Optimization of the Internal Electric Network Configuration of Wind Parks Using Evolutionary Programming Techniques

Fernanda de Oliveira Resende   João Abel Peças Lopes, Senior Member, IEEE

Abstract - This paper describes a new approach that exploits evolutionary methods, to find an optimal solution for the electrical network configuration of a wind park. The project of the electric network of a wind park can be seen as an optimization problem, in which one wants to minimize investments and operation costs due to losses and non delivered energy because of internal lack of reliability. This approach was tested with success in the project of a real wind park and the results prove to be quite interesting.

***Index Terms*—Genetic Algorithms, Optimization, Wind park, Internal electrical configuration.**

I. Introduction

AFTHER defining the type and the location of wind generators in a wind park, it becomes necessary to proceed with the electrical network project, which involves the definition of the topology, the identification of alternate paths to increase reliability and the dimensioning of the corresponding cables.

The identification of the wind generators location in the wind park terrain is a previous stage that is performed using models of fluid flow mechanics, taking into account the nature and the orography of the terrain using quite mature techniques [1]. This stage is out of the scope of this work.

The approaches used so far to deal the electrical design problem start from a fixed cable topology (connecting the wind generators) and follow with the determination of the cable solution (section of the cables). These are mainly engineering approaches, where a concern in the minimization of the total investment costs is naturally taken into account.

This paper describes a new approach to solve the electrical design problem of a wind park, trying to find simultaneously the best topology for the network and the cable solution, by considering the problem as a global optimization one where reliability is also taken into account. This problem has combinatorial characteristics due to the possibilities of connecting the several wind generators in the field and the type of discrete cable sections available.

For that purpose an evolutionary approach was used to develop a design tool able to find a reduced set of *good solution*s to be presented to the design engineers for further decision. The application of evolutionary methods to solve this optimization problem requires a careful approach as some procedures may lead to a single solution and to a local optimum. To deal with that problem, nitching methods were used in a successful way in this approach.

The application of such philosophy has also been tried successfully namely in distribution expansion planning [6] and in optimal reactive power planning [7] problems.

II. The Problem

The initial data of the problem includes the coordinates in an (X,Y,Z) space, regarding the location of each wind turbine and main substation (connecting the wind park to the main grid). Also information related with the capacity of each generator and preferred voltage level to be used in the wind park should be provided.

As mentioned before, the solutions related with the internal electrical network of the wind park can be obtained solving a global optimisation problem that involves minimisation of investments and minimisation of operation costs. If reliability is taken into account in the design procedure, an evaluation of the interest on supplementary connections that provide alternative paths for the delivery of the energy is performed.

Mathematically, the problem can be written as:

$$\min c = CI + CE \tag{1}$$

Subjected to:

Technical restrictions

Regulation type restrictions

Where:

CI - is the cost of investment, which includes the costs of cables and trenches, protection and switching equipment that is supposed to be installed on the extremities of the branches.

Fernanda Resende is with the Instituto Politécnico de Bragança,, Escola Superior de Tecnologia e Gestão - Quinta de Santa Apolónia – Bragança - PORTUGAL (e-mail: fresende@ipb.pt).

João A. Peças Lopes is with the Department of Electrical and Computer Engineering of the Faculty of Engineering of Porto University and with the Power Systems unit of INESC Porto - Largo de Mompilher, 22, 4007 Porto Codex - PORTUGAL (e-mail: jpl@duque.inescn.pt

CE - is the cost of operation, which includes energy losses on network cables of the wind park, due to Joule's effect, and the energy non delivered to the grid, due to internal faults on the wind park lines or cables.

Regarding the technical restrictions we have:

- Thermal limits in branches, $I_{ij} < I_{ij\ max}$;
- Limits in voltage drops, $U_{min} < U_i < U_{max}$. (a typical value for the max and min values of voltage is 5%).

For the regulation type restrictions, in Portugal it has been imposed that:

$Q_{tot} > 0.4P_{tot}$, for the period out the light load hours;

$Q_{tot} < 0$, during the light load hours.

