An International Journal of Optimization and Control: Theories & Applications
ISSN: 2146-0957 eISSN: 2146-5703
Vol.9, No.2, pp.154-164 (2019)
https://doi.org/10.11121/ijocta.01.2019.00614

RESEARCH ARTICLE

Developing a package for analysis and design optimization of wind turbine systems

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ARTICLE INFO

Article history:
Received: 17 May 2018
Accepted: 27 March 2019
Available Online: 29 April 2019

Keywords:
Energy cost
Design optimization
Graphical user interface
Modelling
Wind turbine system

AMS Classification 2010:
65K99, 68N99, 90C47, 90C29, 90B23, 90B56

ABSTRACT

The installation of wind turbines and consequently the use of wind energy is increasing day by day, since the rapid development in semiconductor technology has led to more advance in the wind turbine technologies. On the other hand, it is well known that a Graphical User Interface (GUI) application provides great advantages to the user such as; the use of programming language and data input for systems without coding, getting the results with the help of symbols, icons and other visual graphics. Accordingly, in this paper, to determine the amount of energy production, cost of energy and etc., of a Wind Turbine System (WTS) that has been established or will be installed, a tool is introduced by the presented software package. Besides the analysis option, the package also offers optimization algorithms that would be used for the layout design of types of Wind Turbine Systems which are called fixed-speed and variable-speed Wind Turbine Systems seperately by keeping in consideration the wind speed and geographic features of the regions. The graphical user interface, which is the one of important features of C# program were used and called Analysis & Design Optimization Package (A&DOP).

1. Introduction

User interface implementations are crucial in providing connectivity between the user and the software or command directories. Graphical User Interface (GUI) applications provide a great advantage to the user in terms of the usage of any programming language and access to information by means of input data, icons and other visual graphics for systems without coding [1]. Accordingly, several number of tools have been developed and published on the modeling and/or simulation for different areas of electrical power systems such as; voltage stability analysis and distributed generation allocation in distribution systems [2], designing DC motor control systems [3], the simulation and control of wind turbines [4], performance estimating tool for transmission lines [5], analyses and design tools for WTS [6-9] and etc. in the literature. Although modelling and design optimization problems for WTSs are being analysed by using a number of programs i.e., developed in [6-9], these programs commonly used classical power computation model (fundamental equations of wind power) that requires determination of rotor efficiency (power coefficient) for WTSs. The determination of power coefficient for a wind turbine requires a field test with the knowledge of aerodynamic design parameters or actual power curve provided by the manufacturers. In these programs, consequently, special requirements of wind turbines, especially variable type, are not well treated.

In recent years, the increase in energy demand and government support has led to a significant increase in the use of wind turbine systems (WTS) in energy production [10]. Therefore, in order to lower the costs and the investments for the operation in a WTS, a great number of theoretical and practical applications in terms of power output controlling [11], power curve modeling and optimal designing of WTSs have been presented in the literature, i.e. [12-18]. Optimal designing of a WTS reduces the energy costs to the minimum level and/or to produce maximum amount of energy. Most of these studies were carried out by utilizing an optimization algorithm in order to obtain highest energy production with the lowest possible cost by considering the wind potential in the region.

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Mathematical methods for computation of rotor power coefficient, resulting of power output [14] and modelling of power curve with respect to wind speed [13, 16-18] were also presented in these studies. Furthermore, there are some studies in the literature [19-23] which mainly focused on the reliability analyses of these mathematical methods developed for characterization of output power for WTSs.

It has been emphasized that the usage of a powerful method for characterizing the power curve for a WTS is an important task for the determining the amount of energy produced and its cost, accurately, results in determining the optimum size/value of design parameters [20]. Additionally, the size of components such as; generator, blades (rotor radius) and tower must be compatible. And, wind characteristic of the site has to be undertaken into design process to get high efficiencies in electrical energy production with lower cost [12-18]. The paper presents a package developed for power and energy cost analyses, and design optimization procedure that implements the life cycle cost model [12] with a powerful power curve method presented in [22]. The package was designed using C# [23] and it is executables to be run on a personal computer even without using any program. The package also facilitates analyzing and design optimization of fixed type of WTSs implementing our output power computation model proposed in [14]. Additionally, new mathematical formulations between the value of rated power, the size of tower and blades for a WTS are defined and used as a constraint for the purpose of increasing the reliability and the computational efficiency. Results clearly indicate that the package enables user to perform power and energy cost analyses, and design optimization to determine optimal size/value of design parameters yielding minimum cost of energy for both types of WTSs, accurately. Organization of the proposed paper can be listed as: output power and energy models for wind turbines are given in Section 2. Section 3 starts with relations between design parameters for WTSs, and a brief description of the package and its validation are then given in the same section. Section 4 relates with the conclusions.

