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A New Optimization Algorithm for Solving Optimal Power Flow

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ABSTRACT: This paper States a new and well-Organized method for solving optimal power flow (OPF) problem in power systems. In the proposed approach, Artificial Bee Colony (ABC) algorithm is hired as the main optimizer for optimal adjustments of the power system control variables of the OPF problem. Unique objective functions such as Minimization of fuel costs, total active power loss, improvement of voltage profile, enhancement of voltage stability and all emission cost are selected for this graciously constrained nonlinear non-convex optimization problem. The strength and effectiveness of the proposed method is tested with the Institute of Electrical & Electronic Engineering 30 bus system, and the test results are assessed with the results found by other experimental methods reported in the pamphlets newly. The simulation results attained show that the ABC algorithm provides accurate solutions for any type of the objective functions.

KEYWORDS: Optimal Power Flow, Artificial Bee Colony Algorithm, Minimization of Fuel Cost, Improvement of Voltage Profile, Enhancement of Voltage Stability and emission cost.

I. INTRODUCTION

Optimal load flow (OPF) is one of the most significant problems for power system planners and operators. The main aim of OPF is to discover the optimal settings of a given power system network that improve a selected objective function such as total generation cost, system loss, bus voltage deviation or social welfare while fulfilling its load flow equations, system protection, and equipment operating limits. Many established optimization techniques such as Genetic Algorithm (GA) [1], Particle Swarm Optimization (PSO) [2,3], Differential Evolution (DE) [4], Modified Differential Evolution (MDE) [5], Biogeography-Based Optimization (BBO) [6], Gravitational Search Algorithm (GSA) [7], Modified Shuffle Frog Leaping Algorithm (MSFLA) [8], and Harmony Search (HS) Algorithm [9] have been proposed to tackle the OPF problem. In [1] Bakirtzis et al. proposed an enhanced GA to solve the OPF problem with both continuous and discrete control variables. Abido hired PSO [2] for solving OPF problems with unique objective functions. Also, Abido and co-workers [4] established DE for solving the OPF problem. The MDE algorithm was used in [5] to solve the OPF problem with non-smooth cost function. Bhattacharya and Chatto padhyay in [6] hired BBO algorithm, which was based on two fundamental mechanisms namely migration and mutation to solve the OPF problem. They tested their method on two different versions of IEEE 30-bus system. The GSA which is based on the Newton’s law of gravity and mass interactions was hired for solving the OPF problem, and was applied on the IEEE 30-bus and IEEE 57-bus test systems in [7]. In [9] a multi-objective harmony search algorithm was proposed for the OPF. The authors tested their approach on the IEEE 30-bus test system and compared their results with fast non-dominated sorting GA. One of the newly proposed experimental algorithms is the Artificial Bee Colony (ABC) algorithm. It was enveloped by Karaboga in 2005 [10]. Each cycle of the ABC algorithm consists of three phases: employed bees phase, onlooker bees phase, and scout bees phase. Comparative studies have shown that ABC is faster and well-Organized than other experimental algorithms in yardstick problems. Due to its advantages, ABC algorithm have been successfully used in several power systems problems, including reactive power optimization , real and reactive power tracing in deregulated power systems [11], fault section estimation [12],automatic generation control [13], distributed generation allocation and sizing [14] and so on.

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II. OPF PROBLEM FORMULATION

The optimal load flow (OPF) problem can be arithmetically formulated as follows:

Minimize f(x,u) (1)
Subjected to g(x,u)=0 (2)
h(x,u) $\leq$ 0 (3)

Where f is the objective function to be optimized, g is the equality constraints representing nonlinear load flow equations, and h is the system operating constraints. Also, u is the vector of independent control variables including:
1. Generator active power output P_G except at slack bus P_{G1}
2. Generator bus voltage V_G
3. Transformer tap setting T.
4. Shunt VAR compensation Q_C.

