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Optimal Power Flow Using Firefly Algorithm with Consideration of FACTS Devices "UPFC"

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Abstract: This paper present solution of optimal power flow problem using a firefly algorithm (FA) with consideration of FACTS devices "UPFC". The objective is to minimize the total fuel cost of generation and also maintain an acceptable system performance in terms of limits on generator real power and reactive power outputs, bus voltages and power flow of transmission lines. In order to maximize the relief of congestion in power system, to reduce the total system real power loss and improves the loadability of the system we propose also the optimization of the placement of FACTS devices in the power system (UPFC). The proposed method is tested on IEEE 30-bus system and the Algerian electrical network. The result of this method is compared with those obtained by biogeography based optimization (BBO), genetic algorithm (GA), and artificial bee colony (ABC) algorithm.

Keywords: Optimal power flow (OPF), Firefly algorithm (FA), Electrical network, FACTS, UPFC.

1. Introduction

The problem of optimal power flow (OPF) has been one of the most widely studied subjects in the power system community [1]. He was first discussed by Carpentier in 1962[2]. The main goal of a generic OPF is to minimize the total thermal unit fuel cost, total emission, and total real power loss while up keeping the security of the system.

In recent years, environmental constraint started to be considered as part of electric system planning. That is, minimization of pollution emission. The total emission can be reduced by minimizing the three major pollutants: nitrogen oxide (NOx), sulfur oxide (SOx), and carbon dioxide (CO2). In this study, Nitrogen-Oxide (NOx) emission is taken as the index from the viewpoint of environment conservation. So the total emission in the objective function will be considered in the OPF problem. In general, the total emission can be expressed as a non-linear function of power generation [3].

The unified power flow controller (UPFC) is an advanced member of the group of Flexible Alternating Current Transmission Systems (FACTS) with very attractive features [4]. This device can independently control many parameter, so it is the combination of the properties of a static synchronous compensator (STATCOM) and static synchronous series compensator (SSSC) [5]. It is able to control, simultaneously all the parameters affecting power flow in the transmission line: voltage, impedance, and phase angle [6].

Firefly algorithm (FA) is a meta-heuristic algorithm, developed by Xin-She Yang [7] for solving multimodal optimization problem. It based on the idealized behavior of the flashing characteristics of fireflies, including the light emission, light absorption and the mutual attraction.

The objective of this paper is to develop an algorithm to simultaneously find the minimization of the total fuel cost of generation, maintain an acceptable system performance in terms of limits on generator real power, reactive power outputs, bus voltages and power flow of transmission lines and also to choose the best location of UPFC. This problem is solved using Firefly algorithm FA and Newton Raphson's load flow method. It is tested on IEEE 30-bus system and the Algerian electrical network. The result of this method is compared with

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those obtained by biogeography based optimization (BBO) [8], genetic algorithm (GA) [9], and artificial bee colony (ABC) algorithm [10].

This paper is organized as follows; The Problem formulation is presented in Section 2. In section 3, Modeling of UPFC is represented. The application of FA into optimal power flow is discussed in Section 4. In section 5, the case study including discussion is presented. Finally, conclusion is stated in Section6.

2. Problem formulation

The standard OPF problem can be written in the following from:

$Min(F(x))$

Subject to:

$$g(x) = 0$$

and

$$h(x) \leq 0 \tag{1}$$

Where,

$F(x)$ is the objective function.
$g(x)$ is the equality constraints.
$h(x)$ is the inequality constraints.

and x is the vector of control variables, the control variable can be generated active power P_g, generation bus magnitudesV_g, and transformers tap T… etc.

$$x = [P_g, V_g, T \ldots] \tag{2}$$

In this paper OPF is formulated as two objectives optimization problem as follows:

A. Minimization of cost of generation

The OPF problem can be expressed as minimizing the cost of production of the real power which is given by a quadratic function of generator power output P_{g_i}as [11, 12].

$$F(x) = \sum_{i=1}^{ng}(A_i + B_i P_{Gi} + C_i P_{Gi}^2) \tag{3}$$

Where:

F is The fuel cost function.
A_i, B_i, C_i are the fuel cost coefficients.
i represent the corresponding generator (1,2,.....ng).
P_{G_i} is the generated active power at bus i.
ng is number of generators including the slack bus.

B. Minimization of NOx emission

The amount of NOx emission is given as a function of generator output (in Ton/hr), that is the sum of quadratic and exponential functions.

The objective function that minimizes the total emissions can be expressed as [13, 14]:

$$Min(F_E)$$
$$F_E(x) = \sum_{i=1}^{ng}(a_i + b_i P_{Gi} + c_i P_{Gi}^2 + d_i \exp{(e_i P_{Gi})}) \tag{4}$$

Where a_i, b_i, c_i, d_i and e_i are the parameters estimated on the basis of unit emissions test results.

C. The total objective function

The pollution control can be obtained by assigning a cost factor to the pollution level expressed as:

$$F_{pc} = \psi F_E \quad (\$/h) \tag{5}$$

Where ψ is the emission control cost factor in \$/Ton. $\psi = 550.66\ \$/\text{Ton}$.

Fuel cost and emission are conflicting objective and can not be minimized simultaneously. However, the solutions may be obtained in which fuel cost an emission are combined in a single function with different weighting factor. This total objective function is described by [15]:

$$F_{tot}(x) = \omega F + (1 - \omega) \ \left(\frac{\$}{h}\right) \tag{6}$$

$$0 \leq \omega \leq 1 \tag{7}$$

D. The equality and inequality constraints

The OPF equality constraints g*(x)* reflects the physics of the power system, equality constraints are expressed in the following equation:

$$\sum_{i=1}^{ng} P_{g_i} - P_D - P_L = 0 \tag{8}$$

Where; P_D is the total power demand of the plant.

