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Modelling and Optimisation of Wind Energy Systems

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Abstract

This paper presents the study of methodology for calculation the optimum size of a Wind system. A Long term data of wind speed for every hour of the day were used. These data were used to calculate the average power generated by a wind turbine for every hour of a typical day in a month. A load of a typical house in south of Algeria(desert area) was used as a load demand of the system. For a given load and a mixed multiple-criteria integer programming problem, the types and sizes of wind turbine generators (WTG) was calculated based on the minimum cost of system. In our research, we investigated the genetic algorithm (GA) for optimally sizing a wind power system.
We define that the objective function is the total cost, where the total cost is the sum of initial cost, an operation cost, and a maintenance cost. We determine an optimal configuration of wind generating systems, where total cost is more optimal using GA. A computer program has been developed to size system components in order to match the load of the site in the most cost. A cost of electricity, an overall system cost is also calculated for each configuration. The study was performed using a graphical user interface programmed in MATLAB

Keywords: Wind System; Optimal Configuration; Genetic Algorithm; Programming, Modelling,.

1. Introduction

The rapid depletion of fossil-fuel resources on a world has necessitated search for alternative energy sources. Wind energy has been considered as promising toward meeting the continually increasing demand for energy. The wind sources of energy are inexhaustible, the conversion processes are pollution-free, and their availability is free. For isolated systems such as rural electrification, the wind energy has been considered as attractive and preferred alternative sources.

Generally the main objectives of the optimization design are power reliability and cost.

In this paper an optimal sizing method using the genetic algorithm (GA) is proposed. The types and sizes of wind turbine generators, the highly of turbine can be optimized when sizing a standalone wind power system, which may be defined as a mixed multiple-criteria integer programming problem.

We propose the optimum configurations for wind generating systems in residences using hourly data over a year. We assume that a residence is one house consuming average electrical energy in south of Algeria (Sahara area). Genetic algorithm (GA) is used as an optimization method in this paper. The purpose of this study is to minimize the objective function of GA. The objective function is the total cost, which is the sum of initial cost, operation cost, and maintenance cost per year.

Minimizing the total cost, we can achieve an inexpensive and clean electric power system. In addition, the proposed method can adjust the variation in the data of load, location.

An alternative methodology for the optimal sizing of stand-alone Wind systems is proposed. The purpose of the proposed methodology is to suggest, among a list of commercially available system devices, the optimal number and type of units ensuring that the 20-year round total system cost is minimized subject to the constraint that the load energy requirements are completely covered. The 20- year round total system cost is equal to the sum of the respective components capital and maintenance costs. The decision variables included in the optimization process are the number and type of Wind turbine, the installation height of the WGs. The minimization of the cost (objective) function is implemented employing a genetic algorithms (GA) approach, which compared to conventional optimization methods, such as dynamic programming and gradient techniques, has the ability to attain the global optimum with relative computational simplicity.

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The cost improvement of a wind system varies with the location and cost ratios of the wind power systems, and electrical machine. The present work provides the results of a study on the optimization of a wind system to meet a certain load distribution demand in the city of Bechar, Algeria. The method is applied to the satisfaction of a domestic load demand

2. System Configuration

The configuration of standalone wind power systems is shown in Figure 1. In this paper, we investigated the case that a system has permanent magnet synchronous generator (PMSG) directly coupled to the wind turbine shaft of the wind energy conversion chain.

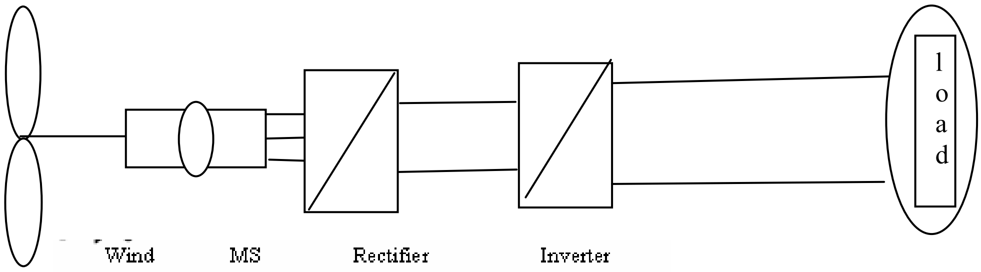


Fig 1. Wind power systems.

