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CUCKOO SEARCH ALGORITHM TO SOLVE THE PROBLEM OF ECONOMIC EMISSION DISPATCH WITH THE INCORPORATION OF FACTS DEVICES UNDER THE VALVE-POINT LOADING EFFECT

Larouci Benyekhlef [1*], Sitayeb Abdelkader[2], Boudjella Houari[1], Ayad Ahmed Nour El Islem[1]

[1]Department of Electrical Engineering, Faculty of Applied Sciences, University Kasdi Merbah Ouargla, Ouargla, Algeria,
[2]Applied Research Unit on Renewable Energies "URAER Ghardaia", Ghardaïa, Algeria

Abstract. *The essential objective of optimal power flow is to find a stable operating point which minimizes the cost of the production generators and its losses, and keeps the power system acceptable in terms of limits on the active and reactive powers of the generators. In this paper, we propose the nature-inspired Cuckoo search algorithm (CSA) to solve economic/emission dispatch problems with the incorporation of FACTS devices under the valve-point loading effect (VPE). The proposed method is applied on different test systems cases to minimize the fuel cost and total emissions and to see the influence of the integration of FACTS devices. The obtained results confirm the efficiency and the robustness of the Cuckoo search algorithm compared to other optimization techniques published recently in the literature. In addition, the simulation results show the advantages of the proposed algorithm for optimizing the production fuel cost, total emissions and total losses in all transmission lines.*

Key words: *Combined economic emission dispatch, OPF, Cuckoo search algorithm, VPE, FACTS devices.*

1. INTRODUCTION

The production of electrical power is marked by several orientations as limiting the environmental impact of the generating and use of energy, increasing the energy efficiency of systems and developing low-cost production and minimizing gas emissions toxic in the atmosphere under the valve-point effect [1].

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Corresponding author: Larouci Benyekhlef
Department of Electrical Engineering, Faculty of Applied Sciences, University Kasdi Merbah Ouargla, Street Ghardaia, 30000, Ouargla, Algeria
E-mail: larouci.benyekhlef@univ-ouargla.dz

The impact of power plants on the environment has changed the way power grids are managed [2]. However, recent awareness of the toxic effects of gases emitted by fossil fuel power plants and the new stringent environmental laws imposed on power producers have led to the incorporation of environmental considerations into the methods that govern the production of electricity [3] so, the emissions and fuel cost must be considered simultaneously to provide the true measure of optimum production [4]. Currently, with the new energy market deregulation system [5], there is increased interest in FACTS (Flexible Alternative Current Transmission Systems) for the operation and control of power systems [6], this is due to the new load constraints and new contingencies. The installation of FACTS has become essential to increase the transmission capacity of the power system, reduce losses, and improve the safety and the controllability of an electrical network [7]. These FACTS devices are capable of changing network parameters quickly and efficiently to achieve better system performance [8].

The mathematical formulations of all the above tasks to be performed by power producers are therefore becoming more and more complex [9]. This growing complexity has led many researchers to turn to nature-inspired algorithms to solve these problems [10]. These algorithms are those developed by imitating natural phenomena and biological models [11-12]. They offer robust and competitive solutions.

The objectif of this article is to propose a nature-inspired algorithm known as Cuckoo search algorithm (CSA) [10], in order to provide the optimal solution to the optimal power flow problems. The proposed technique is applied on IEEE 30-bus system considering valve-point effect (VPE) with and without installing two FACTS devices (Static Var Compensator (SVC) and Statcom), to reach the lowest values of fuel cost, installation cost of FACTS devices, and to reduce toxic gas emissions. The statistical results are as compared with other algorithms existing in the recent literature.

The rest of this article is structured as follows: the definition and mathematically formulation of the OPF problem are offered in section 2, while section 3 addresses a brief description of the CSA. The simulation results are carefully studied and analyzed in section 4. Finally, conclusion and future suggestions are given in section 5.

2. Optimal Power Flow

The optimal power flow (OPF) was conceived as an extension of the conventional economic and emission dispatch [13-14]. The OPF problem is large-scale non-convex optimization problem, which may also have uncertain variables. In general, the OPF problem seeks to optimize the steady state performance of a power system in terms of an objective function while satisfying several equality and inequality constraints [15]. In contrast, OPF aims to optimize an objective function by finding optimal free variables while keeping the network constraints in their acceptable limits [16].

2.1. Mathematical model of economic dispatch

The cost of each generating unit is typically represented by fuel cost. Generator curves are generally represented as quadratic convex curves of second order function [17-18]. The total fuel cost function is formulated as follows:

$$F_i(P_{gi}) = a_i P_{gi}^2 + b_i P_{gi} + c_i \tag{1}$$

The coefficients a_i, b_i and c_i are numerically known.
The optimal functioning of a set of thermal production units can be seen by the model:

$$Minimize\, C_1\left(P_{gi}\right) = \sum_{i=1}^{N_g} \mathrm{F_i}(P_{gi}) \tag{2}$$

Where: N_g is the total number of generators on the system under the constraints of equality and inequality type.

2.1.1. Constraints

a. Equality constraint

These constraints are represented by nonlinear power flow equations [20]. The sum of the active and reactive generated powers in the network must be equal to the sum of the active and reactive powers consumed with transmission losses, this constraint is given by [21]:

$$P_{gi} - P_{di} - \sum_{j=1}^{Ng} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{3}$$

$$Q_{gi} - Q_{di} - \sum_{j=1}^{Ng} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{4}$$

b. Inequality constraints

These constraints represent the operating limits of the power system (Generator voltages, real and reactive power, transmission lines, transformers, FACTS, etc.) [22-23].

