Optimization of the Substation Location within an Offshore Wind Farm using Particle Swarm and Genetic Algorithms

CHAKIB EL MOKHI
National School of Applied Sciences
Ibn Tofail University,
Kenitra, Morocco
chakib.elmokhi@uit.ac.ma

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

***Abstract*—This paper presents the optimization of the substation location of a wind farm using metaheuristic algorithms. Using this method, the total length of the cables can be reduced, which has a direct impact on the electrical power losses. The cost of the electrical system is estimated to be 15-30% of the total investment cost. By optimizing the substation location, these high costs can be avoided during the design phase of the wind farm. The optimization methods are tested on both a regular and an irregular wind farm. To verify the reliability of the optimization methods, a real existing offshore wind farm is used. The results of the proposed optimization show that substation location optimization is an effective way to design the wind farm layout with low cost.**

***Index Terms*—Wind farm cable layout, substation, power collection system, power losses, metaheuristic optimization.**

I. Introduction

Interest in renewable energies has grown worldwide, especially in wind energy. However, installation costs are high for both onshore and offshore wind farms. In particular, the cost of electrical cabling for the collection and transmission system, based on offshore wind experience, is estimated to be $15-30\%$ of the total investment cost [1]. Therefore, the application of optimization techniques in the development phase of such an electrical system can lead to significant economic gains by finding the optimal location of the substation and the optimal routing of the grid. This minimizes not only the construction costs, but also the other costs associated with power losses and system maintenance.

Several studies have addressed the optimal locations of wind turbines considering the wake effects [2] [3] [4] to improve energy efficiency and minimize energy losses. However, very few works are devoted to the optimization of substation location, optimization of electrical cabling, and selection of proper cable cross-sections for the electrical system. This article focuses on the optimization methods to find the best solution for the substation location.

The energy generated by each wind turbine is first collected via the electrical lines and transmitted to the substation. At this substation, the voltage is converted to the desired transmission voltage levels and can then be fed into the main grid.

This article is organized as follows. Section II presents the metaheuristic optimization algorithms such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), which are used to optimize the substation location. Section III presents the optimization results on a regular and irregular power collection system with some assumptions. In Section IV, the optimization process is performed on a real existing offshore wind farm. The conclusions and future work are presented in Section V.

II. Optimization Algorithms

A. Genetic Algorithm

Genetic algorithms, also called evolutionary algorithms, are inspired by Charles Darwin's concept of natural selection. GA belong to a family of bio-inspired populations based on heuristic optimization algorithms that borrow ideas from natural evolution. The concept of genetic algorithm was proposed in 1975 by John Holland of the University of Michigan to describe adaptive systems [5]. It involves the optimization of individuals competing against each other for resources. Some individuals are better suited for this purpose and therefore have a greater chance of survival and can pass on their traits to their offspring, while others do not. These traits are defined in the hereditary material. A single parameter describing a trait is called a genome. A whole set of such genomes is a chromosome. It is important to define a coding of the information so that the genomes can always be assigned to the same property. There are three criteria for further development:

- **Selection**: According to certain defined criteria, the most suitable individuals are selected for reproduction.
- **Crossing**: The new genome consists of a part of the parent **A** and a part of the parent **B**. The genetic information is thus recombined.
- **Mutation**: Errors that occur lead to a change in the genetic information.

When optimizing the substation site with GA, the proposed solutions within the population are formulated in such a way that the coding can be viewed as a genome that defines each solution. The evaluation function is used to determine the fitness of each solution. In this case, the fitness is the position of the substation to all turbines, where the sum of all distances should take the smallest value. If this is the case, the optimal location of the substation has been found.

The flowchart in Fig. 1 shows the main steps of a GA. First, single pairs of individuals are selected from the population to generate new proposed solutions. Then, the pair undergoes what is called crossover [6]. In this crossover, the two parents are combined to generate two new children that receive 50% of their genome from each parent. To ensure that the GA does not stick to a local solution, a mutation operator is used to randomly change the child solutions. These steps are repeated until the solutions converge or the remaining population no longer has sufficient differences.

