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A New Tool for Wind Farm Optimal Design

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Abstract-- An Evolutive Algorithm (EA) for wind farm optimal design is presented. The algorithm objective is to optimize the profits given an investment on a wind farm. Net Present Value (NPV) will be used as a figure of the revenue in the proposed method. To estimate the NPV is necessary to calculate the initial capital investment and net cash flow throughout the wind farm life cycle. The maximization of the NPV means the minimization of the investment and the maximization of the net cash flows (to maximize the generation of energy and minimize the power losses). Both terms depend mainly of the number and type of wind turbines, the tower height and geographical position, electrical layout, among others. Besides, other auxiliary costs must be to keep in mind to calculate the initial investment such as the cost of auxiliary roads or tower foundations. The complexity of the problem is mainly due to the fact that there is not analytic function to model the wind farm costs and most of the main variables are linked.

***Index Terms*--Wind farms, genetic algorithm, evolutive algorithm, optimization.**

I. Introduction

Nowadays the weight of the electrical generation based on renewable energy sources has grown in a spectacular way with regard to other conventional energies. This is mainly due to factors such as a bigger social environmental concern (Kyoto protocol and white book EU), the high and growing prices of the traditional fossil fuel, among others. Focusing on the types of renewable energy, it is a well-known fact that the wind energy has experienced the biggest grown. At the beginning of the year 2008 there were 57.1 GW in the European Union and 93.9 GW were in operation all over the world, with a yearly growing ratio of 25%, almost constant level during the last decades. That is why the development of an effective tool for the design and lay out of wind farms has a special relevance.

However, in spite of the huge growing experienced by this technology still nowadays there is scarce significant literature about the optimization of wind farm problem, probably due to its complexity. To date, there are only three relevant papers that use a mathematical model to optimize only the solution of the wind turbines location problem (positioning or micrositting) in a wind farm [1-3].

This paper describes a new global optimization tool to determine the optimal wind farm configuration [4-7]. This global optimum design is performed by choosing the type, height rated capacity and layout (geographical individual location) of the wind turbines, designing the auxiliary roads as well as the configuration of the electrical infrastructure, including the inner MV distribution network, the substations and the HV evacuation lines. This problem is subjected to several constraints such as the radial configuration of the electrical network, the voltage or thermal limits, as well as physical routing lines constraints, such as obstacles or forbidden zones, among others.

The algorithm proposed to solve the global wind farm optimization problem integrates the performance of two nested EA [8-10]. The master EA calculates the type, rated capacity, tower height and position of every turbine to be placed in the wind farm as well as the inner auxiliary road of the wind farm. This first main algorithm controls a second slave EA that optimize the design of the whole electrical infrastructure. This second EA calculates the configuration of the inner distribution network, the substation and the evacuation line that connects the wind farm with the transmission system.

The content of the paper is organized in three main sections as follows:

- Analysis of the wind farm costs, where the purpose of the developed tool will be stated, showing the main problem variables and how they affect the investment and the profits.
- Implementation of the evolutionary algorithms, paying special care on the genetic operators specifically developed for this tool.
- Results and conclusions, where the results of a test case is analyzed and the advantages of using the proposed global optimization tool are summarized.

II. Analysis the Wind Farm Cost

As often done in the investment analysis, the Net Present Values is used as a figure of merit to compare the profitability of a wind farm investment. A wind farm with a certain turbine configuration (turbine rated capacity, type, height and location), x, requires an initial capital investment to build and put the facility in production, $I_{WF}(x)$. This initial investment is necessary mainly to afford the wind turbine acquisition costs,

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as well as the civil and the electrical infrastructure costs. The wind farm, once in operation, delivers a stream of both financial benefit (profits from the generated electric energy selling), $P_{ES}(x)$, and ordinary operation and maintenance costs, $C_{O\&M}(x)$, year after year, during the installation life time or production period, LT. A final present cost for the installation decommissioning, $C_D(x)$, and a present residual value, $V_R(x)$, after the production period, must also be considered. This way, the net present value of the wind farm initial capital investment, $I_{WF}(x)$, for an installation live spam of LT years with an equivalent discount rate, r, can be written as:

$$NPV(x) = -I_{WF}(x) - C_D(x) + V_R(x) + \sum_{k=1}^{LT} \frac{N_k(x)}{(1+r)^k} \quad (1)$$

Where the net cash flow, N_k, represents the net incomes produced by the wind farm during the *k-th* year.

