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Economic power dispatch of power systems with pollution control using artificial bee colony optimization

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Abstract: This paper presents a solution for the emission-controlled economic dispatch (ECED) problem of medium-sized power systems via an artificial bee colony algorithm. The ECED problem, which accounts for the minimization of both the fuel cost and the emission, is a multiple objective function problem. The objective is to minimize the total fuel cost of the generation and environmental pollution caused by fossil-based thermal generating units and to also maintain an acceptable system performance in terms of the limits on the generator's real and reactive power outputs, bus voltages, shunt capacitors/reactors, and power flow of transmission lines. The proposed algorithm is validated on an IEEE 30-bus system with 6 generating units. The results of the proposed technique are compared with that of the particle swarm optimization technique. The proposed approach is also tested on the Algerian 59-bus network and compared with global optimization methods (fuzzy genetic algorithm and ant colony optimization). The results show that the approach proposed can converge to a near solution and obtain a competitive solution in a critical situation and within a reasonable time.

Key words: Optimal power flow, power systems, pollution control, NO_x emission, artificial bee colony

1. Introduction

Optimal power flow (OPF) was developed long ago with the introduction of a generalized formulation of the economic dispatch problem, including voltage and other operating constraints.

The OPF calculation optimizes the static operating condition of a power generation-transmission system. The main benefits of the OPF are 1) to ensure static security of quality of service by imposing limits on the generation-transmission system's operation, 2) to optimize the reactive-power/voltage scheduling, and 3) to improve the economy of operation through the full utilization of the system's feasible operating range and by the accurate coordination of the transmission losses in the scheduling process. The OPF has usually been considered as the minimization of an objective function representing the generation cost and/or the transmission loss. The constraints involved are the physical laws governing the power generation-transmission systems and the operating limitations of the equipment.

A wide variety of classical optimization techniques have been applied in solving the OPF problems considering a single objective function, such as nonlinear programming, quadratic programming, linear programming, Newton-based techniques, the sequential unconstrained minimization technique, interior point methods, and the parametric method. Effective OPF is limited by the high dimensionality of power systems and by the incomplete domain-dependent knowledge of power system engineers [1,2].

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The first limitation is addressed by numerical optimization procedures based on successive linearization using the first and the second derivatives of the objective functions and their constraints as the search directions, or by linear programming solutions to imprecise models [3]. The advantages of such methods are in their mathematical underpinnings, but disadvantages exist also in their sensitivity to problem formulation, algorithm selection, and usual convergence to local minima [4].

The second limitation, incomplete domain knowledge, also precludes the reliable use of expert systems where rule completeness is not possible.

As modern electrical power systems become more complex, the planning, operation, and control of such systems using conventional methods face increasing difficulties. Intelligent systems have been developed and applied for solving problems in such complex power systems.

Swarm intelligence is an innovative computational way to solve hard problems. This discipline is inspired by the behavior of social insects, such as fish schools, bird flocks, and colonies of ants, termites, bees, and wasps. In general, this is done by mimicking the behavior of the biological creatures within their swarms and colonies.

In a previous paper [5], the authors proposed the use of particle swarm optimization (PSO) on the OPF problem, using as the objective function the minimization of the fuel cost and NO_x emission control. More than 6 small-sized test cases were used to demonstrate the performance of the proposed algorithm. Consistently acceptable results were observed.

The purpose of the economic emission load dispatch problem is to obtain the optimal amount of generated power for the fossil-based generating unit in the system by minimizing the fuel cost and emission level simultaneously, subject to various equality and inequality constraints of the power system.

In [6], we proposed the use of an ant colony search algorithm to solve the economic power dispatch with pollution control. To accelerate the processes of the ant colony optimization (ACO), the controllable variables are decomposed to active constraints that directly affect the cost function and are included in the ACO process along with passive constraints, which are updated using conventional power flow.

The authors of [7] proposed a combined genetic algorithm (GA)-fuzzy–based approach for solving the OPF. The GA parameters, e.g., crossover and mutation probabilities, were governed by a fuzzy rule base.

In this paper, the artificial bee colony (ABC) algorithm, inspired by the foraging behavior of honeybees, is proposed to solve the OPF problem, using as the objective function the minimization of the fuel cost and NO_x emission level simultaneously, subject to various equality and inequality constraints of the power system. Central processing unit times can be reduced by decomposing the optimization constraints of the power system to active constraints manipulated directly by the ABC and passive constraints maintained in their soft limits using a conventional constraint load flow. The standard IEEE 30-bus with 6 generators and the Algerian 59-bus network are considered as the test systems. The results obtained are compared with the conventional methods and with global optimization methods, and the effectiveness of ABC-OPF to solve the emission-controlled economic dispatch (ECED) problem is demonstrated.

2. Problem formulation

The main objective of an OPF strategy is to determine the optimal operating state of a power system by optimizing a particular objective while satisfying certain specified physical and operating constraints. In its most general formulation, the OPF is a nonlinear, nonconvex, large-scale, static optimization problem, with both continuous and discrete control variables.