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \tag{5}$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \tag{6}$$

$$V_{ki}^{\min} \le V_{ki} \le V_{ki}^{\max} \tag{7}$$

$$S_{FACTS}^{\min} \le S_{FACTS} \le S_{FACTS}^{\max} \tag{8}$$

$$Q_{svc}^{\min} \le Q_{svc} \le Q_{svc}^{\max} \tag{9}$$

2.2. Mathematical model of economic dispatch with valve-point loading Effect

In some large generators, their cost functions are also non-linear, due to the effect of valve-point loading (VPE) [24]. This effect will increase several local minimum points in the cost function and make the problem more difficult. The fuel cost function with the effect of the valve-point loading can be expressed as follows [25]:

$$F_i(P_{gi}) = a_i P_{gi}^2 + b_i P_{gi} + c_i + \left| e_i \times \sin(f_i \times (P_{gi,\min} - P_{gi})) \right| \quad (10)$$

Where P_{gi} is the real power generation of unit i in (MW), e_i, and f_i are cost coefficients of i^{th} generator due to VPE.

Chiang in [26-28], presented a realistic economic dispatching problem by simultaneously considering the fuels cost and the effect of the valve-point loading to make the economical dispatching solution more precise.

2.3. Mathematical model of environmental dispatch

The total emission can be expressed as [29]:

$$E_i(P_{gi}) = \alpha_i P_{gi}^2 + \beta_i P_{gi} + \gamma_i \quad (11)$$

Where: The coefficients γ_i, β_i and α_i are NO_X emission coefficients numerically known [30].

2.4. Mathematical model of Combined Economic Emission Dispatch Problem

The study of economic-environmental dispatch consists of the simultaneous minimization of the two functions given by equations (1) and (11). We therefore transform the bi-objective optimization problem into a single-objective optimization problem, by introducing a price penalty factor [31]. This factor is defined as the ratio between the maximum cost and the maximum emissions of each generator [32]:

$$F_p = \frac{C(P_{gi}^{\max})}{E(P_{gi}^{\max})}\left(\frac{\$}{\text{Kg}}\right); \quad \text{i} = 1,2,\ldots\ldots,\text{Ng} \quad (12)$$

The steps to determine the price penalty factor specific for a given load are:
Determine the ratio of the maximum cost and the maximum emissions for each generator.
Rank the values of these factors in ascending order.
The sum of the maximum powers of each generator starting with the power of the plant with the lowest factor up to: $\sum_{i=1}^{Ng} P_{\text{gi}}^{\max} \geq P_D$

At this point, F_P tied to the last unit in the process and the price penalty factor for the given load. After determining this factor, we can represent the Economic-Environmental Dispatch function by the following equation [33-34]:

$$\psi(P_{gi}) = \sum_{i=1}^{N_g} (a_i P_{gi}^2 + b_i P_{gi} + c_i) + \sum_{i=1}^{N_g} F_p (\alpha_i P_{gi}^2 + \beta_i P_{gi} + \gamma_i) \quad (13)$$

Equation (14) can be rewritten as follows [35]:

$$\psi(P_{gi}) = \sum_{i=1}^{N_g} (C_i P_{gi}^2 + b_i P_{gi} + A_i) \quad (14)$$

With:

$$A_i = a_i + F_p.\alpha_i \,,\; B_i = b_i + F_p.\beta_i \,, \quad C_i = c_i + F_p.\gamma_i \qquad (15)$$

The minimization of this function is done by taking into account the type of the equality and inequality constraints.

2.5. OPF with cost function model of SVC devices

The cost of SVC device, was developed by the manufacturer Siemens. The cost function of the SVC in ($/KVar) is as follows [36]:

$$C1_{svc} = 0.0003S_{SVC}^2 - 0.3051S_{SVC} + 127.38 \qquad (16)$$

Where: S_{SVC} is reactive power of SVC in MVar. The formulation of the optimal choice problem of SVC locations can be expressed as follows [37-38]:

$$Min\ C_{Total} = C_1\left(P_{gi}\right) + C_2\left(f\right) \qquad (17)$$

$$E_1(f,g) = 0 \qquad (18)$$

$$B_1(f) \succ 0 \;,\; B_2(g) \succ 0 \qquad (19)$$

C_{Total}: the total objective function comprising the SVC investment cost and the cost of production.

$F_i\,(P_{gi})$: the generator cost function given by equation (1).

$C_1\,(f)$: the investment cost function of SVC given by the equations (16) and (17).

E_1: represents the power flow equations.

B_1, B_2: are the inequality constraints of the SVC and the optimal power flow, respectively. f, P_{gi} : represent the variables parameters of the SVC and the powers supplied by the alternators.

The fuel cost is expressed in ($/hour) while the investment costs of FACTS are expressed in ($). These must be expressed in $/hour. Normally FACTS are designed to be in service for several years [39]. However, they are only used for a portion of their lifetimes for power flow control. In this research, three years are used to estimate the average cost of FACTS, i.e. the depreciation (from a financial view point) of FACTS is estimated at three years [40]:

$$C_1(f) = \frac{c(f)}{8760 \times 3} \quad (\$/\text{Hour}) \qquad (20)$$

Where: $C(f)$ is the investment cost of SVC.

The SVC device, is composed of a capacitor, which is the VAR generator, and a TCR (Thyristor Controlled Reactor), which behaves as a variable VAR absorbing load (depending on the firing angle of the Thyristor valve) [41]. Thus, the SVC can inject or absorb a variable amount of reactive power to the power system, adapting the compensation to the load conditions at each instant (see Fig.1) [42].

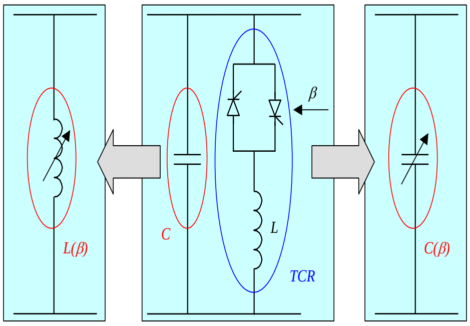

Fig. 1 Static VAR compensator configuration.

