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Steady State Load Shedding to Prevent Blackout in the Power System using Artificial Bee Colony Algorithm

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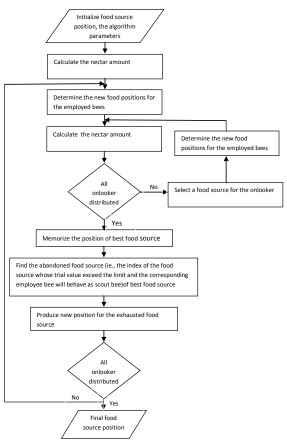
Graphical abstract



Abstract

Real and reactive power deficiencies due to generation and overload contingencies in a power system may decline the system frequency and the system voltage. During these contingencies cascaded failures may occur which will lead to complete blackout of certain parts of the power system. Under such situations load shedding is considered as an emergency control action that is necessary to prevent a blackout in the power system by relieving overload in some parts of the system. The aim of this paper is to minimize the amount of load shed during generation and overload contingencies using a new meta-heuristic optimization algorithm known as artificial bee colony algorithm (ABC). The optimal solution for the problem of steady state load shedding is done by taking squares of the difference between the connected and supplied real and reactive power. The supplied active and reactive powers are treated as dependent variables modeled as functions of bus voltages only. The proposed algorithm is tested on IEEE 14, 30, 57, and 118 bus test systems. The applicability of the proposed method is demonstrated by comparison with the other conventional methods reported earlier in terms of solution quality and convergence properties. The comparison shows that the proposed algorithm gives better solutions and can be recommended as one of the optimization algorithms that can be used for optimal load shedding.

Keywords: Optimal load shedding; artificial bee colony algorithm; overload contingency; generation contingency; voltage dependent load model

1.0 INTRODUCTION

During normal conditions and those due to small perturbation, power systems are well designed to operate and meet the load requirements without violating the constraints of the system. Even under emergency conditions, the disturbed system state can be made to regain its normal state with the help of the control loops like automatic voltage regulator (AVR) and automatic load frequency control (ALFC). But under extreme emergency conditions like sudden increase in the system demand or unexpected outages, the system constrains and operational limits are violated. Load shedding is considered as the ultimate measure to restore the system back to its normal operating conditions. Load shedding is defined as coordinated sets of controls that decrease the electric load in the system. By carrying out load shedding, the perturbed system can be forced to settle to a new equilibrium state. Different methods of load shedding either in steady state or in transient state have been proposed. An optimal load shedding program finds a best steady-state stable operating point for a post fault system with a minimum amount of load shed.
Ref. [1] has formulated the optimal load shedding problem which uses the sum of the squares of the differences between connected and supplied real and reactive power.

The optimization package MINOS [11], developed to solve large scale dense or sparse linearly or nonlinearly constrained or unconstrained optimization problems is used to simulate the algorithm.

An algorithm to minimize the amount of load curtailment which is based on Newton-Raphson (NR) method for solving the power flow equations, and Kuhn-Tucker theorem for the optimization has been described in [2]. Here, the load shedding policy, defining the priority schedules is obtained first, and then the minimum load to be shed at each bus is calculated. In the problem formulation of this work the system reactive power and losses are not considered. Also the active and reactive powers of loads are assumed to be independent of bus voltages.

A method for optimal load curtailment that considers generator control effects, voltage and frequency characteristics of the load has been proposed in [3]. Second-order gradient technique is used here to solve the resulting nonlinear optimization problem. This method is presumed to be an improvement on the method of [2]. Inability to curtail system loads during an emergency is the major drawback of the formulation in [3]. Moreover this algorithm does not converge under emergency conditions since the system generation is over defined through governor action and does not sufficiently reconcile frequency variations applied to the load model equations.

Ref. [4] has presented a reformulated optimal load shedding policy that takes into account generator control effects and voltage and frequency characteristics of loads. Ref. [5] has presented another work of optimal load shedding problem that uses the sum of squares of the difference between the connected active and reactive load and the supplied active and reactive power. In the formulation, the supplied active and reactive power is considered as dependent variables modeled as a function of bus voltages only. Minimization of load loss using a sensitivity based approach has been proposed in [6]. In order to limit the size of the load being dropped, different priorities to loads are assigned using a weighted error criterion.

Ref. [7] and [8] have formulated a non-linear optimization problem for the optimal load shedding and rescheduling of generators during an emergency state. The non-linear problem has been approximated by an accurate sensitivity model which takes into account the real and reactive nodal injections, voltage magnitudes and angles and loads' sensitivity to voltage magnitudes. The accuracy of the solution in both these papers is affected by the linearization approach.

In [9] and [10] two different methods for generation rescheduling and load shedding to alleviate line overloads, based on the sensitivity of line overloads to bus power increments have been developed. In [11] a mesh approach has been developed for the formulation of the network equations in the load flow analysis. A hybrid approach using a combination of an impedance matrix method and a nodal-admittance matrix method which exploits the salient characteristics of the impedance and admittance method is also developed.

In [12] differential evolution algorithm has been implemented for optimal allocation o repair times and failure rates to segments of a meshed distribution system. An optimal under voltage load shedding scheme to provide long term voltage stability using a new hybrid particle swarm based simulated annealing optimization technique has been presented in [13]. The technical and economical aspects of each load are considered by including the sensitivities of voltage stability margin in to the cost function. In [14] a new voltage stability margin index considering load characteristics has been introduced in under voltage centralized load shedding scheme. In [15] quantum inspired evolutionary programming has been implemented for the optimal location and sizing of DG in radial distribution system.

In the present paper the optimal load shedding problem to minimize the sum of squares of the difference between the connected loads and the supplied power has been formulated. The ABC algorithm is implemented to solve the formulated optimization problem. The performance of the proposed algorithm for generation and overload contingencies are analyzed. Testing is done using IEEE 14, 30, representing small and 57, 118, representing medium power system. Currently only conventional methods have considered both real and reactive power loads to be shed. Evolutionary computation has been used already for different load shedding strategies that have considered shedding of real power loads only [12]–[15]. However there has been no work reported in the literature that considers both real and reactive power loads for shedding. Therefore in this work both real and reactive power loads are considered for shedding and solved by one of the meta-heuristic algorithms viz. ABC algorithm. The optimal solutions obtained with the proposed algorithm are compared with those reported in [1]-[3] and [5].

2.0 PROBLEM FORMULATION

During emergency conditions an operational objective is to minimize the difference between the connected load and the supplied power subjected to equality and inequality constraints [1]. The objective function can be expressed as

$$F = \sum_{i=1}^{NB}\left[\alpha_i\left(P_{di} - \bar{P}_{di}\right)^2 + \beta_i\left(Q_{di} - \bar{Q}_{di}\right)^2\right] \tag{1}$$

where NB is the number of buses in a system, P_{di}, and Q_{di} are the active and reactive powers supplied to the load. $\bar{P}_{di}$, and $\bar{Q}_{di}$ are the connected active and reactive load. The weighting factors α_i and β_i are the parameters related to priority assigned to the demand at each bus. Flat values are assigned to the priorities of the loads. The objective function given in Eq. (1) is subjected to both network and system limits constraints resulting in a non-linear optimization problem.

