Optimal Installation of Wind Turbines to Minimize Energy Losses ⋆

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Abstract: Over the years, new methods have emerged in order to optimize the installation of wind turbines in distribution systems to meet the loads demand, reduce technical energy losses and avoid exceeding the voltage limits in the system. In this context, an algorithm for the optimal installation of wind turbines in radial distribution systems is presented here. The Genetic Algorithm and the Cuckoo Search are used as optimization methods and, to calculate the power flow, the Sum of Powers Method is used, respecting the voltage limits imposed by ANEEL and not exceeding a 20% wind generation penetration. The segmented annual load curve was used and it was considered that the load curve in all buses and the feeder are the same, as well as the wind speed curve. The analysis of the results has shown that the proposed algorithm has been able to install wind generators reducing the energy losses as well as estimating the investment value of installation and operation of the turbines. The algorithm was applied to three radial test systems (36, 134 and 1080 buses) and was successful in the case studies.

Keywords: radial distribution system; distributed generation; wind turbine; genetic algorithm; cuckoo search.

1. INTRODUCTION

As demand increases, ways to supply it are being developed and Distributed Generation (DG) has emerged as a solution to this problem. Among the possibilities of DG, wind energy stands out as an alternative to reduce or replace common generation sources, in addition to be one of the most ecological, clean and safe resources. Due to the increase in the number of Wind Farms (WF), it is necessary to connect them at suitable locations in the system, as this connection point influences the stability of the power system and the power quality. WF should preferably be connected to a reference bus, so as not to affect the stability of the electrical system (Molina-Moreno et al., 2015). The intermittent nature of the wind has resulted in technical and economic challenges with large-scale integration. The optimal installation minimizes the cost of the initial investment and the operating costs of WF (Mitchell-Colgan et al., 2015).

Data from November 2021 shows that Brazil has more than 750 plants and the wind source has reached a 11.11% share in the Brazilian energy matrix (ANEEL, 2021). As a result, wind energy became the second largest source of the Brazilian electric matrix, even though it is recent and has been intensely developed only in the last ten years (ABEEólica, 2017). At the end of 2021, the installed capacity was approximately 20 gigawatt (GW), which allowed Brazil to occupy the 7th position in world generation ranking. These are some of the data that show the importance of wind generation, its growth capacity and the benefits that it can bring to the Brazilian electrical system. Taking into account wind generation performance, it was already possible to serve almost 14% of the National Interconnected System since 2019 (ONS, 2020).

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2. MATERIALS AND METHODS

A widely accepted general definition was suggested by Ackermann et al. (2001): DG is a source of electrical energy connected directly to the distribution network or to the consumer. From the point of view of distribution, DG is a viable alternative for bringing several benefits such as short installation time and low investment risk, since it is built in modules that can track load variation more closely.

For these reasons, technological changes are beginning to appear internationaly, which may involve the presence of a more consistent DG, generated in low and medium voltages and connected directly to the distribution network that would be characterized by good efficiency and low pollutant emissions. However, the large-scale insertion of DG can lead to new problems (such as the reverse flow of power and injection of harmonics in the network) and, consequently, the need for new tools for better management of these systems (Alinejad-Beromi et al., 2007).

The distributed wind generation, if used correctly in distribution networks, can bring several advantages such as:

reduction of technical losses, improvement in the voltage profile of the feeder, pollutants emission reduction, increase in energy efficiency, power quality improvement and increase of system reliability and security (Kazemi and Sadeghi, 2009). However, some studies demonstrate that the location and dimensioning of the generation inappropriately distributed may result in an increase of the system's operating costs (Hernández et al., 2007).

These problems can be avoided by using optimization methods, as they make it possible to determine the optimal location and dimensioning of the DG. Several researchers have already solved problems of location and dimensioning of DG. However, the topic is not exhausted, being a current topic, of growing interest and deserves attention.

2.1 Power Flow

The power flow determines the power traffic through the network, starting from the generating centers until reaching the consumers. It is a simulation of the system operation in a steady state from which it is possible to check if the voltages are within the permitted limits, what is the static stability index, what is the economic and reliable load dispatch and if the losses are not excessive.