2.5.1. OPF with model and mathematical analysis of STATCOM

A static synchronous compensator (STATCOM), also known as a static synchronous condenser [43] is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. It is inherently modular and electable. STATCOM is modelled as a controllable voltage source (Ep) in series with impedance [43]. The real part of this impedance represents the copper losses of the coupling transformer and converter, while the imaginary part of this impedance represents the leakage reactance of the coupling transformer. STATCOM absorbs requisite amount of reactive power from the grid to keep the bus voltage within reasonable range for all power system loading. Fig. 2 shows the circuit model of a STATCOM connected to the i^{th} bus of a power system.

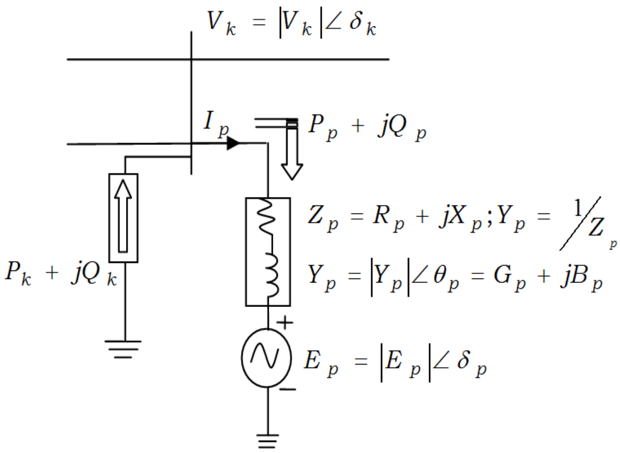

Fig. 2 Schematic static model of STATCOM

The injected active and reactive power flow equation of the i^{th} bus are given below:

$$P_p = G_p \left|V_k^2\right| - \left|V_k\right| \left|E_k\right| \left|Y_p\right| \cos(\delta_k - \delta_p - \theta_p) + \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \tag{21}$$

$$Q_p = -B_p \left|V_k^2\right| - \left|V_k\right| \left|E_p\right| \left|Y_p\right| \sin(\delta_k - \delta_p - \theta_p) + \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \tag{22}$$

The implementation of STATCOM in transmission system introduces two state variables ($|E_p|$ and δ_p); however, $|V_k|$ is known for STATCOM connected bus.

3. Cuckoo Search Algorithms

The Cuckoo Search Algorithm (CSA) is one of the newer nature-inspired metaheuristic algorithms developed by Xin-She Yang and Suash Deb in 2009 [10], [44]. CSA is a population-based search method that is used as a tool for optimization to solve complex, nonlinear and non-convex optimization problems.

The algorithm of CSA uses three idealized rules [45]:

(a) Each cuckoo lays an egg Place them in time and randomly chosen nest.

(b) The best nest with high quality eggs is passed on to the next generation.

(c) The number of available host nests is fixed and a host bird can discover an exotic egg with a conversation of pa э [0, 1]. In this case, the host bird can either drop the egg or leave the nest to build a brand new nest in a new location.

The CS method's key steps can be described as [46-47]:

1. Select the value of the CSA parameter, which is the number of nests (eggs) (n), step size parameter (β), probability of discovering (pa), and maximum number of iterations to end the cycle.
2. Randomly generate an initial population of n host nests $\{x_i\},(i=1,2,....,n)$. Each nest represents a possible solution to an optimization problem using objective functions $f(x)$ and decision variables $\{x_i\}=\{x_1,x_2,...,x_m\}^T$.
3. Use Levy Flights to get a cuckoo randomly and evaluate its fitness F_i.

$$x_i^{v+1} = x_i^{v} + \beta.\lambda \tag{23}$$

Where λ is a random walk based on Levy flight ($1 < \lambda \le 3$).

4. Randomly choose a nest among *n* (say *j*) and evaluate its fitness F_j.

If $F_j < F_i$, replace *j* with the new solution.

5. Abandon a fraction of the worst nests behind and create new ones. This is done depending on the probability parameter (*pa*). First, check whether each nest maintains its current position (equation (24)). The matrix R stores the values 0 and 1 so that each of them can be assigned to any component of the ith nest. 0 means that the current position is kept and 1 means that the current position is updated.

$$R_i \longleftarrow \begin{cases} 1 & if \quad rand \langle pa \\ 0 & if \quad rand \ge pa \end{cases} \tag{24}$$

The new nest is carried out by Eq. 25:

$$x_i^{t+1} = x_i^t + r \times R_i \times \left(perm1_i - perm2_i \right) \tag{25}$$

Where: r is a random number from 0 to 1. Perm1 and Perm2 are two row permutations of the corresponding nests. R defines a probability matrix.

