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A Technique to Optimize Reactive Power Using Gbest Guided Artificial Bee Colony Algorithm

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Abstract – Reactive power play an important role in voltage stability and economic activities of power system. To maintain power quality and security, voltage at each bus should be within its acceptable limit. Reactive power is one of the important aspects of active power loss minimization. Optimizing reactive power is a process of minimizing total active power loss by handling all the parameters of generation and transmission network without violating any specified constraints. The complex non linear optimization problem can be solved by classical optimization technique and experimental based technique. For handling wide complex network the experiment based techniques gives good results over numerical technique in most of the cases. This paper presents an application of gbest ABC algorithm to solve reactive power optimization problem. Gbest guided ABC algorithm uses swarm intelligence techniques. To check the effectiveness and robustness of gbest- guided ABC algorithm it is applied on IEEE 30, IEEE57 and IEEE 118 standard test bus system. To validate results of gbest – guided ABC algorithm for the application of reactive power optimization problem it is compared with existing available literature data. The statistical analysis of gbest guided ABC algorithm is also carried out for IEEE 30, IEEE57 and IEEE 118 standard test bus system.

Key words – Reactive Power Optimization (ROP), gbest –guided ABC algorithm (GABC).

1. Introduction

Today’s power network is very complex and dynamic in nature. To analyze this highly complex power system, power flow study is important. The power flow study is essential for power system economics, stability, security, and reliability [1] point of view. In restructured power system market economic dispatch has great importance. The Carpentier introduced the constrained classical economic dispatch problem [2]. This problem is then called as optimal power flow (OPF) [3]. This is multi objective optimization problem such as minimizing fuel cost, minimizing active power loss, enhancing voltage stability, maintaining reliability etc. Since reactive power is an important factor in achieving voltage stability enhancement problem, active power loss minimization hence the study of optimal reactive power flow is essential. The reactive power optimization is nothing but minimizing real power loss but not at cost of operating and security constraints.

Normally, any optimization problem can be solved by using numerical technique or heuristic techniques. Numerical techniques such as linear, nonlinear, quadratic and mixed integer programming are used to solve complex optimization problem. Recently, heuristic methods such as Particle Swarm Optimization algorithm, Genetic algorithm, Artificial Bee Colony algorithm etc. are mostly used to solve any optimization problem. The reactive power optimization problem is also solved by numerical technique such as Newton method [4], linear programming [5], mixed integer programming [6], interior point method [7], quadratic interior point method [8], quadratic programming [9], and improved interior point method [10]. These methods are dependent on some initial guesses. Depending on this the solution may convergence or divergence. So, probability of getting solution is very less. Hence, the experiment based technique i.e. heuristic techniques are now becoming popular for the solving optimization problem. Optimization of reactive power problem is also solved by heuristic technique such as Genetic algorithm [11], Adaptive Genetic algorithm [12], Particle Swarm optimization [13], GA/SA/TS combined algorithms [14], Cauchy-based evolution strategy [15], Improved Hybrid Evolutionary programming [16] and Artificial Bee Colony algorithm [17] etc. In this paper an application of gbest - Guided Artificial Bee Colony (guided ABC) algorithm used to solve reactive power optimization problem.

In gbest - Guided ABC algorithm is swarm intelligence based algorithm. The agent of this algorithm is natural honey bee. Likewise, GABC, marriage in honeybees [18], bee system [19], beehive [20], virtual bee algorithm [21], bee adhoc [22], the bee's algorithm [23], bee colony optimization [24], and ABC [25] are some well known swarm intelligence techniques. Between these swarm intelligence based algorithms, ABC algorithm is most commonly used. The gbest - Guided ABC algorithm is the modification of ABC algorithm. Since ABC algorithm is having problem in finding either local best or global best solutions, so this algorithm is modified to GABC algorithm. Same as other nature inspired algorithm, food foraging task in GABC is collective effort by each agent. Here GABC is used to solve RPO problem.

2. Mathematical formulation for reactive power optimization problem

The optimization is a process of achieving the formulated objective function without violating boundary conditions for defined problem. In general the mathematical model of any optimization problem is formulated as below:

$$\begin{aligned} &\text{Maximize / Minimize} \quad && \mathrm{f(x,u)} \\ &\text{With constraint} && \mathrm{h(x,u)} = 0 \qquad (1) \\ & && \mathrm{lower}^{\mathrm{limit}} \leq \mathrm{g(x,u)} \geq \mathrm{upper}^{\mathrm{limit}} \end{aligned}$$

here, f is formulated objective function of the defined problem, h is the equation or equality constraint of the defined problem, g is the inequality constraint of the defined problem, x is the state variable of the defined problem, u is the control variable of the defined problem, $\mathrm{lower}^{\mathrm{limit}}$ is the lower limit of inequality constraint and $\mathrm{upper}^{\mathrm{limit}}$ is the upper limit of inequality constraint.

2.1 Optimization of reactive power problem

Optimization of reactive power problem is defined as minimize the active power loss without violating security constraint of grid. The mathematical formulation of the objective function for optimization of reactive power problem is given below:

$$\mathrm{Minimize}\ F(x,u) = \mathrm{Minimize}\ P_{\mathrm{Loss}} = \sum_{k=1}^{N_b} \mathrm{Transmission\ Loss}_k \tag{2}$$

where, P_{Loss} is the objective function for optimization of reactive power problem,N_b is total number of branches or line in network and $\mathrm{Transmission\ Loss}_k$ is active power loss in kth branch or line.

The active power loss:

$$P_{\mathrm{Loss}} = \sum_{k=1}^{N_b} G(k)\Big(\mathrm{Vm}\big(F_B(k)\big)^2 + \mathrm{Vm}\big(T_B(k)\big)^2 - 2\mathrm{Vm}\big(F_B(k)\big)\mathrm{Vm}\big(T_B(k)\big)\cos\Big(\mathrm{Vaa}\big(F_B(k)\big) - \mathrm{Vaa}\big(T_B(k)\big)\Big)\Big) \tag{3}$$

where,G(k) is conductance of k^{th} line, Vm is the voltage magnitude of respective bus, Vaa is the voltage angle of respective bus voltage, $F_B(k)$ is the notation for from bus and $T_B(k)$ is the notation for to bus. $F_B(k)$ and $T_B(k)$ specifies the connection between buses.