3. Modelling Of Wind Energy System Components

Various modelling techniques are developed by researchers to model components of Wind system. Performance of individual component is either modelled by deterministic or probabilistic approaches [1]. General methodology for modelling wind system components like wind turbine, machine generator, and inverter is described below:

3.1 MODELING OF THE WIND SPEED

The wind speed is one of the most important variables in the modeling of a wind energy conversion chain and is the main input variable in the chain synoptic diagram. Consequently, the simulation's accuracy depends on the representation of wind speed. Unfortunately, it has a random behavior inducing a fluctuating characteristic. So, in order to reproduce accurately the wind speed dynamic behavior, two approaches can help us. The first consists in considering measurements of long duration on an actual wind site and the second consists on representing the wind characteristic by an analytical model. The first solution is obviously more precise. Nevertheless, it does not easily permit to simulate various types of configurations of wind sites.

The speed of wind is a random process; therefore it should be described in terms of statistical methods.

The windspeed data were recorded near the ground surface. To upgrade wind speed data to a particular hub height, the following equation is commonly used:

$$v = v_i . \left(\frac{h}{h_i} \right)^{\alpha}$$

Where:v: wind speed at projected height, $\boldsymbol{h}$

v_i: wind speed at reference height, $\boldsymbol{h_i}$

$\boldsymbol{\alpha}$**:** power-law exponent (- 1/7 for open land).

The wind speed distribution is assumed to be a Weibull distribution. Hence the probability density function is given by

$$f(v) = \frac{k}{c} . \left(\frac{v}{c} \right)^{k-1} . \exp\left[-\left(\frac{v}{c} \right)^{k} \right]$$

Where: c : scale factor, unit of speed

k : shape factor, dimensionless

v : wind speed.

The wind speed distribution functions were calculated for each hour of a typical day in every month

3.2 Modeling of the Wind Turbine

The mechanical quantities which will connect the wind turbine with the generator are the wind turbine torque and the rotational speed on the shaft. It should be noticed that the torque depends on the rotational speed. The wind turbine modeling consists on modeling the torque induced by the blades.

The available maximum wind power for a given wind speed is expressed by [1]:

$$S = \pi R^2$$

Where

ρ is the air density, R the blade radius and S the frontal area of the wind turbine.

This maximum power is defined by global aerodynamic coefficients. These two coefficients are bond by the following relation:

$$\lambda = \frac{R\Omega}{v}$$

Where

λ is the tip speed ratio, Ω the rotational speed of the shaft, C_p the power coefficient and C_Γ the torque coefficient.

The power and the wind turbine torque are then given by

$$P_t = P_w C_p = \tfrac{1}{2} \rho \pi R^2 v^3 C_p$$

$$\Gamma_t = \frac{P_t}{\Omega} = \tfrac{1}{2} \rho \pi R^3 v^2 C_\Gamma$$

If the power or torque coefficient is provided by the manufacturer, modeling can be made by a N order polynomial regression [1]:

$$C_\Gamma(\lambda) = a_0 + \sum_{i=1}^{N} a_i \lambda_i \quad (1)$$

The figure illustrates the wind speed torque obtained by modeling with 6 order polynomial regression. The inconvenient of this type of modeling resides on the fact that it does not make it possible to vary the blade pitch angle. The torque model obtained depends only on the wind speed and the shaft rotational speed

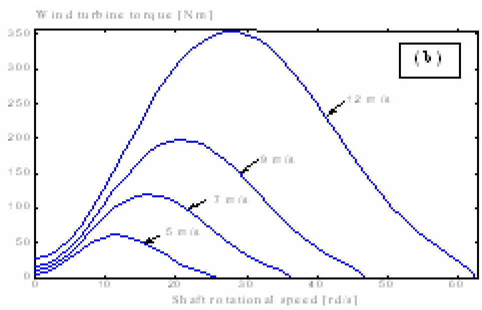


Figure 2 . wind turbine torque versus shaft speed rotational .