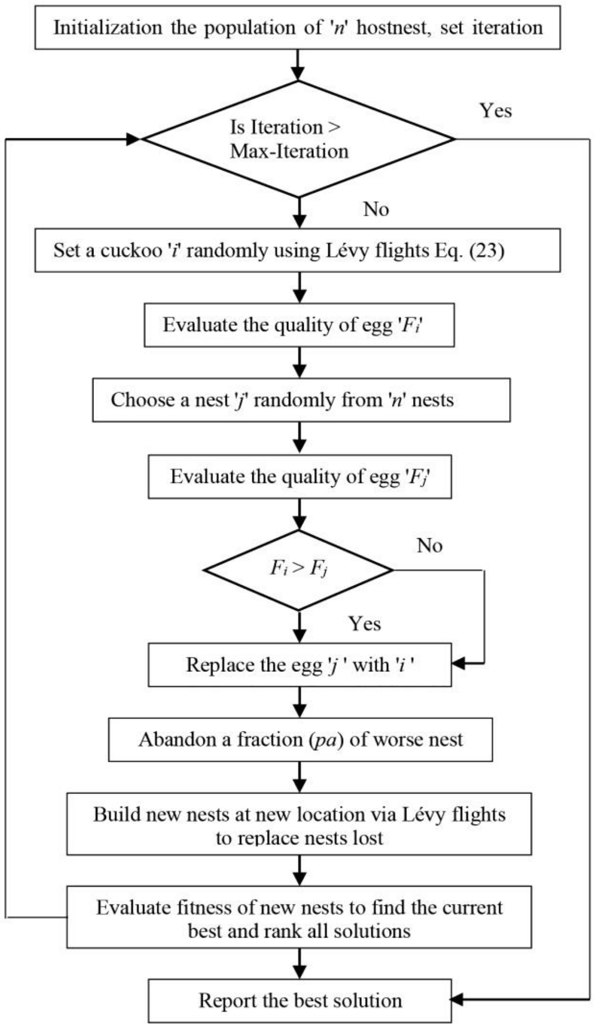

Fig. 3 A simplified flowchart of the CSA

6. Rank solutions and find the current best one.
7. Repeat steps 3-6 until completion criteria is satisfied, which are usually considered the maximum number of iterations.

A simplified flowchart of the CS algorithm is demonstrated in Fig. 3 [48]:

4. Numerical Results and Discussion

In this work, four cases of OPF problem are studied; the proposed algorithm is applied on standard IEEE 30-bus system considering VPE in presence of two FACTS devices, SVC and Statcom, in order to solve the optimal power flow and solving the combined economic emission dispatch problem. The single-line diagram of which is illustrated by the Fig. 4. All the cases studies are executed in MATLAB 2017 under windows 8.1 on Intel Core(TM) i5-3110 CPU 2.40 GHz, with 4 GB RAM.

Table 1 and Table 2 groups the values of the coefficients of the cost an emission functions of the 06 generators, and the limit powers Pmax and Pmin. The cost functions of generators 1 and 2 are obtained based on the ripple curve; this curve contains a higher order of non-linearity and discontinuity due to the valve-point effect.
The cost coefficients of these units are given in Table 1.

The parameters of the Cuckoo search algorithm are:

- Maximum number of iterations (K_{max}) is 100.
- The rate of discovery of eggs (pa) / solutions is 0.25.
- The number of nests is 70.

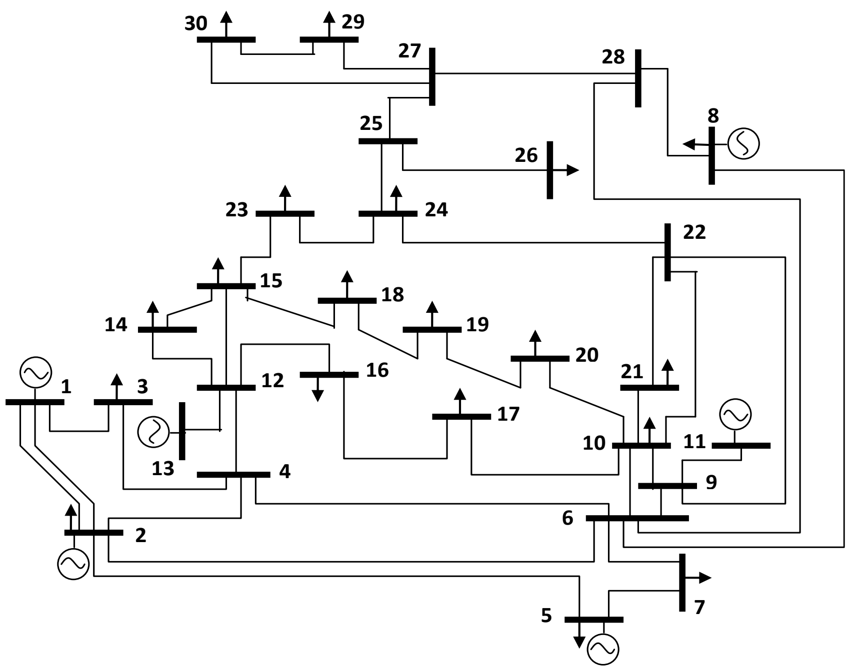

Fig. 4 IEEE 30 bus system structure

Table 1 Cost coefficients of generators for IEEE 30-bus system

Bus	Pmin (MW)	Pmax (MW)	c_i (\$/h)	b_i (\$/MWh)	a_i (\$/MW²h)	d_i (\$/MWh)	e_i (\$/MW²h)
1	50	200	150	2	0.0016	50	0.0630
2	20	80	25	2.5	0.0100	40	0.0980
5	15	50	0	1.00	0.0625	/	/
8	10	35	0	3.25	0.00834	/	/
11	10	30	0	3.00	0.025	/	/
13	12	40	0	3.00	0.025	/	/

The coefficients of the gas emission function are shown in Table 2.

Table 2 Emission coefficients of generators for IEEE 30-bus system

Node	γ_i (\$/h)	β_i (\$/MWh)	α_i (\$/MW²h)
1	22.983	-1.1000	0.0126
2	25.313	-0.1000	0.0200
5	25.505	-0.0100	0.0270
8	24.900	-0.0050	0.0291
11	24.700	-0.0040	0.0290
13	25.300	-0.0055	0.0271

4.1. Case 1: Optimal Power Flow (OPF)

An optimal power flow program with the valve-point loading effect based on the Newton-Raphson method, to determine the voltages at the different bus, the generated powers and the transmission losses. The results obtained for case1 are shown in Table 3.