The standard OPF problem can be formulated as a constrained optimization problem as follows:

$$\begin{array}{ll} \min & f(x) \\ s.t. & g(x)=0 \\ & h(x)\le 0 \end{array}, \tag{1}$$

where $f(x)$ is the objective function, $g(x)$ represents the equality constraints, $h(x)$ represents the inequality constraints, and x is the vector of the control variables, such as the generator's real power Pg, generator voltages Vg, transformer tap setting T, and reactive generations of volt-ampere reactive (VAR) sources Qc. Therefore, x can be expressed as:

$$x^T = \left[Pg_1 \cdots Pg_{ng}, Vg_1 \cdots Vg_{ng}, T_1 \cdots T_{nt}, Qc_1 \cdots Qc_{nc}\right], \tag{2}$$

where ng is the number of generator buses, nt is the number of transformer branches, and nc is the number of shunt compensators.

The essence of the OPF problem resides in reducing the objective function and simultaneously satisfying the load flow equations (equality constraints) without violating the inequality constraints.

2.1. Objective function

2.1.1. Economic objective function

The most commonly used objective in the OPF problem formulation is the minimization of the total operation cost of the fuel consumed for producing the electric power within a scheduled time interval (1 h). The individual costs of each generating unit are assumed to be the function of only the real power generation and are represented by quadratic curves of the second order. The objective function for the entire power system can then be expressed as the sum of the quadratic cost model at each generator [8,9]:

$$F_{ec}(x) = \sum_{i=1}^{ng} \left(a_i + b_i Pg_i + c_i Pg_i^2\right) \$/h, \tag{3}$$

where a_i, b_i, and c_i are the cost coefficients of the generator at bus i.

2.1.2. Emission objective function

The emission control cost results from the requirement for power utilities to reduce their pollutant levels below the annual emission allowances assigned for the affected fossil units. The total emission can be reduced by minimizing the 3 major pollutants: nitrogen oxide (NO_x), sulfur oxide (SO_x), and carbon dioxide (CO_2). The objective function that minimizes the total emissions can be expressed in a linear equation as the sum of all 3 of the pollutants resulting from the generator's real power, Pg_i [10].

In this study, the NO_x emission is taken as the index from the viewpoint of environmental conservation. The amount of NO_x emission is given as a function of the generator's output (in t/h), i.e. the sum of the quadratic and exponential functions [11]:

$$F_E = \sum_{i=1}^{ng} \left(a_i + b_i Pg_i + c_i Pg_i^2 + d_i \exp\left(e_i Pg_i\right)\right), \tag{4}$$

where a_i, b_i, c_i, d_i, and e_i are the coefficients of the generator's emission characteristic.

The pollution control cost (in \$/h) can be obtained by assigning a cost factor to the pollution level, expressed as:

$$F_{pc} = w \cdot F_E \$/h \ , \tag{5}$$

where w is the emission control cost factor in \$/t [11].

2.1.3. Total objective function

The total objective function considers at the same time the cost of generation and the cost of pollution level control. These objectives have complicated natures and are conflicted in some points (the minimization of the generation cost can maximize the emission cost and vice versa). However, solutions may be obtained in which the fuel cost and emission are combined in a single function with a different weighting factor. This objective function is described by [5]:

$$\min F = \alpha \cdot F_{ec} + (1 - \alpha) \cdot F_{pc}, \tag{6}$$

where α is a weighting that satisfies $0 \leq \alpha \leq 1$. The boundary values $\alpha = 1$ and $\alpha = 0$ give the conditions for the pure minimization of the fuel cost function and the pure minimization of the pollution control level.

2.2. Types of equality constraints

While minimizing the objective function, it is necessary to make sure that the generation still supplies the load demands plus the losses in the transmission lines. The equality constraints are the power flow equations describing the bus-injected active and reactive powers of the ith bus.

Here, active and reactive power injections at bus i are defined in the following equations:

$$P_i = Pg_i - Pd_i = \sum_{j=1}^{nb} V_i V_j \left(g_{ij} \cos \theta_{ij} + b_{ij} \sin \theta_{ij} \right), \tag{7}$$

$$Q_i = Qg_i - Qd_i = \sum_{j=1}^{nb} V_i V_j \left(g_{ij} \sin \theta_{ij} - b_{ij} \cos \theta_{ij} \right), \tag{8}$$

where Qg_i is the reactive power generation at bus i; Pd_i and Qd_i are the real and reactive power demands at bus i; V_i and V_j are the voltage magnitudes at bus i and j, respectively; θ_{ij} is the admittance angle; b_{ij} and g_{ij} are the real and imaginary parts of the admittance; and nb is the total number of buses.