This type of modeling is computational time consuming. However, it allows parametric studies of the variation of the blade pitch angle of the turbine. In this case, the torque depends on three quantities: the wind speed, the rotational speed of the shaft and the blade pitch angleβ.

$$\text{where } [v_g] = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix};\ [i_g] = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix};$$

$$[\Phi_A] = \Phi_M \begin{bmatrix} \sin(\theta) \\ \sin(\theta - 2\pi/3) \\ \sin(\theta + 2\pi/3) \end{bmatrix};$$

$$[r_g] = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix};\ [l_g] = \begin{bmatrix} l & m & m \\ m & l & m \\ m & m & l \end{bmatrix}$$

v_g is the stator voltages, i_g the stator currents, Φ_A the permanent magnet flux, θ the angular position, Φ_M the amplitude of the flux linkages established by a permanent magnet r_s the stator resistances, l the main stator phase inductance and m the stator mutual inductance between two stator phases.

To the previous equations, one must add the mechanical equation of the generator shaft

$$\frac{d\Omega}{dt} = \frac{p}{J}\left(\Gamma_t - \Gamma_{em} - f\,\Omega\right)$$

3.4 Modeling of the Static Converters

The static inverter used is a full wave three-phase voltage inverter (Figure) [ ]. Each switch is made up of IGBT in antiparallel with a free wheel diode. The switches are admitted as ideals, thus as in the case of the rectifier, their conduction correspond to a short circuit and their blocking corresponds in its turn to an open circuit. On the other hand, the overlapping is taken here into account. The following figure represents the inverter feeding a three-phase load which has Z_{ch} impedance.

At the output of the inverter, one obtains the three-phase and symmetrical voltage systems. The theory of the three-phase and symmetrical systems shows that the voltages and the currents of these systems have the

following properties:

$$\mathbf{i_{ach} + i_{bch} + i_{cch} = 0\ ;\ u_{ab} + u_{bc} + u_{ca} = 0}$$

$$v_{cch} = \frac{u_{ca} - u_{bc}}{3} \qquad v_{bch} = \frac{u_{bc} - u_{ab}}{3} \qquad v_{ach} = \frac{u_{ab} - u_{ca}}{3}$$

i_{jch} and v_{jch} are respectively the load currents and load voltages where $j = a, b, c$.

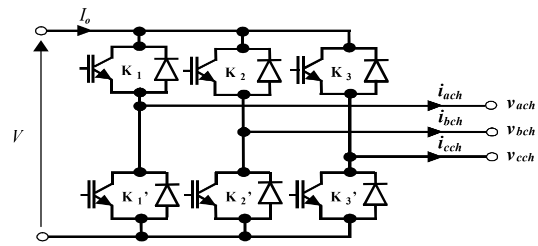


Figure 3. Electric scheme of the inverter.

$K_i = (T_i, D_i)$, $K_i' = (T_i', D_i')$, i = 1, 2, 3 and I_0 is the inverter input current Modeling of the wind energy converter

This part consists on implementing the wind energy converter (Figure1) by connecting the studied components. For that, the below equations are established in order to supplement the previous established equations.

The generator is connected with the rectifier by the following equation

$$\frac{dI}{dt} = \frac{1}{2(l-m)}\left(-\frac{d\Phi_{+A}}{dt} + \frac{d\Phi_{-A}}{dt} - 2rI - V\right)$$

Φ_{+A} and Φ_{-A} corresponds respectively to the PM flux passing by the stator phases which has the most positive potential and the most negative potential.

A filtering capacity is placed in the continues part, between the rectifier and the inverter. This is expressed as follows:

$$\frac{dV}{dt} = \frac{1}{C}\left(I - I_0\right)$$

The input inverter current is then obtained by this equation. For each case, this current is equal to the load current which corresponds to the load voltage which has the most positive potential (absolute value).

4. Optimal Sizing Using the Genetic Algorithm

4.1. Cost Analysis

A global cost model of a wind system has been derived from cost models of all the components for the wind installation and of some other project costs. For most of the components the models are derived from electrical design laws and from the calibration of these models. For the generator and electrical equipment the price is derived from the value of the nominal power. The total wind system cost is the sum of all the costs, and a calibration factor F_{act} allows us to use real wind costs and take into account some unknown project parameters such as the manufacturer's margins [2]

$$C_{PV} = F_{act} \times \sum_i C_i$$

$$i : component$$

The evaluation of the total cost of a project must take into account some additional costs due to:
Land purchase and development of the site;
Transport of the wind generator;
Installation of the wind module;
Foundations building;
Financing and insurance;
Miscellaneous costs (engineering, unexpected costs, etc.).