2.2 Constraint for optimization of reactive power problem

Here two types of constraints one is equality and second is inequality constraints. The equality constraint for reactive power optimization is stated as below:

$$P_{gk} - P_{dk} - |V_k| \sum_{i=1}^{N_{bus}} |V_i||Y_{ik}| \cos(\theta_{ik} + \delta_i - \delta_k) = 0 \tag{4}$$

$$Q_{gk} - Q_{dk} - |V_k| \sum_{i=1}^{N_{bus}} |V_i||Y_{ik}| \sin(\theta_{ik} + \delta_i - \delta_k) = 0 \tag{5}$$

where, k = 1, 2, 3,……., N_{bus}

where, $P_{gk}$is the active power fed at kth bus by thermal generator, P_{dk} is active power load at kth bus, $Q_{gk}$is the reactive power fed at kth bus by thermal generator, Q_{dk} is the reactive power load at kth bus, $V_k$is the kth bus voltage, Y_{ik} is the admittance of line connected between ith to kth bus, θ_{ik} is admittance angle of line connected between ith to kth bus and $\delta_k$is the kth bus voltage angle and N_{bus} depicts the total number of buses in network.

The inequality constraint for reactive power optimization is stated as below:

$$V_{generator_k}^{upper\_limit} \geq V_{gk} \geq V_{gk}^{lower\_limit}\ k = 1, \dots \dots \dots, N_g \tag{6}$$

$$V_{Lk}^{upper\_limit} \geq V_{Lk} \geq V_{Lk}^{lower\_limit}, k = 1, \dots \dots \dots, N_l \tag{7}$$

$$P_{gk}^{upper\_limit} \geq P_{gk} \geq P_{gk}^{lower\_limit}\ k = 1, \dots \dots \dots, N_g \tag{8}$$

$$Q_{gk}^{upper\_limit} \geq Q_{gk} \geq Q_{gk}^{lower\_limit}, k = 1, \dots \dots \dots, N_g \tag{9}$$

$$Q_{shk}^{upper\_limit} \geq Q_{shk} \geq Q_{shk}^{lower\_limit}, k = 1, \dots \dots \dots, N_q \tag{10}$$

$$S_{Lk}^{upper\_limit} \geq S_{Lk}, k = 1, \dots \dots \dots, N_b \tag{11}$$

$$T_k^{upper\_limit} \geq T_k \geq T_k^{lower\_limit}, k = 1, \dots \dots \dots, N_t \tag{12}$$

where, $V_{gk}^{upper_limit}$represent maximum limit or upper limit of voltage of k^{th} generator bus, $V_{gk}^{lower\_limit}$ is the minimum limit or lower limit of voltage of k^{th} generator bus, $V_{Lk}^{upper_limit}$is the maximum limit or upper limit of voltage of k^{th} load/PQ bus, $V_{Lk}^{lower_limit}$is the minimum limit of voltage of k^{th} load/PQ bus, $P_{gk}^{lower\_limit}$ is the minimum limit or lower limit of active power of k^{th}thermal generator,$P_{gk}^{upper\_limit}$ is the maximum limit or upper limit of active power of k^{th} thermal generator,$Q_{gk}^{upper\_limit}$ is the maximum limit or upper limit of reactive power of k^{th} thermal generator, $Q_{gk}^{lower\_limit}$ is the minimum limit or lower limit of reactive power of k^{th} thermal generator, $Q_{shk}^{upper\_limit}$ is the maximum limit or upper limit of reactive power fed by k^{th} reactive power compensator,$Q_{shk}^{lower_limit}$is the minimum limit or lower limit of reactive power fed by k^{th} reactive power compensator, $S_{Lk}^{upper\_limit}$ is the maximum limit or upper limit MVA loading of k^{th} transmission line,$T_{k}^{lower_limit}$is the minimum limit or lower limit of tap ratio of k^{th}transformer tap,$T_{i}^{upper_limit}$is the maximum limit or upper limit of tap ratio of k^{th} transformer tap, N_g is the total number of generators in the power system network, N_l is the total number of load or PQ buses,N_q is the total number of reactive power compensators in the power system network and N_t is the total number of tap changing transformers in the power system network.

2.3 Independent and dependent variables for optimization of reactive power problem

Independent (control) variables for optimization of reactive power problem are stated as below in independent variable vector:

$$u^T = \left[P_{gi}, \dots \dots, P_{N_g}, V_{g1}, \dots \dots, V_{N_g}, Q_{sh1}, \dots \dots, Q_{N_q}, T_1, \dots \dots, T_{N_t}\right] \tag{13}$$

where, $i = 1, 2, 3, \dots \dots, N_g$but $i \neq$ sclack bus where, P_g represents active power fed by thermal generator, V_g stand for terminal voltage of generator bus or PV bus, Q_{sh} represent reactive power fed by reactive power compensator and T stand for tap ratio of transformer.

Dependent (state) variables for optimization of reactive power problem are stated as below in independent variable vector:

$$x^T = \left[P_{gi}, Q_{g1}, \dots \dots, Q_{N_g}, V_{L1}, \dots \dots, V_{N_{PQ}}, \delta_k, \dots \dots, \delta_{N_{bus}}\right] \quad (14)$$

where, $i = \text{sclack bus}$

$k = 1, 2, 3, \dots \dots, N_b \text{but } k \neq \text{sclack bus}$

where, P_{gi} represents active power fed by slack or reference bus generator, Q_g represents reactive power fed by thermal generator, V_L stand for terminal voltage of load or PQ bus, N_{PQ} represents total number of PQ or load buses in power system network and δ stand for voltage angle.

2.4 Final Mathematical model of reactive power optimization problem

$$\text{Minimize}$$

$$P_{Loss} = \sum_{k=1}^{N_b} \text{Transmission Loss}_k$$

Subject to constraint

$$P_{gk} - P_{dk} - |V_k| \sum_{i=1}^{N_{bus}} |V_i||Y_{ik}| \cos(\theta_{ik} + \delta_i - \delta_k) = 0$$

$$Q_{gk} - Q_{dk} - |V_k| \sum_{i=1}^{N_{bus}} |V_i||Y_{ik}| \sin(\theta_{ik} + \delta_i - \delta_k) = 0$$

$$V_{generator_k}^{upper\_limit} \geq V_{gk} \geq V_{gk}^{lower\_limit} \; k = 1, \dots \dots \dots, N_g$$

$$V_{Lk}^{upper\_limit} \geq V_{Lk} \geq V_{Lk}^{lower\_limit}, k = 1, \dots \dots \dots, N_l$$

$$P_{gk}^{upper\_limit} \geq P_{gk} \geq P_{gk}^{lower\_limit}\ k = 1, \dots \dots \dots, N_g$$

$$Q_{gk}^{upper\_limit} \geq Q_{gk} \geq Q_{gk}^{lower\_limit}, k = 1, \dots \dots \dots, N_g$$

$$Q_{shk}^{upper\_limit} \geq Q_{shk} \geq Q_{shk}^{lower\_limit}, k = 1, \dots \dots \dots, N_q$$

$$S_{Lk}^{upper\_limit} \geq S_{Lk}, k = 1, \dots \dots \dots, N_b$$

$$T_{k}^{upper\_limit} \geq T_{k} \geq T_{k}^{lower\_limit}, k = 1, \dots \dots \dots, N_t$$