With Q_{tot} and P_{tot} being respectively the total reactive and active power production of the wind park.

The wind park internal topology, including extra capacitors that may be needed to full fill the reactive power production imposed by the regulation restrictions, presents typically a solution of the type described in figure 1.

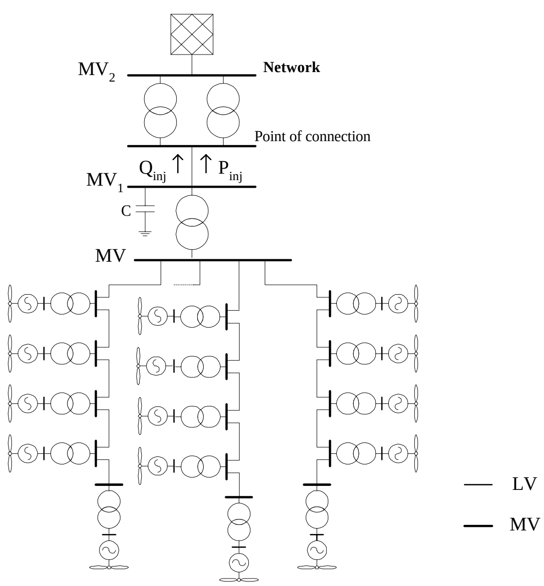

Fig. 1. – Typical configuration of a wind park

Having in mind the different theoretical possibilities of connecting the wind generators among them and to the substation, as well as the number of possibilities of different cable sections that can be used in each cable line, the problem becomes a typical combinatorial type problem. Naturally also the number of possible solutions becomes extremely high.

A. Evaluation of the Cost of Losses

The evaluation of the energy lost in the internal wind park grid is obtained from the solution of the load flow problem. As during the annual operation generators are not always delivering the nominal power, the generated power was assumed to follow a probability distribution function (pdf) of generation (given by the convolution between a normal pdf, related with the expected wind speed, and the power curve of the generator). This function was discretized in a few steps, corresponding to each one a given generated power and a probability. The same generated power was assumed to take place at the same time in each generator inside the wind park.

Therefore the losses of energy in one year can be obtained after the solution of the following simple algorithm:

1. Define generation level at each wind generator;
2. Solve the load flow, assuming complete availability of the network, and compute losses;
3. Annual energy losses = Annual energy losses + computed losses * probability of the generation level * 8760 h.
4. Repeat steps 1. to 3. until number of power stages is complete.

The cost of this dissipated energy must then be evaluated as an annual economic charge taking into account the expected life period (n years) for the wind park. The capitalised cost is then given by:

$$C_{PJ} = \text{Annual energy of losses} \times \frac{(1+tj)^n - 1}{tj \times (1+tj)^n} \times C_V \qquad (2)$$

Where CV is the mean cost of energy non delivered (Euros/Kwh) and tj is a rate of interest .

B. Reliability Evaluation

As in our problem the total cost of operation also includes the *energy that is non delivered* to the network, due to possible internal faults inside the wind park, an evaluation of the amount of such energy is needed.

At the same time, the interest in having alternate paths to reduce this energy may lead to a cable topology (together with different cable sections) of the type described in figure 2, which increases complexity to the problem.

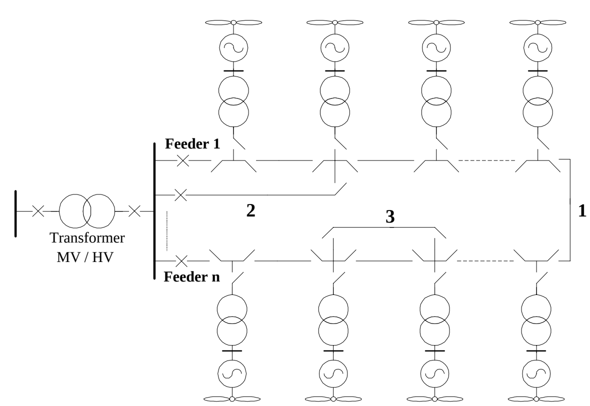

Fig. 2. – Topology model including reliability

In this topology model we included three different types of paths, identified as **1**,**2**,**3** in figure 2, to deal with the reliability needs, as they provide alternative branches to assure the deliver of energy being produced in the wind generators.

