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Optimal power flow solution including wind power generation into isolated Adrar power system using PSOGSA

S. Makhloufi [1*], A. Mekhaldi [2†], M. Teguar [2], D. Saheb-Koussa [1] and A. Djoudi [1]

[1] Centre de Développement des Energies Renouvelables, CDER
B.P. 62, Route de l'Observatoire, Bouzaréah, 16340, Algiers, Algeria

[2] Laboratoire de Recherche en Electrotechnique, Département de Génie Electrique
Ecole Nationale Polytechnique, Avenue Hassan Badi, El Harrach, Algiers, Algeria

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Abstract - *In this paper, hybrid particle swarm optimization and gravitational search algorithm is proposed to find the optimal solution for the optimal power flow problem including three wind farms connected to the isolated Adrar Algerian power system. In order to get the cost model, the economic problem is converted into a single objective function considering the fuel cost and cost of wind generation by the calculation of the overestimation and underestimation cost of available wind energy based on the Weibull distribution of wind speed. In reason of the wind speed intermittent and unpredictability, two seasonal demand scenarios correspond to the summer and winter peak load of the year 2015 have been considered. The effects of the incorporation of wind power generation on isolated Adrar power system operation and planning are investigated. The simulation results obtained from the proposed algorithm shows that this algorithm is capable to give higher quality solutions to solve optimal power flow dispatching problem with a fast convergence.*

Résumé - *Dans cet article, l'algorithme d'optimisation hybride de l'algorithme d'essaim de particule avec l'algorithme de recherche de gravité est proposé pour trouver la solution optimale du problème de l'écoulement de puissance optimale, tenant compte du raccordement des trois parcs éoliens au réseau isolé d'Adrar. Afin d'obtenir le modèle du coût, ce problème est transformé en une seule fonction objective, tenant compte des coûts du carburant et de production d'énergie éolienne par le calcul des coûts dû à la surestimation et la sous-estimation de l'énergie disponible du vent en fonction de la distribution de Weibull de la vitesse du vent. En raison de l'intermittence et l'imprévisibilité de la vitesse du vent, deux scénarios de la demande saisonnière de la charge de l'année 2015 ont été considérés à savoir, les pics d'été et d'hiver. Les effets d'intégration de la production d'énergie éolienne sur le fonctionnement du système électrique isolé d'Adrar et leur planification ont été étudiés. Les résultats de simulation obtenus par l'algorithme proposé montrent que ce dernier est capable de donner des solutions de qualité supérieure pour résoudre le problème de répartition de l'écoulement de puissance optimal avec une convergence rapide.*

Keywords: Optimal power flow - Fuel cost - Wind cost - Particle swarm optimization - Gravitational search algorithm - PSOGSA - Wind power generation - Weibull probability function.

1. INTRODUCTION

Recently, with the large scale incorporation of wind power generations into an electric power system, optimal power flow, 'OPF' becomes one of the most important problems in modern power system planning and operation, especially in an isolated weak power system which is generally located in remote areas. As commonly defined,

* s.makhloufi@cder.dz , d.koussa@cder.dz , a.djoudi@cder.dz
† abdelouahab.mekhaldi@enp.edu.dz , madjid.teguar@g.enp.edu.dz

the main goal of OPF dispatching solution is to determine the most efficient outputs schedule of all available generation units in the power system to supply the required demand plus transmission losses in order to minimize the total generation cost without violating of the requirements of equipment operation constraints [1-3].

Delivering high large-scale levels of intermittent generation such wind power generation to produce the electricity will bring new challenges for planners, investors and for those operators of the power systems. A significant effect appears when the wind power generations are connected into an isolated power system. The isolated power systems present some particularities in comparison with interconnected power systems. Indeed, their weak inertia and the limit of the reserves make them more sensitive to the variations of the production and the consummation.