P_L is the total power losses of the plant.

The inequality constraints *h(x)* reflect the generators constraints and power system security limits. The inequality constraints on the problem variables considered include:

- Upper and lower bounds on the active generations at generator buses

$$\mathrm{P_{g_i}}^{\min} \leq \mathrm{P_{g_i}} \leq \mathrm{P^{\max}}_{\mathrm{g_i}} \tag{9}$$

- Upper and lower bounds on the reactive power generations at generator buses and reactive power injection at buses with VAR compensation

$$\mathrm{Q_{g_i}}^{\min} \leq \mathrm{Q_{g_i}} \leq \mathrm{Q^{\max}}_{\mathrm{g_i}} \tag{10}$$

- Upper and lower bounds on the voltage magnitude at the all buses

$$\mathrm{V_i}^{\min} \leq \mathrm{V_i} \leq \mathrm{V^{\max}}_{\mathrm{i}} \tag{11}$$

- Upper and lower bounds on the bus voltage phase angles

$$\theta_i^{\min} \leq \theta_i \leq \theta^{\max}{}_i \tag{12}$$

- Upper and lower transformer tap setting T limits are set as:

$$\mathrm{T^{\min}} \leq \mathrm{T} \leq \mathrm{T^{\max}} \tag{13}$$

3. Modeling of UPFC

Unified Power Flow Controller (UPFC) is a multipurpose FACTS's device which allows simultaneous control of active power flow, reactive power flow and the voltage magnitude at the UPFC terminals [16].

A simpler schematic representation of UPFC is shown in figure 1 with its equivalent circuit [17].

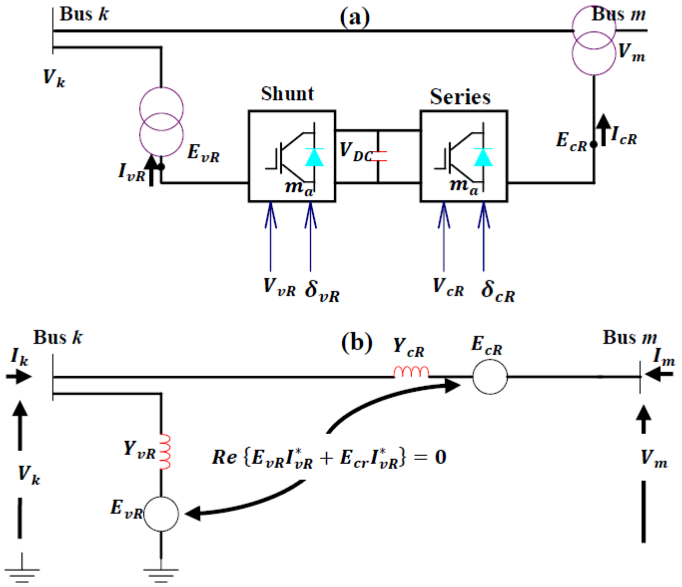

Figure 1. The UPFC equivalent circuit

The UPFC equivalent circuit shown in Figure 1(b) consists of a shunt-connected voltage source, a series-connected voltage source, and an active power constraint equation, which links the two voltage sources. The two voltage sources are connected to the AC system through inductive reactance representing the VSC transformers.

The UPFC voltage sources are [18]:

$$E_{vR} = V_{vr}(cos\,\delta_{vR} + j\,sin\,\delta_{vR}) \tag{14}$$
$$E_{cR} = V_{cr}(cos\,\delta_{cR} + j\,sin\,\delta_{cR}) \tag{15}$$

Where: V_{vr} and δ_{vR} are the controllable magnitude and phase angle of the voltage source representing the shunt converter respectively (equation (18),(19)).

$$V_{vR\,min} \leq V_{vR} \leq V_{vR\,max} \tag{16}$$
$$0 \leq \delta_{vR} \leq 2\pi \tag{17}$$

V_{cr} and δ_{cR} are the controllable magnitude and phase angle of the voltage source representing the series converter respectively (equation (20),(21)).

$$V_{cR\,min} \leq V_{cR} \leq V_{cR\,max} \tag{18}$$
$$0 \leq \delta_{cR} \leq 2\pi \tag{19}$$

The équation of the active power and reactive power at bus k and m are:

$$\begin{aligned} P_k = V_k^2 G_{kk} &+ V_k V_m[G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_k - \theta_m)] \\ &+ V_k V_{cR}[G_{km}\cos(\theta_k - \delta_{cR}) + B_{km}\sin(\theta_k - \delta_{cR})] \\ &+ V_k V_{vR}[G_{vR}\cos(\theta_k - \delta_{vR}) + B_{vR}\sin(\theta_k - \delta_{vR})] \end{aligned} \tag{20}$$

$$\begin{aligned} Q_k = -V_k^2 G_{kk} &+ V_k V_m[G_{km}\cos(\theta_k - \theta_m) - B_{km}\sin(\theta_k - \theta_m)] \\ &+ V_k V_{cR}[G_{km}\cos(\theta_k - \delta_{cR}) - B_{km}\sin(\theta_k - \delta_{cR})] \\ &+ V_k V_{vR}[G_{vR}\cos(\theta_k - \delta_{vR}) - B_{vR}\sin(\theta_k - \delta_{vR})] \end{aligned} \tag{21}$$

