Wind Farm Layout Optimization using Real Coded Multi-population Genetic Algorithm

M[d] AMINE HASSOINE
Faculty of Sciences
Ibn Tofail University,
Kenitra, Morocco
romema@yahoo.fr

FOUAD LAHLOU
Faculty of Sciences
Ibn Tofail University,
Kenitra, Morocco
lahloufouad@hotmail.com

ADNANE ADDAIM
National School of Applied Sciences Ibn Tofail University, Kenitra, Morocco
adnane.addaim@uit.ac.ma

ABDESSALAM AIT MADI
National School of Applied Sciences
Ibn Tofail University,
Kenitra, Morocco
abdessalam.aitmadi@uit.ac.ma

Abstract— Finding the optimal location of wind turbines is a challenging work by reason of the various effects of the turbine wake. Indeed, on a site gathering several wind turbines, if the turbines are too close the loss of power grows with the wake effect. In this paper, an RC-MPGA (Real Coded Multi-population Genetic Algorithm) method is proposed to search the optimal location of WTs (Wind Turbines) in Square shaped WF (wind farm), Installed on an area of 4000000 m2 (2000m×2000m), with the aim to maximize the electrical power generated by all WTs and grows the annual economic profitability of the WF. By using the same WF environment conditions, we can see that the proposed method is promising and presents an improvement in terms of maximum power generation when compared to other works previously studied in the literature.

Keywords: Wind Energy, Wind Farm, Power, Cost, layout, Optimization, RC-MPGA, Genetic Algorithm.

I. INTRODUCTION

Wind power is increasingly becoming the first alternative renewable energy resource, this energy is greener than traditional sources such as coal or oil . Wind farms (WFs) becoming bigger than ever before, every year the part of wind energy in the world production grows, at 2017 the total capacity installed of all WTs in the world exceeds 539 000 Megawatt [1].

Wind weather data is generally insufficient to design a renewable energy project such as WF. In addition to these data, the model of the speed frequency distribution and the model of wind direction frequency distribution for a long time are decisive to feasibility in this category of project. The geographic location of WTs and its positions are so the two major critical factors in wind farms design.

The perfect wind conditions would be strong regular wind and unidirectional. To realize these conditions, in order to extract a maximum total power from wind farms, with minimum investment cost, site farms are usually screened, on the basis of the factors cited above. The optimal positions, geographic location of WTs in wind farms, and detailed wind maps are constructed before installing wind generators.

in the real case, the implantation of a new WF is based on an iterative approach, once the site is selected, the most appropriate WT is achieved by simulation of different types of WTs, the optimal number of WTs is calculated and arranged within the WF, this process is repeated until the best configuration of WF.

To carry out the best WF layout and choose the best known WTs positions, optimization methods are usually used. Especially, genetic algorithms, which propose the solutions to successfully achieve this task. Notable studies, using a genetic algorithm, have been done in the layout process of WF by different previous researchers [2, 3, 4, 5]. The first genetic algorithm approach for WTs layout was used by Mosetti [4]. In this research, Jensen's wake model [6] is used to model the wakes of the WTs. In fact, if the wake effects, reduction in wind velocity caused by turbines placed in front of other turbines [7], are not taking into account in WTs farms design, WTs produces less energy than predicted. In the model proposed in [6], a hypothetical 2000m ×2000m WT farm was segmented into 100 squares. in these subdomains, the WTs are arranged. The objective function was the ratio of cost per power to obtain the best WF layout.

In this work, we propose the use of the previous RC-MPGA (Real Coded Multi-population Genetic Algorithm) for the best WF layout searching, taking into account the wake influence. In order to appraise the performance of this algorithm, some obtained results of the present study, which followed an identical wake model are compared to the antecedent studies proposed in the literature.

The organization of this paper is presented as follows. Section 2 presents a brief presentation of the wind farms model. Section 3 gives the optimization method. The results and their interpretations are discussed in section 4. The conclusion of this proposed work is given in section 5.