In order to use the Power Sum Method (PSM) created by Cespedes (1990), it is necessary to know the configuration of the feeder, the amplitude of the substation bus voltage and an initial power losses estimate in each bus, which is considered null. For each iteration, the voltage per bus must be calculated. Then, the active and reactive power losses are calculated. The last iteration ends when the above procedure is repeated for all buses and converges when the difference between the total losses in an iteration and the previous one is less than the specified tolerance (Souza, 2005). To insert Wind Turbines (WT) as generators in the calculation of the power flow, the negative load concept was used in order to indicate their ability to supply power to the system (Molina-Moreno et al., 2015).

2.2 Genetic Algorithm

The Genetic Algorithm (GA) theory developed by Holland (1992) works by discovering, emphasizing and recombining good traces of solutions, which are combinations of bit values that make the chains more suitable. This means that, in a given generation, while GA is explicitly assessing the suitability of the n chains in the population and implicitly estimating the average suitability of a much larger number of schemes (Mitchell, 1998).

The chromosome is filled with genes, that are the alphabets used and can be binary, decimal or floating. The main operators of GA are crossing, selection and mutation. A crossing operation is processed between two chromosomes in a population, generating two new descendants.

After the crossing comes the selection, which consists of selecting the most suitable requirements to survive and discarding the least able. The technique used here was the arena combat, in which the chromosomes are randomly selected and fight two by two. One continues to the next generation and the other is eliminated. After that, a mutation takes place, which occurs with low frequency in the population. It is processed in a single individual causing changes in their genes at random.

The mutation has an opposite effect to the crossing, tending towards an optimal solution (which may be local or global), while the mutation is opposed to the tendency to stay at the optimum found. If the optimum is local, the mutation is likely to succeed. In addition to the mutation, there are penalties, which are ways to reduce the value of the suitability of compliance that do not fit the restrictions that were imposed by the problem (Souza et al., 2006).

Each GA process iteration is called by generation. According to Souza (1997), a GA is typically executed for any value between 50 and 500 generations. The entire generations set is called by era or epoch. At the generation end, there are often one or more highly suitable chromosomes to be considered optimal solutions. Since randomness plays an important role in each run, two runs of random numbers often produce different behaviors.

The GA was chosen because it is a very robust and consolidated optimization method in research.

2.3 Cuckoo Search

The evolutionary algorithm known as Cuckoo Search (CS) was developed by Yang and Deb (2009) and is based on the parasitic behavior of some cuckoo species. In the reproduction process, these birds lay eggs in nests that host other birds. As some of these eggs are similar to the eggs in the host nest, cuckoo chicks have the opportunity to grow into adult cuckoos. However, some eggs are discovered and discarded by the host bird, which in this case can still abandon the nest and build a new one in another location. In addition, other studies at the time showed that the use of the Lévy flight, that some birds use to move around, had great potential in the optimization area. To simplify the CS description, they developed 3 basic rules, and, once the algorithm was defined, they were compared with the results of GA and Particle Swarm.

Due to its simplicity and efficiency, in addition to fast convergence and the ability to escape local optima, CS is commonly used in optimization problems. There are also works that use CS in areas such as image processing, scheduling, planning, feature selection and forecasting (Yang and Deb, 2009; Biswas et al., 2014).

In CS, each solution is represented by an egg in a nest and is evaluated according to the fitness that analyzes its ability to solve the problem. Each new solution is represented by a cuckoo egg. If the new solutions have better skills, they replace the worst current solutions. Using the Random-Walk search style, candidate solutions are obtained in order to explore possible new solutions. Finally, a cuckoo egg present in the worst nests is discarded based on a probability of abandonment.

According to Yang and Deb (2009), there are 3 basic rules in CS: 1. Each cuckoo lays an egg at a time in a randomly chosen nest; 2. The best nests are maintained for the next generation; 3. Each nest contains only one egg, the number of available nests is fixed and the egg deposited by the cuckoo is discovered by the host bird with a certain probability value.

2.4 Load Levels

The methodology consists of determining the optimal installation of WT in radial distribution systems in order to minimize energy losses and respecting the following restrictions: do not exceed the voltage limits adopted by Agência Nacional de Energia Elétrica (ANEEL), the Brazilian electrical energy agency; maximum of 20% DG penetration (Diuana, 2017); do not locate turbines on the substation bus. Three load levels were used by segmenting the feeder load duration curve over a year, located at the substation output. The load curves at each bus were considered identical to that of the feeder. The wind speed curve was also segmented into three levels.