Hence, u can be expressed as:

$$u^T = [P_{G2} \ldots P_{Gng}, V_{G1} \ldots . V_{GNg}, T_1 \ldots T_{N_t}, Q_{C1} \ldots Q_{CN_c}] \quad (4)$$

Where N_g, N_t and N_c denote the number of generating units, number of regulating transformers and number of shunt compensators, respectively. Generators active powers (except slack bus) and generators bus voltages are continuous variables, while the tap settings of the tap changing transformers and VAR injections of the shunt capacitors are discrete variables. Also, x is the vector of dependent variables including:
1. Slack bus generated active power P_{G1}
2. Load (PQ) bus voltage V_L
3. Generator reactive power output Q_G
4. Transmission line loading (line flow) S_L

Hence, x can be expressed as:

$$x^T = [P_{G1}, V_{L1} \ldots . . V_{LN_{Pq}}, Q_{G1} \ldots . . Q_{QN_g}, S_{L1} \ldots . . S_{LN_l},] \quad (5)$$

Where N_{Pq} the number of PQ buses and N_l the total number of transmission lines.

1. Objective Function

1.1. Minimization of Total Fuel Cost
This objective function can be expressed as follows:

$$f_c = \sum_{i=1}^{N_g} f_i\,(P_{Gi}) \quad (6)$$

These fuel cost characteristics are expressed below

$$f_i P_{Gi} = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (7)$$

Where a_i, b_i, c_i, d_i and $e_i$are the fuel cost coefficients of the i^{th} generating unit, and a_{ik}, b_{ik}, and c_{ik} are the fuel cost coefficients of the i^{th} unit for fuel type k.

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1.2. Voltage Profile Improvement

The aim of this objective function is to minimize all PQ bus voltage deviations from 1.0 per unit.

$$VD = \sum_{i=1}^{N_{pq}} |V_i - 1.0| \quad (8)$$

Combining both the fuel cost-based objective function and the voltage profile improvement objective function leads to the following two fold objective function:

$$f_1 = f_c + w_1 VD = \sum_{i=1}^{N_g} f_i\,(P_{Gi}) + w_1 \sum_{i=1}^{N_{pq}} |V_i - 1.0| \quad (9)$$

Where w_1 is a suitable weighting factor, to be selected by the user.

1.3. Voltage Stability Enhancement

The bus with the highest L-index value will be the most vulnerable bus in the system. The L-index calculation for a power system is briefly discussed below [6 and 7]: Consider an N-bus system in which there are Ng generators. The relationship between voltage and current can be expressed by the following expression:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (10)$$

Where I_G, I_L and V_G, V_L represent complex currents and voltages at the generator buses and load buses.

$$\begin{bmatrix} V_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (11)$$

Where

$$F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}] \quad (12)$$

The Line (L)-index of the j^{th} node is given by the following expression:

$$L_j = \left|1 - \sum_{I=1}^{N_g} F_{ji} \frac{V_i}{V_j} (\theta_{ji} + \delta_i - \delta_j\right| \quad j = 1,2,\ldots, N_{Pq} \quad (13)$$

where V_i is the voltage magnitude of i^{th} generator bus, V_j is the voltage magnitude of j^{th} PQ bus, θ_{ji} is the phase angle of the term F_{ji}, δ_i is the voltage phase angle of i^{th} generator unit, δ_j is the voltage phase angle of j^{th} generator unit, and N_{Pq} is the number of PQ buses. L-index is computed for all PQ buses. As mentioned above, L-index at each PQ bus has a value between zero and one. Therefore, a global power system L-index describing the voltage stability of the entire system can be defined by

$$L = \max(L_j) \qquad j = 1,2,\ldots, N_{Pq} \quad (14)$$

The lower the value of indicator L is, the larger the voltage stability margin will be. Combining both the fuel cost-based objective function and the voltage stability enhancement objective function leads to the following two fold objective function [2,4,6 and 7]

$$f_1 = f_c + w_1 L = \sum_{i=1}^{N_g} f_i\,(P_{Gi}) + w_2 L \quad (15)$$

Where w_2 is Weighting factor, have to be selected by the user.

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1.4. Minimization of Total Power Losses

Total power loss in the transmission network can be mathematically formulated as follows

$$P_L = \sum_{K=1}^{N_l} \frac{r_k}{r_k^2+x_k^2}\left(V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)\right) \tag{16}$$

WhereN_l is the number of transmission lines, r_k and x_k are, respectively, the resistance and reactance of the transmission line k connecting bus i and bus j. V_i and V_j are the voltage magnitudes at bus i and bus j, respectively; δ_i and δ_j are the voltage angles at bus i and bus j, respectively.