2.1 Equality Constraints

The power flow equations of the networks are the equality constraints. These equations of a network with NB number of nodes can be written as

$$P(V) = P_{Gi} - P_{di}(V) - P_i(V,\delta) = 0$$
$$\text{for} \quad i = 1,..NB \tag{2}$$

$$Q(V) = Q_{Gi} - Q_{di}(V) - Q_i(V,\delta) = 0$$
$$\text{for} \quad i = 1,..NB \tag{3}$$

where P_{Gi} and Q_{Gi} represents the respective active and reactive power generations at bus i. P_i and Q_i represents the active and reactive power injections at bus i. The active and reactive power injections at bus i in terms of bus voltage magnitude and phase angle is expressed as

$$P_i(V,\delta) = V_i \sum_{i=1}^{NB} V_j Y_{ij} \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{4}$$

$$Q_i(V,\delta) = V_i \sum_{i=1}^{NB} V_j Y_{ij} \sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{5}$$

2.2 Inequality Constraints

The inequality constraints considered are the limits of real and reactive power generations, bus voltage magnitudes and angles, and line flows.

The limits of real and reactive power generations of the system are

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad i = 1, \ldots NG \qquad (6)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad i = 1, \ldots. NB \qquad (7)$$

where $P_{Gi}^{\min}$ and $Q_{Gi}^{\min}$ are the minimum real and reactive power generations and $P_{Gi}^{\max}$ and $Q_{Gi}^{\max}$ are the maximum available real and reactive power generations .

The limits of bus voltages of the system are

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1, \ldots. NB \qquad (8)$$

where $V_i^{\min}$ and $V_i^{\max}$ are the minimum and maximum limits of bus voltages of the system.

Either current magnitude constraint due to thermal considerations or electrical angle (difference in voltage angle across a line) constraint due to stability considerations, can be considered for transmission line loading limits.

In the present formulation the electrical angle inequality constraint is used, which can be expressed as

$$LF = \left|\delta_i - \delta_j\right| \le \epsilon_{ij} \qquad i = 1, \ldots. NB-1; \; j = i+1, \ldots\ldots. NB \qquad (9)$$

where δ_i and δ_j are the voltage angles at bus i and bus j, and ϵ_{ij} is the maximum voltage phase angle difference between i and j.

2.3 Load Model

There are different load models to express the system active and reactive power demands in terms of bus voltage and system frequency. Here a polynomial function of the bus voltage is used to express the active and reactive power demands at any given bus as

$$P_{di} = \overline{P}_{di}\left[P_p + P_c\left(\frac{V_i}{\overline{V}_i}\right)^{N1} + P_z\left(\frac{V_i}{\overline{V}_i}\right)^{N2}\right] \qquad (10)$$

$$Q_{di} = \overline{Q}_{di}\left[Q_q + Q_c\left(\frac{V_i}{\overline{V}_i}\right)^{N3} + Q_z\left(\frac{V_i}{\overline{V}_i}\right)^{N4}\right] \qquad (11)$$

where P_p, P_c, P_z, Q_q, Q_c and Q_z are constants associated with this voltage dependent load model (VDLM) and $N1$, $N2$, $N3$ and $N4$ are the powers of polynomial.

2.4 Modified Objective Function

The optimal load curtailment problem can be described by Equations (1)-(11). Substituting Equations (2) and (3) in to Equation (1) results in a modified objective function in terms of P_{Gi} and P_i as

$$J = \sum_{i=1}^{NB}[\alpha_i(P_{Gi} - P_i - \overline{P}_{di})^2 + \beta_i(Q_{Gi} - Q_i - \overline{Q}_{di})^2 \qquad (12)$$

■3.0 IMPLEMNTATION OF ARTIFICIAL BEE COLONY ALGORITHM (ABC) FOR OPTIMAL LOAD SHED

The ABC algorithm was formed by observing the activities and behavior of the real bees, while they were looking for the nectar resources and sharing the amount of the resources with the other bees. The flow chart for the artificial bee colony algorithm [19] is shown in Figure 1.This algorithm is implemented in the following steps.

Step-1: Initialize the artificial bee colony algorithm parameters

- CS : Colony size = Number of employed bees + Number of onlooker bees
- SN : Number of food sources (ie., Number of solutions) = Number of employee bee = $CS/2$
- D : Dimension of the problem (ie., Number of parameters of the problem)
- Limit: Limit for scout bee $[\lim it = CS/2 * D]$
- Trial : It is a vector of dimension equal to [1,Number of food source] Initially its value is set to zero.
- Maximum cycle: Gives the total number of iterations.

Initial food source of dimension $[SN, D]$ is randomly generated within the given range and the objective function f_i is calculated from Equation (12) and the fitness of each food source is evaluated using Equation (13) and Equation (14)

$$(fitness)_i = \frac{1}{1+f_i} \quad if \; f_i >= 0 \qquad (13)$$

$$(fitness)_i = 1 + abs(f_i) \quad if \; f_i <= 0 \qquad (14)$$

Then the iteration counter starts.

Step-2: Employee Bee Phase: New food source is determined using Equation (15)

$$v_{i,j} = x_{i,j} + \varphi_{i,j}(x_{i,j} - x_{k,j}) \qquad \textbf{(15)}$$

Where $'i'$ is the i^{th} employee bee, $'j'$ is the random index based on the dimension D of the problem. $'k'$ is the random index neighbour to $'i'$. $'\phi_{i,j}'$ is the randomly generated number between $[-1,1]$

For each employee bee the objective function f_i & $(fitness)_i$ value is evaluated and compared with previous (old) food source and the best one is replaced by the worst. For each discard of new food source $'v'$, the trial counter is incremented. The probability of all the food sources is determined using Equation (16).

$$P_i = fit_i / \sum_{j=1}^{SN} fit_j \qquad (16)$$

where fit_i, fit_j is the fitness value of i^{th}, j^{th} employee bee respectively.

Step-3: Onlooker Bee Phase: Each onlooker bee selects a food source to exploit with the probability. The search for the best new source is done in the same manner as that of **Step-2** and the best source replaces the worst. Here also for each discard of new food source $'v'$, the trial counter is incremented.

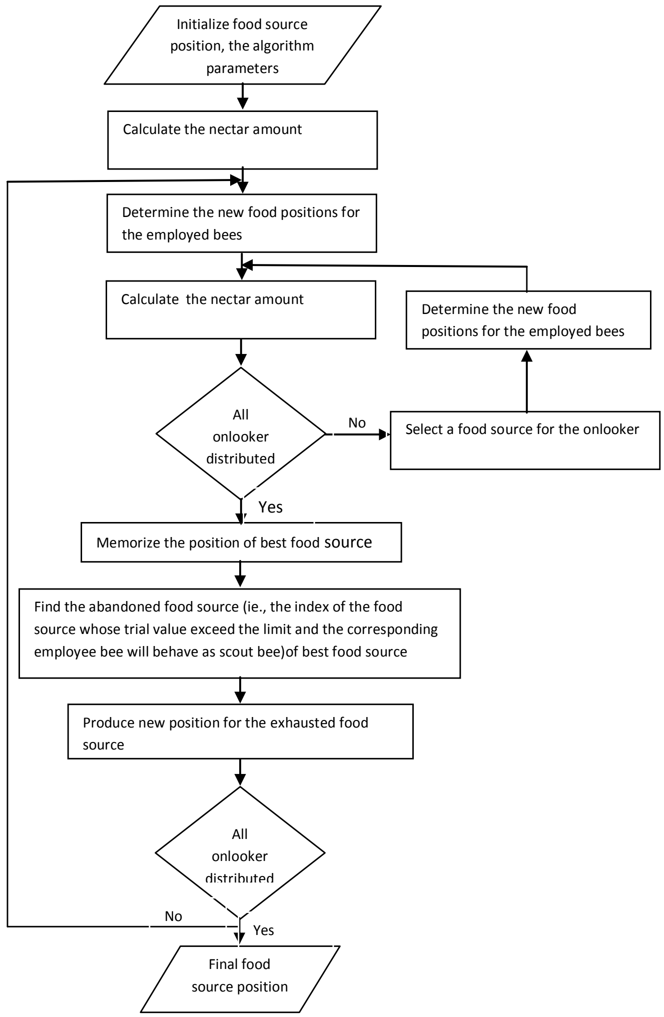


Figure 1 Flow chart for artificial bee colony algorithm

Step-4: The selection of which employee bee will behave as scout bee depends on the index of the food source (which is not improved) whose trial value is exceeded the limit and abandoned. For that index the scout bee randomly search for a food source independent of previous history using Equation (17) and iteration counter is incremented.

$$x_{i,d} = x_d^{\min} + r\,(x_d^{\max} - x_d^{\min}) \qquad (17)$$

where 'r' is a random real number within the range $[0,1]$

$x_d^{\min}$ and $x_d^{\max}$ are the lower and upper borders in the d^{th} dimension of the problem space.