The economic study should be made while attempting to optimize the size of integrated power generation systems favouring an affordable unit price of power produced. The economic analysis of the wind system has been made and the cost aspects have also been taken into account for optimization of the size of the systems.
The total cost of system takes into account the initial capital investment, the present value of operation and maintenance cost, the inverter replacement cost and the wind system replacement cost. The lifetime of the system is assumed to be 20 years.

The total system cost function is equal to the sum of the total capital, $C_c(x)$ (€), and maintenance cost, $C_m(x)$ (€), is given as follows [14]:

$$C_T = C_c + C_m + Co$$

Where Co *is* the total constant costs including the cost of power conditioning equipment, design and installation etc.

The initial capital investment for the integrated system, C_1 is given as

$$C_1 = N_w.C_w + N_w.h.C_h + C_{inv} (X_{inv}+1)+C_o$$

Where N_w : total number of WG

C_w : the capital costs (€) of one WG, h are the WG tower height limits (m)

C_h is the WG tower capital cost per meter (€/m) , C_o : other cost of installation.

The annual cost for all components that do not need certain items replaced is found by multiplying the total initial cost by the capital recovery factor (C_{RF}). The C_{RF} is defined as

$$C_{RF} = \frac{\left[i(1+i)^n\right]}{\left[(1+i)^n - 1\right]}$$

Where i is the annual interest rate (5% in this study) , n is the lifetime of the component.

The operation and maintenance cost is calculated as follows[3]:

$$C_2 = \frac{\beta(P_m)}{8766}.t + \sum_0^t \gamma(x(\tau)).\nabla\tau$$

Where β , γ maintenance and operation coefficients, for 20-year system lifetime
$C_2 = 20.C_{mw} + 20.h.C_{hm}) + C_{m\_inv}(20-X_{inv}-1)$.

WhereC_{mW} are the maintenance costs per year (€/year) of one WG
C_{hm} is the WG tower maintenance cost per meter and year (€/m/year),X_{INV} are the expected numbers of DC/AC inverter replacements during the 20-year system lifetime, CINV is the capital cost of the DC/AC inverter, (€),
C_{m_INV} maintenance costs per year (€/year) of one DC/AC inverter

The optimization procedure is to determine the sizes of wind system, then to use the GA to compute the type and sizes of Wind Turbine and higher, and then to recalculate the optimal fixed system configuration

4.2. The Genetic Algorithm
The GA is a stochastic global search method that mimics the metaphor of natural biological evolution and does not require derivative information or other auxiliary knowledge [4].
Genetic algorithms are very different from traditional search and optimization methods used in engineering design problems. Fundamental ideas of genetics in biology are borrowed and used artificially to construct search algorithms that are robust and require minimal problem information. A typical constrained, single variable optimization problem can be outlined as follows:
Maximise $_x$ or Minimise $_x$ f(x)
Subject to the constraint: $x_{min} \le x \le x_{max}$
For the solution of such a problem with GAs the variable x is typically coded in some string structures. Binary-coded or floating point strings can also be used, while the length of the string is usually determined according to the accuracy of the solution desired. The GA, as any evolution procedure for a particular problem, must have the following components (Michalewicz, 1994)[5]:
• A generic representation for potential solutions to the problem, similar to the system modelling presented in the previous section.
• Genetic operators (such as crossover and mutation) that alter the composition of children. In the proposed method, the GA optimal sizing methodology outputs the optimum number of WGs, WGs installation height and comprising the set of decision variables, such that the 20-year round total system cost itial population of potential solutions.
• An evaluation function that plays the role of the environment, rating solutions in terms of their ''fitness '' and function.
Multi-objective optimization is achieved by minimizing the total cost function consisting of the sum of the individual system devices capital and 20-year round maintenance cost:
$C_T = N_w.C_w + N_w.h.C_h + C_{inv} (X_{inv}+1) + 20.C_{mw} + 20.h.C_{hm}) + C_{m\_inv}(20-X_{inv}-1) + C_o$

$$F(N_w, h) = \min\{C_T(N_w, h)\}$$

Subject to the constraints

$$N_w \geq 0$$

$$h_{max} \leq h \leq h_{min} \qquad \forall t \in [0, t]$$

$$P_{cons} = \eta[P_w].P_w \quad [\quad]$$

And $\quad |P_{cons}| \leq P_w$

Where h_{max}, h_{min} are the WG tower upper and lower height limits (m), respectively, specified by the WG manufacturer, P_{cons} the load consumption , P_w the wind power production[6]