1.5. Total Emission Cost Minimization

In this paper, two significant types of emission gasses, namely, SO_x and NO_x are taken as the pollutant gasses. The emission gasses generated by each generating unit may be approximated by a combination of a quadratic and an exponential function of the generator active power output. Here, the total emission cost is defined as bellow [8]

$$E = \sum_{i=1}^{N_g}(\alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 + \varepsilon_i \exp(\lambda_i P_{Gi})) \quad ton/h \tag{17}$$

Where E is the total emission cost (ton/h) and α_i, β_i ,γ_i and ε_i are the emission coefficients of the i^{th} unit.

2. Equality Constraints

The equality constraints g represented by (2), are typical load flow equations which are defined as follows

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{N} V_j\left(G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right) \tag{18}$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{N} V_j\left(G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)\right) \tag{19}$$

Where N is the number of buses in the system. P_{Gi} and Q_{Gi} are, respectively, the active and reactive power generations at bus i, P_{Gi} and Q_{Di} are the active and reactive power loads at bus i, respectively; G_{ij} and B_{ij} are the real and imaginary parts of the ij^{th} element of the bus admittance matrix, respectively; V_i and V_j are the voltage magnitudes at bus i and bus j, respectively; δ_i and δ_j are the voltage angle at bus i and bus j, respectively.

3. Inequality Constraints

The inequality constraints h represented by (3), are the power system operating limits including

(a) Generator Constraints: Generator active power PG, generator reactive power QG, and generator voltage magnitude VG are restricted by their lower and upper limits

$$P_{Gi,min} \le P_{Gi} \le P_{Gi,max} \qquad i = 1 \ldots\ldots, N_G \tag{20}$$
$$Q_{Gi,min} \le Q_{Gi} \le Q_{Gi,max} \qquad i = 1 \ldots.\ldots, N_G \tag{21}$$
$$V_{Gi,min} \le V_{Gi} \le V_{Gi,max} \qquad i = 1 \ldots.\ldots, N_G \tag{22}$$

(b) Transformer Constraints: Transformer taps have minimum and maximum setting limits

$$T_{i,min} \le T_i \le T_{i,max} \qquad i = 1 \ldots.\ldots, N_T \tag{23}$$

(c) Switchable VAR Sources: The switchable VAR sources have restrictions as follows

$$Q_{Ci,min} \le Q_{Ci} \le Q_{Ci,max} \qquad i = 1 \ldots\ldots, N_C \tag{24}$$

(d) Security Constraints: These include the limits on the load bus voltage magnitudes and transmission line flows limits

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$$V_{Li,min} \le V_{Li} \le V_{Li,max} \qquad i = 1 \ldots\ldots, N_{pq} \tag{25}$$

$$S_{Li} \le S_{Li,min} \qquad i = 1 \ldots.\ldots, N_L \tag{26}$$

4. Incorporation of Equality Constraints

The equality constraints of power balance equations shown in (18) and (19) are forced by an unconstrained Newton–Raphson based load flow calculations; therefore, there is no need to integrate them into the objective function.

5. Incorporation of Inequality Constraints

A common way for handling the inequality constraints is the use of a penalty function. By penalizing the inequality constraints, the original constrained optimization problem is transformed to an unconstrained one. The penalty function illustrated in (27) is used here to impose inequality constraints of PG1 and the constraints shown in (21), (25), and (26).

$$\mathrm{h}(x_i) = \begin{cases} \left(x_i - x_{i,max}\right)^2 & if\, x_i > x_{i,max} \\ (x_{i,min} - x_i)^2 & if\, x_i < x_{i,min} \\ 0 & if\, x_{i,min} \le x_i \le x_{i,max} \end{cases} \tag{27}$$

Where h (x_i) is the penalty function of variable x_i. Here, thex_i shows a dependent variable. Also,x_i, max and x_i,min are, respectively, the upper and lower limits of the variable x_i. Note that the value of penalty function grows with a quadratic form when the constraints are violated, and is 0 if the constraints are not violated. By adding penalty functions of the active power generation of the slack bus, reactive power generation, PQ bus voltage magnitude and transmission line loading to the objective function in (1).