Step-5: Best food source which is having the highest fitness value is printed.

■4.0 SIMULATION RESULTS AND ANALYSIS

The proposed ABC approach has been verified on two small systems–IEEE 14-bus and 30-bus, two medium systems–IEEE 57-bus and 118-bus test systems. The results obtained by the proposed approach are compared with those obtained by using conventional methods reported earlier, such as projected augmented lagrangian method implemented using MINOS–an optimization package [1], gradient technique based on Kuhn-Tucker theorem [2] and second order gradient technique [3]. The single line diagram and the detailed data of IEEE-14, 30, 57 and 118-bus systems are given in [11]. The software was written in Matlab and executed on 2.4 GHz, Intel i3 processor with 2 GB RAM PC.

The decision variables of this problem are the real and reactive power loads to be shed at each bus. Thus for a 14-bus system the number of decision variables will be 28. The permissible amount of load shed in each bus is assumed as 10 % to 80 % of the total load connected at each bus. The rest 20 % of the load is reserved for emergency conditions. The violation of the inequality constraints are penalized in the objective function.

The constants and the powers of the polynomial associated with the load model given in Equation (10) and (11) were assumed as follows:

P_p =0.2, P_c =0.3, P_z =0.5, Q_q =0.2, Q_c =0.3 and Q_z =0.5. $N1$ =1, $N2$ =2, $N3$ =1 and $N4$ =2.

4.1 Application to Small Size Systems

IEEE 14, 30-bus test systems [11] are considered here. The two cases of contingencies analysed are loss of generation and overload. The food number of the proposed ABC algorithm for these test systems is 100.

4.1.1 IEEE 14-bus System

This system consists of 20 lines, two generators, three synchronous condensers, three transformers and one static capacitor. The generated reactive power limits are:

$-150 \le Q_{G1} \le 150$, $0 \le Q_{G2} \le 140$, $0 \le Q_{G3} \le 140$, $0 \le Q_{G6} \le 140$ and $0 \le Q_{G8} \le 140$

The generated active power limits are:

$0 \le P_{G1} \le 200$, $0 \le P_{G2} \le 200$

The connected load for this test system is 259 MW. Under normal operating conditions the supplied power to the connected load using NR method with VDLM is 258.801 MW. The reactive power supplied by the method used here is 72.92 MVAR. The supplied powers in Refs. [2] , [3] and [5] are 259.0 MW , 258.81 MW and 258.59 MW respectively for a connected load of 259 MW. For the same connected load the supplied power In [1] is 258.59 MW. The reactive power supplied by the methods reported in Refs. [2], [3] and [5] are 73.5 MVAR, 73.42 MVAR and 73.51 MVAR respectively.

The deficit in the supplied power obtained in this paper and in Refs. [1], [3] and [5] represents the effect of using a voltage dependent load model (VDLM) to express the active power. The total active and reactive power generation obtained in this paper under normal operating condition is 272.00 MW and 82.50 MVAR respectively. The total real power loss obtained here is 13.2 MW. The total active power generation obtained by the method reported in Refs. [2], [3] and [5] for the normal operating conditions were 271.85 MW, 270 MW and 269.250 MW respectively. The corresponding reactive power generation reported in these Refs. [2], [3] and [5] were 8.56 MVAR, 80.220 MVAR and 79.1700 MVAR respectively. The total active power loss presented in the Refs. [2], [3] and [5] were 12.8454 MW, 11.3274 MW and 10.6685 MW respectively. The bus voltages vary between 1.01 pu and 1.08 pu in the NR method with VDLM, whereas the voltages vary from 0.98 pu to 1.07 pu in Ref. [1,5], 0.93 pu to 1.035 pu in [2] and 0.9765 pu to 1.016 pu in [3].

The aim of optimal load shedding is to restore normal operating conditions following generation and overload contingencies by minimum load shedding.

4.1.1.1 Loss of Generation Contingency

An abnormal operating condition representing the loss of generating unit-2 generating 72.0 MW or 26% of normal generation is considered in this section.

The amount of load shed using the proposed ABC approach is 67.0977 MW and the active power supplied is 191.902 MW. Whereas the load shed and the active power supplied reported by Mostafa in Refs. [1] and [5] are 71.11 MW and 187.89 MW respectively. It can be observed that the proposed approach has yielded lower amount of load shed and higher supplied active power demand when compared with other methods. The total active power supplied reported in Refs. [2] and [3] for this contingencies were 192 MW and 231.57 MW respectively. Reactive powers supplied by the proposed method and by the methods used in the Refs. [2], [3] and [5] are 56.5950 MVAR, 54.59 MVAR, 65.2 MVAR and 51.13 MVAR respectively.

The total active and reactive power generation obtained by the proposed ABC approach for this abnormal condition is 200.00 MW and 80 MVAR respectively. The corresponding system loss obtained by this approach is 8.677 MW.

Whereas the total active power generation obtained by the method reported in Refs. [2], [3] and [5] for this loss of generation contingency were 200 MW, 200.00 MW and 200.00 MW respectively. The corresponding reactive power generation reported in these Refs. [2], [3] and [5] were -21.75 MVAR, 67.950 MVAR and 62.280 MVAR respectively. The corresponding active power losses reported in the Refs. [2], [3] and [5] are 7.9952 MW, -31.581 MW and 12.111 MW respectively.

From the above stated data it can be observed that the proposed approach has yielded lower amount of load shed and higher supplied active power when compared with other methods reported in [2], [1] and [5].

In [1] it is reported that the method of [3] fails to converge for this contingency. At the end of the optimization the active power supplied is 231.57 MW with a system generation of 200.00 MW. This shows that the system generation is less than the supplied power. Therefore the active power loss becomes negative in this work.

The bus voltages vary between 1.01 pu and 1.09 pu in the proposed ABC approach. Whereas the voltages vary from 0.8065 pu to 0.917 pu in Refs. [1, 5] and 1.04883 pu to 1.1pu in [2] . The proposed approaches yields better bus voltage profile as compared with those reported in other approaches.

Figure 2 shows the convergence characteristics of the proposed ABC algorithm for the test system operated under the generation contingency considered here. The maximum iterations to converge for the proposed approach is 19 iterations.