2.3. Types of inequality constraints

The inequality constraints of the OPF reflect the limits on the physical devices in the power system, as well as the limits created to ensure the system's security. The most usual types of inequality constraints are the upper bus voltage limits at the generations and load buses, lower bus voltage limits at the load buses, VAR limits at the generation buses, maximum active power limits corresponding to the lower limits at some generators, maximum line loading limits, and limits on the transformer tap setting.

The inequality constraints on the problem variables considered include:

- Upper and lower bounds on the active generations at the generator buses $Pg_i^{min} \leq Pg_i \leq Pg_i^{\max}, i = 1, ng$.

- Upper and lower bounds on the reactive power generations at generator buses $Qg_i^{min} \leq Qg_i \leq Qg_i^{\max}, i =$ *1, ng*.
- Upper and lower bounds on the reactive power injection at the buses with VAR compensation $Qc_i^{min} \leq Qc_i \leq Qc_i^{\max}, i =$ *1, nc*.
- Upper and lower bounds on the voltage magnitude at the all of the buses $V_i^{min} \leq V_i \leq V_i^{\max}, i =$ *1, nb*.
- Upper and lower bounds on the bus voltage phase angles $?_i^{min} \leq ?_i \leq ?_i^{\max}, i =$ *1, nb*.
- For secure operation, the transmission line loading S_l is restricted by its upper limit as $S_{li} \leq S_{li}^{\max}, i =$ *1, nl*, where S_{li} and $S_{li}^{\max}$ stand for the power of the transmission line and the limit of the transfer capacity of the transmission line, and *nl* is the number of transmission lines.

It can be seen that the generalized objective function F is nonlinear and the number of equality and inequality constraints increases with the size of the power distribution systems. Applications of a conventional optimization technique, such as the gradient-based algorithms, to a large power distribution system with very nonlinear objective functions and a great number of constraints are not good enough to solve this problem, because it depends on the existence of the first and second derivatives of the objective function and on the efficient computing of these derivatives in a large search space.

3. Overview of the ABC algorithm

The ABC algorithm is one of the most recently defined algorithms, motivated by the intelligent behavior of honeybees. The ABC algorithm as an optimization tool provides a population-based search procedure, in which individuals called food positions are modified by the artificial bees with time and the bee's aim is to discover the locations of food sources with a high nectar amount and, finally, the one with the highest nectar amount.

In the ABC algorithm, the colony of artificial bees contains 3 groups of bees: employed bees, onlookers, and scouts. A bee waiting on the dance area to make a decision about choosing a food source is called an onlooker and a bee going to a food source visited by it previously is called an employed bee. A bee carrying out a random search is called a scout. In the ABC algorithm, the first half of the colony consists of employed artificial bees and the second half constitutes the onlookers. For every food source, there is only one employed bee. In other words, the number of employed bees is equal to the number of food sources around the hive. The employed bee whose food source is exhausted by the employed and onlooker bees becomes a scout [12,13].

4. Application of the ABC algorithm on the OPF problem

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 associated solution. The number of employed bees is equal to the number of food sources, each of which also represents a site being exploited at the moment, or to the number of solutions in the population. In ABC optimization, the steps given below are repeated until a stopping criterion is satisfied [4].

The following steps describe how the ABC algorithm is applied to the problem under consideration:

Step 1: Input data.

Line data, bus data, generator cost coefficients, and generation limits for each unit are read.

Step 2: Initialization of parameter setup.

The 5 control parameters used in the ABC algorithm, i.e. the colony size, number of employed bees, number of unemployed bees or onlooker bees, value of *limit* initialized, and number of cycles for foraging {a stopping criteria, maxCycle} .

Step 3: Initialization of population with random solutions.

In this step, an initial population of N solutions is generated randomly, where N denotes the size of the employed bees, which is equal to the number of food source positions. Each solution $x_i = (i = 1, 2........N)$ is represented by a D-dimensional vector, where D is the number of parameters to be optimized and each parameter is real-coded.

Step 4: Evaluation of the fitness of the population.

Evaluate the fitness value for each employed bee using the following the formula:

$$fitness = 1/\left(1 + F_i\right), \tag{9}$$

where F_i is the cost value of the objective function.

Step 5: Modification of position by employed bees.

An employed bee produces a modification on the position (solution) in her memory depending on the local information (visual information) and tests the nectar amount (fitness value) of the new source (new solution). In order to produce a candidate food position from the old one in memory, the following equation is used:

$$V_{ij} = x_{kj}. + \Phi_{ij}\left(x_{ij} - x_{kj}\right), \tag{10}$$

where $k \in \{1, 2........, N\}$ and $j \in \{1, 2........, D\}$ are randomly chosen indexes (D is the number of parameters to be optimized and each parameter is real-coded), and although K is determined randomly, it has to be different from i. Φ_{ij} is a random number in [–1, 1]. If the resulting value falls outside of the acceptable range for parameter j, it is set to the corresponding extreme value in that range.

Step 6: Select sites for the neighborhood search.

Bees that have the highest fitness are chosen as the selected bees and sites visited by them are chosen for the neighborhood search.