$$\mathrm{F{=}f{+}}C_P{*}\mathrm{h}(P_{G1}){+}C_q \sum_{i=1}^{N_g} h\,(Q_{Gi}){+}C_v \sum_{i=1}^{N_{Pq}} h\,(V_{Li}) + C_s \sum_{i=1}^{N_l} h\,(S_{Li}) \tag{28}$$

whereC_P, C_q, C_v and C_s are penalty factors (weights) of active power generation of the slack bus, reactive power output of the generator buses, PQ bus voltage magnitudes and transmission line loadings, respectively. It should be noted that the active power generation limits of PV buses, voltage limits of all generator buses, transformers tap setting limits and shunt VAR compensations limits are not included in the extended objective function shown in (30), since these optimization (control) variables are randomly created within their feasible limits during the proposed ABC algorithm process.

III. ARTIFICIAL BEE COLONY ALGORITHM

Artificial Bee Colony (ABC) algorithm is a novel optimization algorithm inspired from the intelligent behaviour of honeybee swarms. Food sources and forager bees are two essential components in the ABC algorithm. In the ABC algorithm, the position of a food source represents a possible solution to the optimization problem, and the nectar amount of a food source corresponds to the quality (fitness) of the solution represented by that food source. Forager bees consist of two groups of bees: employed bees and unemployed bees. Onlookers and scouts are two types of unemployed foragers. The number of employed bees or the onlooker bees is equal to the number of solutions in the population. The first half of colony consists of employed artificial bees and the second half includes the artificial onlookers. The employed bee whose food source has been exhausted becomes an artificial scout [29–33]. The main phases of the ABC algorithm are carried out for a predetermined number of cycles or until a stopping criterion is satisfied. The main phases of the algorithm are given below.

1. Initialization Phase

A single individual in an initial population of the solutions is randomly generated using a set of uniform random numbers ranging over the feasible limits of each control variable. At the beginning of the ABC algorithm, SN numbers of initial solutions (individuals) are randomly generated over the D-dimensional problem space by using the following expression.

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$$x_{ij} = x_{j,min} + rand[0,1] \times (x_{j,max} - x_{j,min}) \quad (29)$$

Where SN is the number of food sources, i e {1. . . SN} and
j ε{1. . . D}. Also, $x_{j,min}$ and $x_{j,max}$ are, respectively, the lower and upper limits of the jth optimization variable, and rand [0, 1] denotes a uniformly distributed random number within [0, 1].

2. Employed Bees Phase

After initialization, all the employed bees try to discover new food sources within the neighbourhood of the food sources they memorized before. In order to produce a new food source from the old one saved in the memory, the following expression is used

$$v_{ij} = x_{ij} + \emptyset_{ij} + (x_{ij} + x_{kj}) \quad (30)$$

Where k ε {1 . . ., SN} and j e {1, . . . , D} are randomly chosen indices, x_{kj} is a randomly chosen solution different from x_{ij}, and v_{ij} is the new solution (food source). Also, $\emptyset_{ij}$ denotes a random number in the interval [1, 1].

If the value of a variable produced by the above operation exceeds its predetermined limits, that variable is set to its limit value. After a new solution v_{ij} is produced, its performance (profitability) is assessed with that of its old one. If the new food source has equal or better nectar than the old source, it is interchanged with the old one in the memory. Otherwise, the old one is hired in the memory. In different words, a greedy selection method is hired as the selection operation between x_i and v_i.

3. Onlooker Bees Phase

When all the employed bees complete their search for food sources, they share their obtained food source information with onlooker bees. Each onlooker bee chooses a food source depending on the nectar amount fit_i of that food source, which shows the fitness value corresponding to the solution i. As the nectar amount of the food source increases, the probability with the preferred source by an onlooker bee increases proportionality. Therefore, the probability with the food source (solution i) is calculated as the following

$$P_i = \frac{fit_i}{\sum_{n-1}^{SN} fit_n} \quad (31)$$

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

$$fit_i = \begin{cases} \frac{1}{1+f_i} & if\ f_i \geq 0 \\ 1 + |f_i| & if\ f_i < 0 \end{cases} \quad (32)$$

Where f_i is the value of the objective function.