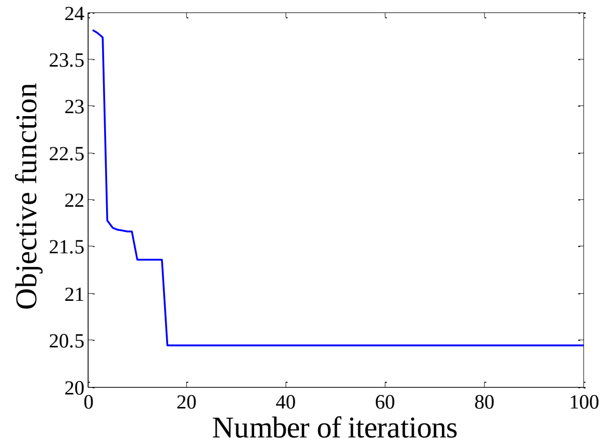


Figure 2 Convergence characteristics of ABC approach for IEEE 14-bus system under loss of generation of 72 MW

4.1.1.2 Range of Generation Deficit Contingencies

The test system is also subjected to certain range of generation deficit contingencies. The range of generation is varied from 260 MW to 160 MW, with a connected load of 259 MW, which means, the resulting generation deficit varies from 0 to 99 MW.

Figure 3 shows that the minimum iterations to converge for the proposed ABC algorithm is 26 corresponding to 160 MW generation. Since the severity of the contingency considered in this case is increased as compared with previous case (Generation loss of 72 MW), the number of iterations needed to converge is increased. Figure 4 (a) shows the total supplied power obtained by the proposed ABC approach decreases from 249.42 MW at 260 MW generations to 154.23 MW at 160 MW generations. Figure 4 (b) shows the corresponding active power loss decrease from 10.6 MW to 5.91 MW.

Whereas the total supplied power in Refs. [1] and [5] decreases from 249.30 MW at 260 MW generation to 153.78 MW at 160 MW generation with corresponding active power loss decrease from 10.70 MW to 6.22 MW and in [2] the supplied load decreases from 252.92 MW to 157.22 MW with the corresponding active power loss decrease from 7.08 MW to 2.78 MW for the same range of generation deficits.

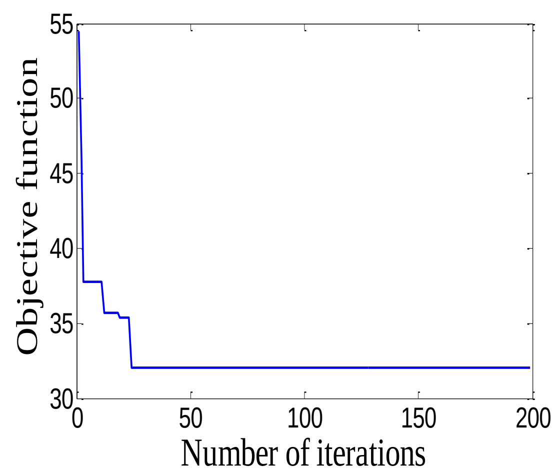


Figure 3 Convergence characteristics of ABC approach for IEEE 14-bus system under generation deficits contingency

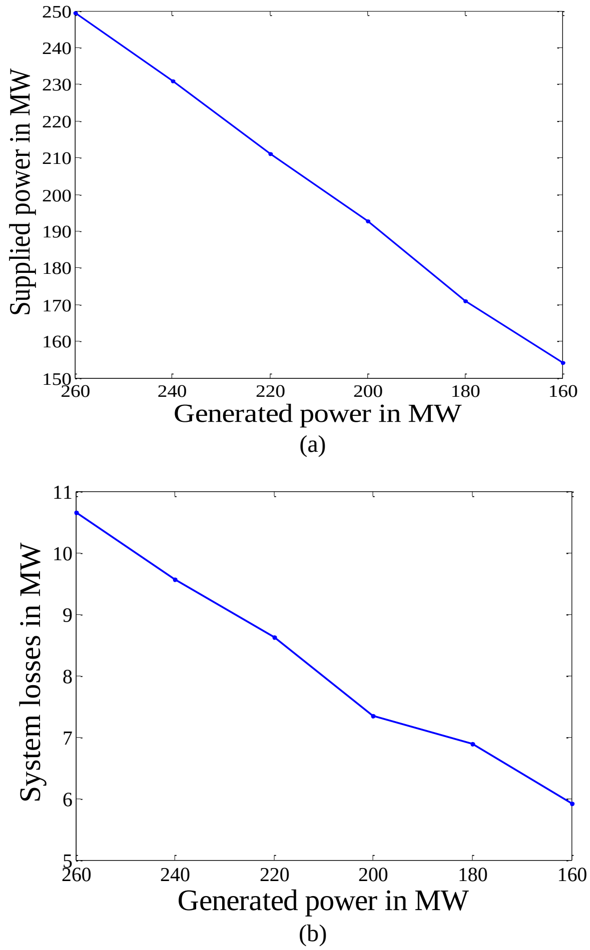


Figure 4 IEEE 14-bus system under generation deficit contingencies using ABC approach a- Optimal supplied load, b- System losses

For this generation deficit contingencies the maximum voltage obtained by the proposed ABC method remains constant at 1.03 pu and the minimum voltage varies between 1.00 pu and 1.0183 pu. Whereas in Refs. [1] and [5] the maximum voltage decreases from 1.062 pu to 0.85838 pu and the minimum voltage magnitude decreases from 0.9507 pu to 0.77 pu.

For IEEE 14 bus system, bus 3 and bus 4 are the first and second heaviest load buses respectively. The supplied powers at bus 3 and bus 4 by the proposed ABC approach are 89.2 MW and 43.40 MW respectively. In Refs. [1] and [5] the supplied powers at bus 3 and bus 4 are 85.52 MW and 39.70 MW respectively. The supplied powers at bus 3 in [2] is 78.02 MW and at bus 4 it is 36.69 MW. The proposed approach supplies more power at the heaviest loaded buses- bus 3 and bus 4- as compared to Refs. [1], [2] and [5].

4.1.1.3 Overload Contingencies

In this contingency it is considered overloading up to 55.4% above the maximum available generation of 400 MW. This corresponds to a connected load between 388.5 MW (150% of the nominal load) to 621.6 MW (240% of the nominal load). Figure 5 shows the maximum number iterations required for the proposed approach is 27 iterations corresponding to connected load of 388.5 MW. For this contingency the supplied power obtained using the proposed method decreases from 377.875 MW at 150% overload to 376.993 MW at 240% overload. Whereas for the same range of overload contingencies, in Refs. [1, 5] and [2] the supplied power decreases from 376.121 MW to 363.785 MW and from 383.3MW to 383.45 MW respectively. Figure 6 a shows the decrease in supplied power from 377.875 MW at 150% overload to 376.993 MW at 240% overload for the proposed ABC approach. The corresponding increase in the system losses is shown in Figure 6b. For this range of overload contingencies the system losses obtained by the proposed method increases from 22.121 MW to 22.994 MW. Whereas in Refs. [1, 5] and [2] the system losses increases from 23.879 MW to 36.215 MW and from 16.7 MW to 16.55 MW respectively.