II. WIND FARM MODEL

A. Wake model

When wind flows through the rotor of a WT behind another WT, the wake expands with down-stream distance. The model used here is a Jensen wake model [6]. This model assumed that the wake expands linearly with down-stream distance as illustrated in Fig1. The velocity deficit is a loss due to the interaction between two WTs placed one behind the other, velocity deficit calculation at down-stream distance is given by equation 1:

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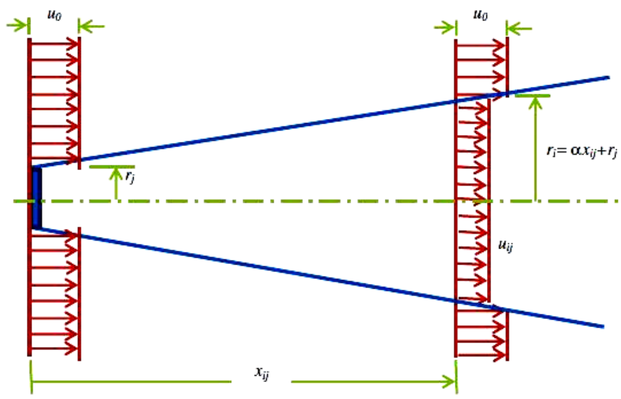

Fig. 1. WT wake model [15]

$$u_{ij} = u_0 \left[1 - \left(\frac{2a}{\left[1 + \alpha \left(x_{ij} / r_i \right) \right]^2} \right) \right] \quad (1)$$

Here, u_{ij} and u_0 is respectively wind speed in the downstream region and the free speed of the wind in front of the WT, x_{ij} and r_i is respectively the distance from WT to the downstream region and the rotor radius at downstream region and a is the axial induction factor.

the entrainment constant α depends on the nature of the terrain (Surface Roughness Length) and the height of the WT, α is given as shown in [8] by the equation 2.

$$\alpha = \frac{0.5}{\ln\left(z / z_0 \right)} \quad (2)$$

Here, z_0 and z is respectively the surface roughness and the hub height.

The Betz relations allow the calculation of downstream rotor radius, The Betz relations are given as shown in [8] by the equation below.

$$r_i = r_j \sqrt{\frac{(1-a)}{(1-2a)}} \;\; ; \; a = \frac{1 - \sqrt{1 - C_T}}{2} \quad (3)$$

Here, C_T is the thrust coefficient.

In the superposition of several wakes of N turbines, at downstream region the resulting velocity of WT i can be expressed by equation 4 [9].

$$\left(1 - \frac{u_i}{u_0} \right)^2 = \sum_{\substack{j=1 \\ j \neq i}}^{N} \left(1 - \frac{u_{ij}}{u_0} \right)^2 \quad (4)$$

where u_{ij} is the velocity in the downstream wake region of the turbine j which affects the turbine i.

So to decrease the speed deficit caused by all the turbines, WTs should be spaced as far as possible in the direction of the prevailing winds.

B. Power calculation

The WT converts the kinetic energy of the wind into electrical energy, this energy depends directly on the wind force, the power is approximately proportional to the cube of wind speed. In the process of energy conversion, the size of the rotor diameter and the value of velocity greatly affect the power value produced by the WT. The power generated from a WT is given as shown in [10], by equation 5.

$$P_{WT} = \frac{1}{2} \eta \rho A u^3 \quad (5)$$

Where, η is efficiency of WT, ρ is density, A is area which generated by the rotor of the WT and u is wind speed. The WF specifications [2, 3, 4, 5] used in our study are given by the Table I below.

TABLE I. WF AND WT PARAMETERS

Parameters	Specifications
Hub height (Z)	60 m
Rotor radius (Rr)	20 m
Downstream rotor radius (Rd)	27.881 m
Thrust coefficient (C_T)	0.88
Roughness length of ground (Z_0)	0.3 m
The entrainment constant (α)	0.09437
The axial induction factor (a)	0.326795

In the case where the efficiency of WT η equals to 40%, the equation 5 will become as follows:

$$P_{WT} = \frac{40}{100} \times \frac{1}{2} \times 1.2 \times \pi \times (20)^2 \times u^3$$
$$P_{WT} = 0.3 u^3 KW \quad (6)$$

C. Wind farm efficiency

The total power generation in the WF is given by:

$$P_{wf} = \sum_{i=1}^{N} P_i \quad (7)$$

where, N is the number of WT and P_i is the power of WT i .