Step 7: Recruit onlooker bees for the selected sites and evaluate the fitness.

If the nectar amount of the new position is higher than that of the previous one, the bee memorizes the new position and forgets the old one. Otherwise, the position of the previous one is kept in memory. After all employed bees complete the search process, they share the nectar information of the food sources and their position information with the onlooker bees in the dance area. An onlooker bee evaluates the nectar information taken from all of the employed bees and chooses a food source, where the probability Pi of selecting a food source i is determined using the following expression:

$$Pi = Fit_i / \sum_{n=1}^{S_N} Fit_n, \tag{11}$$

where Fit_i is the fitness of the solution and is represented by the food sources i, and S_N is the total number of food sources.

Step 8: Modification of the position by the onlookers.

As in the case of the employed bee, the onlooker produces a modification on the position in its memory using Eq. (16) and checks the nectar amount of the candidate source. If the new food has equal or better nectar than the old source, it is replaced with the old one in the bee's memory. Otherwise, the old one is retained in the memory.

Step 9: Abandon sources exploited by the bees.

Determine the abandoned solution, if it exists, and replace it with a new randomly produced solution xi for the scout bees using the following equation:

$$x_{ij} = x_{j\,\min} + rand\,(0,1) * (x_{j\,\max} - \ x_{j\,\min})\,,$$

where $x_{j\,\min}$ and $x_{j\,\max}$ are the minimum and maximum limits of the parameter to be optimized.

Step 10: Memorize the best solution achieved so far.

Step 11: Cycle = cycle + 1.

Step 12: Stop the process if the termination criterion is satisfied. Otherwise, go to Step 5.

5. Application study

The OPF using the ABC method has been developed by the use of MATLAB 7, tested on a Pentium 4 with 1.5 GHz and 128 MO, and consistently acceptable results were observed. The IEEE 30-bus system with 6 generators is presented here. The total load was 283.4 MW. The upper and lower active power generating limits and the unit costs of all of the generators of the IEEE 30-bus test system are presented in Table 1. The NO_x emission characteristics of generators are grouped in Table 2. The emission control cost factor for IEEE 30-bus system was taken as 550.66 $/t [5].

Table 1. Power generation limits and cost coefficients for IEEE 30-bus system.

Bus	$Pg_{\min}$(MW)	$Pg_{\max}$ (MW)	a ($/h)	b ($/MW h)	c. 10^{-4} ($/MW^2 h)
1	50.00	200.00	0	2.00	037.5
2	20.00	080.00	0	1.75	175.0
5	15.00	050.00	0	1.00	625.0
8	10.00	035.00	0	3.25	083.0
11	10.00	030.00	0	3.00	250.0
13	12.00	040.00	0	3.00	250.0

Table 2. Pollution coefficients for the IEEE 30-bus system.

Bus	a. 10^{-2}	b. 10^{-4}	c. 10^{-6}	d. 10^{-4}	e. 10^{-2}
1	4.091	–5.554	6.490	02.00	2.857
2	2.543	–6.047	5.638	05.00	3.333
5	4.258	–5.094	4.586	00.01	8.000
8	5.326	–3.550	3.380	20.00	2.000
11	4.258	–5.094	4.586	00.01	8.000
13	6.131	–5.555	5.151	10.00	6.667

The results, including the generation cost, the emission level, and power losses, are shown in Table 3, where the optimum generations for the minimum total cost in 3 cases is given: the minimum generation cost without taking into account the emission level as the objective function ($\alpha = 1$), an equal influence of the generation cost and pollution control in this function, and, finally, a total minimum emission is taken as the objective of main concern ($\alpha = 0$). The active powers of the 6 generators as shown in Table 3 are all within their allowable limits. We can observe that the total cost of the generation and pollution control is the highest at the minimum emission level ($\alpha = 0$), with the lowest real power loss (3.8912 MW). As seen by the optimal results shown in Table 3, there is a trade-off between the fuel cost minimum and the emission level minimum. The difference in the generation cost between these 2 cases (802.1649 \$/h compared to 935.275 \$/h) in the real power loss (9.7286 MW compared to 3.8912 MW) and in the emission level (0.3781 t/h compared to 0.2176 t/h) clearly shows this trade-off. To decrease the generation cost, one has to sacrifice some of the environmental constraints. The minimum total cost at $\alpha = 0.5$ is of the order of 969.511 \$/h. The security constraints are also checked for the voltage magnitudes, angles, and branch flows. The voltage magnitudes and the angles are between their minimum and maximum values. The results, including the voltage magnitude of the different values of α, are shown in Figure 1. The transmission line loadings do not exceed their upper limits. In addition, it is important to point out that this algorithm converges in an acceptable time, where for this test system, it was approximately 8 s.

Table 3. Results of minimum total cost for IEEE 30-bus system in 3 cases ($\alpha = 1$, $\alpha = 0.5$, and $\alpha = 0$) by ABC.