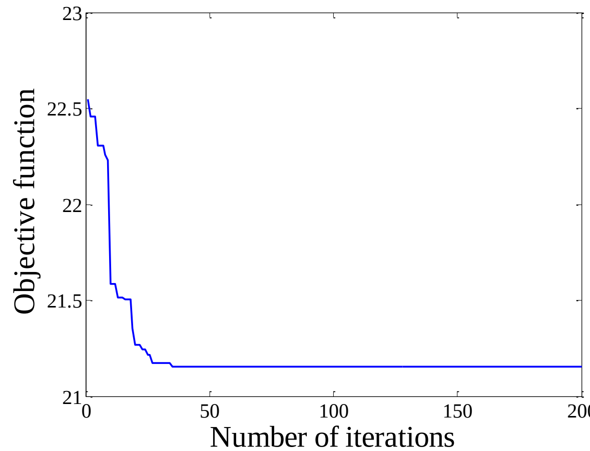
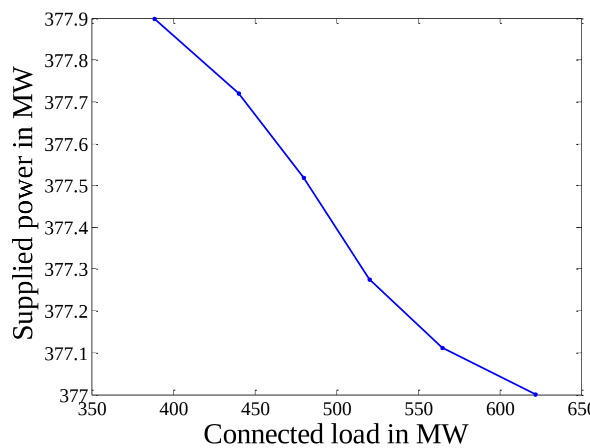
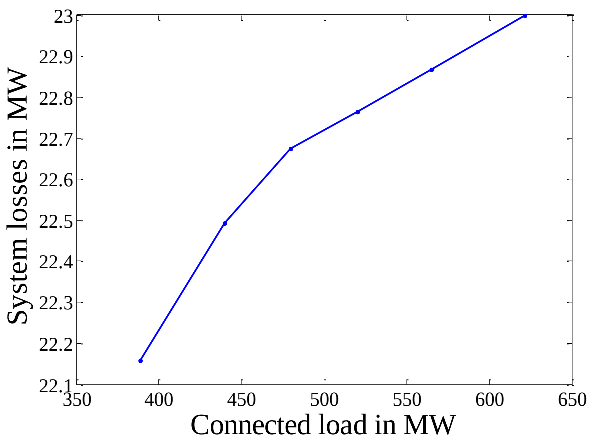


Figure 5 Convergence characteristics of ABC approach for 14-bus system under overload contingency



(a)



(b)

Figure 6 IEEE 14-bus system under overload contingencies using ABC Approach a - Optimal supplied power, b - System losses

The proposed approach supplies 158.64 MW to bus 3 and 73.31 MW to bus 4. Whereas Refs. [1,5] supplies 155.33 to bus 3 MW and 70.63 MW to bus 4. Ref [2] supplies 139.38 MW and 71.01 MW to buses 3 and 4 respectively. So, during the overload contingency considered the proposed method supplies more power to these heaviest load buses as compared to the power supplied by the other methods to these buses. A better voltage profile is obtained by the proposed method during this contingency. Maximum voltage obtained using the proposed approach is constant at 1.051 pu and the minimum voltage increases from 0.988 to 1.0354 pu.

In Refs [1, 5] the maximum voltages vary between 1.1352 pu and 0.974 pu. and the minimum voltage increases from 0.77 pu to 0.95 pu. The maximum voltage reported in [2] is constant at 1.2 pu and the minimum voltage increase from 1.1096 pu to 1.1104 pu.

4.1.2 IEEE 30-bus System

This system consists of 41 lines, three generators, three synchronous condensers, two static capacitor and three transformers. The generated reactive power limits are:

$$-20 \le Q_{G1} \le 43, \qquad -10 \le Q_{G8} \le 30,$$
$$-20 \le Q_{G2} \le 43, \qquad -10 \le Q_{G11} \le 45,$$
$$-20 \le Q_{G5} \le 50, \qquad -10 \le Q_{G13} \le 50,$$

The generated active power limits are:

$$0 \le P_{G1} \le 175, \qquad 0 \le P_{G2} \le 70$$
$$0 \le P_{G5} \le 75$$

The supplied power by the NR method with VDLM used in this paper under normal operating conditions is 281.579 MW for a connected load of 283.40 MW. The reactive power supplied by the method used in this paper is 125.3110 MVAR. The supplied powers in Refs. [2], [3] and [5] are 283.30 MW, 280.313 MW and 279.850 MW respectively for a connected load of 283.40 MW. In [1] the supplied power is 279.85 MW for the same connected load. The reactive power supplied by the methods reported in Refs [2], [3] and [5] are 126.20 MVAR, 127.130 MVAR and 125.02 MVAR respectively. The deficit in the supplied power obtained in this paper and in Refs. [1], [3] and [5] represents the effect of using a VDLM to express the active power.

The total active and reactive power generation obtained in this paper under normal operating condition is 290.00 MW and 125.540 MVAR respectively. The total real power loss obtained here is 8.421 MW. Whereas the total active power generation obtained by the methods reported in Refs [2], [3] and [5] for the normal operating conditions were 294.840 MW, 292.070 MW and 289.410 MW respectively. The corresponding reactive power generation reported in these Refs [2], [3] and [5] were 121.49 MVAR, 123.30 MVAR and 125.540 MVAR respectively. 11.5363 MW, 10.6598 MW and 11.4053 MW are the respective total active power losses reported in the Refs. [2], [3] and [5].

The bus voltages vary between 0.970 pu and 1.082 pu in the proposed approach whereas the voltages vary from 0.93493 pu to 1.10 pu in Ref. [1,5], 0.92475 pu to 1.10 pu in [2] and 0.9319 pu to 1.088 pu in [3].

4.1.2.1 Loss of Generation Contingency

An abnormal operating condition representing the loss of 60 MW or 20.35% of normal generation is considered here. The amount of load shed and the supplied active power demand obtained using the proposed ABC method is 40.2097 MW or 14.167 % of the nominal load and 243.2877 MW respectively. Whereas the load shed and the active supplied power in Refs. [1] and [5] are 42.69 MW or 15.07 % of the nominal load and 240.60 MW respectively. For the same generation loss, the amount of load shed and the supplied power in [2] are 40.73 MW or 14.38% of the nominal load and 242.67 MW respectively. It can be observed that the proposed approach has yielded lower amount of load shed when compared with the other methods. Reactive powers supplied by the proposed ABC approach and by the others methods used in the Refs. [2], [3] and [5] are 107.8229 MVAR, 108.170 MVAR, 115.940 MVAR and 109.320 MVAR respectively.

The total active and reactive power generation obtained by the proposed ABC approach for this case is 250 MW and 124.54 MVAR respectively. The corresponding active power loss obtained by this approach is 6.710 MW.

Whereas the total active power generation obtained by all the methods reported in Refs. [2], [3] and [5] was 250 MW. The corresponding reactive power generation reported in these Refs. [2], [3] and [5] were 85.960 MVAR, 119.780 MVAR and 110.33 MVAR respectively. The corresponding active power losses reported in the Refs. [2], [3] and [5] are 7.4302 MW,-6.7483 MW and 9.4087 MW respectively.

Figure 7 shows the convergence characteristics of the proposed ABC approach for the test system operated under this contingency representing loss of generation of 60 MW. The maximum iterations to converge for the proposed approach is 17 iterations.