Table 3 Optimal Power Flow Results

Bus	V	Angle	Injection		Generation		Load	
No	p.u	Deg	MW	Mvar	MW	Mvar	MW	Mvar
1	1.06	0	200.00	-7.157	200	-7.157	0	0
2	1.043	-4.141	-1.7	26.044	20	38.744	21.7	12.7
5	1.01	-10.6513	-73.418	7.276	20.782	26.276	94.2	19
8	1.01	-7.9854	-6.254	-15.163	23.746	14.837	30	30
11	1.082	-8.0311	15.419	15.324	15.419	15.324	0	0
13	1.071	-9.66	13.613	8.157	13.613	8.157	0	0
Total			10.266	-6.720	293.566	119.48	283.400	126.20

Comparisons of our results with those obtained by other methods are grouped in Tables 4. The results show that the CS-OPF algorithm gives a better result compared to other methods reported in the literature. The total cost found by the CSA small compared with those found by the methods GA, PSO, FPSO and GA-MGA which are of the order of 923.07\$/h, 928.56 \$/h, 923.72\$/h, 923.54\$/h and 922.77 \$/h respectively. The cost ranges from 0.1-0.71% in relation to the values obtained by the CS OPF algorithm.

Table 4 Optimal output power for IEEE 30-bus system with different algorithms

Variable	CS OPF	GA [49]	MGA [49]	PSO [49]	FPSO [49]	GA-MGA [49]
Pg1 (MW)	200.00	199.34	199.66	199.78	199.78	199.73
Pg2 (MW)	20.00	20.03	20.14	20.24	20.00	20.00
Pg3 (MW)	20.78	23.13	18.70	21.60	25.42	18.49
Pg4 (MW)	23.74	22.78	17.18	19.91	22.43	24.29
Pg5 (MW)	15.41	13.97	10.31	14.22	13.37	16.74
Pg6(MW)	13.61	14.56	27.77	18.13	12.94	14.57
PG Total (MW)	293.56	293.81	293.76	293.88	293.94	293.82
Fuel cost ($/hr)	921.88	923.07	928.56	923.72	923.54	922.77
Losses (MW)	10.26	10.41	10.360	10.480	10.55	10.42

The value of the active losses found by CSA is of the order of 10,266 MW; it is smaller compared to those obtained by of GA, PSO, FPSO and GA-MGA techniques.

Figures 5, 6, 7 and 8 respectively, illustrates the variations of fuel cost, transmission losses, the generated powers and the values of the nodal voltages respectively.

These graphs clearly indicate that CSA converges rapidly to the optimal solution.

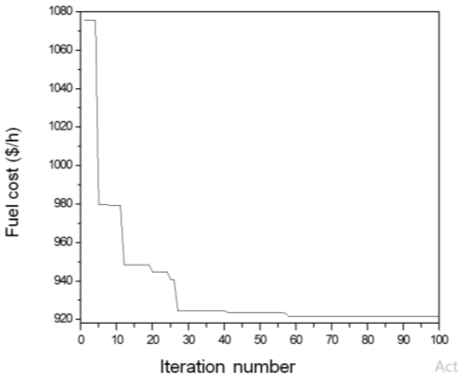

Fig. 5 Convergence of fuel cost

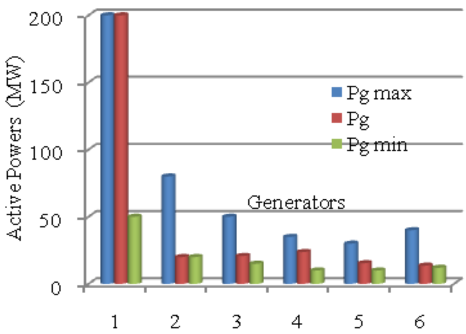

Fig. 6 Optimal values of the powers generated.

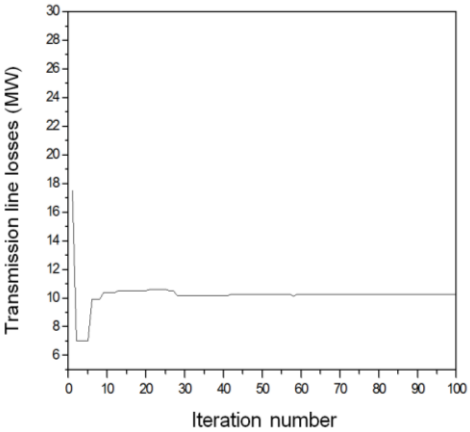

Fig. 7 Variation of active losses

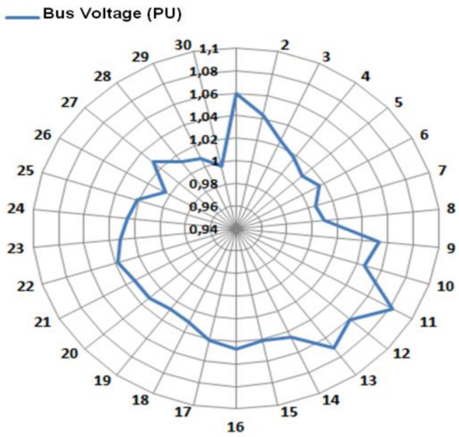

Fig. 8 Nodal voltage values

4.2. Case 2: Economic / environmental dispatch (with variable losses)

To demonstrate the effectiveness of the proposed approach, the combined economic environmental dispatch with the optimal power flow applied by introducing the price penalty factor is resolved. The transmission losses are variable depending on the generated power. The price penalty factors of each generator, are valued at 2.000, 1.9888, 2.2296, 2.0534, 2.2198 and 2.3378 ($/ton) respectively.

The optimal values of generated power, transmission losses, fuel cost, NOx emission and a comparison of our results with those obtained using the HSABC algorithm (Harvest Season Artificial Bee Colony) are given by the table 5.