$$\begin{aligned} P_m = V_m^2 G_{mm} &+ V_m V_k[G_{mk}\cos(\theta_m - \theta_k) + B_{mk}\sin(\theta_m - \theta_k)] \\ &+ V_m V_{cR}[G_{mm}\cos(\theta_m - \delta_{cR}) + B_{mm}\sin(\theta_m - \delta_{cR})] \end{aligned} \tag{22}$$

$$Q_m = -V_m^2 B_{mm} + V_m V_k [G_{mk}\cos(\theta_m - \theta_k) - B_{mk}\sin(\theta_m - \theta_k)] + V_m V_{cR}[G_{mm}\cos(\theta_m - \delta_{cR}) - B_{mm}\sin(\theta_m - \delta_{cR})] \tag{23}$$

The active and the reactive power of the series converter :

$$P_{cR} = V_{cR}^2 G_{mm} + V_{cR} V_k [G_{mk}\cos(\delta_{cR} - \theta_k) + B_{mk}\sin(\delta_{cR} - \theta_k)] + V_{cR} V_m [G_{mm}\cos(\delta_{cR} - \theta_m) + B_{mm}\sin(\delta_{cR} - \theta_m)] \tag{24}$$

$$Q_{cR} = -V_{cR}^2 B_{mm} + V_{cR} V_k [G_{mk}\cos(\delta_{cR} - \theta_k) - B_{mk}\sin(\delta_{cR} - \theta_k)] + V_{cR} V_m [G_{mm}\cos(\delta_{cR} - \theta_m) - B_{mm}\sin(\delta_{cR} - \theta_m)] \tag{25}$$

The active and the reactive power of the shunt converter :

$$P_{vR} = -V_{vR}^2 G_{vR} + V_{vR} V_k [G_{vR}\cos(\delta_{vR} - \theta_k) + B_{vk}\sin(\delta_{vR} - \theta_k)] \tag{26}$$

$$Q_{vR} = V_{vR}^2 B_{vR} + V_{vR} V_k [G_{vR}\sin(\delta_{vR} - \theta_k) - B_{vk}\cos(\delta_{vR} - -\theta_k)] \tag{27}$$

4. Firefly algorithm for optimal power flow

Firefly algorithm (FA) is a meta-heuristic algorithm, developed by Xin-She Yang [7] for solving multimodal optimization problem. It based on the idealized behavior of the flashing characteristics of fireflies, including the light emission, light absorption and the mutual attraction.

For simplicity in describing our new Firefly Algorithm (FA), we now use the following three idealized rules [19-21]:

1. All fireflies are unisex so that one firefly will be attracted to other fireflies regardless of their sex.
2. Attractiveness is proportional to their brightness, thus for any two flashing fireflies, the less brighter one will move towards the brighter one. The attractiveness is proportional to the brightness and they both decrease as their distance increases. If there is no brighter one than a particular firefly, it will move randomly.
3. The brightness of a firefly is affected or determined by the landscape of the objective function. For a maximization problem, the brightness can simply be proportional to the value of the objective function. Other forms of brightness can be defined in a similar way to the fitness function in genetic algorithms.

Based on these three rules, the basic steps of the firefly algorithm (FA) can be summarized as the pseudo code shown in Figure 2.

```
Firefly Algorithm
Objective function f(x), x = ( $x_1$, ..., $x_d$)T
Generate initial population of fireflies $x_i$ (i = 1, 2... n)
Light intensity Ii at xi is determined by f( $x_i$)
Define light absorption coefficient
while (t <MaxGeneration)
    for i = 1 : n all n fireflies
        for j = 1 : i all n fireflies
            if (Ij > Ii), Move firefly i towards j in d-dimension; end if
            Attractiveness varies with distance r via exp[−r]
        Evaluate new solutions and update light intensity
    end for j
end for i
Rank the fireflies and find the current best
end while
Postprocess results and visualization
```

Figure 2. Pseudo code of the firefly algorithm (FA)

In the firefly algorithm, there are two important issues: the variation of light intensity *I* and formulation of the attractiveness *β*. The brightness of a firefly at a particular location *x* can be chosen as:

$$I(x) \propto \frac{1}{f(x)} \tag{28}$$

The light intensity *I* vary with the distance *r*. That is:

$$I\ (x) = I_0 e^{-\gamma r} \tag{29}$$

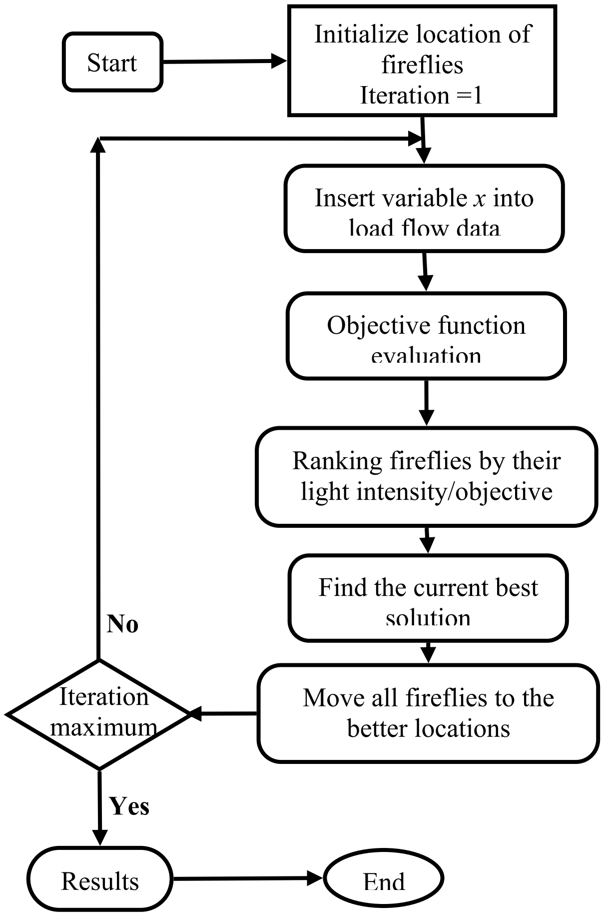

Figure 3. Optimal power flow using FA

Where $I_0$the original is light intensity and γ is the absorption coefficient.

As a firefly's attractiveness is proportional to the light intensity seen by adjacent fireflies, we can now define the attractiveness of a firefly by:

$$\beta(r) = \beta_0 e^{-\gamma m} \quad m \geq 1 \tag{30}$$

Where, β_0 is the attractiveness at r =0, m is the number of the fireflies.

The movement of a firefly *i* is attracted to another more attractive firefly *j* is determined by the equation:

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2}\left(x_j - x_i\right) + \alpha(rand - \tfrac{1}{2}) \tag{31}$$

With

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d}(x_{i,k} - x_{j,k})^{2}} \tag{32}$$

Where, r_{ij} is the distance between two fireflies i and j at x_i and x_j , respectively, α is the size of the random step.

The process of incorporating the firefly algorithm FA into optimal power flow is summarized in Figure 3 Where each firefly represents the values of the active power generated [22].

5. Application study

The OPF with FACTS device using Firefly algorithm (FA) approach has been developed and implemented by the use of Matlab 9. The applicability and validity of this method (FA) have been tested on IEEE 30-bus system and Algerian network (59-bus). To demonstrate the effectiveness of the proposed approach two cases to be discussed:

Case 1: represent the solution of optimal power flow without FACTS device installed.
Case 2: One UPFC device is installed.

A. Application on the IEEE 30-bus system

The IEEE 30-bus system consist of 6 generators (n°:1, 2, 5, 8, 11 and 13), 41 transmission lines and 4 transformers (Figure 4).

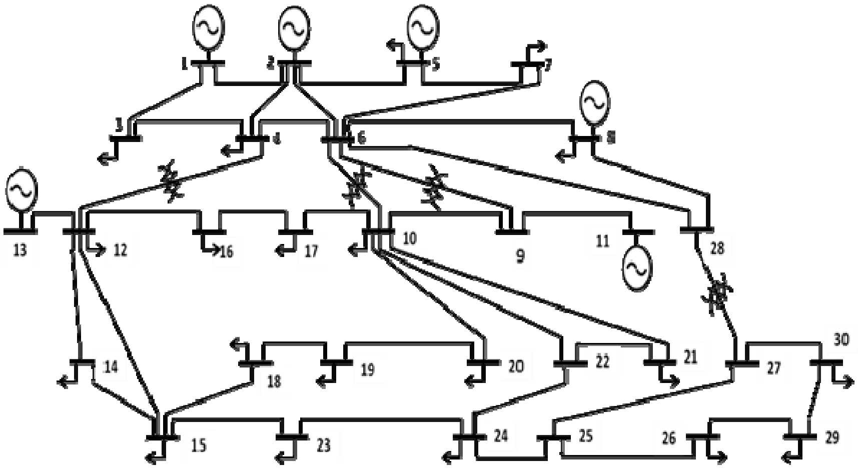

Figure 4. Structure of the tested IEEE 30 Bus System

The active power generating limits and the unit costs of all generators of the IEEE 30-bus test system are presented in Table 1 [15], and the emission coefficients of generators are presented in Table 2 [23].

The total active load in the system was 283.4 MW, and the emission control cost factor for this system was taken as 550.66 $/Ton [24]. The voltage of generator buses and load buses are: $0.90 \leq V_i \leq 1.10$ pu. The upper and lower bounds on the bus voltage phase angles are set between -14 °& 0° and upper and lower transformer tap setting T limits are set between 0.95 & 1.1 pu.

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

Pg_i (MW)	$Pg_{i(min)}$ (MW)	$Pg_{i(max)}$ (MW)	A_i (\$/h)	$B_i.10^{-2}$ (\$/MWh)	$C_i.10^{-4}$ (\$/MW^{2}h)
Pg1	50	200	0.00	200	37.5
Pg2	20	80	0.00	175	175.0
Pg5	15	50	0.00	100	625.0
Pg8	10	35	0.00	325	83.0
Pg11	10	30	0.00	300	250.0
Pg13	12	40	0.00	300	250.0

Table 2. Emission coefficients for IEEE 30-bus system

bus	$a.10^{-2}$ (Ton/h)	$b.10^{-4}$ (Ton/ MWh)	$c.10^{-6}$ (Ton/ MW^{2}h)	$d.10^{-4}$ (Ton/ MWh)	$e.10^{-2}$ (Ton/MWh)
1	4.091	-5.554	6.490	2.00	2.857
2	2.543	-6.047	5.638	5.00	3.333
5	4.258	-5.094	4.586	0.01	8.000
8	5.326	-3.550	3.380	20.00	2.000
11	4.258	-5.094	4.586	0.01	8.000
13	6.131	-5.555	5.151	10.00	6.667