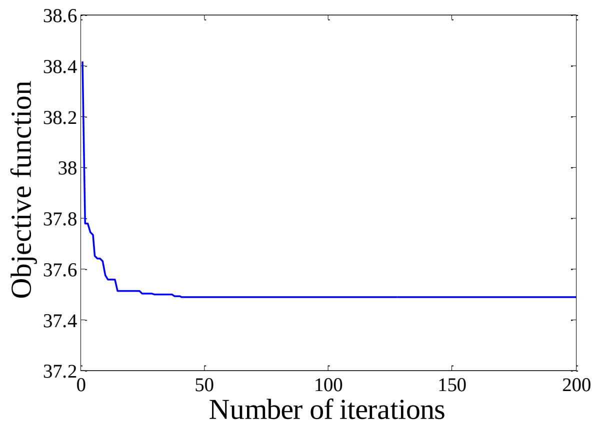


Figure 7 Convergence characteristics of ABC approach for the IEEE 30-bus system under loss of generation of 60 MW

The bus voltages vary between 0.9562 pu and 1.0680 pu in the proposed ABC approach .Whereas the voltages vary from 0.8920 pu to 1.0630 pu in Refs. [1,5], 0.99806 pu to 1.10 pu in [2].

4.1.2.2 Range of Generation Deficit Contingencies

The test system is also subjected to a range of generation deficit contingencies. The range of generation is varied from 300 MW to 190 MW, with a connected load of 283.3 MW, which means, the resulting generation deficit varies from 0 to 93.3 MW. Figure 8 shows the convergence characteristics of the proposed ABC approach for the generation of 190 MW and the minimum iterations being 20. The number of iterations required is increased in this case because the severity of the contingency considered here is more than the previous case representing loss of generation of 60 MW.

Figure 9(a) shows the total supplied power obtained by the proposed ABC approach decreases from 282.14 MW at 300 MW generations to 183.252 MW at 190 MW generations and Figure 9(b) shows the corresponding active power loss decreases from 9.75 MW to 3.820 MW. Whereas the total supplied power in Refs. [1] and [5] decreases from 279.82 MW at 300 MW generation to 183.25 MW at 190 MW generation with corresponding active power loss decrease from 10.51 MW to 6.76 MW and in [2] the supplied power decreases from 283.3 MW at 300 MW generation to 186.06 MW at 190 MW generation with the corresponding active power loss decrease from 9.87 MW to 3.94 MW for the same range of generation deficits.

For this generation deficit contingencies the maximum bus voltage obtained by the proposed ABC method remains constant at 1.058 pu and the minimum voltage varies between 1.01 pu and 0.984 pu. Whereas in Refs. [1] and [5] the maximum voltage decreases from 1.1 pu to 0.8786 pu and the minimum voltage magnitude varies from 0.9353 pu to 0.77 pu and in [3] the maximum voltage is constant at 1.1 pu and minimum voltage magnitude increases from 1.0125 pu to 0.9576 pu.

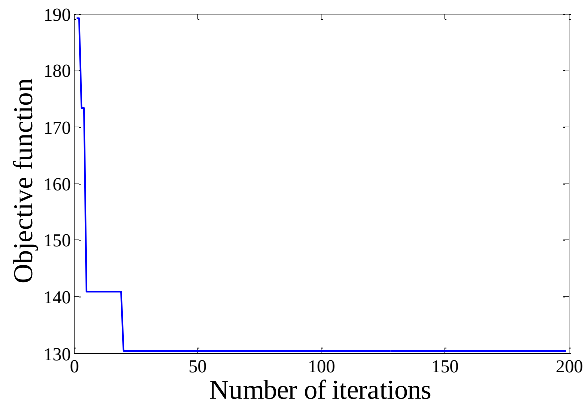


Figure 8 Convergence characteristics of ABC approach for IEEE 30-bus system under generation deficits contingency

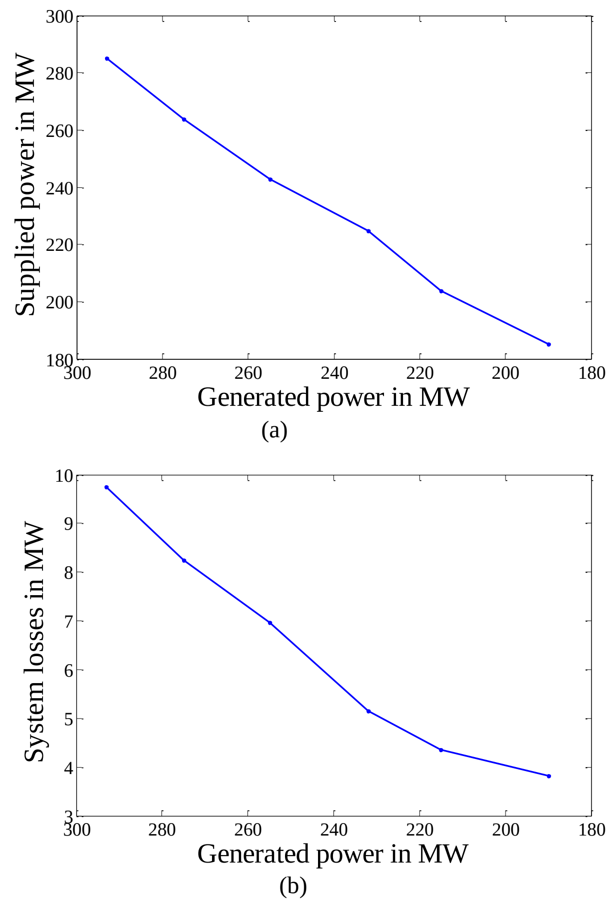


Figure 9 IEEE 30-bus system under generation deficit contingencies using ABC approach a- Optimal supplied power, b- System losses

For IEEE 30 bus system, bus 5 is the bus with heaviest load and bus 8 is the bus with second heaviest load. The supplied powers by the proposed ABC approach at bus 5 and bus 8 are 88.21 MW and 25.34 MW respectively at a generation of 250 MW. In Refs. [1] and [5] the supplied powers at bus 5 and at bus 8 are 88.46 MW and 26.89 MW respectively. The supplied power at bus 5 in [2] is 80.70 MW and at bus 8 it is 25.80 MW. The proposed approach supplies more power at the heaviest loaded buses- bus 5 as compared to Refs. [2].

4.1.2.3 Overload Contingencies

Overloading up to 41.65 % above the maximum available generation of 320 MW is considered here. This corresponds to a connected load between 311.63 MW (110% of the nominal load) to 453.26 MW (160 % of the nominal load). Figure 10 shows the minimum iterations to converge is 73 corresponding to connected load of 425.1 MW. For this contingency the supplied load obtained using the proposed method decreases from 308.001 MW at 110% overload to 307.22 MW at 160 % overload. Whereas for the same range of overload contingencies, the supplied power decreases from 306.836 MW to 304.562 MW and from 309.19 MW to 304.562 MW in Refs. [1, 5] and [2] respectively. Figure 11 (a) shows the decrease in supplied power from 308.037 MW at 110% overload to 307.75 MW at 160 % overload for the proposed ABC approach.

For this range of overload contingencies the system losses obtained by the proposed method increases from 12.01 MW to 12.32 MW which is shown in Figure 11(b). Whereas the system losses for this condition reported in Refs. [1, 5] and [2] increases from 13.164 MW to 15.438 MW and from 10.81 MW to 10.62 MW respectively.

The proposed approach supplies 112.835 MW to bus 5 and 33.672 MW to bus 8. Whereas Refs. [1, 5] supplies 111.9 to bus 5 MW and 34.6 MW to bus 8. Ref. [2] supplies 102.761 MW and 32.92 MW to buses 5 and 8 respectively. So, during the overload contingencies considered the proposed method supplies more power to these heaviest load buses as compared to the power supplied by the other methods to these buses. A better voltage profile is obtained by the proposed method during this contingency. Maximum voltage obtained using the proposed approach is constant at 1.062 pu and the minimum voltage increases from 0.9443 to 0.959 pu.