Therefore, the maximization of the NPV means a balance between the minimization of the investment and the maximization of the net cash flows (to maximize the generation of energy and minimize the power losses) (1). Both terms depend on the number and type of wind generators, the tower height, geographical position, position substation, electrical layout, among other. Table I shows a typical cost distribution of a wind farm, adapted from [11].

TABLE I: TYPICAL INITIAL COST STRUCTURE OF A WIND FARM.

Item			%
Wind turbines			65-75
Substation and electrical infrastructure			10-15
	Inner electrical distribution installation	*6-9%*	
	Substation and evacuation line	*4-6%*	
Civil work			5-10
Component installation			0-5
Other			5
Overall wind turbine cost (€/kW)		800-1100	

Once carried out the investment it is necessary to calculate net cash flow at the year k. This term is the difference between the income resulting from the energy sale, $N_{ESk}(x)$, and the operation and maintenance cost, $N_{O\&Mk}(x)$, $N_k(x) = N_{ESk}(x) - N_{O\&Mk}(x)$. In order to obtain a wind farm NPV as realistic as possible, the evolution of the prices of the sold energy as well as the increment of the operation and maintenances cost must be considered. Assuming that $E_k(x)$ is the annual net amount of electric energy produced and sold at year k, p_{kWh} is the price of the kilowatt-hour of sold energy, Δp_{kwh} is its annual increment, $C_{O\&Mk}(x)$ is the yearly cost of operation and maintenance at year k, and $\Delta C_{O\&M}$ is its annual increment, then the NPV of the cash flow along the wind farm life span yields:

$$NPV(x) = -I_{WF}(x) - C_D(x) + V_R(x) + \sum_{k=1}^{LT} \frac{E_k(x)\,p_{kWh}(1+\Delta p_{kWh})^{k+1}}{(1+r)^k} - \sum_{k=1}^{LT} \frac{C_{O\&M\,k}(x)(1+\Delta C_{O\&M})^{k+1}}{(1+r)^k} \quad (2)$$

To properly evaluate the potential energy supplied by the wind farm during a year, the wake speed decay effect must be considered due to the perturbation of the wind speed profile due to the operation of the turbines located upstream [12-15]. As can be seen from the energy flow diagram of Fig. 1, the actual net energy produced and sold by a set of turbines in a wind farm is lower that the sum of the energies of the turbines if they were isolated. This is due to three kinds of losses, the wake effect previously mentioned, the electrical losses in the wind farm distribution network and the unavailability loss of production must be considered to foresee the days that the turbines have been put out of production for maintenance, reparation or technical restrictions. The wake decay wind speed losses and the electrical losses are calculated by the master and the slave EAs, respectively, but the non delivered (1)(1) energy due to wind turbine unavailability, as a first approach, is considered as a global factor (unavailability factor, 2-5%).

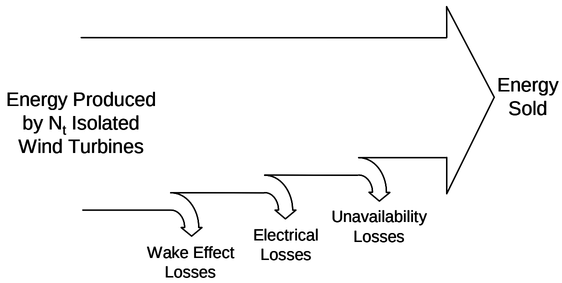

Fig 1: Energy flow diagram.

The three main economic components of the wind farm -initial investment, operation costs and sale of the energy- are rather difficult to evaluate, even simplifying the problem, because there are many interrelated variables that affects each other. For instance, the individual location of the turbines determines the foundations, paths and internal network of distribution, and in turn, the electrical network interferes with the operation costs. On the other hand the type, height and location of a turbine determine the maximum amount of electrical energy that can be obtained, but this energy must be reduced due to interferences in the wind speed field derived from the presence of other near turbines.