2.5 Modified fitness function

The modified fitness function for optimization of reactive power problem is stated below:

$$\text{Minimize Modified objective function (MOF)} = P_{Loss} + \text{constraints}$$

$$\begin{aligned} MOF = P_{Loss} + \lambda_1\left(P_{g\_reference} - P_{g\_reference}^{lim}\right)^2 + \lambda_2 \sum_{i=1}^{N_g}\left(Q_{gi} - Q_{gi}^{lim}\right)^2 \\ + \lambda_3 \sum_{i=1}^{N_{PQ}}\left(V_{Li} - V_{Li}^{lim}\right)^2 + \lambda_4 \sum_{i=1}^{N_T}\left(S_{Li} - S_{Li}^{lim}\right)^2 \end{aligned} \quad (15)$$

where, $P_{g\_reference}^{lim}$ represent the lower or upper limits of the active power fed by reference bus generator, Q_{gi}^{lim}represent the lower or upper limits of the reactive power fed by i^{th}thermal generator, V_{Li}^{lim}represent the lower or upper limits for voltages of i^{th} load bus, S_{Li}^{lim} represent MVA loading limit of i^{th} transmission line, and λ_1, λ_2, λ_3 and λ_4 are penalty weights applied to dependent variables such as reference bus power, reactive power of generator, load bus voltage and MVA loading of transmission line respectively.

The constraint has great importance in optimization. There are different ways to handle constraints. Here penalty weight method is used to handle the constraints. Depending upon penalties, optimized solution may diverge or converge. So penalties should be selected precisely.

3. Overview of g-best guided ABC algorithm

Recently the heuristic methods are mostly used to solve complex scientific and engineering problems. There are different types of heuristic technique but swarm intelligence based techniques are now widely used to solve complex optimization problem.

ABC algorithm has great exploration and exploitation ability. That's why ABC algorithm is now widely used in solving complex power system optimization problem like unit commitment problem [26], economic dispatch problem [27], optimal power flow [28], allocating capacitor banks [29], PMU's [30] and filter design [31], and optimization of reactive power problem [32] etc.

ABC algorithm mimics the behavior of food foraging by natural honey bees. The ABC algorithm is proposed by Karaboga in 2005. A home of bees is called as hives. In bee colony, separate special group of bees are formed. These groups performed different tasks and collective efforts of these groups' results in finding good quality and quantity of food. There are mainly two types of bees in a home of natural honey bees i.e. employed and unemployed bees. ABC algorithm consist of four main phases such as initialization phase, employed bee phase, unemployed or onlooker bee phase and scout bee phase. Decision criteria for deciding quality of food source are the quantity, position and easiness in extracting food source. The main four phases of artificial bee colony algorithm are as follows:

3.1 Initialization phase

The initial food source set is generated randomly in the initialization phase. If we relate bee's behaviour and its application for reactive power optimization, then food source is nothing but one solution. This initial food source or solution vector is represented as bellow:

$$X_j = \{x_{j1}, x_{j2}, \dots, x_{jN_D}\} \tag{16}$$

where, $j = 1,2, \dots\dots N_S$

Here, N_D represent total number of decision or control variables, X_j is the jth food or solution, and N_S represents the total number of foods or solutions.X_j is the food or solution consisting of total N_D number of control or decision variables. Each decision or control variable is generated randomly in between their upper and lower limit and it generated as below:

$$x_{ji} = x_i^{lower} + rand(0,1) * \left(x_i^{upper} - x_i^{lower}\right) \tag{17}$$

where,$j = 1,2, \dots\dots N_S$ and $i = 1,2, \dots\dots N_D$

where,$x_i^{upper}$is the upper limit of i^{th} control or decision variable,x_i^{lower}isthe lower limit ofi^{th} control or decision variable, $x_{ji}$is the i^{th} control or decision variable of i^{th} solution set.The function value or quality of food source is then calculated by putting set of control variables into the objective function i.e. $f(X_j)$. Apply greedy selection and memorize the best value. Then after find the fitness values of each solution and it is calculated as below:

$$fit_j = \begin{cases} \dfrac{1}{(1+f_j)} \text{if } f_j \geq 0 \\ 1 + abs(f_j) \text{ if } f_j \leq 0 \end{cases} \tag{18}$$

where, fit_j represent fitness value of j^{th}objective function value, f_j for function value of j^{th}solution set. In this phase number of employed bees and onlooker bees are also decided. The maximum trail counter number is initialized in this phase and the trail counter of each solution is also initialized to zero.

3.2 Role of employed bees

Bees which exploit initial food source in a vicinity of the food source are called as employed bees. Generally number of employed bees is half to total population of hive. The initial food source is exploited by making changes in some control variables. The control variables are exploited as below:

$$v_{ji} = x_{ji} + \mathrm{rand}(-1,1)\left(x_{ji} - x_{li}\right) \tag{19}$$

where, $j \neq l$ and $l = 1, 2, 3, \dots\dots, N_S$

where, x_{ji} is the i^{th} control variable of j^{th} initial food source or solution set, v_{ij} is the change in x_{ji} control variable of j^{th} initial food source or solution set and l should be selected randomly. Then after function value and fitness value is calculated. Increase the trail counter if the fitness value is not improved else vice versa. Memorize best solution.

3.3 Role of Unemployed or Onlooker bees

In a hive, employed bees share information about exploited solution of the food source after coming back to hive and unemployed or onlooker bee phase start. The availability of food source decides the number of onlooker bees to be sent to exploit available food source. The availability of food source is calculated as below:

$$P_j = \frac{\mathrm{fit}_j}{\sum_k^{N_s} \mathrm{fit}_j} \tag{20}$$

Where, P_j is the availability of j^{th} food source. The onlooker bees again exploit the food source by making some changes in the parameter of employed bee’s food source or solution set. The food source is exploited by eq. (19). Once again function value and fitness value is calculated. Increase the trail counter if the fitness value is not improved else vice versa. Memorize best solution.