Table 3**.** The optimum generations for minimum total cost obtained by FA-OPF

Variables	ω =1	ω =0.5	ω =0
P1 (MW)	177.1034	129.6699	68.0558
P2 (MW)	48.8809	56.9540	70.9006
P5 (MW)	21.3295	25.4238	50.0000
P8 (MW)	20.8003	35.0000	35.0000
P11 (MW)	12.2012	23.1468	30.0000
P13 (MW)	12.0000	19.2363	32.8166
V1 (p.u)	1.0900	1.0900	1.0900
V2 (p.u)	1.0900	1.0818	1.0838
V5 (p.u)	1.0900	1.0585	1.0634
V8 (p.u)	1.0800	1.0706	1.0700
V11 (p.u)	1.0900	1.0900	1.0616
V13 (p.u)	1.0900	1.0900	1.0900
T6-9 (p.u)	0.9588	1.1000	1.0861
T6-10 (p.u)	1.0817	1.0975	1.1000
T4-12 (p.u)	1.0874	1.0048	1.1000
T28-27 (p.u)	1.1000	1.1000	1.0997
Power losses (MW)	8.9153	6.0308	3.3730
Generation cost (\$/h)	800.0811	818.4117	933.6162
Emission (ton/h)	0.3684	0.2698	0.2174
Total cost (\$/h)	1002.9442	966.9797	1053.3296

The FA properties are set as follow:

- Number of fireflies: 50.
- Number of Iterations: 200.
- Alpha (scaling parameter): 0.5
- Minimum value of betta (attractiveness): 0.2
- absorption coefficient: 1

Case 1: in this case the OPF is running without using the UPFC device and the vector of control variables include the generated active powers, magnitude voltages of generators and transformer tap settings.

$$x = [P_{g_2}, P_{g_5}, P_{g_8}, P_{g_{11}}, P_{g_{13}}, V_1, V_2, V_5, V_8, V_{11}, V_{13}, T_{6-9}, T_{6-10}, T_{4-12}, T_{28-27}] \quad (33)$$

The results including the generation cost, the emission level, total cost, generated active power, magnitude voltage, power losses and transformer tap settings are shown in Table 3.

This table represent the optimum generations for minimum total cost in three cases:

ω = 1: Minimum generation cost without using into account the emission level as the objective function.

ω = 0.5: Equal influence of generation cost and pollution control in the objective function.

ω = 0: A total minimum emission is taken as the objective of main concern.

Table 4. Comparison with FA-OPF, BBO-OPF, GA-OPF and BBO-OPF

Variables	FA-OPF	BBO-OPF	GA-OPF	ABC-OPF
P1 (MW)	176.7311	171.9231	176.7307	180.5218
P2 (MW)	48.8454	8.8394	48.8488	48.7845
P5 (MW)	21.4931	1.4391	21.4941	21.2598
P8 (MW)	21.6923	1.7629	21.6881	18.6469
P11 (MW)	12.1535	2.1831	12.1530	11.8145
P13 (MW)	12.0000	6.5588	12.0009	12.1011
Power losses (MW)	9.5155	9.3064	9.5156	9.7286
Generation cost ($/h)	802.3646	802.717	802.3647	802.1649

The active powers of the 6 generators as shown in this table are all in their allowable limits. We can observe that the total cost of generation and pollution control is the highest at the minimum emission level (ω=0) with the lowest real power loss (3.3730MW). As seen by the optimal results shown in the table 3, there is a trade-off between the fuel cost minimum and emission level minimum. The difference in generation cost between these two cases (800.0811$/hr compared to 933.6162$/hr), in real power loss (8.9153MW compared to 3.3730MW) and in emission level (0.3684Ton/hr compared to 0.2174 Ton/hr) clearly shows this trade-off. To decrease the generation cost, one has to sacrifice some of environmental constraint. The minimum total cost is at ω =0.5 of the order of 966.9797$/h.

- Comparison with FA-OPF, BBO-OPF, GA-OPF and BBO-OPF

The comparisons of the results obtained by the proposed approach FA with those found by the biogeography based optimization BBO [8], genetic algorithm GA [9] and artificial bee colony ABC algorithm [10] are reported in the Table 4.

This table gives the optimum generations for minimum total cost for ω =1 and the vector of control variables include only the generated active powers.

The comparisons of the results between FA-OPF, BBO-OPF, GA-OPF and ABC-OPF show that the firefly algorithm gives acceptable solution. The FA gives very near results of fuel cost (802.3646$/hr) compared with the results obtained with those methods (802.717$/hr, 802.3647$/hr & 802.1649$/hr) and in the active power loss also.

Case 2: in this case the OPF is running with using the UPFC device and the vector of control variables include only the generated active powers. The objective is to minimize the total fuel cost of generation, the power losses and the voltage deviations, we propose also the optimization of the placement of UPFC device in the power system.

Table 5. Parameters of UPFC

	Xcr (pu)	Xvr(pu)	Qmax (MVar)	Qmin (MVar)
UPFC	0.45	0.3	35	-35

The total generation, active power, reactive power, total losses and optimal location of UPFC are shown in table 6.