III. IMPLEMENTATION OF THE EVOLUTIONARIES ALGORITHMS

The method proposed used two EA. The main algorithm takes into account position, the type and tower height of the generators. An integer codification has been used to codify every possible solution of this problem (individual). The type of wind generator will be codified with a number, which will be the index in the generator database that uses the algorithm as an input. The above-mentioned database will content all the necessary information of the wind generators that can be installed in the wind farm (i.e. maximum and minimum height of the towers, capital cost and curve power-wind speed). An example of this codification is showed in the Fig 2.

It should be note that it is possible to find out individuals within a family with different number of wind generators, being necessary to assure this variability during the algorithm evolution. For this purpose, specific operators for crossing and mutation have been developed.

	1st. Generator	2nd. Generator		k-th Generator
x coordinate	X_1	X_2	...	X_k
y coordinate	Y_1	Y_2	...	Y_k
Generator type	T_1	T_2	...	T_k
Tower height	H_1	H_2	...	H_k

Fig 2: Codification of an individual in the master EA (turbine layout).

For each individual it is possible to calculate most part of the terms of NPV (2), except for those corresponding to the electrical infrastructure and power losses. To cover this lack, the hybrid slave EA is executed for every one of the turbine layout individual in order to determine a factible electrical infrastructure. The objective of this hybrid slave EA is to minimize the investment and the operation costs of every potential wind farm (turbine layout individual). The total wind farm network cost depends on the connection among the generators and its connection to the high voltage lines. In order to solve this coupled problem, a hybrid method is proposed. This method calculates the location of the substations and the inner MV distribution sequentially. An evolutive algorithm calculates the MV distribution network and uses a numeric method in order to place the substations.

The slave EA is used to find the optimum layout of the low voltage lines. It uses the following codification: each every possible solution of the problem is represented by means of a vector, $\boldsymbol{A_i}$. The size of $\boldsymbol{A_i}$ is twice the generation points (*np*), 2*np*. The first *np* elements are a permutation of the *np* generation points and the second *np* elements are the connection points of the first ones. The $a_{i,j}$ and $a_{i,j+np}$ elements of $\boldsymbol{A_i}$ are related and they represent the extreme points of a low voltage line. When an $\boldsymbol{A_i}$ element is a positive number, it means that the connection is to a substation. To indicate that the connection is to another point, a negative number is used. To maintain the tree structure of the network the connections between points are limited: each point only can be connected with a previous point of its permutation. For example, if $a_{i,j+np} = -4$ it means that the point *j* of the permutation is connected with the fourth point of this permutation. If $a_{i,j+np} = 4$ it means that the point *j* of the permutation is connected with the substation 4. These conditions limit the values of $a_{i,j+np}$ to the array :{-*j*+1, -*j*+2, ..., -1, 1, 2, ..., *ns*}, when *ns* is the number of substations. Fig. 3 shows an example of this codification.

The advantage of this codification system is that always generates a radial structure in the network, avoiding spending time in a later checking process. Besides, this codification does not consider either the coordinates of the substations nor their connections to the HV lines. The criterion is to have, at most, the same number of substation as existing lines, and the substation number *k* is connected to the line number *k*. This codification is enough to run the EA to calculate the exact coordinates of the substations *k* (x_{0k},y_{0k}). The optimal position of substations only depends on the HV layout lines, the position of generator connected to the substation and the sum of all power that arrive at this generator.

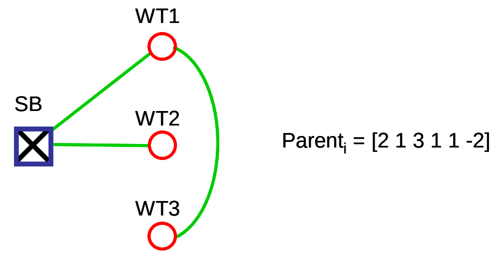

Fig 3: Codification of an individual in the slave EA (electrical infrastructure).