In addition, the absence of an interconnection with neighboring systems increases the probability of frequency collapse in case of an unexpectedly large deficit of generation. In this context, in recent years, same researchers have been proposed several optimization techniques to solve OPF problem with the incorporation of the wind energy sources [4-8].

Indeed, two large categories of the optimization algorithms have been used to solve this problem; the conventional algorithms and the heuristic algorithms. The conventional algorithms include the gradient method; Lagrange relaxation method and linear programming method have been traditionally used to solve the OPF. For the reason of the nonlinear characteristics of the problem which presents many local optimum solutions and a large number of constraints, the classical methods cannot find a good solution in solving the problem. Most of the aforementioned methods often suffer from large computational requirements or just give a good estimate of the optimal or near optimal solution of the problem [9].

To improve the solution quality, recently, many heuristic algorithms have been proposed in the literature to solve this problem because of their robustness to overcome the deficiencies of the conventional methods. Todorovski *et al.* [11] proposed a new procedure for selection of an initial set of complex voltages at generator-buses in solving OPF by employing genetic algorithm. The procedure permits to start the optimization process with a set of control variables, causing few or no violations of constraints. Simulation results show that the proposed initialization procedure improves the performance of the whole genetic algorithm and OPF procedure.

Other studies [12-16] proposed a novel particle swarm optimization, ‘PSO’ approach to solve the optimal power flow problem with embedded security constraints and transient stability constraints. Case studies show that PSO is useful as an alternative to solve the challenging OPF problem. The authors of [17] proposed an efficient parallel genetic algorithm for the solution of large-scale OPF with consideration of practical generators constraints. Computational results indicate that the proposed method is able to provide satisfactory performance and obtains the solution with high accuracy.

In [18], a multi-objective harmony search algorithm is reported for OPF problem. Results show that the proposed method is able to ensure the operating constraints of the system and determine a lower fuel cost solution compared with other results in the literature.

However, few publications take in count the wind power generation cost on power system OPF operations. The literature rarely discusses the problem of how to solve the OPF problem with the integration of a wind power generation on a real power system and how a location of wind turbine can be affect the voltage profile, transmission loss, and fuel costs of a power system?

In this paper, the effects of the integration of three wind farms into the isolated Adrar power system is investigated by solving the OPF dispatching problem using a new hybrid heuristic algorithm.

One of the recently improved heuristic algorithms is the Gravitational Search Algorithm, 'GSA' based on the Newton's law of gravity and mass interactions [19]. GSA has been verified high quality performance in solving different optimization problems in the literature [20-23].

Based on the abilities of PSO and GSA, a hybrid PSO and GSA (PSOGSA) for solving OPF dispatching problem is proposed in this paper.

The impact on a power system of intermittence and fluctuation of wind generation on static operation can be considered as the cost of wind generation by the calculation of the overestimation and underestimation cost of available wind energy based on the Weibull distribution of wind speed and wind turbine model, the frequency distribution of wind farm power output.

The proposed algorithm is demonstrated and the results are compared between them. The results show that the proposed algorithm is capable to give higher quality solutions efficiently in OPF dispatching problem.

2. DESCRIPTION OF ADRAR POWER SYSTEM

The isolated Adrar power system is a small network and poorly meshed. The system consists of five gas turbine units; Adrar, In Salah, Zaouiet El Kounta, Kabertane and Timimoun. Furthermore, an additional of three new wind farms (3 x 10 MW) of the Gamesa G52-850 kW will be integrated in horizon 2015. These wind farms will be connected respectively at Adrar, Kabertane and Timimoun 30 kV stations.

The demanded load varies during different months of the year and during different times of the day following such as climate (winter / summer) conditions and human activity (day / night). The following table shows the forecast of the peaks demanded load and the assumed power factor for the year 2015.