Table 6. Comparison of results obtained by FA-OPF with-without UPFC

	Min	Without UPFC	With UPFC	Max
Pg1 (MW)	50	176.7311	177.5808	200
Pg2 (MW)	20	48.8454	48.8800	80
Pg5 (MW)	15	21.4931	21.3200	50
Pg8 (MW)	10	21.6923	20.8000	35
Pg11 (MW)	10	12.1535	12.2000	30
Pg13 (MW)	12	12.0000	12.0000	40
Qg1 (MVar)	-20	-4.3000	-4.7000	200
Qg2 (MVar)	-20	25.8000	24.3000	100
Qg5 (MVar)	-15	25.5000	24.9000	80
Qg8 (MVar)	-15	13.9000	10.0000	60
Qg11 (MVar)	-10	28.8000	26.6000	50
Qg13 (MVar)	-15	31.8000	28.7000	60
Generation cost ($/h)	-	802.3646	800.0336	-
Active power losses (MW)	-	9.5155	9.3808	-
Reactive Power losses (MVar)	-	- 4.8	-5.9	-
Optimal location of UPFC	-	-	Ligne 33 (24-25) Q24=10.6 MVar	-

The objective function is described by:

$$Min\{F_{TOT} = \sum_{i=1}^{ng}(A_i + B_i P_{Gi} + C_i P_{Gi}^2) + Pen_{\,1} \sum_{i=1}^{nb} P_{L_i} + Pen_{\,2} \sum_{i=1}^{JB}(V_i - V_{ref})^2] \quad (36)$$

With: nb is number of branches on the network.

JB is number of buses.

V_{ref} is the reference value of the bus voltage magnitude,:$V_{ref} = 1.0\ pu$.

Pen_1, Pen_2 are called the penalty factors.

The control parameters of UPFC are showed in Table 5.

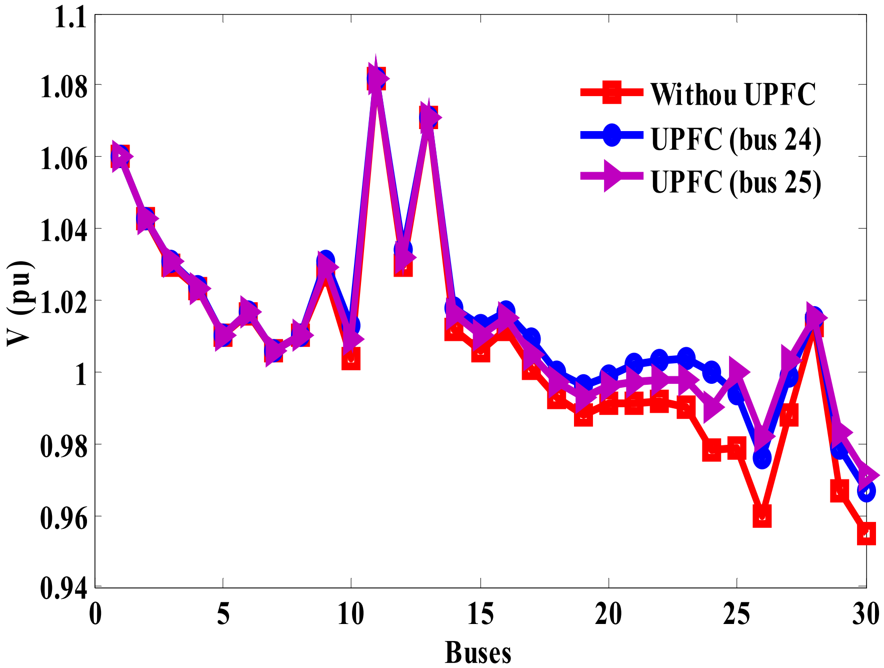

Figure 5. Voltage profile of all buses for IEE 30-bus system with &without UPFC

The proposed approach with optimal installation of UPFC at line 33 (between buses 24 & 25) gives better results than without UPFC installation. For example with installation of UPFC, the fuel cost is 800.0336$/h, active power losses 9.3808MW and the reactive power losses -5.9 MVar which are better compared with the results found at the base case (without UPFC) (802.3646$/h, 9.5155MW and - 4.8 MVar).

The FA method proposes other location of UPFC in critical lines; 16, 17, 18, 19, 22, 25, 26, 27, 28, 29, 30, 32, 39.

We can observe also that the active powers and the reactive powers of the 6 generators as shown in the table 5 are all in their allowable limits.

Figure 5 shows the voltage magnitudes profiles, it is clearly identified that all voltage magnitudes profiles are within the constraints limits and it was optimize after UPFC installation.

B. *Application on the Algerian network*

The FA-OPF has been also tested on the Algerian network. It consists of 59 buses, 83 branches and 10 generators. The slack bus is the bus N° 4. The generator of the bus 13 is not in service. (Figure 6).