The reliability model used is based in hypothesis that include the independence of events, rate of failures and repair times given by a an exponential distribution. The following hypothesis need also to be considered:

a) If a disturbance occurs in one feeder, the circuit breaker that protects it is opened and all the feeder will become out of service; Operation is reestablished after fault location and isolation using the switching devices installed on the extremities of each branch, in a time T_{li}, and, if necessary only after cable repair.

b) If an alternate path is available it will be used to reestablish generation production during fault repair;

c) Alternate paths when needed are considered to be always available;

d) The wind park internal grid is usually operated adopting an open loop policy, namely in areas where loops could be used;

Therefore the introduction of alternate paths in the wind park grid topology demands the installation of additional switching devices, for paths of type 1 and 3 and an additional circuit breaker and a switching device for path of type 2.

The identification of the energy non delivered to the grid demands the calculation of the unavailability of each generator, adopting several reliability expressions that can be found in [2,3].

This energy non delivered to the grid (EPNE) is then given by:

$$EPNE = \sum_{i=0}^{ng-1} U_i E_i \qquad (3)$$

where U_i is the unavailability of bus i (h/year), E_i is the mean annual energy delivered to bus i in kwh, and ng is the number of generating buses in the wind park internal network. The mean annual energy that can be produced by a generator is an information that can be obtained from the wind generator location study, performed previously.

As in the case of energy related with losses, the cost of EPNE, C_{PF}, should be capitalised for the expected life period of the wind park. As C_V is the mean cost of the energy non delivered to the grid, this cost can be obtained as in (2) by:

$$C_{PF} = EPNE \times \frac{(1+tj)^n - 1}{tj \times (1+tj)^n} \times C_V \qquad (4)$$

III. USING GENETIC ALGORITHMS TO SOLVE THE PROBLEM

For the identification of *good solutions* for the global optimization problem described, Genetic Algorithms (GA) were adopted. This approach is a powerful optimization procedure particularly well suited to deal with combinatorial problems with a large number of possible solutions, like the one described, and where discrete variables are used [4].

The adoption of such a procedure demands the following main stages:

a) a suitable codification of each possible solution – the chromosome;

b) the definition of an adequate fitness function in order to represent the quality of each solution (measured by the total costs) and involving namely the use of a load flow simulation tool and reliability calculations;

c) the use of a GA procedure (in this case a nitching method);

A. Codification

The chromosome is a string of bits, each bit having a binary value (0 or 1). In our problem this string has for each generator 8 bits that represent:

L_1 to L_4 - type of connections in terms of topology (with L_1 and L_3 are mandatory lines, L_2 and L_4 alternative lines, used for reliability purposes);

W_{gui} – contains an information associated to situations where generator i is the last in the feeder;

S_{eci} – are 3 bits used to codify the section type of the cable to be used;

The length of each chromosome is therefore 8xn, with n being the number of wind generators in the park. Figure 3 describes the chromosome coding adopted.

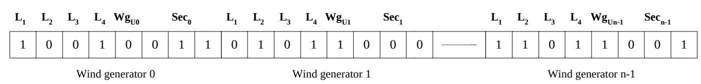

Fig. 3 - The chromosome coding

B. Fitness evaluation

The problem of minimizing the objective function described in equation (1), when subjected to the restrictions identified, can be treated as maximization problem where the restrictions are included in the new objective function. The fitness is them given by expression (5).

$$FIT = C - (k_1 \times nf + k_2 \times L_{NC} + k_3 \times |ngu - nf| + k_4 \times (V_T + V_C) + C_C + C_{JL} + C_{ND}) \qquad (5)$$

Where:

C – a constant with a value larger than the maximum of the cost of investment and costs of operation;

nf –number of feeders of the solution;

ngu – number of generators in the end of the feeder;

$\mathbf{L_{NC}}$ - lines not connected correctly;

$\mathbf{V_c}$ - violations of the voltage profile;

$\mathbf{V_T}$ - violation of the thermal limits;

$\mathbf{C_C}$ - Cable costs, including feeders protection equipment;

$\mathbf{C_{JL}}$ - Cost of energy losses on network cables of the wind park, using expression (2) ;

$\mathbf{C_{ND}}$ - Cost of energy losses not delivered to the grid, due to internal faults on the wind park, using expression (3);

k1..k4 – penalty factors.