3.4 Role of Scout bees

Initial food source is exploited first by employed bees and then unemployed or onlooker bees. Someway the exploited food source or solution may not improve continuously. This reflects amount of food source in particular trajectory is not of good quality i.e. solution is diverged. So to avoid this condition, the employed are converted to scout bees and again generate the solution randomly in the search trajectory. Trail counter is decision criteria to start scout bee mode. If the trail counter of food source reaches its maximum limit, respective solution is then rejected and scout bees generate new solution randomly to replace rejected one. The scout bees generate solution by equation (17).

3.5 Proposed gbest GABC algorithm

The ABC algorithm has problem in either exploration or exploitation of solution. To improve exploration or exploitation capability of ABC algorithm, likewise particle swarm optimization more wattage is given to current best solutions parameter. The control parameter in gbest guided ABC algorithm is modified by equation stated below:

$$v_{ji} = x_{ji} + \mathrm{rand}(-1,1)\left(x_{ji} - x_{ki}\right) + \mathrm{rand}(0,2) * (\mathrm{local\_best}_i - x_{ki}) \qquad (21)$$

Where, $j = 1, 2, 3, \ldots \ldots, N_S$

$i = 1, 2, 3 \ldots N_D$, $k \neq j$, $k = 1, 2, 3, \ldots \ldots, N_S$

Where, $\mathrm{local\_best}_i$ is the i^{th}best control variable of j^{th} solution set. The gbest guided ABC algorithm use equation (21) in exploiting food source or solution in employed bee mode and onlooker bee mode.

4. Application of g-best guided ABC algorithm for optimization of reactive power problem:

a) Initialization phase

Initialize population of hive. Select half the population as employed bees and half onlooker bees. Initialize maximum trail counter and maximum number of cycles. Initialize upper and lower limits for control variable vectors i.e. $P_{gk}^{upper\_limit} \geq P_{gk} \geq P_{gk}^{lower\_limit}$, $V_{generator_k}^{upper\_limit} \geq V_{gk} \geq V_{gk}^{lower\_limit}$, $T_k^{upper\_limit} \geq T_k \geq T_k^{lower\_limit}$ and

$Q_{shk}^{upper\_limit} \geq Q_{shk} \geq Q_{shk}^{lower\_limit}$. Randomly generate initial food source or solutions by generating control variables in between upper and lower limit by equation (17) i.e.$u^T = \left[P_{g1}, \dots\dots, P_{N_g}, V_{g1}, \dots\dots, V_{N_g}, Q_{sh1}, \dots\dots, Q_{N_q}, T_1, \ \dots\dots, T_{N_t}\right]$ but except generator connected at slack bus. Use control variables and run newton Raphson power flow. Check whether constraints satisfies there upper and lower limit or not i.e.$V_{Lk}^{upper\_limit} \geq V_{Lk} \geq V_{Lk}^{lower\_limit}, Q_{gk}^{upper\_limit} \geq Q_{gk} \geq Q_{gk}^{lower\_limit}$ and $S_{Lk}^{upper\_limit} \geq S_{Lk}$. Apply penalty weight method to differentiate violated and unviolated solutions. Memorize the least power loss solution from set of solutions.

Cycle = 1;

While (Cycle >= maximum number of cycle)

For employed bee = 1: number of employed bees

b) Employed bee phase

Exploit initial food source by equation (21) by randomly selecting any control variable from particular initial solution. Use control variables and run newton Raphson power flow. Check whether constraints satisfies there upper and lower limit or not i.e. $V_{Lk}^{upper\_limit} \geq V_{Lk} \geq V_{Lk}^{lower\_limit}, Q_{gk}^{upper\_limit} \geq Q_{gk} \geq Q_{gk}^{lower\_limit}$ and $S_{Lk}^{upper\_limit} \geq S_{Lk}$. Apply penalty weight method to differentiate violated and unviolated solutions. Memorize the least power loss solution from set of solutions.

End

For onlooker bee = 1: number of onlooker bees

c) Unemployed or onlooker bee phase

Exploit initial food source or solution again by equation (21) by randomly selecting any control variable from particular initial solution. Use control variables and run newton Raphson power flow. Check whether constraints satisfies there upper and lower limit or not i.e. $V_{Lk}^{upper\_limit} \geq V_{Lk} \geq V_{Lk}^{lower\_limit}, Q_{gk}^{upper\_limit} \geq Q_{gk} \geq Q_{gk}^{lower\_limit}$ and $S_{Lk}^{upper\_limit} \geq S_{Lk}$. Apply penalty weight method to differentiate violated and unviolated solutions. Memorize the least power loss solution from set of solutions.

End

d) Scout bee phase

Check incremental trail counter. If trail counter reached the predefined maximum number of trail counter then reject the particular initial solution and replace the solution set by generating control variables of solution set randomly in between upper and lower limits.

Cycle = Cycle + 1;

e) Termination criteria

If cycle number is equal to the maximum number of cycles then stop the exploitation.

End

5. Result and discussion

This paper presents an application of gbest guided ABC algorithm to solve problem for optimization of reactive power. This algorithm is applied on three test system i.e. on IEEE 30, 57, and 118 bus system to solve optimization of reactive power problem. The comparative analysis of results obtained for respective test system reflects the advantage of using GABC algorithm. The results are tested in MATLAB 2014^{a} environment.

5.1 IEEE 30 bus test system

In IEEE 30 bus test system data is taken from MATPOWER [26]. Here six thermal generators, nine reactive power compensators, four transformer taps. The overall active power load is 283.4 MW and reactive power load 126.2 MVAr. Six generators are connected to bus 1, 2, 5, 8, 11 and 13 respectively. The bus 1 is considered as reference bus. The compensators are connected at bus 10, 12, 15, 17, 20, 21, 23, 24, and 29 respectively. The transformer branches are (6-9), (6-10), (4-12), and (28-27) respectively. The test system has 41 transmission lines. The upper and lower limits of the variables are stated below in Table I. The base MVA selected is 100 MVA.