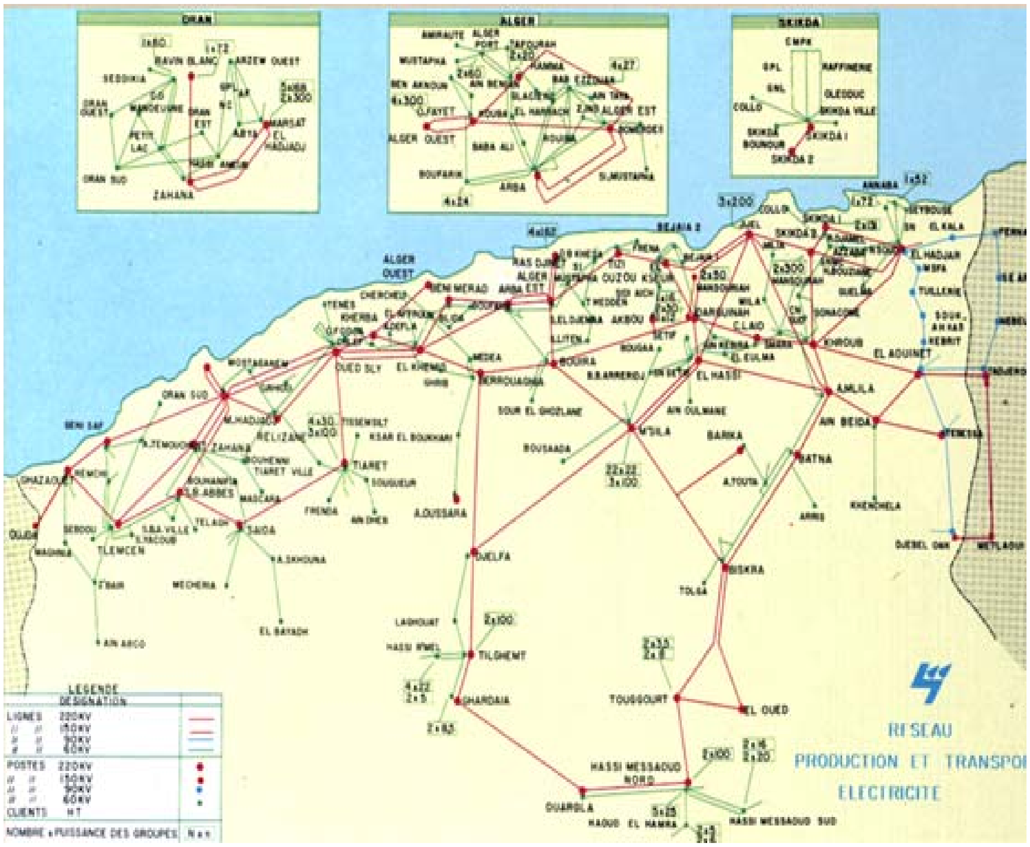

Figure 6. Topology of the Algerian production and transmission network before 1997 (Sonelgaz).

The active power generating limits and the unit costs of all generators of the Algerian network are presented in Table 7, and the emission coefficients of generators are presented in Table 8.

The total active load in the system was 684.10 MW.

Table 7. Power generation limits and cost coefficients for Algerian network

Bus	Pmin MW	Pmax MW	Qmin Mvar	Qmax Mvar	A $/h	B $/MWh	C $/MW^{2}h
1	8	72	-10	15	0	1.50	0.0085
2	10	70	-35	45	0	2.50	0.0170
3	30	510	-35	55	0	1.50	0.0085
4	20	400	-60	90	0	1.50	0.0085
13	15	150	-35	48	0	2.50	0.0170
27	10	100	-20	35	0	2.50	0.0170
37	10	100	-20	35	0	2.00	0.0030
41	15	140	-35	45	0	2.00	0.0030
42	18	175	-35	55	0	2.00	0.0030
53	30	450	-100	160	0	1.50	0.0085

Table 8. Emission coefficients for Algerian network

bus	$a.10^{-2}$ Ton/h	$b.10^{-4}$ Ton/MWh	$c.10^{-6}$ Ton/MW²h	d Ton/MWh	$e.10^{-2}$ Ton/MWh
1	4.091	-5.554	6.490	2.00 e-4	2.857
2	2.543	-6.047	5.638	5.00 e-4	3.333
3	4.258	-5.094	4.586	1.00 e -6	8.000
4	5.326	-3.550	3.380	2.00 e -3	2.000
13	4.258	-5.094	4.586	1.00 e -6	8.000
27	6.131	-5.555	5.151	1.00 e -5	6.667
37	4.091	-5.554	6.490	2.00 e -4	2.857
41	2.543	-6.047	5.638	5.00 e -4	3.333
42	4.258	-5.094	4.586	1.00 e -6	8.000
53	5.326	-3.550	3.380	2.00 e -3	2.000

Case1: FA-OPF without UPFC installation

The table 9 gives the optimum generations for minimum total cost in three cases (total minimum generation cost **ω=**1, total minimum emission ω=0 and an equal influence of generation cost and pollution control in the objective function)

Table 9. The optimum generations for minimum total cost obtained by FA-OPF for the Algerian network

	ω =1	ω =0.5	ω =0
Pg1 (MW)	60.3536	62.9017	70.0891
Pg2 (MW)	27.5474	43.1420	56.0679
Pg3 (MW)	102.8548	99.8792	85.2725
Pg4 (MW)	113.8841	108.4669	88.0140
Pg27 (MW)	24.9015	41.8344	91.5826
Pg37 (MW)	50.4757	50.3362	52.2015
Pg41 (MW)	97.0015	96.0575	91.6294
Pg42 (MW)	132.4250	110.7141	90.5276
Pg53 (MW)	104.7032	101.5773	86.6985
Vg1 (pu)	1.0314	1.0000	1.0114
Vg2 (pu)	1.0456	1.0826	1.0372
Vg3 (pu)	1.0345	1.0796	1.0046
Vg4 (pu)	1.0388	1.0673	1.0023
Vg27 (pu)	1.0382	1.0661	1.0014
Vg37 (pu)	1.0445	0.9976	0.9971
Vg41 (pu)	1.0671	0.9908	0.9874
Vg42 (pu)	1.0631	1.0047	1.0035
Vg53 (pu)	1.0241	1.0353	1.0213
Generation cost ($/h)	1699.9	1725.5	1820.2
Emission (ton/h)	0.4841	0.4455	0.4030
Power losses (MW)	30.0468	30.8094	27.9831
Total cost ($/h)	1699.9	1970.8190	2042.11
Time (s)	123.2973	100.5449	174.3222

The active powers generated as shown in table 9 are all in their allowable limits, the voltages magnitude also are within the constraint limit .We can observe also that the minimum total cost is at ω =1 of the order of 1699.9 $/h

The comparisons of the results obtained by the proposed approach FA with genetic algorithm [9] are reported in the Table 10.