4. Scout Bees Phase

If the nectar quantity of a food source has been pooped or the fruitfulness of the food source decreases under a definite level, the employed bee associated with that food source becomes a scout. This scout starts finding a new food source randomly without any guidance in the search space. The behaviour of scouts can be sported as below: If a solution representing a food source is not enhanced by a predestined number of trials, then that food source is dumped by its employed bee and the employed bee becomes a scout.

The value of predetermined number of cycles is an significant control parameter of the ABC algorithm, known as the ‘‘limit’’. In ABC, it is assumed that only one source can be abandoned in each cycle, and only one employed bee can be a scout. The scout discovers a new food source by using (30).

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5. Application of Artificial Bee Colony Algorithm to the OPF Problem

The proposed ABC algorithm for solving OPF problem is summarized as follows

1. Read the power system data.
2. Set maximum cycle number (MCN).
3. Initialize the SN population of solutions xi, i = 1,. . . ,SN.
4. Evaluate the fitness value for each employed bee by using the following equation

$$fit_i = \frac{1}{1+f_i} \tag{33}$$

Where f_i is the value of the objective function.

5. Set cycle number, cycle = 1.
6. Generate new solutions v_i for the employed bees using (30) and evaluate their fitness values.
7. Apply the greedy selection process for x_i and v_i
8. Calculate the probability value p_i corresponding to the solution xi by (31).
9. Produce the new solutions x_i for the onlooker bees from the old solutions xi selected depending on the p_i and evaluate their fitness values.
10. Apply the greedy selection process between the old solution x_i and new solution v_i .
11. Determine the abandoned solution for the scout, if exists, and replace it with a recent randomly produced solution using (30).
12. Commit to memory the best solution found so far.
13. Set cycle = cycle + 1and if cycle < MCN go back to Step 6, and otherwise STOP.

IV. THE SIMULATION RESULTS

The proposed ABC-based algorithm for solving OPF problem has been applied to the IEEE 30-bus test systems. In this section the numerical results are represented. Loads were modelled as constant powers in the three test systems. The results attained by the proposed approach are assessed with the results found by other heuristic methods reported in the literature. All the simulations were performed on a personal computer with 3 GHz Intel Processor and 2 GB of RAM running MATLAB 7.6. Load flow calculations by Newton–Raphson method were performed using the software package MATPOWER [15].

IEEE 30-Bus Test System

The line and bus data of IEEE 30-bus system can be seen in [16], while upper and lower limits of the control variables are found from [17]. The IEEE-30 bus system has 6 generators at buses 1, 2, 5, 8, 11 and 13, and 4 transformers with off nominal tap ratios at lines 6–9, 6–10, 4–12 and 28–27. In addition, buses 10, 12, 15, 17, 20, 21, 23, 24 and 29 were selected as shunt VAR compensation buses for reactive power control as seen in [2]. The total system demand is 2.834 p.u. For the active power 1.262 p.u. and for the reactive power at 100 MVA base. First Bus was taken as the slack bus. The generator-bus voltage magnitude limits were assumed as 0.95 p.u. to 1.1 p.u., respectively and the maximum and minimum voltage magnitudes of other buses were considered to be 1.05 and 0.95 in p.u., respectively. Furthermore, tap settings of the regulating transformers and VAR injections of the shunt capacitors are considered as discrete (finite) variables. The transformer-tap settings were assumed to vary in the range [0.9, 1.1] p.u., with step size of 0.0125 p.u. [1]. The VAR injections of the shunt capacitors were assumed to vary in the range [0,0.05] p.u., with step size of 0.01 p.u. [1].Fuel cost and emission cost coefficients were taken from [26,27], respectively. This system has a total of 24 control variables including five generators active power outputs, six generator-bus voltages magnitudes, four transformer-tap settings, and nine shunts VAR injections. It should be noted that while searching the optimal solution by the ABC algorithm, the discrete control variables are assigned continuous numbers in their assumed range of variations; however, when evaluating the fitness functions, the discrete variables are rounded to their closest possible discrete values. TABLE 1 shows the optimal control settings and the corresponding objective function values of 20 independent runs with different random seeds for different cases with several objective functions from the proposed ABC algorithm. Cases considered are as follows