Table 1: Peak load and power factor assumption

Scenario	Active Power (MW)	cos (ρ)
Summer	291	0.85
Winter	175	0.90

2. COST FUNCTION FORMULATION

The OPF problem can be solved by minimizing the total cost of all available generator in the power system. The total cost of all available generator can be mathematically formulated by establishing the objective function. This latter is the sum of the operating costs of each available conventional generator and the wind farms. This is expressed as follows [4-8].

$$\begin{aligned} \min(\cos t) = & \sum c_{G_i}(P_{G_i}) + \sum c_{wi}(W_i) \\ & + \sum c_{p.w.j}(W_{i.av} - W_i) + \sum c_{r.w.j}(W_i - W_{i.av}) \end{aligned} \tag{1}$$

Where P_{G_i} is the generated power of i^{th} conventional generators, W_i is the scheduled wind power of i^{th} wind farm, $W_{i.av}$ is the available wind power of i^{th} wind farm, C_{G_i} is the operating cost function of i^{th} conventional generator, C_{Wi} is operating cost function of i^{th} wind farm, $C_{p.W.i}$ is the penalty cost function for not using all available wind power of i^{th} wind farm due to over-generation, $C_{r.W.i}$ is the cost function of i^{th} wind farm for calling the reserves to cover i^{th} wind farm due to under-generation.

- *Fuel cost of the conventional generator*

Generally, the cost function of i^{th} conventional generator $C_{G_i}(P_{G_i})$ is modeled using a second order polynomial function described as follows:

$$C_{G_i}(P_{G_i}) = a_i + b_i P_{G_i} + c_i P_{G_i}^2 \tag{2}$$

Where, a_i, b_i and c_i are the constants of the fuel cost of i^{th} conventional generator.

- *Operating cost function of the wind farm*

According to [7], the linear cost function assumed for the wind farm is given as follows:

$$C_{W.i}(W_i) = d_i \times W_i \tag{3}$$

Where d_i is the direct cost coefficient of i^{th} wind farm.

- *Cost function due to the over-generation*

The penalty cost causing by not using all the available wind power is related to the difference between the available wind power and the actual wind power used. The mathematical model is written as follows [6, 7]:

$$C_{p.W.i}(W_{i.av} - W_i) = k_{p.i}(W_{i.av} - W_i) = k_{p.i}\int_{W_i}^{W_{r.i}} (W - W_i)\, f_W(W) \tag{4}$$

Where $k_{p.i}$ is the penalty cost coefficient for over-generation of i^{th} wind farm, $f_W(W)$ is the probability density function (PDF) of wind power output.

- *Cost function due to the under-generation*

Similarly, the cost function of i^{th} wind farm for calling the reserves to cover i^{th} wind farm due to under-generation is written as follows [6, 7]:

$$C_{r.W.i}(W_i - W_{i.av}) = k_{r.i}(W_i - W_{i.av}) = k_{p.i}\int_{W_i}^{W_{r.i}} (W - W_i)\, f_W(W) \tag{5}$$

Where $k_{r.i}$ is the reserve cost coefficient for under-generation of i^{th} wind farm.

Indeed, the wind speed distribution is modeled as Weibull PDF as shown in the following formula [24, 25]:

$$f_v(V) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{\left[\left(-\frac{v}{c}\right)^{k}\right]} \tag{6}$$

Where v is the wind speed, k is the shape factor, c is the scale parameter (m/s).

For the Weibull function, the discrete portions of wind energy conversation system (WECS) power output random variable will have the following values [8]:

$$\begin{aligned} P_{rated}\{W=0\} &= F_v(v_{cut-in}) + (1 - F_v(v_{cut-off}) \\ &= 1 - \exp\left(-\left(\frac{v_{cut-in}}{c}\right)^{k}\right) + \exp\left(-\left(\frac{v_{cut-off}}{c}\right)^{k}\right) \end{aligned} \tag{7}$$

$$\begin{aligned} P_{rated}\{W=W_{rated}\} &= F_v(v_{cut-off}) + F_v(v_{rated}) \\ &= \exp\left(-\left(\frac{v_{rated}}{c}\right)^{k}\right) + \exp\left(-\left(\frac{v_{cut-off}}{c}\right)^{k}\right) \end{aligned} \tag{8}$$