In Refs. [1, 5] the maximum voltages vary between 1.094 pu and 0.943 pu. and the minimum voltage increases from 0.77 pu to 0.93 pu. The maximum voltage reported in [2] is constant at 1.1 pu and the minimum voltage increase from 0.9634 pu to 0.9797 pu.

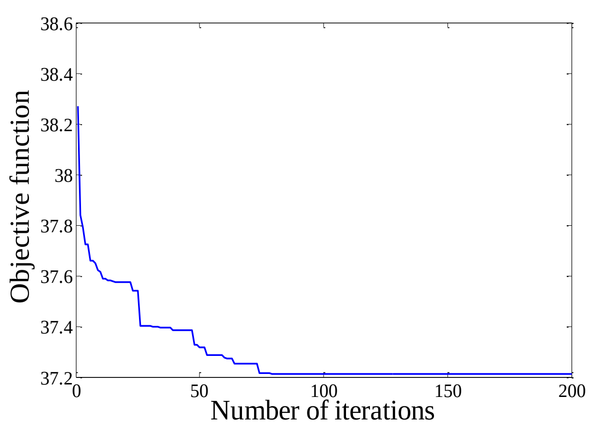


Figure 10 Convergence of ABC approach for 30-bus system under overload contingency

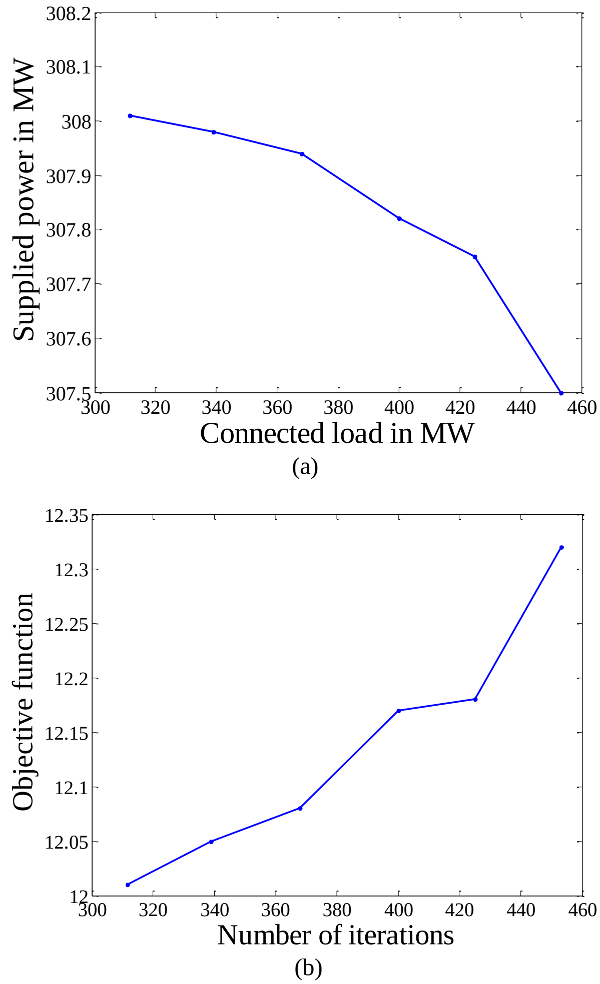


Figure 11 IEEE 30-bus system under overload contingencies using ABC approach a - Optimal supplied power, b - System losses

4.2 Application to Medium Size Systems

IEEE 57 and 118-bus test systems [11] are considered here. In this section the results obtained by the proposed approach under normal and abnormal operating conditions - generation contingencies - are compared with those results obtained in Refs. [1] and [2].

The food number of the proposed ABC algorithm applied to these test systems is assumed as 50.

4.2.1 IEEE 57-bus System

The total connected active load for the 57 bus system is 1251.1 MW with maximum available power generation of 1440 MW including spinning reserve. Under normal operating conditions, the total active power supplied to the connected load and the corresponding system losses obtained using NR method with VDLM used in this paper are 1238.780 MW and 1.76% of the nominal load respectively. Whereas the power supplied to the connected load by the methods reported in Refs. [1] and [2] were 1236.80 MW and 1251 MW respectively. The deficit in the supplied power obtained in this paper and in [1] represents the effect of using VDLM to express the active power. The total system losses under the normal operating conditions obtained by the methods presented in Refs. [1] and [2] were 1.521% and 1.835% of the system nominal load respectively.

Better voltage profile has been obtained using the NR method with VDLM used here. The bus voltage vary between 0.99 pu and 1.04 pu. The bus voltages obtained by the methods reported in [1] vary between 0.81 pu and 1.03 pu. In [2] the bus voltages under normal operating conditions vary between 0.9 pu and 1.14 pu.

4.2.1.1 Loss of Generation Contingency

An abnormal operating conditions representing the loss of generating unit-3 has been considered here as a generation contingency.

The total amount of load shed obtained by the ABC approach during this contingency is 180.2805 MW, which is 14.42% of the nominal load. Whereas for the same contingency, the amount of load shed obtained by the methods presented in [1] and [2] were 190.55 MW or 15.23% of the nominal load and 183.36 MW (or) 14.66 % of the nominal load respectively. The total load shed obtained by the proposed approach is lower when compared with those reported in [1] and [2].

The total system losses obtained during this contingency using the proposed method is 1.39% of the nominal load. Whereas for the same contingency the total system losses obtained by the methods used in [1] and [2] were 1.554% and 0.98% of the system nominal load. The convergence characteristics of the proposed ABC approach for this generation contingency is shown in Figure 12 and from this figure it can be observed that the maximum number of iterations required to converge is 25.

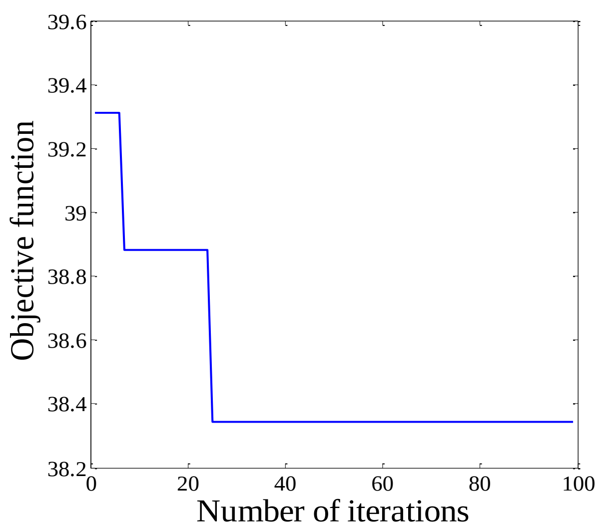


Figure 12 Convergence characteristics of ABC approach for 57-bus system under generation loss contingency

Under this abnormal condition also the proposed ABC approach yields a better voltage profile. The bus voltage vary between 0.9403 pu and 1.07 pu. The bus voltages obtained by the method reported in [1] vary between 0.80 pu and 0.96 pu. In [2] the bus voltages under normal operating conditions vary between 1.0125 pu and 1.2 pu.