The process to compute the coordinates x_{0k} and y_{0k}, is not especially difficult but is very time consuming, especially when it must be repeated a high number of times. So, this coordinates are only computed in the last generations of the slave EA. Previously, three possible substation placements are considered (Fig 4). If P_i is the power injected at node *i*, and C_{LVf} and C_{LVv} are the fixed and variable costs related to the MV conductor lines and power losses, respectively, the electric gravity centre, (x_{gc}, y_{gc}), can be calculated as:

$$x_{gc} = \sum_i w_i x_i \quad y_{gc} = \sum_i w_i y_i \quad w_i = \frac{(P_i\, C_{LVv} + C_{LVf})}{\sum_i (P_i\, C_{LVv} + C_{LVf})} \tag{4}$$

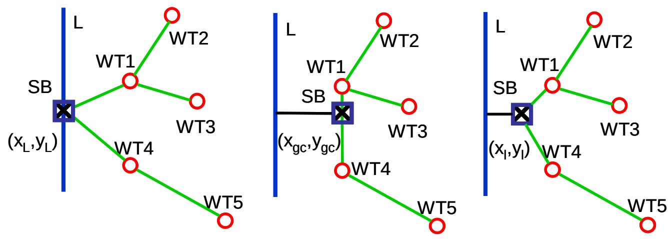

Fig 4: Possible substation placement considered.

Finally, the forbidden zones and incompatible solutions (a wind generator placed out of the zone of study, tower height incompatible with the type of machine, several wind generators placed at the same position, etc.) are analyzed. In the last case, a regenerative algorithm is applied turning the unfeasible individual into a feasible one. However, the treatment of the (electric) forbidden zone for will be different depending on the voltage level. If a HV line crosses through a forbidden zone, the connection between the origins to the target points is redesigned getting around the forbidden zone. On the other hand, if a LV branch crosses through a forbidden zone the slave EA set the probability of any branch that crosses a forbidden zone to null (in the initial solution generation and the mutations). This does not avoid the possibility that, after a crossing operation, one of those forbidden branches appears, so the evaluation of the solutions must test the presence of this kind of violations. When the presence of one of these forbidden branches is detected, its cost is doubled. Other constrains such as voltage or thermal limits are considered too as cost penalties.

IV. Performance of the Algorithm

As mentioned above, the optimization design of a wind farm is a problem that shows a great complexity, both in the technical and economic aspects. Even its mathematical formalization is a rather complex problem. Taking into account this high degree of complexity of the problem, on the one hand, and the typical distribution of investment costs of wind farms (Table I), on the other, justifies, as a first approach, dividing the problem of global optimization of the wind farm in two sub-problems:

- Optimization of the individual wind turbine location. The first problem is the most relevant from a purely economic point of view, since it is responsible for between two thirds and three quarters of total investment. Moreover, it is the factor that more directly determine the wind farm annual production of electricity (return of investment).
  To be precise, with the approach taken in this work, in addition to locating the turbines, the optimal choice includes both the type of turbine hub height, as well as the optimization of the wind farm inner auxiliary roads.
- Optimizing the configuration of the of the wind farm electrical network. The second problem is very similar to the design of a new radial network and has less significance, in terms of initial investment (between 10% and 15% of the total required investment). However, the configuration of the wind farm electrical network affects the net annual energy production of the wind farm, as the electrical losses in the inner wind farm facility means electrical energy generated (from the wind) but not available for injection in the evacuation network (not retailed).

In both cases, the optimization criterion chosen was the maximum economic return of investment required. Both sub-problems are addressed with a common approach: a cost model based on the cost of the life cycle of the wind farm and a method for optimum search driven by a genetic algorithm. It must be said that this approach is very similar to the commonly used in the wind farms configuration by the engineer's team.

A second and more in deep approach is the global optimization of the wind farm as a whole problem, looking for an optimization of the individual turbines location (as well as its type and height of the hub and the internal auxiliary roads) and the design of the electrical network of the wind farm and their interaction as an integrated single problem. This global optimization problem is afforded using a similar strategy: a reasonably detailed cost model of the wind farm, based on the cost of the life cycle of the wind facility, joined to a genetic algorithm. Obviously, this global approach incorporates the entire problem constraints, limitations and restrictions included in the resolution of each separate part of the problem. This makes the range of possibilities to be analyzed virtually intractable if there were not available a systematic tool of analysis such as that proposed in this work. Obviously, it is expected that the solution resulting from this global approach to the problem will be better or at least equal to the solution obtained by any other procedure, including the division of the problem used previously.