The Weibull PDF of the WECS power output random variable in the continuous range takes the form below.

$$f_W(W) = \frac{k\, l\, v_{cut-in}}{c}\left(\frac{(1+\rho\times l)\, v_{cut-in}}{c}\right)^{k-1} \exp\left(-\left(\frac{(1+\rho\times l)\, v_{cut-in}}{c}\right)^{k}\right) \tag{9}$$

Where $\rho = W / W_{rated}$ is the ration of wind power output to rated wind power, $l = (v_{rated} - v_{cut-in}) / v_{cut-in}$ is ration of linear range wind speed to cut-in wind speed.

Where v_{cut-in} and $v_{cut-off}$ are the wind speed in which wind turbine starts the power generation and in which wind turbine is disconnected from network of wind turbine respectively; v_{rated} is the wind speed at which the mechanical power output will be the rated power.

3. MATHEMATICAL FORMULATION OF OPTIMAL POWER FLOW

The main purpose of an OPF dispatching is to determine an optimal scheduling of the available power generation for an economic operation state of the electric power systems by minimizing the total operating costs, while at the same time satisfying the various equality and inequality constraints. The equality and inequality constraints are specified as follows [26]:

Power balance constraints-

$$\sum_{i}^{NG} P_{G,i} + \sum_{i}^{NW} P_{w,i} = \sum P_D + \sum P_L \tag{10}$$

Generation capacity limits-

$$P_{G,i,min} \le P_{G,i} \le P_{G,i,max} \tag{11}$$

$$Q_{G,i,min} \le Q_{G,i} \le Q_{G,i,max} \tag{12}$$

$$0 \le P_{W,i} \le P_{W,i,max} \tag{13}$$

Generation capacity limits-

$$V_i^{min} \le V_i \le V_i^{max} \tag{14}$$

$$\left| S_{ij} \right| \le S_{ij}^{max} \tag{15}$$

4. HYBRID PSOGA ALGORITHM OVERVIEW

The basic idea of PSOGSA is to integrate the ability of social thinking in PSO algorithm with the local search capability of GSA [27].

In GSA, the individuals are a collection of masses which interact with each other by the gravitational force, which an agent represents a solution or a part of a solution.

At the beginning of the algorithm, the initial positions of the agents are randomly fixed and placed in the search space. The position of the i^{th} mass is described as follows:

$$X_i = (x_i^1 \ldots x_i^d \ldots x_i^n) \qquad \text{for} \quad i = 1, 2, \ldots, N \tag{16}$$

where, x_i^d is the position of the i^{th} mass in d^{th} dimension, N is the search space dimension.

According to the Newton gravity theory, the gravitational forces from an agent j acts an agent i at a specific iteration t is calculated using the following equation [19]:

$$F_{ij}^d(t) = G(t) \times \frac{M_{pi}(t) \times M_{ai}(t)}{R_{ij}(t) + \varepsilon} \times \left(x_j^d(t) - x_i^d(t) \right) \tag{17}$$

where M_{pi} is the active gravitational mass related to the agent j, M_{ai} is the passive gravitational mass related to the agent i, $G(t)$ is gravitational constant at time t, ε is a small constant, $R_{ij}(t)$ is the Euclidian distance between i^{th} and j^{th} agents $(\left\| X_i(t), X_j(t) \right\|_2)$.

The gravitational constant $G(t)$ at iteration t is calculated using the following equation:

$$G(t) = G_0 \times \exp\left(-\alpha \times \frac{t}{\max iter} \right) \tag{18}$$

where α and G_0 are descending coefficient and initial value respectively, $\max iter$ is the maximum number iterations.