As the possible installation locations for WT are the system buses, the problem is characterized as a combinatorial optimization. Thus, the objective function of the method was developed according to (1).

$$\text{minimize } \Delta E = \sum_{j=1}^{m} T_j \sum_{k=1}^{n} \Delta P_{jk}, \quad (1)$$

Where ΔE are the energy losses; m is the number of levels in which the load duration curve is segmented; T_j is the load level j duration; n is the number of feeder sections; ΔP_{jk} are the active losses in section k, which ends at the bus k at load level j.

The active power losses are the result of computing the load flow of the PSM, which is used repeatedly for the m load levels. The GA was a heuristic goal used to solve the combinatorial optimization problem. The average demand was estimated from the installed load, demand factor and feeder load factor, where the mean and peak values of the feeder were taken from the load curve at the substation output. Finally, it was considered that the load curves on all buses follow the feeder load curve. For a better representation of the load variation over time, the annual load duration curve of the feeder was segmented in m intervals in order to have an average power value in the $k-bus$ $(k = 1, 2, ..., n)$ for each load level j $(j = 1, 2, ..., m)$.

The original and segmented load curves that correspond to a given daily load curve are shown in Figure 1.

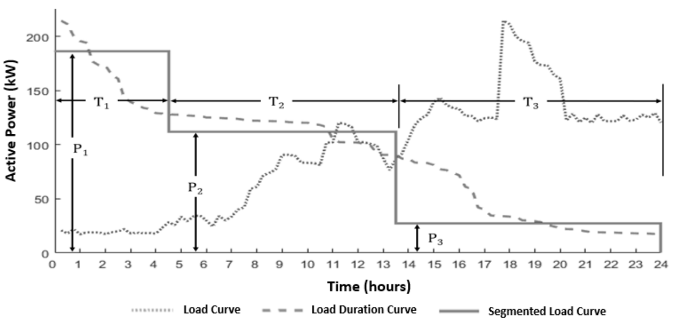

Figure 1. Daily load curve, load duration and segmented load duration.

In order to characterize the active loads in each bus, the annual load duration curve of the feeder was segmented in a certain number of intervals, in which the load was considered constant. Such intervals are equivalent to load levels and represent different levels, the number of levels being defined according to the application and the desired precision degree (Oliveira et al., 2017). The segmentation problem of the duration curve is solved using a GA, as proposed by Souza et al. (2002). The reactive load duration curve follows the same segmentation as the active load duration curve. As shown in Figure 1, the load levels are well identified by the duration T_j and P_j, $j = 1, 2, ..., m$.

2.5 Generation Model

According to Safari et al. (2013), the active power produced by the turbine respects (2):

$$P_{Wind}(v) = \begin{cases} 0, & v < v_c, v_f < v \\ p_r \dfrac{v - v_c}{v_r - v_c}, & v_c \leq v \leq v_r \\ p_r, & v_r \leq v \leq v_f \end{cases}, \quad (2)$$

where $P_{Wind}(v)$ is the active power generated (kW); p_r is the turbine rated power (kW); v_c is the turbine cut-in speed (m/s); v_f is the turbine cut-out speed (m/s); v_r is the rated wind speed (m/s); v is the wind speed (m/s).

2.6 Proposed Algorithm

The energy losses computed in the distribution network requires the execution of the PSM for each established load level. These calculations need to be repeated whenever there is a change in the bus where the turbines are located.

The proposed algorithm starts by loading WT data and the selected system data (nominal voltage, active and reactive power load curves, configuration vector, sections impedance and installed loads). Then, the number of m load durations is read, the curves are segmented and the PSM is performed according to (1) in order to find the initial energy losses ΔE. The data loading and the optimization technique choice in the algorithm constitute a preliminary stage that is only necessary in the first iteration. The remaining steps are performed according to the flowchart of the proposed algorithm in Figure 2

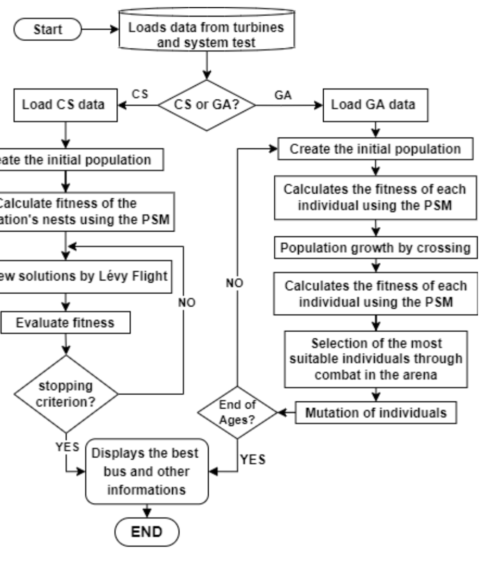

Figure 2. Flowchart of the proposed algorithm.