Case 1: Quadratic Fuel Cost Minimization

The objective function selected was the total generator fuel cost minimization as defined in (6). Here all generators cost characteristics were represented as quadratic. The minimum total fuel cost obtained from the proposed ABC

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approach was 801.5576 $/h. The average computation time of the 20 independent runs with SN equal to 50 and MCN equal to 200 was 130.16s.The results attained from the proposed ABC algorithm were assessed to the PSO algorithm, GSA and the other methods reported in the literature. The control parameters of GSA were taken from [7]. The results of this comparison are given in TABLE 2. It is to be noted that besides the ABC algorithm, the PSO and GSA methods were also implemented in the present case by us i.e., the first three rows of TABLE 2 represent our own implemented results.

The results shown in the reaming rows of TABLE 2 were just quoted from the mentioned references. It can be seen in TABLE2 that the methods reported in [7, 9, 3, 6, 4, 5, & 2] have resulted in lesser minimum fuel cost than our ABC approach. It could be shown that those results marked with a '*' in TABLE 2, are indeed infeasible solutions. For the best solution given in [9], there were bus voltage magnitude violations at all the load buses except at bus 7, and the true value of PG1 is 177.3531MW for this violated case. For the case of results reported in [3], the reactive power of shunt compensators at buses 17 and 29 were not available. Assuming those reactive powers to be zero, the voltage magnitude at bus 9 is obtained as 1.0745 p.u, which violates the upper limit.

Table 1
Comparisons of the results obtained for case 1 of IEEE 30-bus system.

Control variable	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
P_{G2}	0.485039	0.80005	0.675848	0.488994	0.492198
P_{G5}	0.215075	0.50006	0.500004	0.217826	0.190337
P_{G8}	0.213299	0.35008	0.350006	0.214716	0.257128
P_{G11}	0.123019	0.30007	0.300008	0.121517	0.131056
P_{G13}	0.120010	0.40005	0.400009	0.120500	0.120007
V_{G1}	1.0818	1.0629	1.0612	1.0727	1.0579
V_{G2}	1.0589	1.0579	1.0554	1.0627	1.0444
V_{G5}	1.0286	1.0490	1.0356	1.0565	1.0628
V_{G8}	1.0379	1.0749	1.0432	1.0439	1.0467
V_{G11}	1.0978	1.04649	1.0879	1.0287	1.0705
V_{G13}	1.0495	1.05008	1.0534	1.0493	1.0717
T_{6-9}	1.0506	0.93784	1.0127	1.0124	0.9504
T_{6-10}	0.9504	0.9876	1.0124	0.9008	1.0627
T_{4-12}	0.9878	0.9876	1.0006	1.0006	1.0006
T_{28-27}	0.9755	0.9756	0.9874	0.9755	0.9378
Q_{c10}	0.05	0.05	0.05	0.05	0.05
Q_{c12}	0.05	0.05	0.05	0.05	0.05
Q_{c15}	0.05	0.05	0.05	0.03	0.05
Q_{c17}	0.05	0.05	0.05	0.05	0.05
Q_{c20}	0.04	0.04	0.04	0.05	0.05
Q_{c21}	0.05	0.05	0.05	0.04	0.05
Q_{c23}	0.03	0.03	0.03	0.04	0.05
Q_{c24}	0.05	0.05	0.05	0.05	0.05
Q_{c29}	0.03	0.02	0.03	0.03	0.05
Fuel cost ($/h)	**801.5576**	967.685	944.4394	807.6850	809.0116
Power loss (MW)	9.0328	**3.1996**	3.2470	9.2954	11.1757
Emission (ton/h)	0.365141	0.20726	**0.209599**	0.364295	0.361712

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Voltage deviation	0.9209	0.9008	0.8463	0.9380	0.8778
L-index	0.1381	0.1386	0.1402	**0.1380**	**0.1474**
P_{G1}	1.767917	0.51507	0.640621	1.764801	1.755039

For the optimum control variables given in [15], there were voltage magnitude violations at all the load buses except at buses 7, 19, 24, 26, 29 and 30. Reasons for infeasibility of those results are summarized as follows. The best solution mentioned in [7] is an infeasible which violate their corresponding limits as reported in [17].