Variable	Generation cost min.	Gen. cost + emission min.	Emission min.
Pg_{01} (MW)	180.5218	130.3310	68.3474
Pg_{02} (MW)	48.7845	58.2344	71.0885
Pg_{05} (MW)	21.2598	26.2496	50.0000
Pg_{08} (MW)	18.6469	35.0000	35.0000
Pg_{11} (MW)	11.8145	21.3800	30.0000
Pg_{13} (MW)	12.1011	18.9294	32.8553
Production cost (\$/h)	802.1649	820.1666	935.275
Emission (t/h)	0.3781	0.2712	0.2176
Total cost (\$/h)	1010,4	969.511	1055.10
Power loss (MW)	9.7286	6.7256	3.8912
$\Sigma\|Vi - Vref\|$	0.4403	0.3596	0.3773

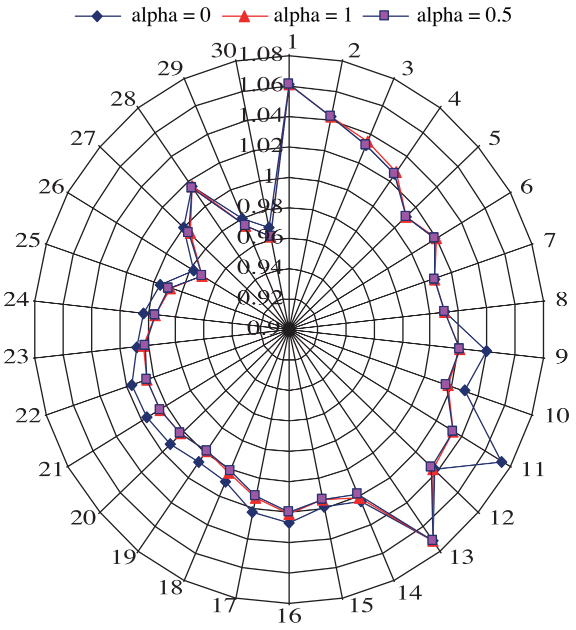

Figure 1. The results of voltage magnitude by different values of α (alpha = 0, alpha = 0.5, and alpha = 1).

5.1. Comparison of the ABC algorithm with the global method (PSO)

A comparison of results between the ABC method and PSO is shown in Table 4, where it can be observed that the proposed method can find the optimum value when compared with PSO [14].

Table 4. Comparison between ABC and PSO applied to OPF for IEEE-30 bus system.

	Generation cost minimum		Generation cost + emission minimum		Emission minimum	
	ABC	PSO	ABC	PSO	ABC	PSO
Generation cost ($/h)	802.1649	802.377	820.1666	822.092	935.275	948.399
Emission (t/h)	0.3781	0.372	0.2712	0.268	0.2176	0.218
Total cost ($/h)	1010.4	1007.577	969.511	969.845	1055.10	1068.854

5.2. Comparison with PSAT and MATPOWER OPF solver

For the purpose of verifying the robustness of the proposed algorithm, we made a second comparison with the Power System Analysis Toolbox (PSAT) and MATPOWER packages under severe loading conditions.

PSAT is a MATLAB toolbox for electric power system analysis and the control was designed by Vanfretti and Milano [15]. A robust method known as the interior point was integrated into PSAT to resolve the OPF problem.

MATPOWER is a package of MATLAB M-files for solving power flow and OPF problems. MATPOWER was developed by Zimmerman et al. [16]. The default OPF solver of the MATPOWER package is a high-performance primal-dual interior point solver implemented in pure MATLAB code.

In this study, the increase in the load is regarded as a parameter that affects the power system to the point of voltage collapse.

$$P_L = Kld \cdot P_{L0}$$
$$Q_L = Kld \cdot Q_{L0}$$

Here, P_{Lo} and Q_{Lo} are the active and reactive base loads, P_L and P_L are the active and reactive loads for the current operating point, and *Kld* represents the loading factor.

The results, including the generation cost, power losses, reactive power generation, and angles, are shown in Table 5. We can clearly observe that the total cost of the generation and the power losses are comparable to the results obtained by PSAT and MATPOWER at both loading factors (*Kld* = 18% and *Kld* = 32%). For example, at loading factor 32% (PD = 374.088), the difference in the generation cost between the ABC algorithm and the 2 packages was 1160.73 $/h compared to 1160.56 $/h and 1164.1706 $/h, and in real power loss it was 13.5558 MW compared to 13.556 MW and 14.385 MW, as obtained from MATPOWER and PSAT, respectively. At loading factor *Kld* = 48%, the 2 simulation packages (PSAT and MATPOWER) did not converge. The ABC algorithm proposed gives an acceptable solution and the minimum total cost is 1401.4 $/h. The security constraints are also checked for the voltage magnitudes, angles, and branch flows at the 3 loading factors (*Kld* = 18%, *Kld* = 32%, and *Kld* = 48%). Figure 2 shows that the voltage magnitudes are within the specified security limits. Figure 3 shows clearly that the voltage angles of the buses do not exceed their upper limits.