4.2.2 IEEE 118-bus System

The total connected load for the 118- bus system is 3668 MW with maximum available power generation of 4080 MW including spinning reserve. Under normal operating conditions the total supplied power to the connected load and the corresponding system losses obtained in this paper are 3663.12 MW and 3.95% of the nominal load respectively. Whereas the supplied power to the connected load obtained by the methods reported in Refs. [1] and [2] were 3662.17 MW and 3668 MW. In this case also the deficit in the supplied power obtained in this paper and in [1] represents the effect of using a VDLM to express the active power. The total system losses obtained by the methods presented in Refs. [1] and [2] were 2.67% and 4.706% of the system nominal load.

For the proposed method the bus voltage vary between 0.95 pu and 1.17 pu. The bus voltages obtained by the methods reported in [1] vary between 0.92 pu and 1.2 pu. In [2] the bus voltages under normal operating conditions vary between 0.914 pu and 1.2 pu.

4.2.2.1 Loss of Generation Contingencies

Here, two cases of generation contingencies are considered. In the first case, loss of generating unit - 54 generating 300 MW along with decrease in the available generation at unit - 12 from 300 MW to 120 MW, which means the loss of 480 MW or 11.77 % of the available power is considered. In the second case the loss of generating units 12, 54 and 111, which means loss of 900 MW or 22.05 % of the available power, is considered.

For the first case of generation contingency, the total amount of load shed obtained by the proposed ABC approach is 196.3834 or 5.36% of the nominal load. Whereas the amount of load shed obtained by the methods presented in Refs. [1] and [2] were 227.33 MW or 6.20% of the nominal load and 189.66 MW or 5.17 % of the nominal load respectively. Therefore the total load shed obtained by the proposed method is lower than that of reported in [1] and slightly greater than that of presented in [2]. The system losses, obtained by the proposed approach for this case is 2.841% of the nominal load and obtained by the methods used in the Refs. [1] an [2] were 4.34% and 3.32% of the nominal load respectively.

For the proposed ABC approach the bus voltage vary between 0.8830 pu and 1.1098 pu for this case. Whereas the bus voltages obtained by the method reported in [1] vary between 0.9 pu and 1.08 pu. In [2] the variation of the bus voltages for this case is between 1.1 pu and 1.2 pu.

The convergence characteristic of the proposed ABC approach for this case is shown in Figure 13(a) and from the this figure it can be observed that the maximum number of iterations required by the proposed approach to converge is 50 iterations.

The second case of generation contingency considered for this test system represents a large disturbance where three units in the system are lost. For this second case of generation contingency, the total amount of load shed obtained by the proposed ABC approach is 606.0553 MW or 16.531 % of the nominal load. Whereas the amount of load shed obtained by the methods presented in Refs. [1] and [2] were 595.59 MW or 16.24% of the nominal load and 563.40 MW or 15.36 % of the nominal load respectively. The system losses, obtained by the proposed approach for this case is 3.01 % of the nominal load and obtained by the methods used in the Refs. [1] an [2] were 2.93% and 2.05% of the nominal load respectively. The system losses obtained by the proposed method for this case is slightly lower than that of those reported in [1].

For the proposed ABC approach the bus voltage vary between 0.955 pu and 1.128 pu for this case. Whereas the bus voltages obtained by the method reported in [1] vary between 0.90 pu and 1.08 pu. In [2] the variation of the bus voltages for this case is between 1.1 pu and 1.2 pu. The convergence characteristic of the proposed ABC approach for this case is shown in Figure 13(b). From the figure it can be observed that this approach took a maximum of 78 iterations to converge. As the severity of generation contingency considered in the second case is more than that of the first case, the proposed algorithm requires more number of iterations to converge in this case as compared to the previous case.

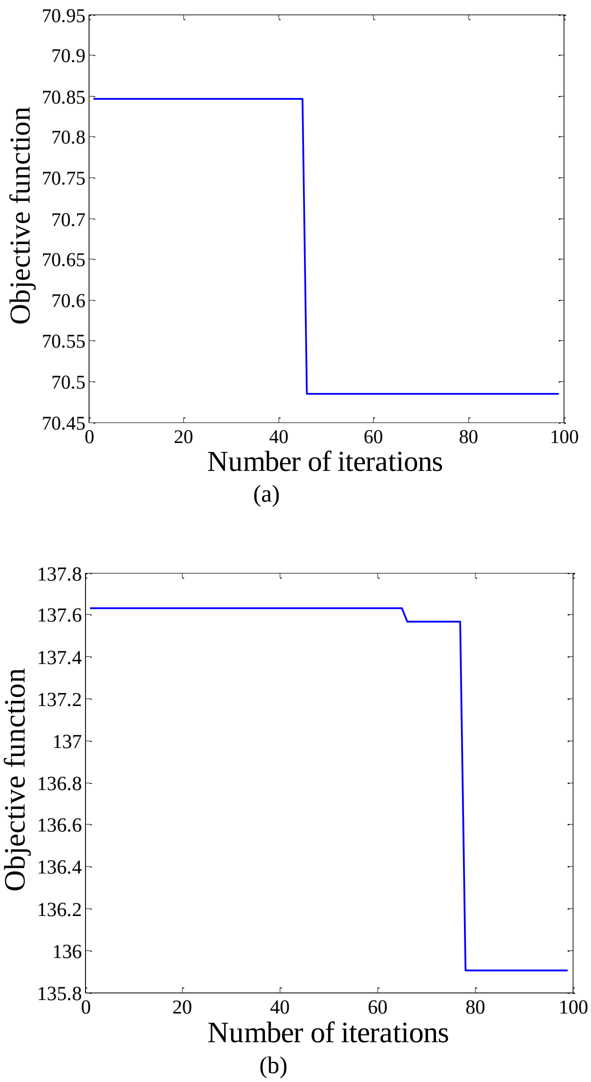


Figure 13 Convergence characteristics of ABC approach for 118-bus system under generation loss contingencies (a)- first case, (b) - second case

■5.0 CONCLUSION

In this paper an optimal load shedding strategy using a meta-heuristic algorithm-ABC approach has been presented. The proposed approach has been tested on IEEE 14, 30, 57 and 118 bus test systems. The results obtained by the proposed approach are compared with the conventional methods, namely, projected augmented Lagrangian method (PALM), gradient technique based on Kuhn-Tucker theorem (GTBKTT) and second order gradient technique (SOGT). The comparison is done on the basis of supplied power, system losses, total load shed and the minimum and maximum bus voltages. The results presented show that the proposed approach provides more supplied power and better voltage profile as compared with those of other methods. Also, the proposed method supplies more power to the heaviest load buses in the case of IEEE 14 and 30 bus test systems, as compared with the power supplied by the other methods.

In the ABC algorithm during the "employed bees" stage, without depending on the quality of the solutions, a trial solution is produced for each solution in the population. Whereas on "onlooker bees" stage, in order to produce trial solutions, the solutions with the highest fitness value were used than those with less fitness. It means that the promising regions of the search space are searched in shorter time and in detail. The diversity in the population of ABC algorithm are controlled by two types of mechanism, (i) The trial solution is obtained by modifying a randomly chosen part of a parent using a magnitude determined randomly. This modification is relatively small and useful for local search and fine tuning. (ii) Instead of changing a part of a solution, a whole solution in the population is removed and then a new one produced randomly is inserted in to the population by a scout. This mechanism of the algorithm improves the global search ability of the algorithm and avoids the premature convergence. Hence there is a good balance between the local search process carried out by employed bees and onlooker bees and the global search process carried by artificial scouts. This improves the exploration and exploitation characteristics of the algorithm. Therefore the ABC algorithm has the ability to perform well on the addressed problem and also has better convergence characteristics. Based on these outcomes, it is concluded that the proposed ABC algorithm can be considered as an effective alternative approach for optimal load shedding.

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