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The flowchart of the proposed algorithm starts by loading the data from the turbine models, the test systems and selecting the optimization technique (GA or CS), as well as loading their respective data. If the GA is chosen, the first individuals of the GA population are created randomly. With the help of the PSM, the skills of individuals are calculated and penalties are applied, if necessary. The crossing operation with the initial population is carried out in order to obtain a population growth. New individuals have their skills calculated with the help of the PSM. Once the population has reached its maximum limit, the algorithm performs the GA selection operation to reduce the population. After these operations, the mutation is performed in some individuals of the "surviving" population. After the mutation, the process is repeated until the end of the pre-established Eras occurs. When the execution of the last Era occurs, the results obtained by the algorithm are made available to the user and the processing ends.

If CS is chosen, the initial population is created randomly and its fitness is calculated with the help of the PSM. Then, new possible solutions are generated through the Lévy flight and their fitness evaluated. If the stopping criterion is not met, the process is repeated from the Lévy flight. However, if the stop criterion is reached, the results obtained by the algorithm are displayed on the screen and the processing ends.

2.7 Data and Hypotheses

The active and reactive power load curves data used refer to 2017 and were provided by Energisa Borborema. The wind speed curves data used are for the year 2017 and were provided by Instituto Nacional de Meteorologia – INMET.

The present work used the decimal alphabet for chromosomes and cuckoo eggs and in one studies cases consists of a 6-position vector, where the first half (from 1 to 3) refers to the system bus where the turbines will be located and their values vary according to the number of system buses, while the second half (from 4 to 6) refers to the turbine models that will be installed in each bus and their values vary according to the used turbine catalog, as shown in Figure 3. Thus, all chromosomes and cuckoo eggs used in this work have an even number in the solution size, as well as the same variation in values for the second half of the vector (ranging from 0 to 6 turbines for all test systems).

1	2	3	4	5	6
15	24	31	2	5	0

Figure 3. Example of chromosome and cuckoo egg used in case studies.

To calculate costs, values were used based on the work on renewable generation costs for the year 2018 carried out by IRENA (2018). Data for Brazil indicate that the installation cost is approximately US$/kW 1,830 and it costs US$/kWh 0.06 to operate the turbines. In order to perform the simulations, curves of active power, reactive power and wind speed were used. Each system has its own curves originated from the curves provided by Energisa, totaling 3 sets of curves for each system that will be explored later. The selected systems data were: the 36-bus system used by Ribeiro (2017), which is a variation of the IEEE 37 bus system; and the 134-bus and 1080-bus test systems found in UNESP (2021).

The data used in the MSP are a maximum of 100 iterations and a tolerance of 10^{-4} , the turbines data used can be seen in Table 1 and, finally, the segmented wind speed data are in Table 2. The characteristics of the WT presented in Table 1 were chosen based on Dantas (2020) in order to provide different ways of analyzing the results in each simulation, since the turbines are different from each other.

Table 1. Turbine data

Manufacturer	Model	Rated power (kW)	Rated speed (m/s)
Enercon	E82/2300	2,300	14.0
Gamesa	G128/4500	4,500	12.5
Nodex	N90/2500	2,500	13.5
Repower	MM82	2,000	15.0
Vestas	V112/2300	3,000	15.5

Table 2. Wind speed data

Load	Duration (days)	Average speed (m\s)	Maximum speed (m/s)
Peak	132,4	4,88	7,5
Mid	135,8	3,36	4,0
Light	96,8	1,87	2,6

Although the cut-in and the cut-out speeds are not shown, they were considered in the simulations and these values can be found in Power (2020). The wind speed data is segmented into three levels in the same way as the active power load curves.

3. RESULTS

In order to evaluate the accuracy of the method, the routine was performed ten times for each case. In all systems, demand, energy losses and energy generated are for one year. Finally, a routine was programmed to install WT in the system buses in order to minimize energy losses. The results obtained for each system will be compared with the best results obtained by Dantas (2020).

It is important to highlight that the results of heuristic methods application depend directly on the initial population, that is, on the initial estimate. This is due to the fact that they incorporate several random processes, such as crossing, selection, mutation, Lévy flight and abandonment probability. As a way to obtain reliable results, ten executions were carried out for each system in order to verify the convergence of the results.