The total force that acts on agent i is given as follows:

$$F_i^d(t) = \sum_{j=1,\, j \neq i}^{N} \text{rand}_j F_{ij}^d(t) \tag{19}$$

According to the law of motion, the acceleration of an agent is calculated as follows:

$$ac_i^d(t) = F_i^d(t) \Big/ M_{ii}(t)' \tag{20}$$

where M_i is the mass of the object i.

The variation in the velocity is given as follows.

$$v_i^d(t+1) = rand \times v_i^d(t) + ac_i^d(t) \quad (21)$$

where $v_i^d(t)$ and $ac_i^d(t)$ are the velocity and acceleration at iteration t and $v_i^d(t+1)$ is the velocity at iteration $t+1$.

Using the equation 21, the new position of an agent is calculated as follows:

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (22)$$

The termination condition of the algorithm is fixed by the maximum iterations.

PSO algorithm was inspired by social behavior of bird flocking or fish schooling. In PSO algorithm, a member in the swarm called a particle and represents a potential solution; the location food represents the global optimum. The particles fly around in the search space to find the best solution.

At first, PSO algorithm is initialized with a population of random solutions and initial random velocities. At each iteration, a particle's velocity is updated using the following equation [28]:

$$\begin{aligned} v_i(t+1) = v_i(t) &+ \left(c_1 \times rand_1 \times (p_{ibest} - p_i(t))\right) \\ &+ \left(c_2 \times rand_2 \times (p_{gbest} - p_i(t))\right) \end{aligned} \quad (23)$$

where $v_i(t+1)$ is the new velocity for the i^{th} particle, c_1 and c_2 are the weighting coefficient for the best and global best positions respectively, $p_i(t)$ is the current position of a particle i at time t, p_{ibest} is the i^{th} particle's nest known position, and p_{gbest} is the best position known to the swarm.

A particle's position is updated using:

$$p_i(t+1) = p_i(t) + v_i(t) \quad (24)$$

The algorithm iterates until the convergence is achieved or the maximal number of iterations is reached. In order to combine the two algorithms (PSO and GSA), the equation (25) is proposed as follows:

$$v_i(t+1) = w \times v_i(t) + c_1' \times rand \times ac_i(t) + c_1' \times rand \times (gbest - X_i(t)) \quad (25)$$

where $v_i(t)$ is the velocity of agent i at iteration t, c_i' is a weighting factor, w is a weighting function, $ac_i(t)$ is the acceleration of agent i at iteration t, and $gbest$ is the best solution so far.

In each iteration, the positions of particles are updated as follows:

$$X_i(t+1) = X_i(t) + V_i(t+1) \quad (26)$$

4. SIMULATION RESULTS

In order find the optimal solution for the OPF of the isolated Adrar power system with the integration of three wind farms planned for the year 2015 for two economic dispatch scenarios; summer and winter peak load, the PSOGSA has proposed in this paper. The procedure for PSOGSA has been implemented in Matlab programming language.

For implementing the PSOGSA, population size of 10 is taken and the stopping criteria corresponding to the maximum iteration is taken as 200. The minimum solution is obtained for four independent trials and the following parameters are assumed:

Table 2: Assumed optimization parameter

	GSA
G_0	1
α	20
	PSO
C'_1	0.5
C'_2	1.5
W_{max}	0.9
W_{min}	0.4

The operating cost coefficient of the three wind farms is neglected. The penalty and the reserve factors are set to be $k_{p.i} = 0.03\,\$/\text{MWh}$ and $k_{r.i} = 0.03\,\$/\text{MWh}$.

The wind turbine parameters are: P_{rated} = 850 kW, v_{rated} = 13 m/s, v_{cut-in} = 4 m/s and $v_{cut-off}$ = 25 m/s.

Figures 1 to 6 illustrate the optimal solution of four independent trails, convergence curve of PSOGSA and the voltage profile at each substation load.