The efficiency of the WF is the ratio of the total power produced by the WF to the sum of the power for each individual WT. The efficiency of the farm can be expressed as shown in [16], by equation 5.

$$\eta_{wf} = \frac{P_{wf}}{\sum_{i=1}^{N} P_{si}} \quad (8)$$

where P_{si} is the power of WT i if it is functioning as a single turbine.

In the case of constant direction with a velocity of 12m/s, the equation 8 will become as follows:

$$\eta_{wf} = \frac{P_{wf}}{\sum_{i=1}^{N} 0.3 u_0^{\,3}} \tag{9}$$

D. Cost model and objective function

In this article, we use the cost function used in the articles [2, 3]. It is a function of WTs number (N) and it is given by the equation below.

$$Cost = N\left(\frac{2}{3} + \frac{1}{3} e^{-0.00174 N^2}\right) \tag{10}$$

Fig. 2 shows the cost plotted against WTs number (N). The first derivative of the cost is also plotted in Fig. 3. From these figures, we can see that the function grows linearly at N > 30. This implies that for (1+N)th turbine the cost is superior compared to the Nth turbine at N > 30.

Further, with the aim to find the best WF layout in-terms of minimum unit cost of energy produced. The goal can be defined as maximizing the power produced P_{farm} while minimizing the installation cost of WF.

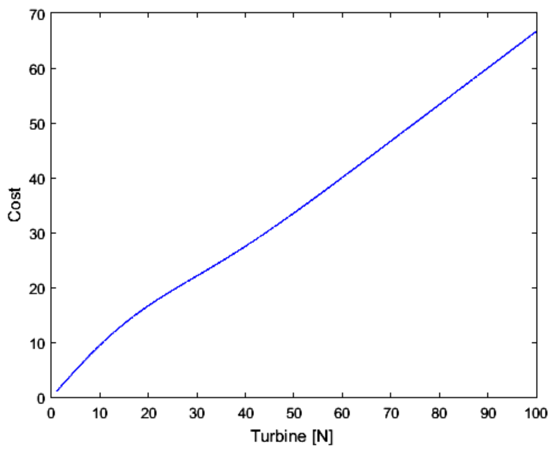

Fig. 2. Cost of WF

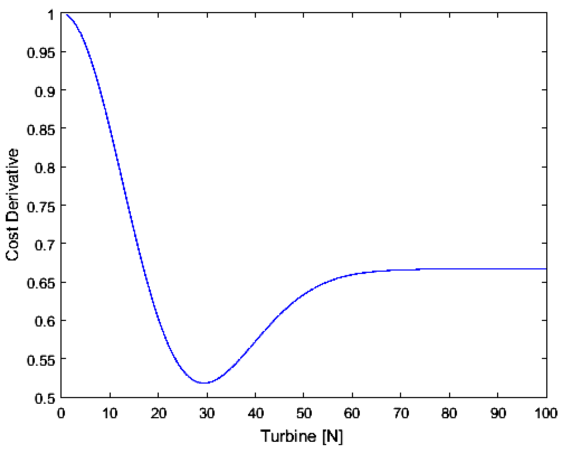

Fig. 3. Rate of change of the cost function

In this article the objective function will be used, this function serves as a criterion for determining the best arrangement of the WF. The goal is then to minimize this function up to the optimum, this function will be used. As shown by Grady [3]. This objective function is expressed by the following equation 11.

$$\text{Objective} = \frac{\text{Cos}\,t}{p_{wf}} \tag{11}$$

III. OPTIMIZATION METHOD

We consider 2000m×2000m wind farm that is segmented into 100 squares (200m×200m). Unlike past approaches in which a WT would be placed in the center of the square, this present analysis restricts the minimum distance between two neighboring WTs to 200m and WTs can be implemented freely in the WF. To execute our approach, we have developed a MATLAB software code using the previous proposed RC-MPGA. The output computing results are the wind speed, WF power, and the cost. The program will be stopped provided that the best fitness stills the same without any change in 500 iterations. The variables for the RC-MPGA code are given by the Table II.