The flowchart of the GA optimization process is depicted in Figure4. An initial population of 50 chromosomes, comprising the 1st generation, is generated randomly and the constraints described by inequalities ( ) are evaluated for each chromosome. If any of the initial population chromosomes violates the problem constraints then it is replaced by a new chromosome, which is generated randomly and fulfils these constraints. The first step of the algorithm iteration is the fitness function evaluation for each chromosome of the corresponding population. If any of the resulting fitness function values is lower than the lowest value obtained at the previous iterations then this value is considered to be the optimal solution of the minimization problem and the corresponding chromosome consists of the hybrid system optimal operational parameter values. This optimal solution is replaced by better solutions, if any, produced in subsequent GA generations during the program evolution. In order to select the chromosomes, which will be subject to the crossover and mutation operations in order to produce the next generation population, a selection operation is applied based on the roulette wheel method (Michalewicz, 1994). The crossover mechanism uses the Simple Arithmetical Crossover with initial probability psac = 85%.[7],[8]

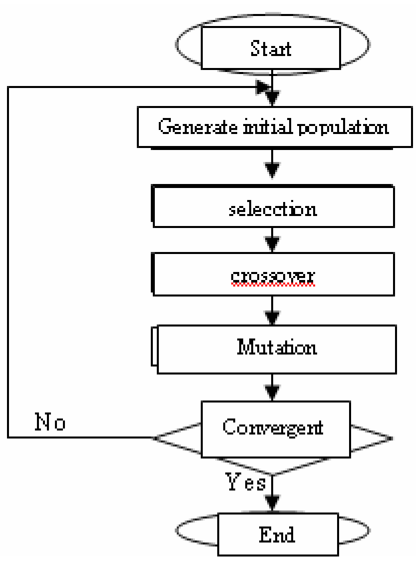


Figure 4 Flowchart of GA.

Next, the selected chromosomes are subject to the mutation mechanism: Uniform Mutation, a gene is randomly selected and it is assigned a new value, randomly selected from the corresponding range of values which fulfil the optimization problem constraints. This range of values is calculated for the selected gene, considering the values of the other genes within the chromosome constant. The mutation probability, P_m is 5.[9]

In case that the application of the crossover or mutation operators, results in a chromosome which does not satisfy the optimization problem constraints, then a ‘‘repair’’ procedure is performed and that chromosome is replaced by the corresponding parent. In case of SC operation, where each new chromosome is generated by two parents, then the chromosome is replaced by the parent with the best fitness function value. The GA optimization process described above is repeated until a predefined number of population generations have been evaluated

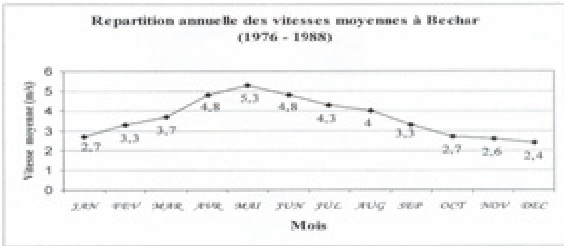


Fig .5: Wind speed in Bechar area.

5. Simulation Results

The proposed method has been applied to the design of a stand alone wind system in order to supply a house located in the south of Algeria (Bechar, Sahara area).

The crossover rate is 0.85. The mutation rate is 0.05. Number of possible different wind types is 3, number of inverter types is 2. The wind turbine lifetime is 15 years. The inverter lifetime is 6 year. The effective interest rate considered is 3%. The wind price (< 5kw$_c$) is 10 Euro/w$_c$. The O&M cost of wind is 1 c€/Wc/year. The cost of the invertors is given related to power [10],[11],[12]

The developed method was used to calculate the optimum number of wind turbine and titles for a stand-alone wind system of the Bechar cite, Algeria. Wind speed data for Bechar obtained from the National Meteo ONM were utilized. The Simulation was specified at the value of 1 year. The load of typical house in Bechar cite, profile plot is shown in Figure6.[13]