Table 5. Results of the minimum cost compared with PSAT and MATPOWER package for IEEE 30-bus.

Variable	ABC	MATPOWER	PSAT	ABC	MATPOWER	PSAT	ABC
	(Kld = 18%)	(Kld = 18%)	(Kld = 18%)	(Kld = 18%)	(Kld = 18%)	(Kld = 18%)	(Kld = 18%)
P1 (MW)	199.6521	200.00	200.00	199.6683	200.0	200.0	199.0635
P2 (MW)	55.8103	55.00	54.9925	70.4857	69.74	69.9368	80.0000
P5 (MW)	23.4431	23.70	23.6957	28.1711	28.40	28.5135	50.0000
P9 (MW)	35.0000	35.00	35.00	35.0000	35.00	35.00	35.0000
P11 (MW)	16.8175	17.01	17.0154	28.3793	28.03	28.2596	30.0000
P13 (MW)	15.8480	15.84	15.8827	25.9394	26.47	26.7635	40.0000
Q1 (MVAR)	–21.33	–13.94	–15.6226	–21.86	–17.66	–9.4127	3.17
Q2 (MVAR)	36.94	37.18	38.5416	49.73	43.69	60.4752	39.04
Q5 (MVAR)	36.87	36.10	36.5254	32.93	42.62	49.5412	40.76
Q8 (MVAR)	37.87	47.96	49.525	51.05	60.00	50.00	50.45
Q11 (MVAR)	25.96	3.680	4.6425	29.57	6.910	21.1631	34.78
Q13 (MVAR)	36.43	–11.68	2.3642	35.97	–2.270	19.7389	37.23
$\theta1$ (deg)	0	0.00	0.00	0	0.00	0.00	0
$\theta2$ (deg)	–4.1603	–4.028	–4.0412	–4.1630	–4.022	–4.026	–3.9513
$\theta5$ (deg)	–12.0129	–11.841	–11.8475	–12.6984	–12.518	–12.6009	–12.4762
$\theta8$(deg)	–9.0074	–8.737	–8.7607	–9.3179	–9.065	–8.7792	–9.5664
$\theta11$ (deg)	–9.2959	8.931	–8.9022	–7.8262	–7.386	–7.0128	–7.8312
$\theta13$ (deg)	–11.0262	–10.642	–10.6419	–10.1305	–9.751	–9.8547	–8.7472
Ploss (MW)	12.1590	12.141	12.174	13.5558	13.556	14.385	14.3430
cost ($/h)	994.0151	993.98	994.1047	1160.73	1160.56	1164.1706	1401.4

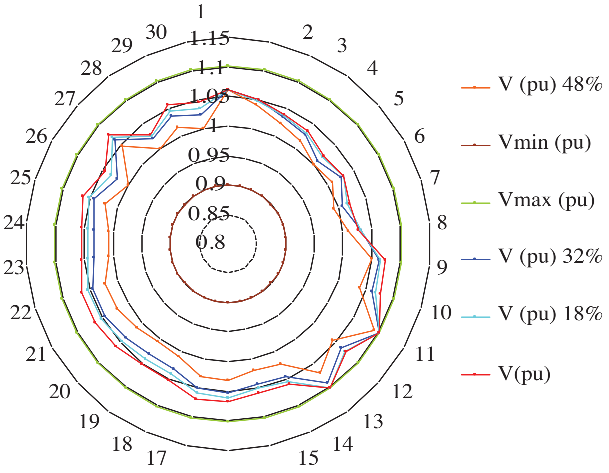

Figure 2. The results of voltage magnitude at the 3 loading factors (Kld = 18%, 32%, and 48%).

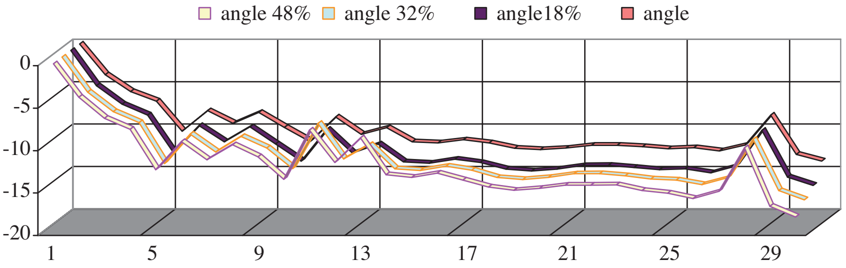

Figure 3. The results of voltage angles at the 3 loading factors (Kld = 18%, 32%, and 48%).

5.3. Application to the 59-bus Algerian network

To verify the proposed approach and for comparison purposes, we perform simulations on a part of the 59-bus Algerian network (Figure 4). It consists of 59 buses, 83 branches (lines and transformers), and 10 generators.