TABLE II. VARIABLES FOR RC-MPGA

Variables	Value
Number of Population	10
Rate of mutation	0.05–0.1
Rate of crossover	0.7–0.9
Population size	45

IV. RESULTS AND DISCUSSION

In the present study, unidirectional velocity of 12m/s is considered, 45 individuals with 10 populations were allowed to evolve over 2000 iterations. After the execution of the RC-MPGA program for 1274 iterations, the best solution for 30 WTs placement in WF is achieved with a best fitness value of 0.0014379. It can be seen that the improvement of the layout evolution is very fast at the beginning in global search and becomes slower and slower as time goes by local search. The comparison results between two cases of WTs (N=26 and N=30) is presented in Table III. For 26 WTs in the WF, the total power is 13377 kW, the fitness value is 0.0014955 and the efficiency is 99.25 %. For 30 WTs, the total power is 15362 kW, the fitness value is 0.0014379 and the efficiency is 98.77 %.

TABLE III. COMPARISON OF SOLUTION —CASE (I) AND CASE (II)

	Case i	Case ii
Fitness value	0.0014955	0.0014379
Total power (kW)	13377.59	15362.17
Efficiency (%)	99.25	98.77
Number of WTs	26	30
Number of iterations	2000	2000

The best solutions of WTs layout are depicted in Fig. 4 (N=30) and Fig.5 (N=26). The optimized result obtained for 30 WTs shows that the optimal arrangement for 30 WTs gives a cost lower than 26 WTs. On the other hand, the arrangement of 26 WTs gives a better yield, but by adding 4 WTs, the research space has become narrower for looking an optimal arrangement, so if the size of the WF is large enough the number of the WTs increases and the search for the best solution becomes beneficial. Fig. 4 shows a denser arrangement than Fig. 5.

The Fig. 6 shows 30 WTs layout evolution over the searching period.

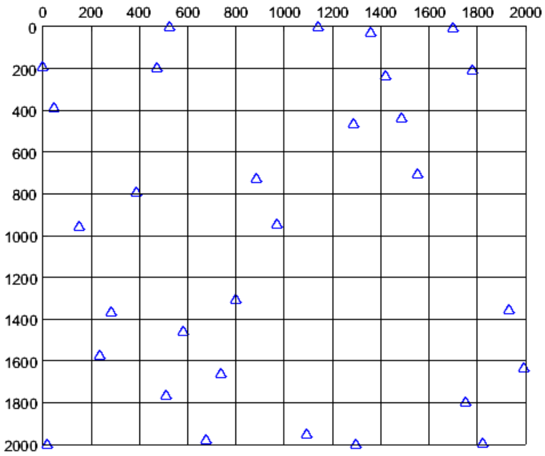

Fig. 4. Optimal solution of 30 WTs layout

Moreover, the fitness evolution, the efficiency evolution and total power evolution of 30 WTs over the searching period are depicted respectively in Fig. 7, 8 and 9.

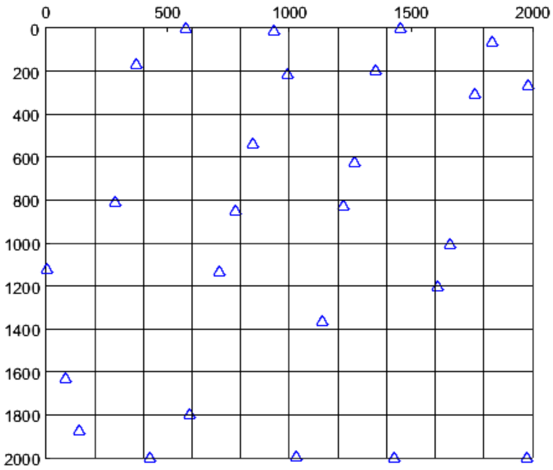

Fig. 5. Optimal solution of 26 WTs layout

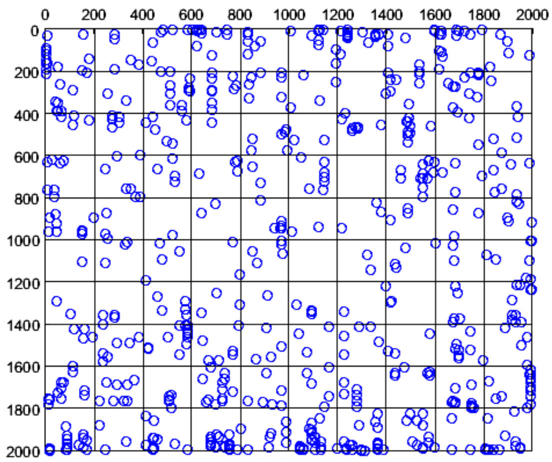

Fig. 6. 30 WTs layout evolution.