This fitness function can them evaluate the quality of each chromosome for all the problems being treated.

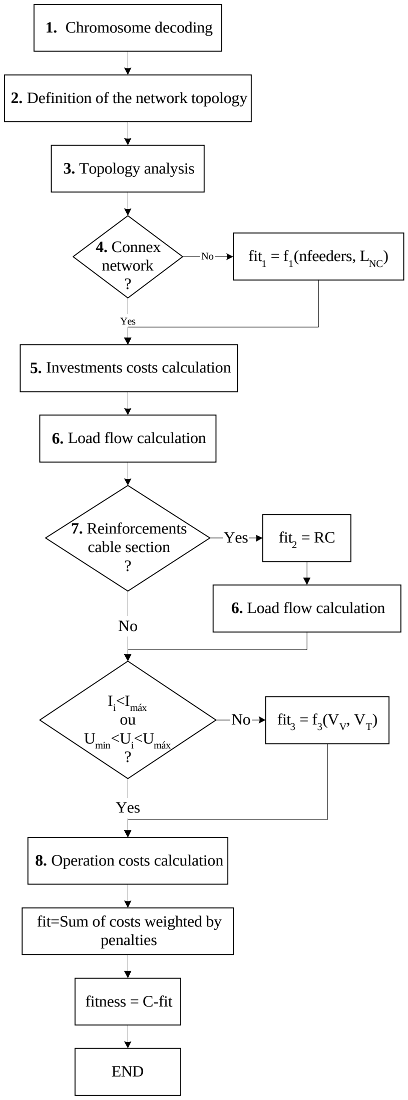

Fig. 4 - Fitness evaluation

The evaluation of this fitness function follows the procedure described in figure 4 and involves an articulation with the load flow for the determination of losses, flows in the lines and voltage profiles inside the wind park network.

In this algorithm the RC parameter is related with the reinforcement costs needed if the thermal limits of cables are not respected.

C. Genetic Algorithm Procedure

In traditional Genetic Algorithms (GA) a population is generated at a time by opposition to the majority of the real populations, where birth and death take place in a random way at different moments. In these traditional GA when the individuals of one generation are born the previous generation is completely eliminated which may lead to a situation where individuals with the best fitness will not survive, although most of their genetic material is passed to the next generation. In this way, in "badly behaved" problems, the probability of the genetic procedure to converge to a local optimum increases, due to the lack of diversity of the individuals in the population. New genetic models have then been developed implementing the concept of geographic isolation, based on a *nitching* scheme [5].

The genetic procedure adopted in this work follows this approach, which allows to identify niches of "good" solutions, enabling the wind park designer to compare some of these solutions and use engineer good sense in the final decision.

This algorithm uses the usual genetic operators (selection, crossover and mutation) in the following way [4]:

- Randomly pairs all population elements to yield n/2 pairs of parents (n is the population size);
- Each pair undergoes crossover, and possibly mutation to yield two children.
- Each of the two children competes with one of the two parents, according to its similarity, for inclusion in the next population.

The size of the population is an important parameter to be adjusted in order to control the quality of the results. A sufficiently large population will produce better results given that the diversity is higher. In this research we use 150 individuals since this preserves an acceptable diversity level while not compromising the computation time. Our experience also indicates that, for the networks that were tested, good results were obtained after 1500 iterations of the GA algorithm.

IV. Numerical Results

This approach has been tested in the electrical design of some wind parks, namely in the case of a 10 MW wind farm with 20 500kW wind generators. The lay-out of these 20 wind generators is presented in figure 5, through the co-ordinates of each generator and substation (represented by the symbol Δ). This information was the input of the problem we wanted to solve.This case corresponds to real wind park presently in operation in Portugal.