V. Test Case

In this section the optimization of a wind farm on a squared shaped 4 km x 4 km terrain subdivided into 20x20 squared parcels (possible turbine locations) is analyzed. Figure 5 shows the scenario, including the presence of a main road crossing the park from west to east (at the north side of the parcel) and a HV evacuation line at the south side of the parcel. Three kind of restrictions are considered, such as a forbidden zone, a low bearing capacity zone where the considered foundation costs are higher (penalty cost) and an investment limit of 4.1 M€. The wind speed is modelled with a Weibull distribution with K = 2 and two scale factor C = 5 m/s and C = 12 m/s as shown in Fig. 5. A prevailing wind coming from the north and a roughness length z_0 = 0.0055 m (shear effect) are considered. Table II summarized the main characteristics of the considered wind turbine and Table III the main economical, wind farm terrain and wind data, as well as the algorithm parameters. The size of the wind turbine rotor diameter can be estimated using the expression [16,17]:

$$D = \sqrt{\frac{P_N}{0.31}} = 1.796\sqrt{P_N} \tag{3}$$

This yields a rotor diameter of D = 44 m for the chosen turbine. This way, since the terrain has been divided in 200 m x 200 m square cells, with a side length equal to 4.54D. As the cell size is greater than 4D, no lateral wake effect is expected.

Sequential optimum solution). Figure 6 shows the sub-optima wind farm layout and electrical wind farm network, found in a sequential procedure. This result (wind farm configuration) is reached in two steeps.

- First, the wind farm lay out module is executed and, as a result, the sub-optimum location of the individual turbine is found.
- Then, in a second steep, and using the previous (sub-optimum) wind turbine lay out, the electrical module is executed in order to find the sub-optimum wind farm electrical network.

This way, in this two steeps process, the so called wind farm sub-optimum sequential solution is found. As can be seen in Fig. 6, in the turbine lay out solution found by the algorithm there are no wind turbines inside any other's wake (from nearby turbines), therefore the produced energy is practically the maximum (no wake reduction). The five turbines are placed avoiding the forbidden area (spatial restriction) and the low bearing capacity soil (foundation cost penalty). They are placed in a horizontal row (there are a few equivalent placement solutions), near the main road in order to minimize the length (cost) of the auxiliary roads, in the area of high wind (C = 12 m/s) and with the higher turbine hub height allowed (h = 100 m) (maximum generation of energy). Table IV summarize the economical results.

TABLE II: MAIN CHARACTERISITCS OF THE CONSIDERED WIND TURBINES.

Rated capacity Min. height Max. height Price	600 kW 60 m 100 m 500 k€
Power (kW) versus wind speed (0, 1, … 25 m/s) characteristic	0.0 0.0 0.0 21.2 49.3 83.2 130.7 202.0 280.8 361.6 433.7 498.6 548.1 577.3 596.0 602.0 601.9 593.4 571.3 545.6 524.7 510.0 500.7 478.7 457.7

TABLE III: MAIN IMPUT DATA.

Economical data	
Limit of investment (*M€*)	4.1
Life time (*years*)	20
Interest rate (%)	3
Price of energy (*c€/kWh*)	8
Increase of energy price (%)	3
Operation and maintenance cost (%)	3
Availability factor (%)	95
Present cost of decommission (%)	3
Present residual value (%)	3
Wind farm terrain and wind data	
Wind farm land surface (*km*^{2})	4x4
Number of cells	20x20
Reference hub height (*m*)	50
Weibull *C* (*m/s*) and *K*	5-12;2
Wind direction	N
Roughness length (*m*)	0.0055
Tower cost (*k€/m*)	1
Foundation cost (*k€*)	70
Foundation cost increase (%)	30
Auxiliary roads cost (*€/m*)	80
Algorithm parameters	
Size of population	100
Initial number of turbines	80
Maximum number of turbines	6
Crossing probability (%)	80
Mutation probability (%)	30
Number of repetitions to finish	20

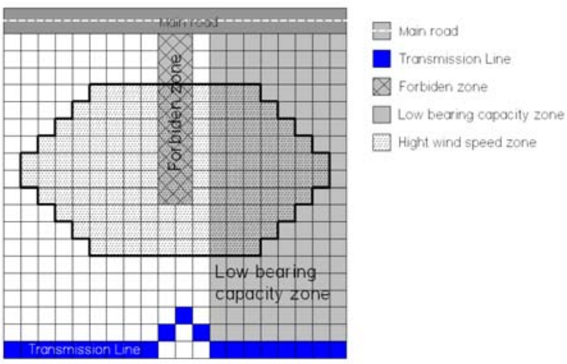

Fig 5: Scenario for the case under analysis.