For the case of economic dispatch (OPF), the value of the production cost is reduced to the minimum (921.88 $/h) and its value is better than that of economic / environmental dispatch (959.94 $/h) and environmental dispatch (1071.64 $/h).

For the case of environmental dispatch, the value of total emission is very low (295.92 Kg/h) compared to the combined economic environmental dispatch (336.98 Kg/h) and economic dispatch (457.43 Kg/h). According to table 5, it is clear that the gas emissions found by our algorithm (295.92 Kg/h) are lower compared to those found by the HSABC technique which are estimated at 309.84 (Kg/h). The total emission, are minimized by 13.92 (Kg/h).

Characteristics convergence of fuel cost, NOx emissions and total cost are depicted in Figures 9, 10, and 11 respectively. The graphs clearly indicate that CSA converges rapidly to the optimal solution.

Table 5 Economic-environmental dispatch with variable losses

Variable	Economic dispatch	Combined economic emission dispatch	Environmental dispatch	
	CS OPF	CS	HSABC [50]	CS
Pg1 (MW)	200.00	149.46	126.07	114.99
Pg2 (MW)	20.00	51.41	49.74	49.07
Pg3 (MW)	20.78	18.37	28.40	37.08
Pg4 (MW)	23.75	31.29	31.80	28.11
Pg5 (MW)	15.42	25.33	26.63	29.69
Pg6 (MW)	13.61	14.99	27.17	30.41
Total PG (MW)	293.56	290.85	289.81	289.36
Cost ($/hr)	921.88	959.95	1048.68	1071.64
Emission ($/hr)	457.43	336.98	309.84	295.92
Total Cost ($/hr)	/	1655.53	/	/
losses (MW)	10.26	7.783	6.41	5.40

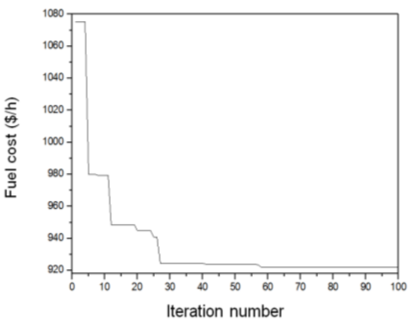

Fig. 9 Production cost

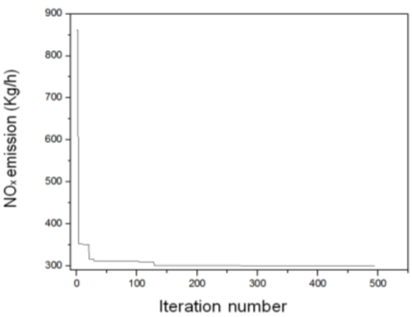

Fig. 10 NOx emissions

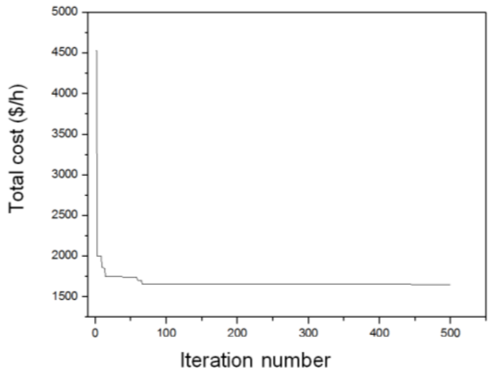

Fig. 11 Total cost

4.3. Case 3: OPF with the presence of SVC

To solving OPF problem with SVC device, the investment cost of SVC is integred in the power system. We are increasing the load from 283.40 MW to 383.40 MW, adding 100 MW at bus 20. The candidate bus at the location of the SVC is the bus where the voltage drop is important, so we have chosen bus 20 to install the SVC. The parameters of the SVC are grouped in table 6:

Table 6 SVC Parameters'

$Qsvc_{max}$ (MVar)	$Qsvc_{min}$ (MVar)	c ($/kVar)	b ($/kVar^2)	a ($/kVar^3)
100	-100	188.22	-0.2691	0.0003

The power flow in power system without and with installation of SVC, are reported in Tables 7 and 8 respectively. From Table 7, the voltage level at bus 20 (without SVC) is considered the lowest (0.8939 p.u) the voltage drop, it is lower than the minimum allowable value (10.61% < 5 %).

Table 7 Optimal Power Flow without SVC (P_{load} = 383.9 MW)

Bus	V	Angle	Injection		Generation		Load	
No	p.u	deg	MW	MVar	MW	MVar	MW	MVar
1	1.06	0.00	199.78	2.31	199.98	2.31	0.00	0.00
2	1.043	-3.70	58.30	28.59	80.00	41.29	21.70	12.70
5	1.01	-10.89	-65.72	12.69	28.48	31.69	94.20	19.00
8	1	-9.46	4.38	1.23	34.38	31.23	30.00	30.00
11	1.062	-11.28	27.02	23.71	27.02	23.71	0.00	0.00
13	1.071	-12.52	39.10	23.96	39.10	23.96	0.00	0.00
20	0.8939	-28.42	-102.20	-0.70	0.00	0.00	102.20	0.70
Total			25.36	51.29	408.76	177.49	383.40	126.20

The results obtained with CSA considering SVC device, are reported in Table 8.

Table 8 Optimal Power Flow with SVC.

Bus	V	Angle	Injection		Generation		Load	
No	p.u	deg	MW	MVar	MW	MVar	MW	MVar
1	1.06	0	200.00	-0.884	200.00	-0.884	0	0
2	1.043	-3.692	58.251	19.767	79.951	32.467	21.7	12.7
5	1.01	-10.75	-64.28	7.724	29.916	26.724	94.2	19
8	1.01	-9.591	4.966	4.719	34.966	34.719	30	30
11	1.082	-11.07	30	24.123	30	24.123	0	0
13	1.071	-13.28	32.222	14.397	32.222	14.397	0	0
20	0.95	-28.34	-102.2	16.908	0	17.608	102.2	0.7
Total			23.692	46.254	407.09	172.45	383.4	126.2

According to Table 8, it is remarkable that SVC device at bus 20 will be more effective in the bus with the greatest voltage drop. The installation of SVC significantly reduces the fuel cost, transmission losses and improve the level of voltages from 0.8939 to 0.95 p.u.