The convergence characteristic for IEEE 30 bus test is shown in Fig. 1. This figure clearly shows; the guided ABC algorithm converges at 28th iteration. The results obtained are given in Table 2. The control variables for the obtained solution are also stated in Table 2. The comparison with the available literature is given in Table 3. The result reported is best in compare to all available literature. To check the robustness of guided ABC, 100 trial runs are taken. The result of 100 trial runs is plotted and it is shown in Fig. 2. With reference to average of 100 trials, the numbers of results obtained below the mean line are more as compared to results obtained above of mean line. This proves GABC is good in tracking global best solution. The standard deviation for this 100 trial run is given in Table 4.

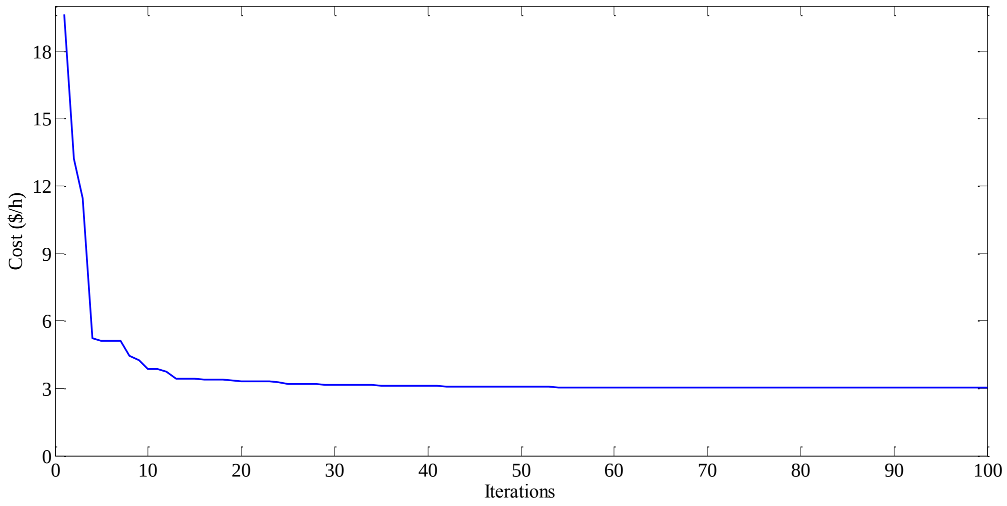

Figure 1: Convergence characteristics of IEEE 30 bus system

Table 1: Limits of the variables for IEEE 30 bus system

Variable	Upper limit	Lower limit	Variable	Upper limit	Lower limit
$P_{G1}\ (p.u.)$	0.50	2.00	$T_{6-10}\ (p.u.)$	0.90	1.10
$P_{G2}\ (p.u.)$	0.20	0.80	$T_{4-12}\ (p.u.)$	0.90	1.10
$P_{G5}\ (p.u.)$	0.15	0.50	$T_{28-27}\ (p.u.)$	0.90	1.10
$P_{G8}\ (p.u.)$	0.10	0.35	$Q_{C10}\ (MVAR)$	0.00	0.05
$P_{G11}\ (p.u.)$	0.10	0.30	$Q_{C12}\ (MVAR)$	0.00	0.05
$P_{G13}\ (p.u.)$	0.12	0.40	$Q_{C15}\ (MVAR)$	0.00	0.05
$V_{G1}\ (p.u.)$	1.00	1.10	$Q_{C17}\ (MVAR)$	0.00	0.05
$V_{G2}\ (p.u.)$	1.00	1.10	$Q_{C20}\ (MVAR)$	0.00	0.05
$V_{G5}\ (p.u.)$	1.00	1.10	$Q_{C21}\ (MVAR)$	0.00	0.05
$V_{G8}\ (p.u.)$	1.00	1.10	$Q_{C23}\ (MVAR)$	0.00	0.05
$V_{G11}\ (p.u.)$	1.00	1.10	$Q_{C24}\ (MVAR)$	0.00	0.05
$V_{G13}\ (p.u.)$	1.00	1.10	$Q_{C29}\ (MVAR)$	0.00	0.05
$T_{6-9}\ (p.u.)$	0.90	1.10			

Table 2: Control variables for IEEE 30 bus system

Control Variables	GABC	Control Variables	GABC
$P_{G2}\ (MW)$	80	$Q_{C12}\ (MVAR)$	5
$P_{G5}\ (MW)$	50	$Q_{C15}\ (MVAR)$	4.858283
$P_{G8}\ (MW)$	35	$Q_{C17}\ (MVAR)$	5
$P_{G11}\ (MW)$	30	$Q_{C20}\ (MVAR)$	4.153956
$P_{G13}\ (MW)$	31.98754	$Q_{C21}\ (MVAR)$	5
$V_{G1}\ (p.u.)$	1.097944	$Q_{C23}\ (MVAR)$	2.604547
$V_{G2}\ (p.u.)$	1.0900352	$Q_{C24}\ (MVAR)$	5
$V_{G5}\ (p.u.)$	1.071557	$Q_{C29}\ (MVAR)$	2.067431
$V_{G8}\ (p.u.)$	1.076513	$T_{6-9}\ (p.u.)$	1.03117
$V_{G11}\ (p.u.)$	1.1	$T_{6-10}\ (p.u.)$	0.918068
$V_{G13}\ (p.u.)$	1.1	$T_{4-12}\ (p.u.)$	0.980552
$Q_{C10}\ (MVAR)$	5	$T_{28-27}\ (p.u.)$	0.965991
	Power loss (MW)	**3.019246043**	

Table 3: Comparison table for IEEE 30 bus system

Algorithm	Power loss (MW)
GABC	**3.019246043**
ABC [17]	3.09
SARGA [28]	4.57401
GS [28]	5.10120
CLPSO [29]	4.5615