The figure of the three system-tests (36, 134 and 1080 buses) are shown in Figures 4 and 5, and the parameters are in Table 3.

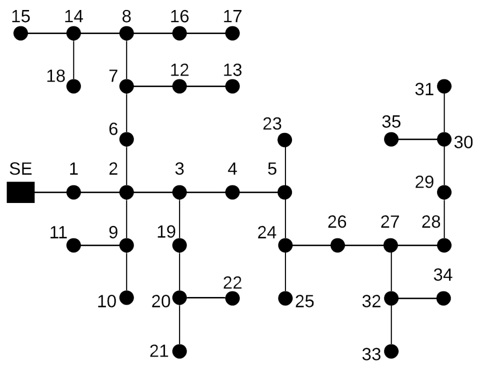

Figure 4. Power system 36 bus.

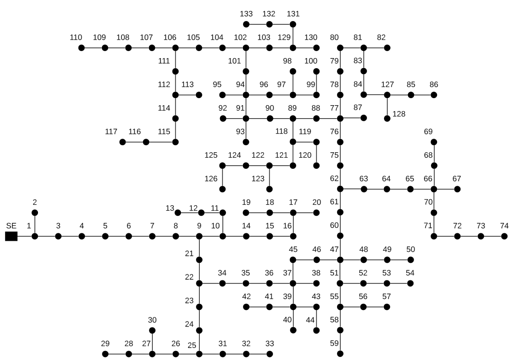

Figure 5. Power system 134 bus.

Table 3. CS parameters for the system-tests

System-test	Cuckoo eggs	Total iterations	Number of nets	Probability of abandonment
36	6	250	25	25
134	10	1500	35	35
1080	14	2000	50	50

These characteristics were determined in advance and through executions prior to the case studies.

3.1 Results of System-Test 36

Initially, the 36-bus test system was selected. The system topology, resistances, reactances, active and reactive powers installed per bus can be consulted in Ribeiro (2017), as well as the total power installed in the system and the demand. The GA characteristics used in the method were chosen based on the system's search space and tests previously performed. Finally, the active and reactive load levels of the 36-bus system, as well as their segmentation, can be found in Dantas (2020).

A chromosome with 6 genes was chosen for the 36-bus system, since in Dantas (2020) the optimum found occured when 3 turbines were installed. The results obtained in the simulations are shown in Table 4.

Table 4. Results of the 36-bus system

Results	Genetic Algorithm	Cuckoo Search
Bus	14 29 29	10 14 29
Turbines	4 3 0	0 4 3
Installed Power (kW)	4,500	4,500
Energy (GWh)	2.46	2.46
Penetration (%)	19.54	19.54
Losses (MWh)	106.32	106.32
Reduction (%)	34.74	34.74
Cost Installation (US$)	8,235,000	8,235,000
Cost Operation (US$)	147.60	147.60
Time elapsed (minutes)	1.36	0.43

3.2 Results of System-Test 134

The 134-bus test system has a configuration in accordance with Safari et al. (2013), the characteristics of GA are in Dantas et al. (2020) and of CS are presented in Table 3. Finally, the active and reactive load levels can be found in Dantas (2020). The results obtained by the method are shown in Table 5.

Table 5. Results of the 134-bus system

Results	Genetic Algorithm	Cuckoo Search
Bus	70 83 87 94 106	70 83 94 106 110
Turbines	4 4 0 4 1	4 4 4 1 0
Installed Power (kW)	8,300	8,300
Energy (GWh)	4.89	4.89
Penetration (%)	19.56	19.56
Losses (MWh)	358.33	358.33
Reduction (%)	37.10	37.10
Cost Installation (US$)	15,189,000	15,189,000
Cost Operation (US$)	293.40	293.40
Time elapsed (minutes)	11.09	5.30

3.3 Results of System-Test 1080

Finally, the 1080 test system is based on the system found in UNESP (2021) and data on resistance, reactance, active and reactive power and system are presented in Dantas (2020). The parameters of GA are in Dantas et al. (2020) and of CS are shown in Table 3. The parameters of AG and CS were chosen based on the execution time of the routine and not on the search space criterion according to the other systems. In this way, values were empirically selected to facilitate the routine execution process.

Due to the considerations made, it was expected that the routine would not converge to the same optimum in all executions. However, the proposed method reached a 70% accuracy in the GA executions and 60% in the CS executions. The results are shown in Table 6.