Table 9 Optimal results with and without SVC.

Variable	CS with SVC	CS without SVC
Pg1(MW)	200.00	199.98
Pg2(MW)	79.95	80
Pg5(MW)	29.91	28.48
Pg8(MW)	34.96	34.38
Pg11(MW)	30	27.02
Pg13(MW)	32.22	39.10
V1 (pu)	1.06	1.06
V2 (pu)	1.043	1.043
V5 (pu)	1.01	1.01
V8 (pu)	1.01	1
V11 (pu)	1.082	1.062
V13 (pu)	1.071	1.071
V20 (pu)	0.95	0.8939
Total PG (MW)	407.09	408.96
Losses (MW)	23.69	25.36
Qsvc (MVar)	2.696	/
Cost SVC $/KVar	187.49	/
Cost ($/hr)	1372.23	1375.49

From Table 9, the total cost (1372.23$/h) obtained by our algorithm with the location of SVC at bus 20 is lower compared to without SVC (1375.49$/h). The cost is minimized by 3.2581$/h. The transmission losses in this case are minimal (23.691 MW) compared to without installing SVC device (25.36 MW). They are reduced by 1.66 MW.

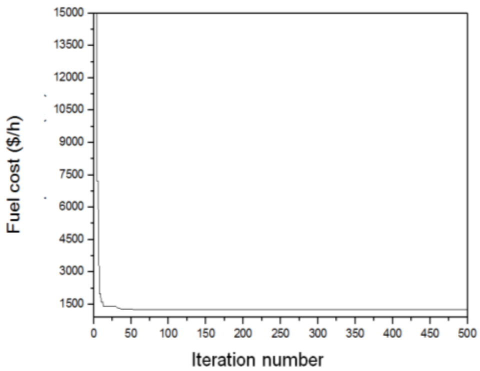

Fig. 12 Production cost

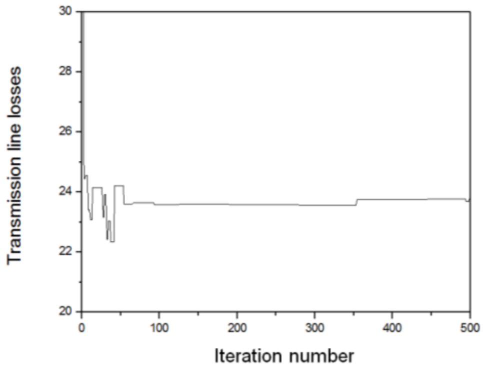

Fig. 13 Variation of active losses

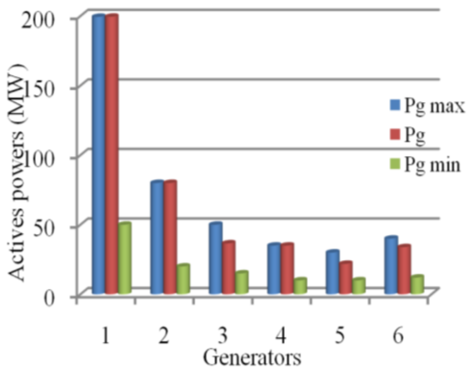

Fig. 14 Optimal values of the generated powers

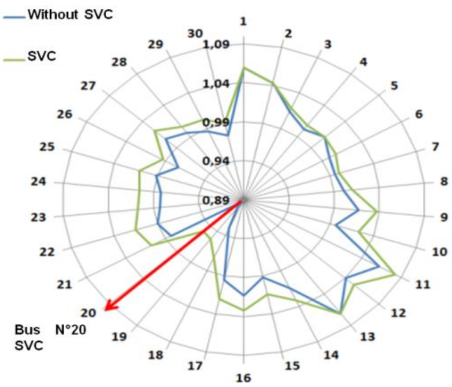

Fig. 15 Voltage profile

We also deduce that the Cuckoo search algorithm quickly converges to the optimal solution.

4.4. Case 4: OPF with the presence of STATCOM

In the third application, we are interested in the resolution of the optimal power flow with the integration of STATCOM in the power system. We increase the load demand from 283.40 MW to 383.40 MW.

To maintain all the voltages at acceptable values, the candidate bus for the STATCOM location is the bus where the voltage drop is important; we have chosen the bus n°20 to install STATCOM. The voltage source value is considered 1.00 p.u.

An optimal power flow program based on the Newton-Raphson method [51, 52] determines the voltages (magnitude and angle) at the different bus, the generated powers and the transmission losses. The OPF results obtained with installation of STATCOM are cited in tables 10 and 11 respectively.

Table 10 Optimal Power Flow with STATCOM

Bus	V	Angle	Injection		Generation		Load	
No	pu	Degree	MW	MVar	MW	MVar	MW	MVar
1	1.06	0	180.245	-5.581	199.868	-5.581	0	0
2	1.043	-3.703	58.3	8.114	80	20.81	21.7	12.7
5	1.01	-10.93	-65.75	-0.161	25.44	18.84	94.2	19
8	1.02	-9.682	4.916	0.653	34.91	30.65	30	30
11	1.082	-11.04	29.97	16.64	29.97	16.64	0	0
13	1.081	-12.57	36.29	9.226	36.29	9.226	0	0
20	1	-27.97	-102.3	34.4	0	35.1	102.2	0.7
Total			23.33	42.5	406.5	168.7	383.4	126.2

The simulation results illustrate in table 10, show that the addition of STATCOM at bus 20 improve the voltage profile (from 0.8939 to 1.00 p.u) and the levels of other voltage buses.