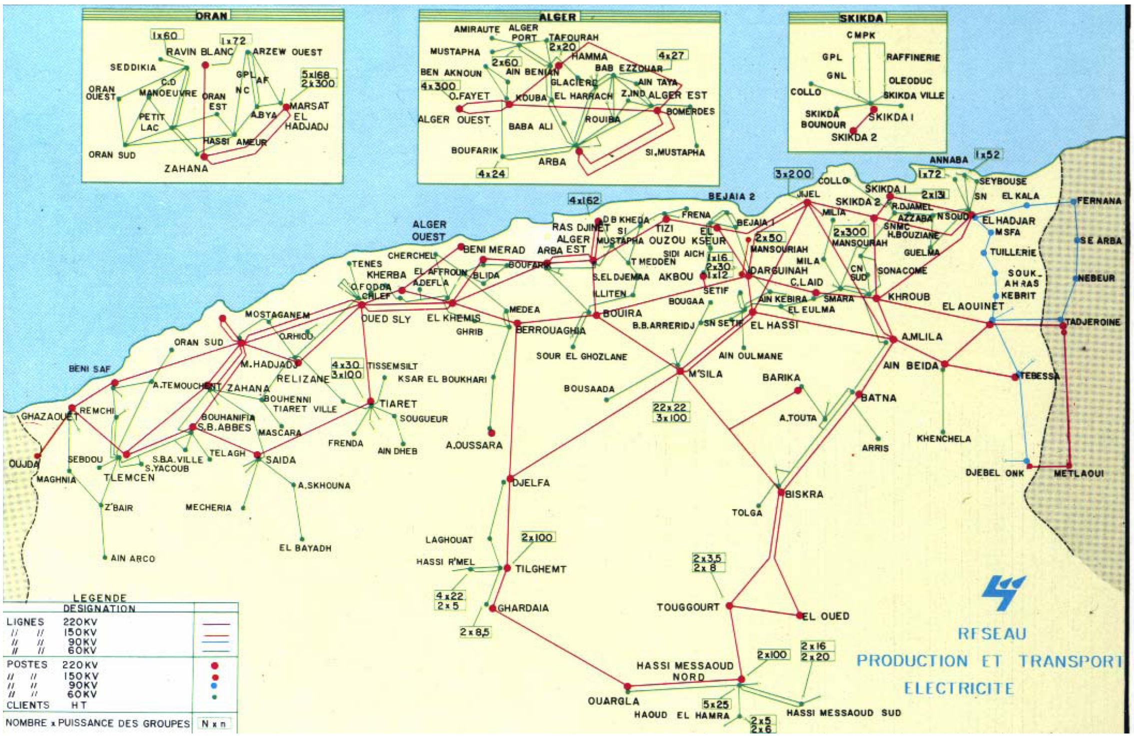

Figure 4. Topology of the Algerian production and transmission network before 1997.

Table 6 shows the technical and economic parameters of the 10 generators of the Algerian electrical network, knowing that the generator of the bus No. 13 is not in service.

Table 6. Power generation limits and cost coefficients for the Algerian network.

Bus number	P_{min} (MW)	P_{max} (MW)	a ($/h)	b ($/MWh)	c ($/MW^2 h)
1	8	72	0	1.50	0.0085
2	10	70	0	2.50	0.0170
3	30	510	0	1.50	0.0085
4	20	400	0	1.50	0.0085
13	15	150	0	2.50	0.0170
27	10	100	0	2.50	0.0170
37	10	100	0	2.00	0.0030
41	15	140	0	2.00	0.0030
42	18	175	0	2.00	0.0030
53	30	450	0	1.50	0.0085

The comparisons of the results obtained by the proposed approach (ABC) with those found by the ACO algorithm [6] and a fuzzy-controlled GA [7] are reported in Table 7. The results obtained with the proposed approach are better than those obtained by the fuzzy GA (FGA) and ACO. The ABC method gives a more important profit in the fuel cost of 1703.80 $/h compared to the results obtained from the FGA (1768.50 $/h) and ACO (1815.76 $/h). The optimum value has been obtained at a reduced execution time. The optimum value of 1768.50 $/h has been obtained after 10 s. This value takes into account the exact cost of the total real power losses by proceeding to a Newton–Raphson type of power flow calculation in order to compute the reactive generated powers and the voltages of all the buses, and to readjust the slack generator that takes into consideration the exact losses of real powers. It is important to note that none of the results obtained by the proposed approach violate the physical generation capacity constraints. The security constraints are satisfied for the voltage magnitudes ($0.9 < V < 1.1$ pu) and line flows.

Table 7. Comparison of the results obtained with conventional and global methods for the Algerian electrical network.