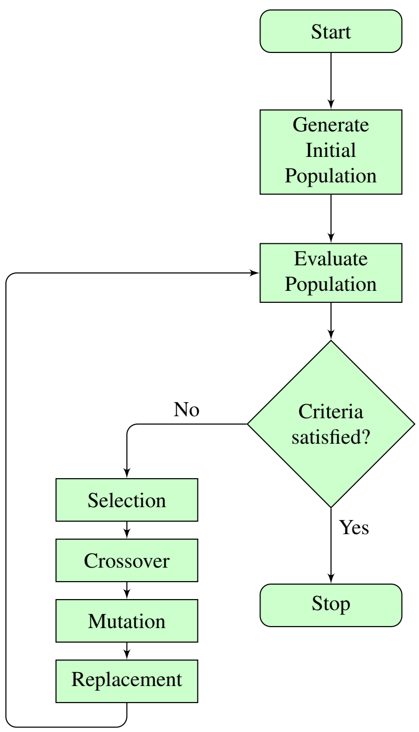

Fig. 1. Flowchart of the Genetic Algorithm

B. Particle Swarm

Particle Swarm Optimization (PSO) is a metaheuristic optimization that originated in the USA in 1995. It was invented by Russel Eberhart (electrical engineer) and James Kennedy (social psychologist) [4] [7]. Like the GA, this algorithm is modeled after a biological system, although unlike the GA, it is not based on an evolutionary process, but on the behavior of birds and fish living in groups, i.e., their behavior. The algorithm starts with a random initialization of the particle swarm in the search space. Each particle is modeled by its position in the search space and by its velocity. At each instant, all particles will adjust their positions and velocities, that is, their trajectories with respect to their best positions, to the particle with the best position in the swarm and to their current position. In reality, each particle is influenced not only by its own experience, but also by that of the other particles. In PSO, the position of each particle in a given iteration is related to its previous position as expressed in Equation (1):

$$x_i = x_{i-1} + v_i \tag{1}$$

where the velocity v_i is given by:

$$v_i = C_1 v_{i+1} + C_2(p - x_{i-1}) + C_3(g - x_i - 1) + C_4 r \tag{2}$$

where C_1, C_2, C_3, and C_4 are coefficients representing the weights of the different contributors determined by tuning PSO to the problem at hand; p is the best position of the particle in question, g is the best position of the swarm, and $r \in [0, 1]$ is a random number [7] [8].
The main approach of PSO is shown in Fig. 2.

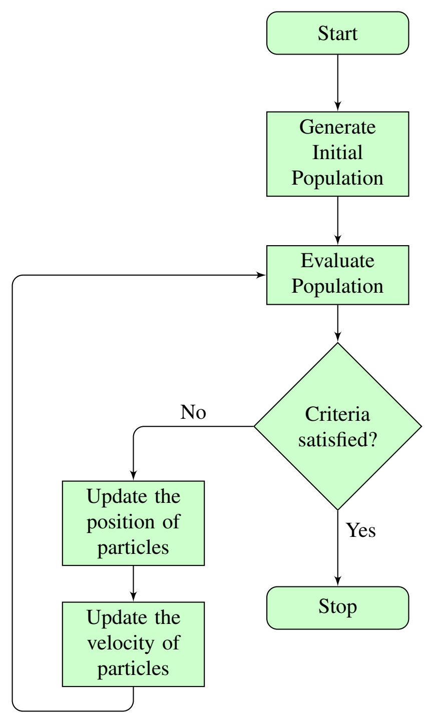

Fig. 2. Flowchart of the Particle Swam Optimization Algorithm

III. Optimization of the Substation Location

A. Regular Wind Farm Layout

To assess the two algorithms GA and PSO, we first consider some assumptions. The case is a regular wind farm array consisting of 64 turbines. The distance between all turbines is $1km$ each. The substation is located outside the turbines and has 8 cable entries. The cables are laid in a string structure. The calculated cable length between the arrays for the power

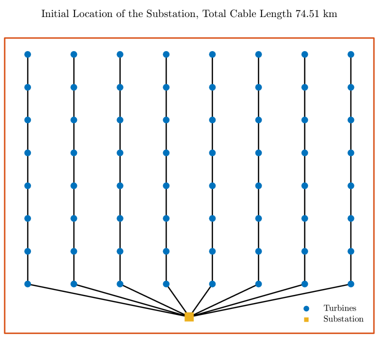

Fig. 3. Initial regular wind farm layout

collection system is approximately $74.5km$. Fig. 3 shows the above assumptions.

After minimizing the objective function with the GA algorithm by minimizing the Euclidean distance from the substation to each of the turbines, we found that the total length of the inter-array cable is $69km$. Fig. 4 shows the optimal location of the substation and the calculated total cable length.

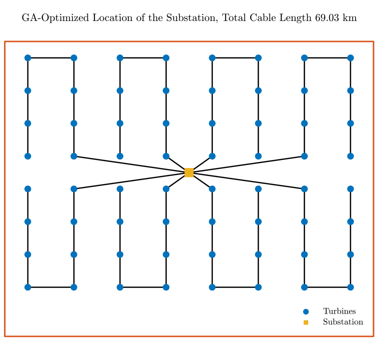

Fig. 4. Optimal substation location with GA algorithm

Using the PSO algorithm, the result for the total cable length of the collection system is also $69km$, similar to the GA algorithm. However, the computation time of the optimization with PSO is much shorter than with the GA algorithm. Fig. 5 shows the result of the PSO algorithm.