As can be seen in Table IV, the initial investment necessary to attend all the necessary costs in order to build and put the wind farm in production is 3.74 M€ and the NPV along the 20 years of the wind farm life time is 20.51 M€.

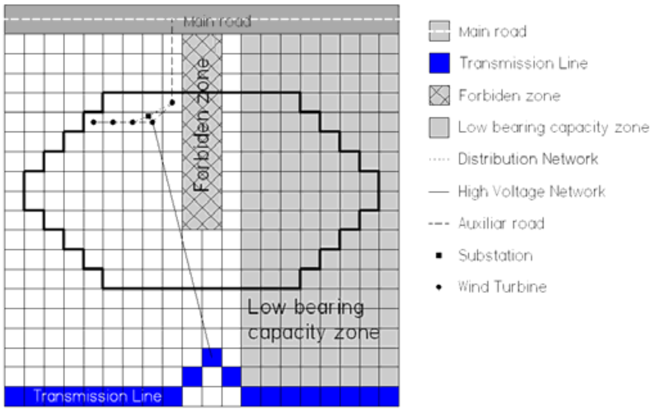

Fig 6: Sequential solution. Sub-optima individual wind turbine location and electrical wind farm network.

The distribution of the wind farm investment is as follows: wind turbines 2.50 (M€), civil work (foundations and auxiliary roads) 0.62 (M€) and electrical infrastructure 0.29 (M€). The wind farm produced energy is 14.927 GWh a year.

TABLE IV: OPTIMIZATION RESULTS FOR THE SEQUENTIAL SOLUTION

	Lay out	Electric network	Sequential optimum
NPV (€)	**20,508,741**	-	**20,747,308**
Investment (€)	**3,739,255**	-	**3,408,702**
Turbines investment (€)	2,500,000	-	2,500,000
Civil work investment (€)	619,627	-	619,627
E. network total invest. (*€*)	-	289,075	289,075
MV network total invest. (€)	-	*26,841*	*26,841*
HV line total investment (€)	-	*6,234*	*62,234*
Substation investment (€)	-	*20,000*	*200,000*
Average power (*MW*)	1.704	-	1.704
Yearly prod. energy (*GWh*)	14.927	-	14.927

Optimum global solution). Figure 7 shows the global optimum wind farm configuration. Is worth to note that now there are one wind turbine more than in the sequential solution, as the global solution is able to manage the restriction in the initial investment. As in the sequential solution, there are no wind turbines inside any other's wake; therefore the produced energy is practically the maximum (no wake reduction). The six turbines are placed avoiding restrictions (forbidden area) and cost penalties (low bearing capacity soil). They are placed in the area of high wind ($C = 12$ m/s) and with the higher turbine hub height allowed ($h = 100$ m). However, the individual turbine location of Figure 7 shows the influence of the electrical installation in the wind farm configuration: three of the wind turbines have been shifted a row down. This will slightly increase the length (cost) of auxiliary roads, but reduces the length of the electrical installation. This reduction does not only imply a lower initial cost but a reduction in the losses that will have its effect throughout the 20 years of the wind farm production cycle. Table V summarize the economical results of both sequential and global optima.

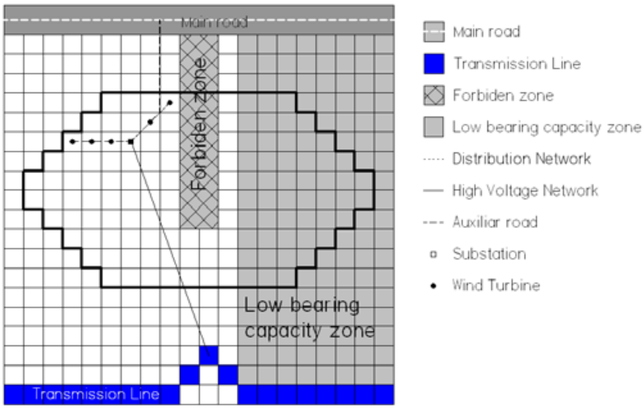

Fig 7: Global solution. Optimum global wind farm configuration.