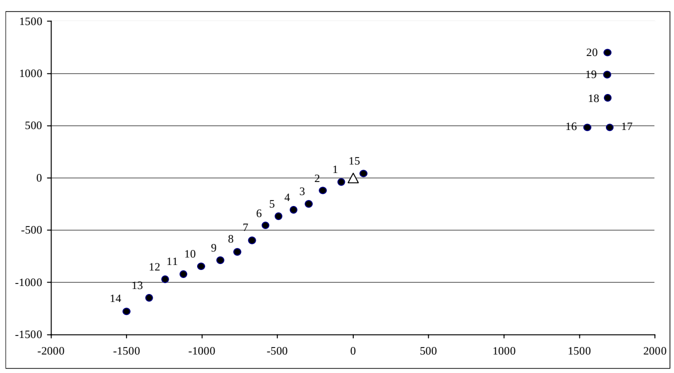

Fig. 5. – Lay-out of wind generators and interconnection substation

The procedure described in the previous sections was applied for the design of this wind park.

The electrical network was to be implemented using MV underground cables (8.7/15 kV) with sections raging from 35 mm^2 to 240 mm^2. A rate of failure of 0.05 failures per Km/year and a mean time to repair of 20 h were assumed for reliability data. The mean switching time and the mean time for fault location were assumed to be respectively 30 and 20 minutes.

An expected life period of 20 years, a rate of interest of 10% and a cost per kWh of =0.06 Euros were adopted for the evaluation costs.

In the GA approach, the values adopted for the crossover probability and the mutation probability were respectively 0.8 and 0.04

After 1500 generations, some of the best individuals found correspond to the solutions described in the next figures. The electrical connection lay-out and the section of the cables to be used are indicated, as well as complementary lines to increase network availability.

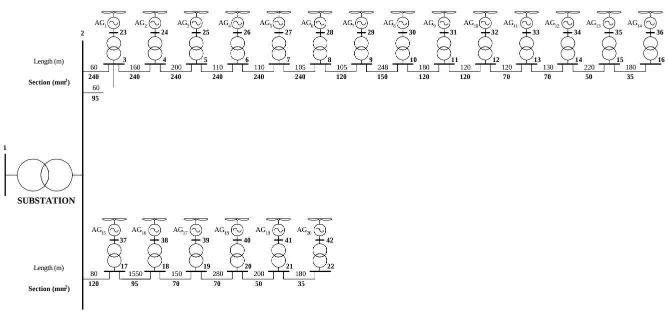

Fig. 6. – One of the best fitness solutions (S1)

In this individual, a two feeder solution was suggested and a complementary line was introduced to increase the availability of feeder 1.

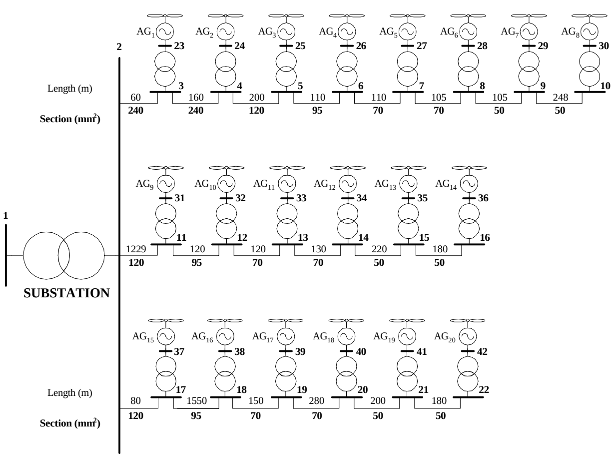

Fig. 7. – One of the best fitness solutions (S2)

The solution that corresponds to figure 7 contains 3 feeders, in order to provide better availability for the network.

The technical solution (ST) adopted by the design engineer was also a three feeder solution, however the cable sections were larger to the ones suggested for S2, which provokes a natural reduction in Joule losses and reduces therefore the costs of operation.