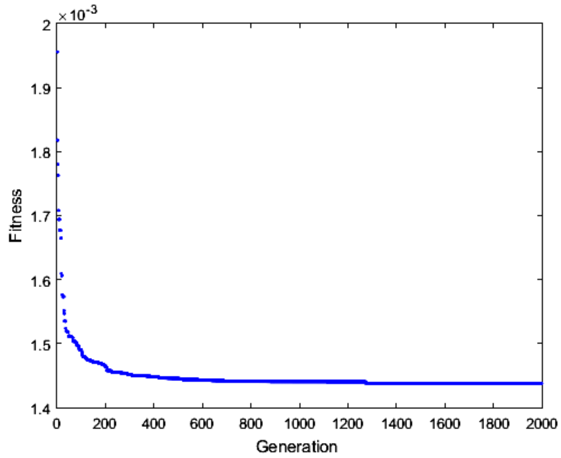

Fig. 7. Fitness evolution of 30 WTs

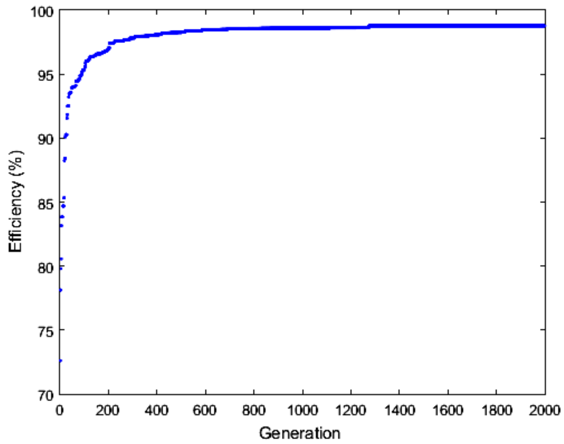

Fig. 8. Efficiency evolution of 30 WTs.

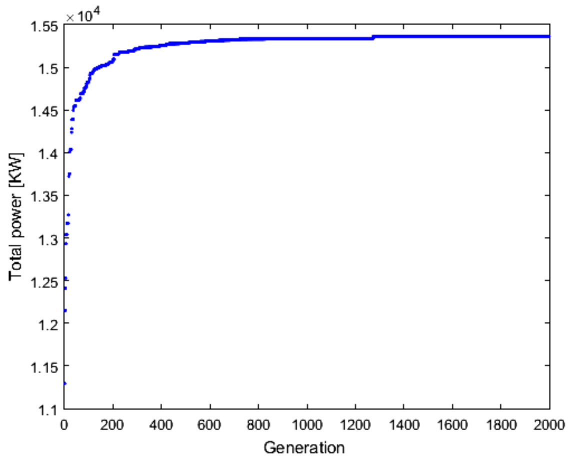

Fig. 9. Total power evolution of 30 WTs.

The Table IV shows a comparison between the results obtained and those of other studies.

TABLE IV. COMPARISON RESULTS

Studies	Number of WT	Total power (kW)	Fitness value ($\times10^{-3}$)	Efficiency (%)
[2]	26	12352	1.620	91.65
[3]	30	14310	1.544	92.02
[11]	30	15262	1.4473	98.1
[4]	30	14310	0.12217	92
[12]	30	14310	1.544	92.02
[13]	30	14336	1.541	92.18
[14]	30	14310	1.544	92.02
[15]	30	14310	1.544	92.02
[5]	26	13141	1.523	97.50
[5]	30	15346	1.440	98.67
[17]	30	15091	1.4637	-
Proposed	**26**	**13377**	**1.4955**	**99.25**
Proposed	**30**	**15362**	**1.4379**	**98.77**

V. CONCLUSIONS

In this article, we have applied a real coded multi-population genetic algorithm (RC-MPGA) approach to achieve the best placement of WTs in order to get the most out of the power production. The carried out results from Matlab Software showed that the proposed method improved the power generation compared to various methods for implementation of GA studied in the literature.

In the ongoing research, we will take into consideration the real complex wind condition of the WFs by varying wind speed intensity and direction.

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