This table gives the optimum generations for minimum total cost for ω =1 and the vector of control variables include only the generated active powers

Table 10. Comparison with FA-OPF and GA-OPF

	FA-OPF	GA-OPF
Pg1 (MW)	51.5427	45,7786
Pg2 (MW)	37.7899	40,6655
Pg3 (MW)	100.3145	104,4367
Pg4 (MW)	111.0000	110.0000
Pg27 (MW)	28.7414	23,8188
Pg37 (MW)	49.6008	51,4785
Pg41 (MW)	105.6506	96,2285
Pg42 (MW)	129.2478	123,4861
Pg53 (MW)	100.1077	117,7484
Generation cost ($/h)	1706.8000	1708.9
Power losses (MW)	29.8000	29.541

Table 11. Comparison of results obtained by FA-OPF with-without UPFC for the Algerian network

	Min	Without UPFC	With UPFC	Max
Pg1 (MW)	8	51.5427	51.5000	72
Pg2 (MW)	10	37.7899	37.8000	70
Pg3 (MW)	30	100.3145	100.3000	510
Pg4 (MW)	20	111.0000	109.6000	400
Pg27(MW)	10	28.7414	28.7000	100
Pg37(MW)	10	49.6008	49.6000	100
Pg41(MW)	15	105.6506	105.7000	140
Pg42(MW)	18	129.2478	129.2000	175
Pg53(MW)	30	100.1077	100.1000	450
Qg1(MVar)	-10	-03.0000	-0.3000	15
Qg2(MVar)	-35	17.4000	15.3000	45
Qg3(MVar)	-35	46.0000	45.0000	55
Qg4(MVar)	-60	46.8000	47.3000	90
Qg27(MVar)	-20	35.0000	35.0000	35
Qg37(MVar)	-20	17.6000	17.6000	35
Qg41(MVar)	-35	45.0000	45.0000	45
Qg42(MVar)	-35	19.0000	19.1000	55
Qg53(MVar)	-100	01.0000	-12.4000	160
Generation cost ($/h)	-	1706.8000	1702.1000	-
Active power losses (MW)	-	29.8000	28.4000	-
Reactive Power losses (MVar)	-	-19.7000	-21.3000	-
Optimal location of UPFC	-	-	Line 66 (36-43) Qg36=14.3 MVar	-

The results obtained with proposed approach FA-OPF are better than those obtained by GA-OPF (1706.8000 $/h & 29.8000 MW) compared to (1708.9$/h & 29.541 MW).

Case2: FA-OPF with UPFC installation

In this case the OPF is running with using the UPFC device and the vector of control variables include only the generated active powers.

From the comparison table 11, the proposed OPF method with UPFC loss is lesser than proposed OPF method without UPFC. The proposed OPF method with UPFC loss is reduced as 28.4000MW when the optimal location of UPFC is at line 66 between buses 36 & 43. Also, the fuel cost is reduced after installation of UPFC (1702.1000 $/h) compared to (1702.1000 $/h). Hence, the solution of optimal power flow problem using a firefly algorithm (FA) with UPFC is better for analyzing power flow of electric power system.

The FA-OPF method proposes other location of UPFC in critical lines: 20, 21, 22, 24, 25, 34, 38, 39, 57, 63, 66, 67, 73, 75, and 76.

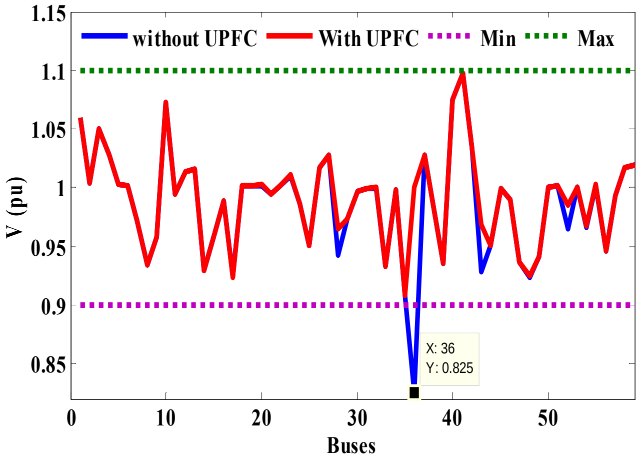

Figure 7. Voltage profile of all buses for Algerian network with & without UPFC

Figure 7 shows the voltage profile with and without UPFC. It is clearly identified that all voltage magnitude profiles are within the constraint limit.

7. Conclusion

In this paper, a new swarm based Firefly Algorithm has been presented to solve the optimal power flow problem with consideration of FACTS devices "UPFC".

The FA-OPF has been successfully implemented to solve optimal power flow problem for minimization of the total cost of the generation, the cost of pollution level control and the active power loss.

The proposed method is tested on IEEE 30-bus system and the Algerian electrical network. Simulation results show that the solution of optimal power flow problem using a firefly algorithm (FA) with installation UPFC in right location is better for analyzing power flow of electric power system.

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