	FGA	ABC	ACO
Pg1 (MW)	11.193	62.1194	64.01
Pg2 (MW)	24.000	23.8331	22.75
Pg3 (MW)	101.70	102.1578	82.37
Pg4 (MW)	84.160	114.3495	46.21
Pg13 (MW)	0.000	0.00	0.00
Pg27 (MW)	35.22	24.7478	47.05
Pg37 (MW)	56.80	50.6371	65.56
Pg41 (MW)	121.38	99.9633	39.55
Pg42 (MW)	165.520	132.1497	154.23
Pg53 (MW)	117.32	106.2719	202.36
PD (MW)	684.10	684.1	684.1
Ploss (MW)	33.1930	31.1785	39.98
Cost ($/h)	1768.50	1703.8	1815.7
Time (s)	-	10	25

6. Conclusion

In this paper, ABC optimization has been presented and applied to the economic power dispatch of a power system with pollution control where minimization of cost occurs. The feasibility of the proposed method for the economic power dispatch of a power system with pollution control is demonstrated on the IEEE 30-bus system. The simulation results show that the ABC method is able to minimize the total cost along with the minimization of loss in the system. Moreover, it is found that the results of the ABC are better than those obtained using PSO. The proposed approach has shown better results in terms of convergence, flexibility, and consistency in different runs and a lower generation cost compared to the PSAT and MATPOWER OPF solver. The performance of the proposed approach was tested on the Algerian 59-bus test case with 59 buses, 83 branches (lines and transformers), and 10 generators. When the proposed algorithm was compared with the conventional method and with recent evolutionary algorithms (ACO, FGA), it was found that the proposed approach can converge at near solutions and obtain a competitive solution at a reduced time.

References

[1] A. Momoh, M.E. El-Hawary, R. Adapa, "A review of selected optimal power flow literature to 1993. Part I: Nonlinear and quadratic programming approaches", IEEE Transactions on Power Systems, Vol. 14, pp. 96–104, 1999.

[2] A. Momoh, M.E. El-Hawary, R. Adapa, "A review of selected optimal power flow literature to 1993. Part II: Newton, linear programming and interior point methods", IEEE Transactions on Power Systems, Vol. 14, pp. 105–111, 1999.

[3] H.W. Dommel, W.F. Tinney, "Optimal power flow solutions", IEEE Transactions on Power Apparatus and Systems, Vol. 87, pp. 1866–1876, 1968.

[4] T. Bouktir, M. Belkacemi, "Object-oriented optimal power flow", Electric Power Components and Systems, Vol. 31, pp. 525–534, 2003.

[5] T. Bouktir, R. Labdani, L. Slimani, "Economic power dispatch of power system with pollution control using multiobjective particle swarm optimization", Journal of Pure and Applied Sciences, Vol. 4, pp. 57–77, 2007

[6] T. Bouktir, L. Slimani, "Optimal power flow of the Algerian electrical network using ant colony optimization method", 9th IASTED International Conference on Artificial Intelligence and Soft Computing, pp. 352–357, 2005

[7] B. Mahdad, T. Bouktir, K. Srairi, "Fuzzy controlled genetic algorithm for environmental/economic dispatch with shunt FACTS devices", IEEE/PES Transmission and Distribution Conference and Exposition, pp. 1–8, 2008.

[8] A.J. Wood, B.F. Wollenberg, Power Generation, Operation, and Control, 2nd ed., New York, Wiley, 1996.

[9] G.W. Stagg, A.H. El Abiad, Computer Methods in Power Systems Analysis, New York, McGraw-Hill, 1981.

[10] L. Slimani, T. Bouktir, "Economic power dispatch of power system with pollution control using multiobjective ant colony optimization", International Journal of Computational Intelligence Research, Vol. 3, pp. 145–153, 2007

[11] B. Mahdad, T. Bouktir, K. Srairi, "OPF with environmental constraints with multi shunt dynamic controllers using decomposed parallel GA: application to the Algerian network", Journal of Electrical Engineering and Technology, Vol. 4, pp. 55–65, 2009.

[12] D. Karaboga, B. Basturk, "Artificial bee colony (ABC) optimization algorithm for solving constrained optimization problems", Proceedings of the 12th International Fuzzy Systems Association World Congress on Foundations of Fuzzy Logic and Soft Computing, LNAI 4529, pp. 789–798, 2007.

[13] D. Karaboga, B. Basturk, "On the performance of artificial bee colony (ABC) algorithm", Applied Soft Computing, Vol. 8, pp. 687–697, 2007.

[14] B. Mahdad, K. Srairi, T. Bouktir, "Improved parallel PSO solution to economic dispatch with practical generator constraints", 15th IEEE Mediterranean Electrotechnical Conference, pp. 314–319, 2010.

[15] L. Vanfretti, F. Milano, "Experience with PSAT (Power System Analysis Toolbox) as free and open-source software for power system education and research", International Journal of Electrical Engineering Education, Vol. 47, pp. 47–62, 2010.

[16] R.D. Zimmerman, C.E. Murillo-Sánchez, R.J. Thomas, "MATPOWER steady-state operations, planning, analysis tools for power systems research and education", IEEE Transactions on Power Systems, Vol. 26, pp. 12–19, 2011.