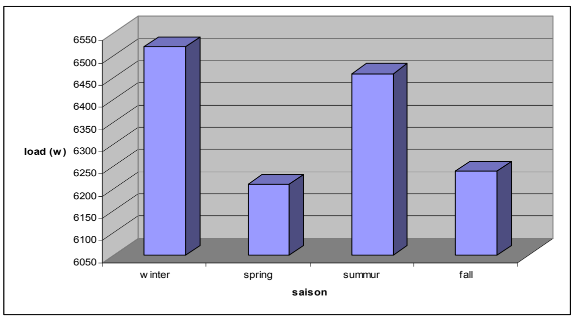
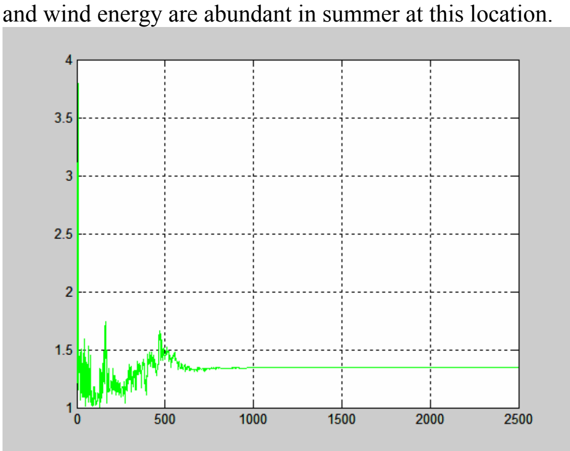


Figure 6 Load profile for all seasons.

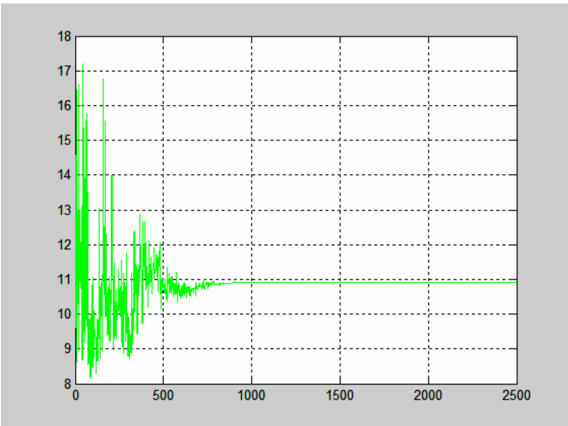
highest load demand values occur in winter. Therefore, the higher of the wind generator was optimising for winter for the considered site. With the use of the program described in the former section, we calculated a series of possible combinations of the number of wind, higher and inverter. For a given unit price of turbine and machine, an optimum solution that minimizes the cost of the system was found. The optimum numbers of wind and higher as indicated in Figure7.

The numbers of wind turbine and higher are determined previously. The GA's results are [1.3, 11] with the total capital cost of wind system as 4715 Euro. The type wind turbine yields the lowest cost for the system.

The optimal configuration is [2, 11]. The cost of Power Supply in the simulation is shown in Figure7, and this is in accordance with the situation that both the solar energy and wind energy are abundant in summer at this location.



(a)



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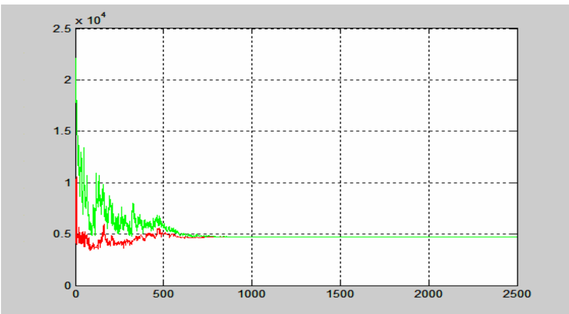

(c)

Figure7 a.optimal number of wind, b. higher of turbine, c. Total cost.

6. Conclusions

A methodology of sizing standalone wind power systems using the genetic algorithm is proposed in this paper. Studies have proved that the genetic algorithm converges very well and the methodology proposed is feasible for sizing standalone wind power systems.

A procedure for optimizing the size of a wind-energy system was presented. The procedure was applied for the sizing of wind system that is considered to produce a power to domestic load in the Bechar area, Algeria. The analysis indicates that a wind system power output can be optimized to suit specific applications with variable or constant power loads. For the specific system considered in this study, the results indicate that the optimal wind system that resulted in the minimum capital cost is (2, 11).

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