As shown in Fig. 1 and 3, it is clearly show that the solutions are very close to each other, which gives a better capability and reliability of the PSOGSA.

Convergence curves of SPOGSA approach to OPF solution are given in figures 2 and 3. Figures illustrate the objective function curve for various numbers of generations. It was clearly shown that after about 20 iterations, the objective function does not rapidly change, which improves that the proposed algorithm has a good convergence and metric.

Figures 6 and 5 show the voltage profile of each substation given in per unit, as shown, the lowest value of the voltage achieves a value of 0.93 p.u in Reggane's substation in the summer and 0.98 p.u in Adrar 2 in the winter which are in the acceptable margins setting between ± 7 % for a normal operation of the isolated Adrar power system.

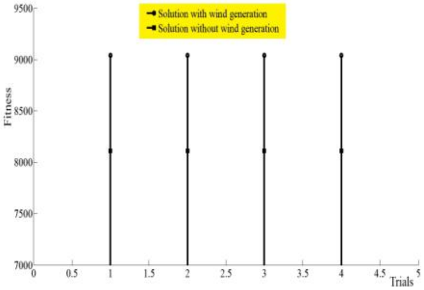

Fig. 1: Trials for the summer scenario

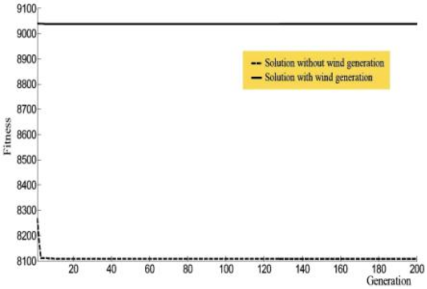

Fig. 2: Convergence curves for the summer scenario

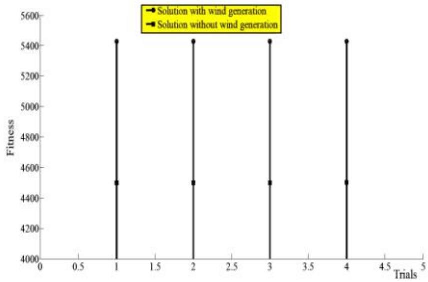

Fig. 3: Trials for the winter scenario

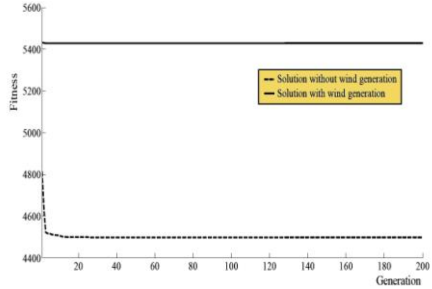

Fig. 4: Convergence curves for the winter scenario

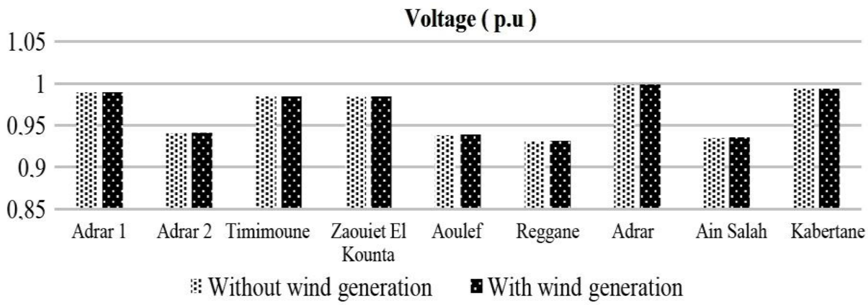

Fig. 5: Voltage profile for the summer scenario

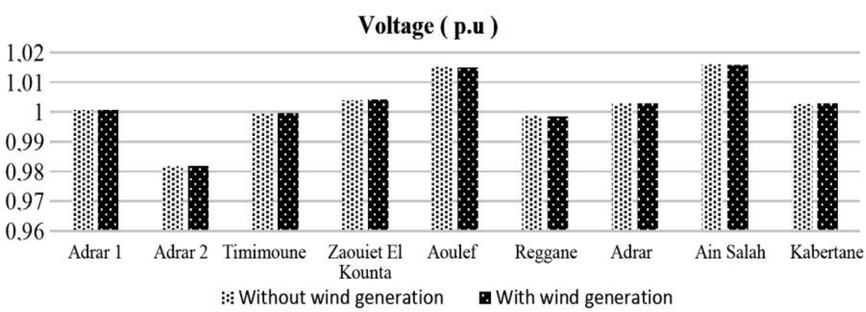

Fig. 6: Voltage profile for the winter scenario

The minimum solutions obtained after four independent trials are summarized in **Tables 3 and 4.** The minimum solutions include, the total cost and active and reactive power losses. The optimum active power generations from the conventional units and the wind farms as shown also and are all within their allowable limits.

Based on the simulation results given in these tables, it is observed that the PSOGSA predicts accurate results while satisfying all inequality and equality constraints.

From the obtained results, due to the low cost of the wind farm compared with the cost of the conventional generators, PSOGSA find that the optimal active power generated by wind farms attain their maximal limits. This improves the reliability and capability of PSOGSA to converge to the optimal solution of the OPF problem.

The integration of three wind farms in Adrar, Kaberten and Timimoun permit to reduce 930 $/MW of the fuel cost; about14 % of the fuel cost.