Both algorithms, GA and PSO, give the same results for a regular wind farm layout. The saved cable length is $5.48km$, which is 7.36% of the total cable savings.

B. Irregular Wind Farm Layout

In this case, the turbines are generated randomly. The minimum distance between the turbines is $1km$. The substation is located outside the turbine field and has 5 cable entries with 6 turbines each. The total cable length for the collection system is $49.24km$. The initial state is schown in Fig. 6.

Applying the GA and PSO algorithms to optimize the substation location when the string structure of the wind farm layout is irregular also gives very good results. The saved cable length is about $4.10km$, which is equivalent to 8.32% cable length savings. Figures 7 and 8 show the results for GA and PSO algorithms, respectively.

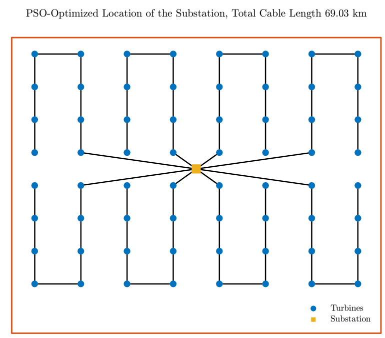

Fig. 5. Optimal substation location with PSO algorithm

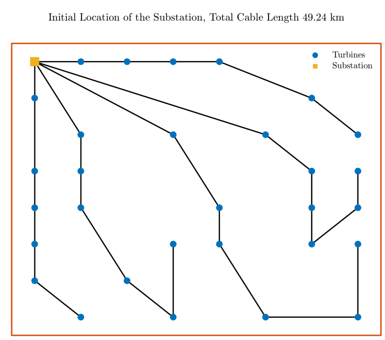

Fig. 6. Initial irregular wind farm layout

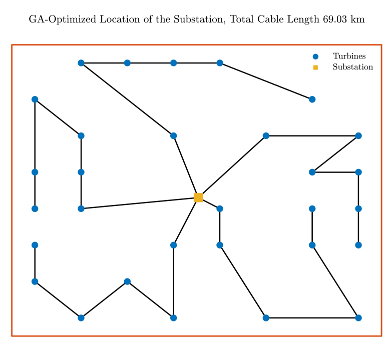

Fig. 7. Optimal substation location with GA algorithm

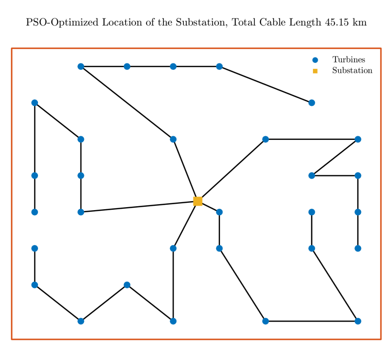

Fig. 8. Optimal substation location with PSO algorithm

IV. Real case study - Horns Rev 1

"Horns Rev 1" was built on an area of $20km^2$ off the coast of Denmark. The offshore wind farm consists of 80 turbines. Table I shows more information about the offshore wind farm and Fig. 9 shows the power curve characteristics for the wind turbine.

TABLE I
Wind Farm Specification [9]

Name	**Information**
Number of turbines	80
Wind farm capacity	$160MW$
Wind turbine capacity	$2MW$
Annual energy production	$600GWh$
Turbine model	$\text{V}80-2MW$
Manufacturer	Vestas
Coordinates	$55.529722, 7.906111$

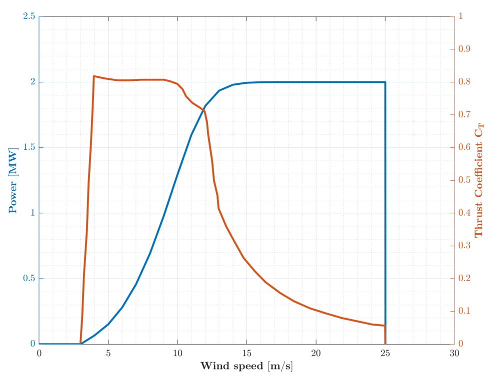

Fig. 9. Power curve of the wind turbine Vestas $V80-2MW$

The initial substation location and the initial layout is shown in Fig. 10.

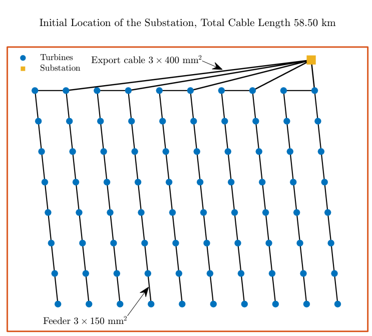

Fig. 10. Wind farm layout of Horns Rev 1

For this case study, it is assumed that the total cable length for the power collection system is $58.50km$. In reality, the length for the cable topology is $63km$ [10]. The distance between the turbines is $560m$, which is 7 times the diameter of the turbines. The substation is located outside the turbine field and has 5 cable entries.