Table 2
Comparisons of the results obtained for case 1 of
IEEE 30-bus system.

Method	Fuel cost ($/h)
ABC	**801.5576**
GSA	805.1752
PSO [2]	800.41 *
GSA [7]	798.675143 *
HS [9]	798.8000 *
BBO [6]	799.1116 *
MSFLA [8]	802.287
Parallel PSO [3]	800.64 *
DE [4]	799.2891 *
MDE [5]	802.376 *
EGA [1]	802.06
* infeasible solution	

For the optimum control variables given in [6], there were voltage magnitude violations at all load buses. For the best solution given in [4], there were voltage magnitude violations at all the load buses except at buses 26, and 30.

The true value of PG1 corresponding to the result reported in [5] is 176.1446 MW as obtained from the load flow computations, and the total fuel cost for this case is 802.9437 $/h. For the best solution given in [2], there were voltage magnitude violations at all the load buses except at buses 3 and 12.

Case 2: Active Power Loss Minimization

The objective function selected was the active power loss minimization PL as defined in (16). Here, all generator cost characteristics were represented as quadratic. Considering PL as the objective function, the total active power loss reduced by as much as 66.59%, but assessed with the case 1, the total fuel cost increased by as much as 21.86%. The average total active power loss found by the proposed ABC approach was 3.1996 MW, with maximum total active loss of 3.2094 MW.

Table 3
Comparisons of the results obtained for case 2 of IEEE 30-bus system

Method	Total active power losses (MW)
ABC	**3.1996**
EGA [19]	3.2008
HS [8]	2.9678*

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The results attained from the proposed ABC algorithm was assessed with the other methods reported in the literature. The results of this comparison are shown in TABLE 3. It can be seen in TABLE 3 that the total active power loss obtained by the proposed ABC algorithm is 3.1996 MW, which is less than the method reported in [19], and is more than the algorithm presented in [9]. However, the best solution reported in [9] is indeed an infeasible solution. Because, there were bus voltage magnitude violations at all the load buses except at bus 7. In addition, the true value of the total active power loss corresponding to the best solution reported in [19] was 3.2608 MW, as obtained from the load flow computations.

Case 3: Emission Cost Minimization

Here, all generators cost characteristics were represented as quadratic. Total emission cost decreased to 0.209599 ton/h (42.90%) in case 3 in comparison to 0.365141 ton/h in case 1.The results obtained from the proposed ABC algorithm was assessed to the PSO, GA, SFLA and MSFLA methods reported in [8]. The results of this comparison are given in TABLE 4. From TABLE 4, it is clear that the result obtained by the ABC algorithm is better than those reported in [8].

Table 4
Comparisons of the results obtained for case 3 of IEEE 30-bus system.

Method	Total emissions (ton/h)
ABC	**0.209599**
PSO	0.209600
SFLA	0.206300
MSFLA	0.205600
GA	0.211700

Case 4: Quadratic Fuel Cost and Voltage Stability Improvement

The objective function selected was the simultaneous optimization of the total fuel cost and voltage stability improvement f2 as defined in (17). Here all generator cost characteristics were represented as quadratic form. The minimum total fuel cost and L-index found by the ABC algorithm were 807.6850 $/h and 0.1380, respectively; which show 0.247 % reduction in the L-index and about 0.129% increase in the total fuel cost in comparison with case 1. The results obtained from the ABC algorithm have been assessed with other algorithms in TABLE 5. As shown in TABLE 5, the ABC algorithm has better performance than other algorithms. Some of those algorithms, however; have resulted in better performance than our proposed ABC approach. Again, it could be shown that those results marked with a '*' in TABLE 5, are indeed infeasible solutions. Reasons for infeasibility of those results are summarized as follows: It can be shown that for the optimal control settings obtained in [7], the load flow program does not converge to an acceptable solution. The best solution given in [9] is an infeasible solution because reactive powers of the generators at buses 8, 11 and 13 were given as 70.1633 MVAR, 21.8574 MVAR, and 24.8971 MVAR, respectively; which violate their corresponding limits as reported in [16]. In addition, the bus voltage magnitudes at all the PQ buses are higher than their upper limits, and the true value of the line flow corresponding to the transmission line connecting bus 6 and bus 8 is 37.3929 MVA. For the optimum control variables given in [6], the voltage magnitudes at buses 27 and 29 come 1.0664 p.u. and 1.0634 p.u., respectively; that violate their upper limits. In addition, the line flow corresponding to the transmission line connecting bus 6 and bus 8 comes 38.1276 MVA.