PSO [29]	4.6282
EGA–DQLF [30]	3.2008

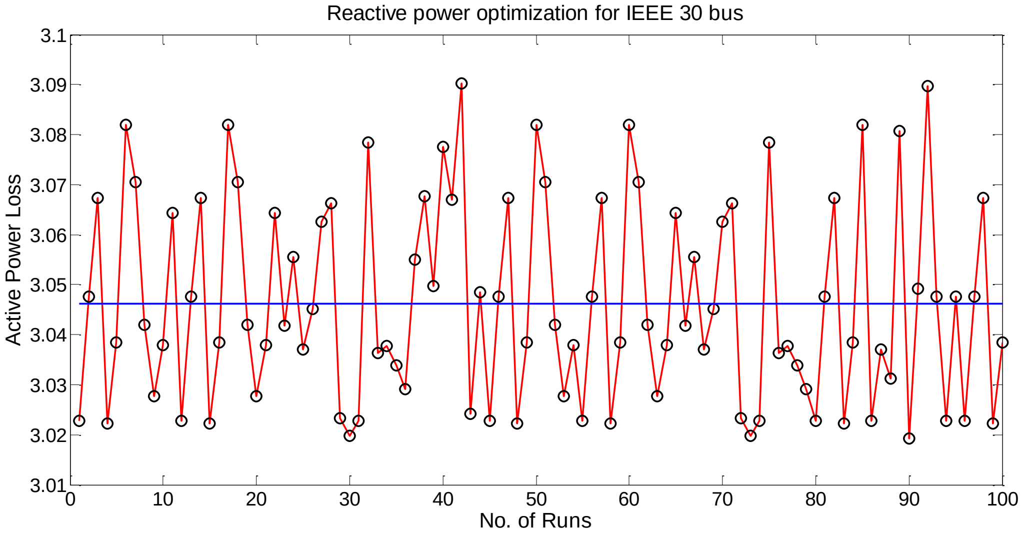

Figure 2: Results of reactive power optimization for hundred trial runs

Table 4: Statistical data for IEEE 30 bus system

Algorithm	Fuel cost ($/h)				Standard Deviation
	Minimum Value	Average Value	Maximum Value	Median	
GABC	**3.019246043**	3.046138854	3.090193904	3.041918205	0.0199488

5.2 IEEE 57 test bus system

In IEEE 57 test bus system data is taken from MATPOWER [26]. Here six thermal generating units, seventeen transformer taps and three reactive power compensators. Six generators are at connected to bus 2, 3, 6, 8, 9, and 12 respectively. The bus 1 is selected as reference bus. The compensators are connected at bus 18, 25, and 53 respectively. The transformer branches are T_{4-18}, T_{21-20}, T_{24-25}, T_{24-25}, T_{24-26}, T_{7-29}, T_{34-32}, T_{11-41}, T_{15-45}, T_{14-46}, T_{10-51}, T_{13-49}, T_{11-43}, T_{40-56}, T_{39-57}, and T_{9-55} respectively. This T stands for Transmission line. The base MVA selected is 100 MVA.

The convergence characteristic for the IEEE 57 test bus system is shown in Fig. 3. This figure clearly shows, the GABC algorithm converges at 22th iteration. The results obtained are given in Table 5. The control variables for the obtained solution are also stated in Table 5. To check the robustness of GABC, 100 trial runs are taken. The result of 100 trial runs is plotted and it is shown in Fig. 4. With reference to average of 100 trials, the numbers of results obtained below the mean line are more as compared to results obtained above of mean line. This proves GABC is good in tracking global best solution. The standard deviation for this 100 trial run is given in Table 6.