A comparative evaluation for the three solutions is provided in figure 8. Investment costs and operational costs are shown for a better evaluation of the quality of the solutions obtained.

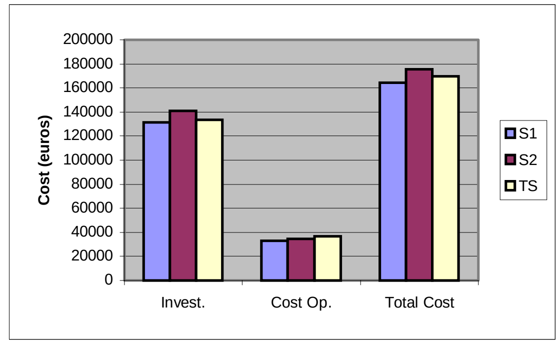

Fig. 8. – Costs for the solutions being analyzed

From the analysis of the economic attributes of these solutions one can see that the approach developed is able to produce, in a systematic way, technical solutions with minor costs than the ones obtained through the use of an engineering procedure.

In all this approach a delicate issue is the tuning of penalty factors, which must be done using a careful procedure based in engineering good sense.

It is important to mention that in this approach the *nitching* strategy, adopted in the GA, was most important for the success of finding *good* solutions. In fact, the use of a conventional GA, that was also tried, was not always able to provide a solution with enough quality.

V.CONCLUSIONS

This paper described a new approach based on evolutionary computation, to be used in the electrical design of wind park internal network. The approach proved to be quite effective in identifying optimal solutions for the electrical network. The GA algorithm adopted, based on a *nitching* methodology, was a crucial piece in the success of this approach due to its capability in handling this problem and providing several solutions to be compared.

The production of several solutions, to be compared by the design engineer, is an interesting feature of the approach, being the final solution always a decision of the specialist.

VI. REFERENCES

[1]– Georg Beyer, Ruger, Schafer, Waldl Peter, "Optimization of wind farm configuration with variable number of turbines", Proc. EWEC Conference, May 1996.

[2]– Billinton, R., Allan, R., "Reliability evaluation of engineering systems: concepts and techniques", Plenum Press, 1985.

[3]– Resende, Fernanda, "Optimization of the electrical internal network of wind farms", (in portuguese), MSc. Thesis, University of Porto, December 1999.

[4]- Goldenberg, D., "Genetic algorithms in search optimization, and machine learning", Addison – Wesley Pub. Company, 1989.

[5]- Mahfoud, S., "Niching methods for genetic algorithms", Ph.D. thesis, University of Illinois at Urbana-Champaign, 1995.

[6]- Proença, L. M., "Genetic Algorithms in Distribution Expansion Planning", (in portuguese), MSc thesis, Faculty of Engineering of Porto University, October 1993.

[7]- Lee, K. Y. and Yang, F. F.. "Optimal Reactive Power Planning Using Evolutionary Algorithms: A Comparative Study for Evolutionary Programming, Evolutionary Strategy, Genetic Algorithms and Linear Programming", IEEE Trans. on PWRS, Vol. 13, Nº 1, February 1998.

VII. BIOGRAPHIES

Fernanda Resende, was born on 1973 in Arouca, Portugal. She graduated in Electrical Engineering from the University of Trás-os-Montes e Alto Douro in Portugal 1996. She got an MSc. Degree from Faculty of Engineering of Porto University in February 2000. Presently she is teaching at the Polytechnic Institute of Bragança in Portugal.

João A. Peças Lopes, was born on 1958 in Sertã, Portugal. He graduated in Electrical Engineering from the Faculty of Engineering of Porto University (FEUP), in Portugal, in 1981. In 1988 and in 1996 he got respectively the PhD. and the Aggregation degrees (Post-Doc) from the same School. He is presently Associate Professor with Aggregation at (FEUP) where he teaches. Prof. Peças Lopes is also Assistant Coordinator of the Power Systems Unit of INESC Porto where he leads a research unit in the Power Systems field. He is a senior member of IEEE.