After optimization with the two proposed algorithms GA and PSO, interesting results are provided. It is assumed that the substation has 6 cable entries to avoid the crossing between the submarine cables. The layout has 6 cable branches, 4 with 16 turbines each and 2 with 8 turbines each. Figures 11 and 12 show the proposed cable routing after the substation site optimization. The saved cable length for the power collection system is very interesting and is $12.63km$, which is a saving of 21.60% of the total cable length.

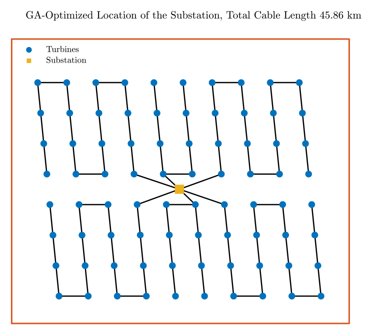

Fig. 11. Optimal substation location with GA

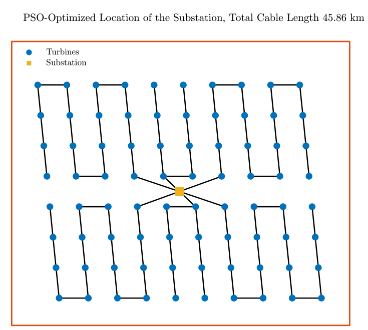

Fig. 12. Optimal substation location with PSO

V. Conclusions and future work

This paper focuses on substation siting optimization using metaheuristic algorithms. These algorithms have been tested on both regular and irregular wind farms and show good results in terms of saving cable length for the power collection system. The length of the cable has a direct impact on the power loss and the total investment cost. That is, the longer the cable, the higher the power losses and the total investment cost. The reliability of the GA and PSO optimization methods was verified using a real existing offshore wind farm. The results were satisfactory. However, to further verify the reliability, this work needs to be extended to optimization and selection of the appropriate cable cross-section.

References

[1] Fischetti, M.; Pisinger, D. Optimizing wind farm cable routing considering power losses. *Eur. J. Oper. Res.* **2018**, *270*, 917–930, doi:10.1016/j.ejor.2017.07.061.

[2] Hassoine, M.A.; Lahlou, F.; Addaim, A.; Ait Madi, A. Wind Farm Layout Optimization using Real Coded Multi-population Genetic Algorithm. In Proceedings of the 2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS 2019), Fez, Morocco, 2019, pp. 1-5.

[3] Hassoine, M.A.; Lahlou, F.; Addaim, A.; Ait Madi, A. A Layout Investigation of Large Wind Farm in Akhfennir using Real Coded Genetic Algorithm. In Proceedings of the Third International Conference on Computing and Wireless Communication Systems (ICCWCS 2019), Kenitra, Morocco, 24–25 April 2019.

[4] Gao, X.; Yang, H.; Lu, L.; Koo, P. Wind turbine layout optimization using multi-population genetic algorithm and a case study in Hong Kong offshore. *J. Wind Eng. Ind. Aerodyn.* **2015**, *139*, 89–99, doi:10.1016/j.jweia.2015.01.018.

[5] Hachimi, H. *Hybridations D'Algorithmes Métaheuristiques en Optimisation Globale et leurs Applications*; HAL Archives: Lyon, France, 2013.

[6] Gass, S.I.; Fu, M.C. *Encyclopedia of Operations Research and Management Science*, 3rd ed.; Springer: Berlin, Germany, 2013; ISBN 978-1-4419-1154-4.

[7] Kiranyaz, S.; Ince, T.; Gabbouj, M. *Multidimensional Particle Swarm Optimization for Machine Learning and Pattern Recognition*, 1st ed.; Springer: Berlin, Germany, 2014; ISBN 978-3-642-37846-1.

[8] Ellaia, R.; Hachimi, H.; ELHami, A. A New Hybrid Genetic Algorithm and Particle Swarm Optimization. *Key Eng. Mater.* **2012**, *498*, 115–125, doi:10.4028/www.scientific.net/KEM.498.115.

[9] Wikipedia contributors. (2019, September 22). Horns Rev Offshore Wind Farm. In Wikipedia, The Free Encyclopedia. Retrieved 18:00, November 12, 2019, from https://en.wikipedia.org/w/index.php?title=Horns_Rev_Offshore_Wind_Farm&oldid=917114470.

[10] Maselis, A. (2016). Layout Optimization of Offshore Wind Farms affected by Wake effects, Cable topology and Support Structure variation.