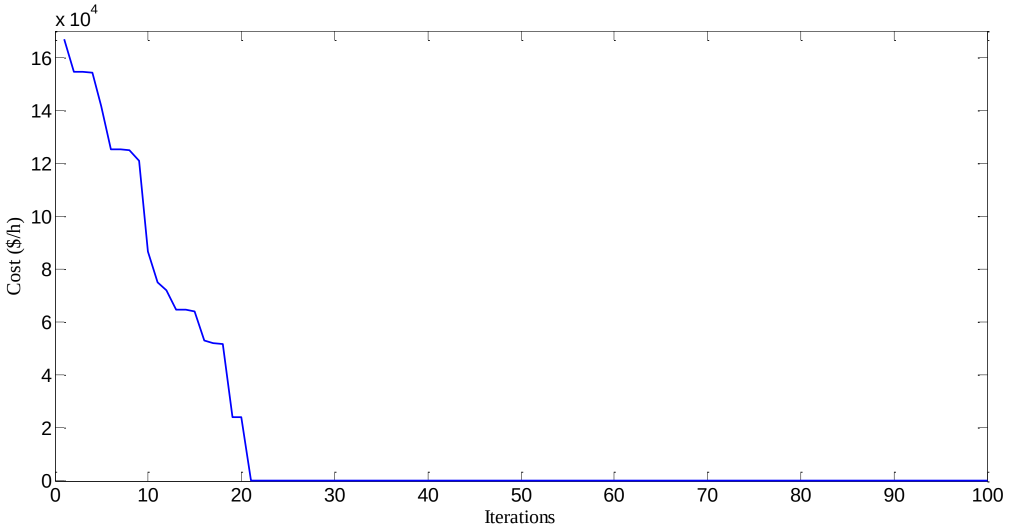

Figure 3: Convergence characteristics of IEEE 57 bus system

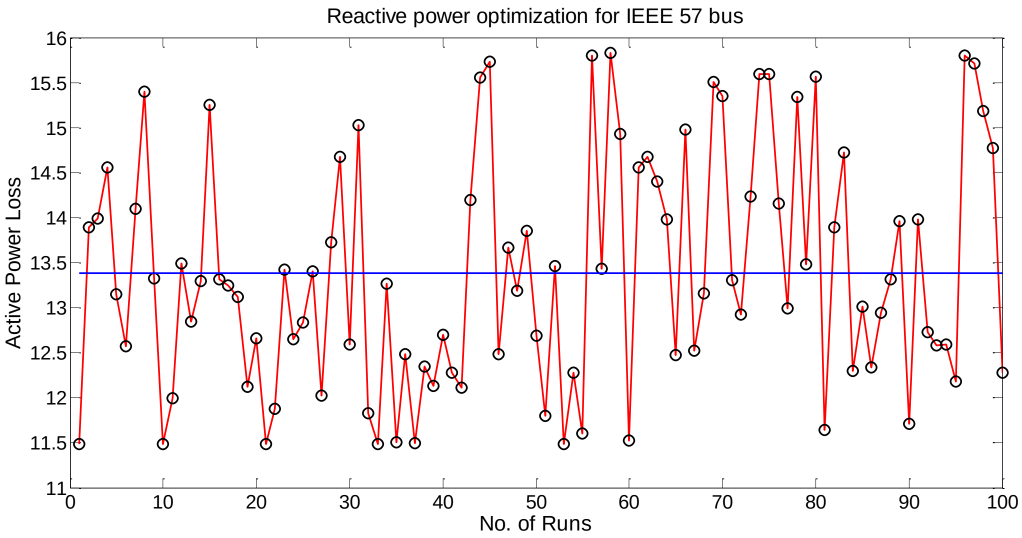

Figure 4: Results of reactive power optimization for hundred trial runs

Table 5: Control variables for IEEE 57 bus system

Control Variables	GABC	Control Variables	GABC
$P_{G2}(MW)$	41.23706	$T_{24-25}(p.u.)$	1.1
$P_{G3}(MW)$	140	$T_{24-26}(p.u.)$	1.01378
$P_{G6}(MW)$	78.56121	$T_{7-29}(p.u.)$	0.984111
$P_{G8}(MW)$	316.445	$T_{34-32}(p.u.)$	0.970969
$P_{G9}(MW)$	100	$T_{11-41}(p.u.)$	1.037281
$P_{G12}(MW)$	410	$T_{15-45}(p.u.)$	0.971975
$V_{G1}\ (p.u.)$	1.071492	$T_{14-46}(p.u.)$	0.971236
$V_{G2}\ (p.u.)$	1.062637	$T_{10-51}(p.u.)$	0.98247
$V_{G3}\ (p.u.)$	1.046926	$T_{13-49}(p.u.)$	0.934971
$V_{G6}\ (p.u.)$	1.028456	$T_{11-43}(p.u.)$	0.936066
$\mathrm{V_{G8}\ (p.u.)}$	1.03151	$\mathrm{T_{40-56}(p.u.)}$	1.008966
$\mathrm{V_{G9}\ (p.u.)}$	1.02084	$\mathrm{T_{39-57}(p.u.)}$	1.076901

V_{G12} (p.u.)	1.034725	T_{9-55}(p.u.)	1.018203
T_{4-18}(p.u.)	1.051845	Q_{C18}(MVAR)	11.92766
T_{4-18}(p.u.)	1.018632	Q_{C25}(MVAR)	14.81389
T_{21-20}(p.u.)	1.051936	Q_{C53}(MVAR)	11.59247
T_{24-25}(p.u.)	0.980744		
Power losses (MW)		11.4883822	

Table 6: Statistical data for IEEE 57 bus system

Algorithm	Fuel cost ($/h)				Standard Deviation
	Minimum Value	Average Value	Maximum Value	Median	
GABC	11.4883822	13.3848426	15.8265669	13.2570702	1.2936065

5.3 IEEE 118 bus test system

In IEEE 118 test bus system data is taken from MATPOWER [26]. Here fifty four thermal units, and nine transformer taps. The overall active power load is 4242 MW and reactive power load 126.2 MVAr. The test system has 186 transmission lines. The base MVA selected is 100 MVA.

The results obtained are given in Table 7. The control variables for the obtained solution are also stated in Table 7. The comparison with the available literature is given in Table 8. The result reported is best in compare to all available literature. To check the robustness of GABC, 100 trial runs are taken. The result of 100 trial runs is plotted and it is shown in Fig. 5. With reference to average of 100 trials, the numbers of results obtained below the mean line are more as compared to results obtained above of mean line. This proves GABC is good in tracking global best solution. The standard deviation for this 100 trial run is given in Table 6.

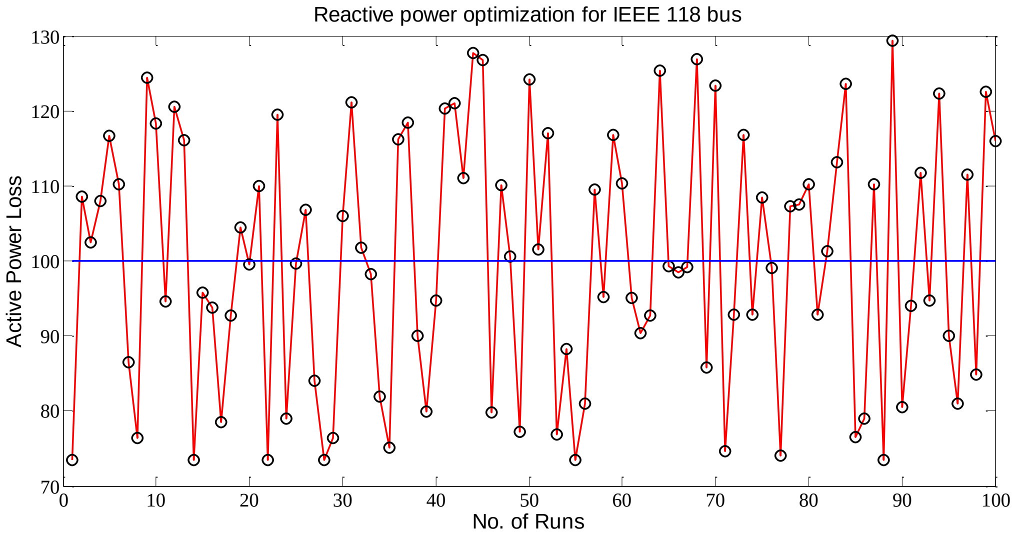

Figure 5: Results of reactive power optimization for hundred trial runs

Table 7: Control variables for IEEE 118 bus system

Control Variables	GABC	Control Variables	GABC	Control Variables	GABC
$P_{G1}(MW)$	59.1457	$P_{G90}(MW)$	52.6602	$V_{G61}\ (p.u.)$	0.9661
$P_{G4}(MW)$	98.6697	$P_{G91}(MW)$	59.6203	$V_{G62}\ (p.u.)$	0.9605
$P_{G6}(MW)$	37.5293	$P_{G92}(MW)$	13.1194	$V_{G65}\ (p.u.)$	0.9809
$P_{G8}(MW)$	0.4668	$P_{G99}(MW)$	10.5497	$V_{G66}\ (p.u.)$	0.9957
$P_{G10}(MW)$	165	$P_{G100}(MW)$	105.6	$V_{G69}\ (p.u.)$	0.999
$P_{G12}(MW)$	150.4258	$P_{G103}(MW)$	42	$V_{G70}\ (p.u.)$	0.9715
$P_{G15}(MW)$	0	$P_{G104}(MW)$	94.014	$V_{G72}\ (p.u.)$	1.0219
$P_{G18}(MW)$	34.5684	$P_{G105}(MW)$	84.2377	$V_{G73}\ (p.u.)$	0.9655
$P_{G19}(MW)$	42.6539	$P_{G107}(MW)$	33.1901	$V_{G74}\ (p.u.)$	0.9515