The best result given in [4] is an infeasible solution because the reactive powers of the generators at buses 8, 11, and 13 come 122.6995 MVAR, 19.5035 MVAR, and 33.1927 MVAR, respectively; which violate their limits as reported in [16]. Also, the voltage magnitudes at all the PQ buses except at bus 4 violate their upper limits, and the line flow

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corresponding to the transmission line connecting bus 6 and bus 8 come 78.0045 MVA. The optimum control variables given in [2] represent an infeasible solution because the reactive powers of the generators at buses 11 and 13 come 10.9947 MVAR, and 16.0325 MVAR, respectively; which violate their limits as reported in [16]. In addition, the voltage magnitudes at buses 9, 10, 12 and 27 violate their upper limits.

Case5: Fuel Cost and Voltage Stability Improvement during Contingency Condition

In the actual operation phase of a power system, there might be many changes in the system configuration, such as outage of the transmission lines and outage of the system generators. It is highly significant that the power system has enough voltage stability margins both in its normal operation phase and in situations where a contingency takes place in the system. All generator cost characteristics were represented as quadratic in this case. A contingency state was simulated as the outage of the transmission line connected between bus 2 and bus 6 [23, 26]. In this case, the minimum L-index obtained from the proposed ABC approach 0.1499. The comparison of the results obtained by the proposed ABC algorithm and those results obtained by the GSA and DE algorithms are shown in TABLE 6. From TABLE 6, it is clear the ABC algorithm has better performance than other algorithms. Furthermore, it could be shown that the best solutions obtained by the GSA and DE algorithms are indeed infeasible solutions as follows

Table 5
Comparisons of the results obtained for case 5 of IEEE 30-bus system.

Method	Average	Max	Min
	L-index	L-index	L-index
ABC	0.1695	0.26190	0.1499
GSA [7]	0.096531	0.099846	0.0930*
DE [4]	NA	NA	0.1347 *

The best result given in [7] is an infeasible solution because the reactive powers of the generators at buses 2 and 8 come 58.3071 MVAR, 141.3719 MVAR, respectively; which violate their limits as reported in [16]. In addition, the voltage magnitudes at buses 3, 4, 6, and 28 violate their upper limits and the line flows of the transmission lines connecting buses 4 and 6, buses 6 and 8, and buses 6 and 10 come 105.8050 MVA, 95.6594 MVA and 39.6999 MVA, respectively. The optimum control variables given in [4] represent an infeasible solution because the reactive powers of the generators at buses 1, 8 and 13 come 30.7093 MVAR, 75.0950 MVAR, and 15.4248 MVAR, respectively; which violate their limits as reported in [16]. In addition, the voltage magnitude at buses 3, 4, 6, 7, 28, and 29 violate their upper limits and the line flows of the transmission lines connecting buses 4 and 6, and buses 6 and 8 come 90.7172 MVA and 40.0888 MVA, respectively.

V. CONCLUSIONS

In this paper, an Artificial Bee Colony (ABC) algorithm based approach was proposed, established and successfully applied to solve different types of optimal load flow (OPF) problems with several types of complexities. The approach was tested and examined with unique objective functions including minimization of total fuel costs, total active power loss, voltage profile improvement, voltage stability enhancement in both normal and contingency conditions, and total emission to show its effectiveness using the IEEE 30-bus system. The results obtained from the ABC approach were assessed with those reported in the recent literature. The superiority and solution quality of the proposed method assessed to other techniques were observed. According to the results obtained, the ABC algorithm has a simple framework and quick convergence characteristic and, therefore, could be used to solve the OPF problem in large-Scale power systems with several thousands of buses utilizing the strength of parallel computing.

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