TABLE V: OPTIMIZATION RESULTS. COMPARISON BETWEEN SEQUENTIAL AND GLOBAL OPTIMA

	Sequential optimum	Global optimum
NPV (€)	**20,747,308**	**24,927,536**
Investment (€)	**3,408,702**	**4,037,039**
Turbines investment (€)	2,500,000	3,000,000
Civil work investment (€)	619,627	739,255
E. network total invest. (€)	289,075	297,784
MV network total invest. (€)	*26,841*	*40,187*
HV line total investment (€)	*62,234*	*57,587*
Substation investment (€)	*200,000*	*200,000*
Average power (*MW*)	1.704	2.044
Yearly prod. energy (*GWh*)	14.927	17.905

As can be seen, the initial investment necessary to attend all the necessary costs in order to build and put the wind farm in production is 4.04 M€, very near the limit (4.1 M€) and the NPV along the 20 years of the wind farm life time is 24.93 M€. The distribution of the wind farm investment is as follows: wind turbines 3.0 (M€), civil work (foundations and auxiliary roads) 0.74 (M€) and electrical infrastructure 0.30 (M€). The wind farm produced energy is 17.905 GWh a year.

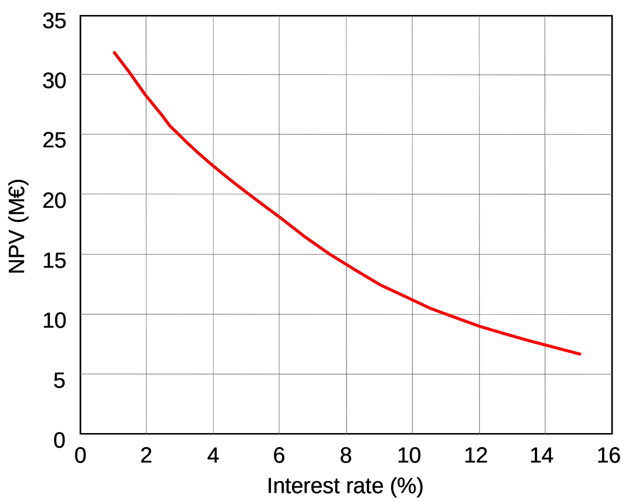

Fig 8: Evolution of the wind farm NPV with the interest rate.

Sensitivity analysis). The influence of some of the economical parameter on the global optimum solution have been also are analyzed. As an example, Figure 8 shows the evolution of the NPV with the interest rate. As can be seen, the lower the interest rate, the higher wind farm NPV.

VI. CONCLUSIONS

The complexity of the optimum wind farm configuration problem has been discussed and a new tool for wind farm optimal design has been presented. This new tool integrates the performance of two nested EA. The master EA basically calculates the turbines layout and the inner auxiliary road of the wind farm and controls the performance of a second slave EA that optimize the design of the whole electrical infrastructure. The optimization itinerary followed by the algorithm's is driven by a global wind farm cost model based on a life cycle cost approach, the cumulative net cash flow present value all over the wind farm life span.

The proposed cost model includes four main blocks to calculate the wind far initial investment, the production, the ordinary operation and maintenance cost and the final removing cost, that made it more realistic. The production block is the more complex of them meanly due to the fact that in order to calculate the income (from selling the net generated energy) must evaluate the individual wind turbine loss of production due to wake decay effect. A realistic data structure of the wind speed (Weibull) and direction distribution (wind rose) has also been incorporated in this block.

The new optimization tool can deal with areas or terrains with non-uniform bearing capacity soil and different roughness length for every wind direction or restrictions such as forbidden zones or limited initial investment.

The performance and suitability of the proposed evolutive algorithm to find the global optimum wind farm configuration have also been demonstrated with a test case. Finally, the global optimum solution sensitivity has been analyzed.

VII. ACKNOWLEDGMENT

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