$P_{G24}(MW)$	12.9529	$P_{G110}(MW)$	42.3264	$V_{G76}\ (p.u.)$	0.94
$P_{G25}(MW)$	214.1414	$P_{G111}(MW)$	40.9881	$V_{G77}\ (p.u.)$	0.982
$P_{G26}(MW)$	203.6137	$P_{G112}(MW)$	15.221	$V_{G80}\ (p.u.)$	1.0244
$P_{G27}(MW)$	21.9194	$P_{G113}(MW)$	0	$V_{G85}\ (p.u.)$	0.9886
$P_{G31}(MW)$	65.0973	$P_{G116}(MW)$	42.2212	$V_{G87}\ (p.u.)$	1.0155
$P_{G32}(MW)$	58.9487	$V_{G1}\ (p.u.)$	0.9807	$V_{G89}\ (p.u.)$	1.0055
$P_{G34}(MW)$	90.8114	$V_{G4}\ (p.u.)$	1.0132	$V_{G90}\ (p.u.)$	0.9936
$P_{G36}(MW)$	91.3301	$V_{G6}\ (p.u.)$	0.9996	$V_{G91}\ (p.u.)$	0.9857
$P_{G40}(MW)$	100	$V_{G8}\ (p.u.)$	0.9793	$V_{G92}\ (p.u.)$	0.9877
$P_{G42}(MW)$	96.1177	$V_{G10}\ (p.u.)$	0.9928	$V_{G99}\ (p.u.)$	0.9981
$P_{G46}(MW)$	116.5559	$V_{G12}\ (p.u.)$	0.988	$V_{G100}\ (p.u.)$	0.9851
$P_{G49}(MW)$	192.5998	$V_{G15}\ (p.u.)$	0.9976	$V_{G103}\ (p.u.)$	0.9831
$P_{G54}(MW)$	80.7583	$V_{G18}\ (p.u.)$	0.9922	$V_{G104}\ (p.u.)$	0.9936
$P_{G55}(MW)$	0	$V_{G19}\ (p.u.)$	0.9937	$V_{G105}\ (p.u.)$	0.9956
$P_{G56}(MW)$	0	$V_{G24}\ (p.u.)$	1.0241	$V_{G107}\ (p.u.)$	1.0291
$P_{G59}(MW)$	76.5	$V_{G25}\ (p.u.)$	1.06	$V_{G110}\ (p.u.)$	0.9754
$P_{G61}(MW)$	78	$V_{G26}\ (p.u.)$	1.0093	$V_{G111}\ (p.u.)$	0.9424
$P_{G62}(MW)$	0.3851	$V_{G27}\ (p.u.)$	1.0074	$V_{G112}\ (p.u.)$	0.9954
$P_{G65}(MW)$	316.7806	$V_{G31}\ (p.u.)$	1.0403	$V_{G113}\ (p.u.)$	1.06
$P_{G66}(MW)$	147.6	$V_{G32}\ (p.u.)$	1.0201	$V_{G116}\ (p.u.)$	0.9695
$P_{G70}(MW)$	7.9261	$V_{G34}\ (p.u.)$	1.0311	$\mathrm{T}_{8-5}(\mathrm{p.u.})$	0.9626
$P_{G72}(MW)$	100	$V_{G36}\ (p.u.)$	1.0303	$\mathrm{T}_{26-25}(\mathrm{p.u.})$	0.9391
$P_{G73}(MW)$	59.9424	$V_{G40}\ (p.u.)$	0.9644	$\mathrm{T}_{30-17}(\mathrm{p.u.})$	1.0178
$P_{G74}(MW)$	87.7513	$V_{G42}\ (p.u.)$	0.9567	$\mathrm{T}_{38-37}(\mathrm{p.u.})$	0.9

$P_{G76}(MW)$	56.7542	$V_{G46}\ (p.u.)$	1.0071	$T_{63-59}(p.u.)$	1.0566
$P_{G77}(MW)$	5.3969	$V_{G49}\ (p.u.)$	1.0008	$T_{64-61}(p.u.)$	1.0362
$P_{G80}(MW)$	208.4631	$V_{G54}\ (p.u.)$	1.0105	$T_{65-66}(p.u.)$	0.9678
$P_{G85}(MW)$	99.0974	$V_{G55}\ (p.u.)$	0.994	$T_{68-69}(p.u.)$	0.9876
$P_{G87}(MW)$	31.2	$V_{G56}\ (p.u.)$	0.9982	$T_{81-80}(p.u.)$	0.9316
$P_{G89}(MW)$	215.5064	$V_{G59}\ (p.u.)$	0.9548		
Power losses (MW)			73.4556		

Table 8: Comparison table for IEEE 118 bus system

Algorithm	Power loss (MW)
GABC	**73.4556**
ABC [17]	119.6923
PSO [31]	131.908
IPM [31]	132.110
DE [32]	128.318
QEA [33]	**122.2227**

Table 9: Statistical data for IEEE 118 bus system

Algorithm	Fuel cost ($/h)				Standard Deviation
	Minimum Value	Average Value	Maximum Value	Median	
GABC	73.4556	99.9808	129.319	99.58649	16.717

5.4 Statistical analysis

To validate results of gbest guided ABC algorithm student t-test and Wilcoxon rank sum test [34] is carried out. Since other researcher does not report the result for hypothetical tests, these tests are carried out on only gbest guided ABC algorithm. The statistical analysis is useful tool in deciding the results are to be retained or reject. This test is carried out at $\alpha=0.05$ significance level. In case of Wilcoxon rank sum test, if the statistical value is greater than significance level i.e. α, hypothesis will be retained by or vice versa. The results for Wilcoxon rank sum test are provided in Table 10. In case of student t-test, if statistical value is greater than $t_{critical}$, result will be accepted else vice versa. The $t_{critical}$ calculated for this analysis is 1.983971519.

Table 3: Statistical analysis for RPO problem

Standard IEEE systems	Standard deviation	Paired t-test $t_{critical} = 1.983971519$	Wilcoxon rank sum test
IEEE 30 Bus System	0.0199488	35.46778	0.850216995
IEEE 57 Bus System	1.2936065	30.92146	0.850359749
IEEE 118 Bus System	16.717	27.65849	0.986315668

6. Conclusion

In this paper an application of gbest guided artificial bee colony algorithm to solve optimization of reactive power problem is discussed. The systems taken for study are IEEE 30, IEEE 57 and IEEE 118 test bus system. The results for these case studies reflect the ability of GABC algorithm to track optimal solution for optimization of reactive power problem.

Apart from reactive power optimization problem, the guided gbest ABC algorithm can be important tool for nonlinear complex engineering optimization problem.

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