Table 6. Results of the 1080-bus system

Results	Genetic Algorithm	Cuckoo Search
Bus	65 234 244 420 615 736	65 234 244 420 564 615 736
Turbines	1 1 1 0 1 1 1	1 1 1 1 0 1 1
Installed Power (kW)	13,800	13,800
Energy (GWh)	15.61	15.61
Penetration (%)	9.99	9.99
Losses (MWh)	74.89	74.89
Reduction (%)	64.56	64.56
Cost Installation (US$)	25,254,00	25,254,000
Cost Operation (US$)	936.60	936.60
Time elapsed (hours)	3.70	1.94

4. DISCUSSION

For the 36-bus system, all executions reached the same optimum, as can be seen in Table 4. The two methods suggest the installation of two turbines, on bus 14 should be installed turbine 4 (Repower-MM82) and on bus 29, turbine 3 (Nordex-N90/2500), totaling 4,500 kW of installed power and generating approximately 2.46 GWh of electricity with a 19.54% penetration. This configuration achieves a 34.74% reduction in energy losses and did not exceed the voltage limits established by ANEEL, in addition to costing approximately US$ 6,052.50 to install the turbines and US$ 147.60 to operate them for a year. The best result was obtained by the proposed algorithm that used CS as optimization method. The focus is the electrical energy losses reduction and the CS achieves a reduction equal to that found by GA, however, quicker.

In the 134-bus system, executions converged in 90% of the cases when using the GA and in 100% of the cases when using the CS, and this result is shown in Table 5. From the GA's ten executions, a single one found a reduction of 36.66% in energy losses, which is close to the 37.10% suggested by the other 9 executions. The algorithm suggested as an optimal result the installation of model 1 (Enercon-E82/2300) on bus 102 and model 4 (Repower-MM82) on buses 70, 83 and 108 of the system. This configuration will result in 8,300 kW of installed power, generating 19.56 GWh of electricity for one year, reducing 37.10% the energy losses, costing approximately US$ 15,189,00 to install the turbines and US$ 293.40 to operate them. Again, CS excelled in relation to GA since it was able to converge in all executions, being twice faster than GA.

For the 1080 bus system, 70% of the GA executions culminated in the optimum shown in Table 6, while in the CS only 60% of the simulations culminated in the same optimum found by the GA method. The optimum result found by GA and CS suggest using 6 turbines of model 1 (Enercon-E82/2300), with 13,800 kW of installed power and a generation of approximately 15.61 GWh. With a penetration of only 9.99%, losses are reduced by 64.56%, costing approximately US$25,254,000 to install the turbines and US$ 936.60 to operate them in the period of one year. The proposed CS method is considerably faster to converge than the GA method.

In all systems, after the installation of the turbines, the voltages of some buses have changed. As the test systems do not have voltage regulators, lower voltages are commonly found at the end of the feeder, and these have obtained voltage gains. It is worth mentioning that in none of the buses the voltage exceed the limits required by ANEEL (2010), where the minimum threshold is 0.93 pu and the maximum is 1.05 pu.

It is important to highlight that the method reduces the technical losses of energy, which are inherent to the energy distribution process, being caused due to the passage of electric current in the various elements that make up a distribution network.

5. CONCLUSIONS

An optimal method of dimensioning and locating wind turbines to minimize energy losses in radial distribution systems has been proposed. The method used two metaheuristic targets separately, Genetic Algorithm (GA) and Cuckoo Search (CS).

Unlike most works presented in the bibliographic review, the problem was solved considering the segmentation of the load duration curve in three levels, in addition to the segmentation of the wind speed curve, also in three levels, one for each level of load.

The methodology was applied to three different test systems: 36-bus, 134-bus and 1080-bus, in which the algorithm defined the quantity and the optimum models of turbines to be located in the system. As in practice it is not advisable to use a penetration greater than 20%, this restriction has been incorporated into the problem by applying a penalty function to unanswered solutions.

It was concluded that the proposed algorithm, when using the Cuckoo Search as optimization method, proved to be adequate to solve the problem of optimal installation of wind turbines for the test systems of 36-bus and 134-bus, since it did not need a large amount of data and complex load representation models. Besides, it is simple, fast and effective. Even with a performance reduction when applied to the 1080-bus system, the algorithm was able to install the turbines in a satisfactory manner. However, it is still necessary to improve the method by using better initial estimates instead of random values or restricting the search space to install turbines close to large load centers.

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