The results clearly showed that the impact of the integration of wind power generation close to the existing thermal generators does not influence the total active and reactive power loss. Contrariwise, the influence is observed on the generated power by the conventional units that decrease.

For the summer peak load, despite the integration of the three wind farms, Zaouiet El Kounta's thermal unit exceed its maximum capacity limit, and hence re-dispatch is performed. Contrariwise, the integration of the wind farm of 10 MW at Kaberten allows a reduction in the generation power of Kaberten's generation unit, a reduction about 7 MWin summer scenario.

Table 3: The minimum solution obtained without wind generation

Units	Summer	Winter
Adrar	108.9	55.2
Timimoun	35.7	21
Zaouet El Kounta	50	37.6
In Salah	80.1	51.2
Kaberten	17	10.2
Total	**291.7**	**175.2**
Total fuel cost ($/hr)	**9038.7**	**5428.6**
Fitness ($/hr)	**9038.7**	**5428.6**
Total loss (MW)	**0.7**	**0.2**

Table 4: The minimum solution obtained with wind generation

Units	Summer	Winter
Adrar	97	39.2
Timimoun	24.4	10
Zaouet El Kounta	50	34.3
In Salah	80.1	51.7
Kaberten	10	10
Total	**261.5**	**145.2**
Total fuel cost ($/hr)	**8108.7**	**4498.7**
Adrar (Wind Power)	10	10
Kaberten (Wind Power)	10	10
Timimoun (Wind Power)	10	10
Total wind power	30	30
Total wind cost ($/hr)	0.1212	0.1212
Fitness ($/hr)	**8108.8**	**4498.8**
Total loss (MW)	**0.5**	**0.2**

5. CONCLUSION

In this paper, based on the abilities of PSO and GSA, the proposed PSOGSA for solving optimal power flow dispatching problem is applied to the isolated Adrar Algerian power system consisting of five gas turbine units and with the integration of three new wind farms of a Gamesa G52 type expected for the horizon 2015.

The results showed that the integration close the gas turbineunits of the wind farms into the isolated Adrar power system permit to reduce of about 14 % of the fuel cost.

The PSOGSA predicts accurate results while satisfying all inequality and equality constraints, this algorithm has achieved very fast solutions after about 20 iterations. The paper demonstrated that the PSOGSA method can be applied easily to the economic optimal power flow dispatching problems.

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