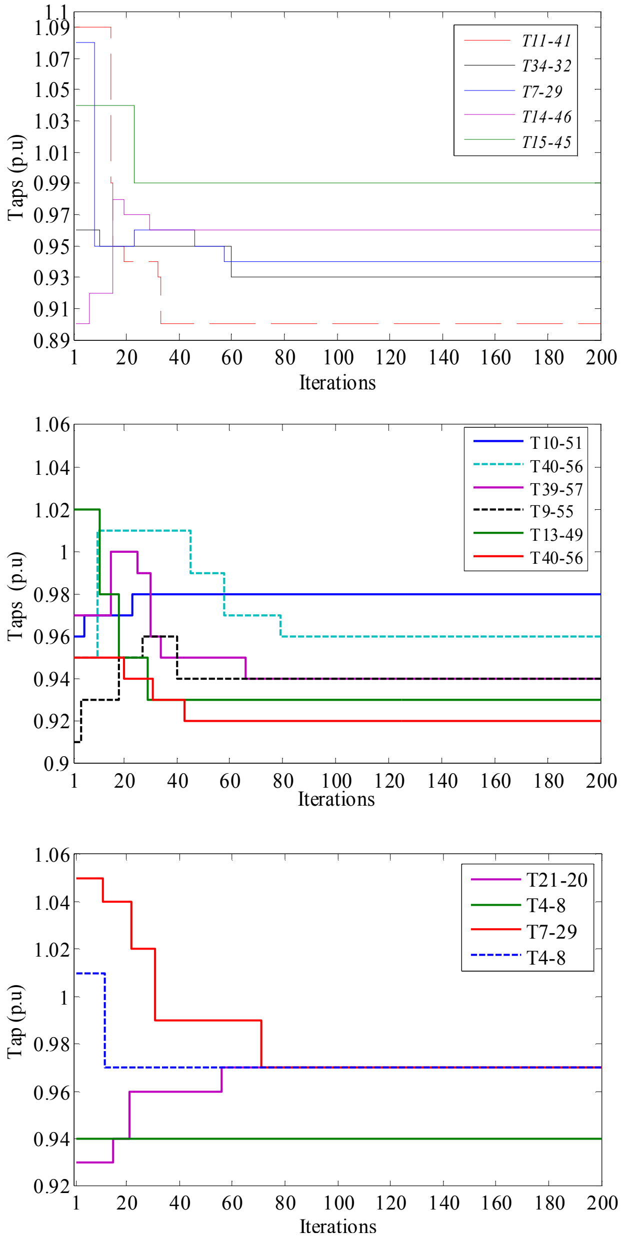


Fig. 7. Convergence of transformer taps for IEEE 57 bus test power system

CONCLUSION

In this paper, the ABC algorithm has been proposed, and successfully applied to solve the discrete ORPD problem. Three IEEE test power systems (14, 30, 57) are used to demonstrate the consistency of obtain optimal or near optimal solution of the control variables of ORPD problem. The obtained results are compared to those reported in the recent literature which proves superiority of ABC over other algorithms in terms of solution quality and computational efficiency.

Therefore, the numerical results confirm the capability of ABC in balancing global search ability and convergence speed than other algorithms. Then it may be concluded and without doubt that the proposed algorithm is very suitable to be applied to discrete ORPD problem.

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