Table 11 Simulation results of optimal values

Variable	CS with SVC (bus N°20)	CS with STATCOM	CS without SVC
Pg1(MW)	200.00	199.8688	199.98
Pg2(MW)	79.95	80.0000	80
Pg5(MW)	29.91	25.4363	28.48
Pg8(MW)	34.96	34.9129	34.38
Pg11(MW)	30	29.9736	27.02
Pg13(MW)	32.22	36.2903	39.10
V1 (pu)	1.06	1.06	1.06
V2 (pu)	1.043	1.043	1.043
V5 (pu)	1.01	1.01	1.01
V8 (pu)	1.01	1.02	1
V11 (pu)	1.082	1.082	1.062
V13 (pu)	1.071	1.081	1.071
V20 (pu)	0.95	1.000	0.8939
Total PG (MW)	407.09	406.4819	408.96
Losses (MW)	23.69	23.3280	25.36
Cost ($/hr)	1372.23	1363.83387	1375.49

Table 12 STATCOM Parameter result

Vsh of STATCOM		Thst of STATCOM	Qsh of STATCOM
Bus	p.u	deg	p.u
20	1.00	-28.1606	-0.3505

We can see from the Table 11, that the obtained OPF results indicate that CSA with STATCOM give a better fuel cost (1363.83387 $/h) compared to case without STATCOM (1375.49069$/h), the cost is reduced by 11.65 $/h. The power losses have considerably decreased from 25.3580 MW to 23.3280 MW, they are minimized by 2.03 MW. Therefore, the OPF problem with STATCOM using the proposed algorithm performing well represented a best solution. The fuel cost and the transmission losses are reduced and voltage magnitude are maintained at the specified value.

The variations of fuel cost, transmission losses, optimal values of generated powers and nodal voltages values are illustrated in Figures 16, 17, 18 and 19 respectively.

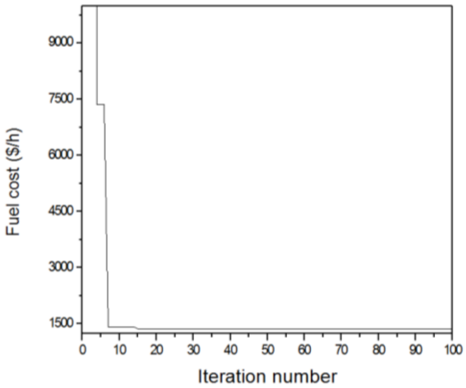

Fig. 16 Production cost

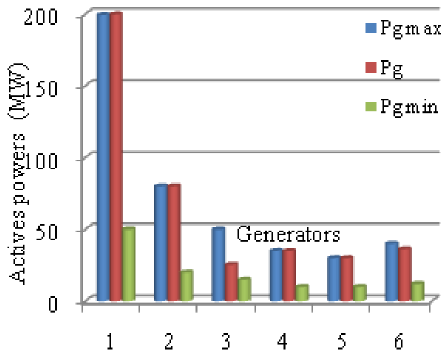

Fig. 17 Variation of the powers generated.

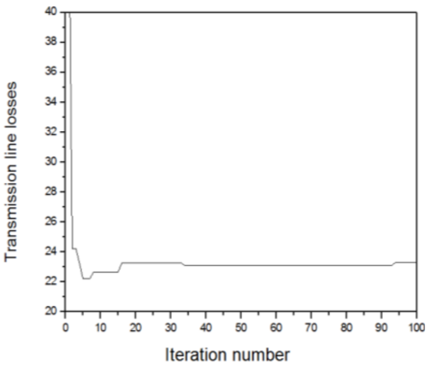

Fig. 18 Variation of active losses

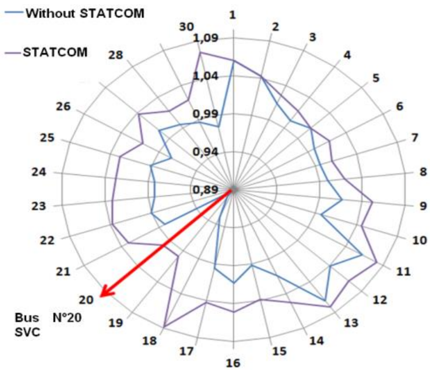

Fig. 19 Voltage profile

We also deduce that the Cuckoo search algorithm quickly converges to the optimal solution.

5. Conclusions

The main difficulty of such an optimization problem is linked to the presence of a conflict between the production cost function, the toxic gas emission function, the valve-point loading effect and the control function cost of the FACTS. It requires the transformation of this multi-objective problem into a single-objective optimization problem. To do this, we have changed the problem of optimizing economic-environmental dispatching into a single-objective optimization problem, by introducing a price penalty factor.

The CSA tests were validated on the IEEE 30-bus system. The simulation results prove that the proposed technique present as a competing algorithm for the resolution of the mentioned problems. A comparison of obtained results with those recently published in the literature confirms the efficiency and robustness of the algorithm in finding precise solutions.

In this paper, we have proved the positive contribution of the insertion of FACTS devices in the power system to improve voltage profile, maximize power flow capability, and reduce active power losses on the optimal management of the electrical system. We also conclude that although the complexity of the problems associated with power networks by changing their topologies by inserting FACTS devices and taking into account the valve-point loading effect, the CSA presents a better solution of the optimal power flow and economic-environmental dispatch.

To ensure good results, in the future, we will endeavor to find a parameter-free developed technique combined with the CSA algorithm and introduce it to other kinds of optimization issues, such as multi-objective ED problems with many complex constraints, dynamic ED problems and large-scale ELD problems integrated renewable energy sources.

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