2. Power and energy calculation for WTS

2.1 Output power calculation

A WTS is an electromechanical system and it converts the kinetic energy to the mechanical energy firstly, and then to the electrical energy through a generator. In this system, the power transmitted to the rotor shaft is described as given in following equations [6].

$$P_m = \frac{1}{2}\rho A u^3 C_p(\lambda, v) \tag{1-a}$$

$$C_p(\lambda, v) = c_1\left(c_2\frac{1}{\Lambda} - c_3 v - c_4 v^x - c_5\right)e^{\left(\frac{-c_6}{\Lambda}\right)} \tag{1-b}$$

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08v} - \frac{0.035}{1+v^3} \tag{1-c}$$

$$\lambda = \frac{R w_r}{u} \tag{1-d}$$

where, R and ρ stands for the rotor radius and the air density, respectively, and A is the swept area of a blade, v is the pitch angle, u shows wind speed, w_r represents the rotor angular velocity in rad/s [6]. Rotor efficiency is denoted by $C_p(\lambda, v)$. Occasionally, it is based on the aerodynamic parameters of blades (c_1 - c_6 and x), blade angle and the rotor tip-speed ratio (λ) and called power coefficient. Its maximum value is smaller than Betz limit which is the theoretical maximum value determined as 0.593 [10]. The usage of this type of methods based on the power coefficient is cumbersome to use. This is due to the fact that the determination of maximum power coefficient (rotor efficiency) is difficult, since its value varies with the blade angle and tip-speed ratio which depends on variable wind speed, as can be seen in Eq. (1). It requires a field test with the complex aerodynamic knowledge of design parameters provided by manufacturers, if the actual power curve of that WTS is not available. In some cases, accordingly, the value of power coefficient is taken as its maximum value (C_{p_max}) or constant equivalent values ($C_{p,eq}$) for all steady wind speed which is called approximate power curve model [19].

Wind turbine systems have two types of power generations, namely fixed- and variable-speed. The first type of WTS whose speed is fixed has generally operated with stall principle to keep rotor speed at constant. Even though, variable-speed WTSs is the most favorite type of the WTSs in recent years, the installed capacity of the WTSs is commonly based on the fixed-speed induction generator. Therefore, power curve modeling and analysis of this type of WTS is still an important task. For this reason, we have developed a mathematical method to estimate rotor efficiency in [14] for power curve characterization in both analyses and design optimization studies. The model has been developed by using Weibull probability function. The mathematical expression for the model is as follow:

$$C_p(u) = \frac{C_{p\_max}}{w_m}\left(\frac{u}{u_{ci}} - 1\right)\left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^k\right] \tag{2}$$

Here, C_{p_max} represents the maximum value of rotor efficiency, which depends on the λ_{opt} as:

$$C_{p\_max} = 0.59\left(\frac{\lambda_{opt}\, p^{0.67}}{1.48 + \lambda_{opt}(p^{0.67} - 0.04) + 0.0025\,\lambda_{opt}^{\ 2}} - \frac{1.92\lambda_{opt}^{\ 2}\, p}{1 + 2\lambda_{opt}\, p}\frac{C_d}{C_L}\right) \tag{3}$$

where, C_l/C_d stands for the lift-to-drag ratio, u_{ci} denotes cut in wind speed, and p is the number of blades [13].

The parameter k, c and w_m are computed with respect to design wind speed (u_{des}) for which rotor efficiency is in maximum. The model validation and the value of coefficients for these parameters are given in [14], in detail.

The second type is called variable-speed WTS. Although a fixed-speed WTS is more efficient when a single wind speed is considered, adjusting the rotor speed to wind speed is the ability of variable-speed wind turbine. As a result, it can operate in the maximum level in almost every time [11]. In order to predict the performance of this type of WTSs, various methods have been developed to calculate the output power depending on the wind speed as reviewed in [19]-[21]. These methods have been evolved by taking into account the change in power curve, and are simpler to use. Accordingly, a functional method was also developed to compute the output power for variable-speed WTSs in [22]. The method is based on the capacitor charging voltage equation and characterizes the whole power curve even without knowledge of manufacturers' data. The mathematical formulation of the model is given in following equations.

$$P = P_{rated}(1 - e^{-\left(\frac{u}{a}\right)^b}) \quad (4\text{-a})$$

$$a = 0.70335986 \; x \, u_r - 0.00049995 \quad (4\text{-b})$$

where, u is the steady wind speed in m/s and P_{rated} denotes the generator rating in kW and b is a constant, $b=5$. The method has great advantages comparing to the classical computation method and other approximate methods considered in comparison in terms of number of parameters, and the necessity of the rotor efficiency or actual power provided by the manufacturers [22].

2.2 Energy model for WTSs

In order to characterize the wind potential for any site, the probability function called Weibull distribution is used commonly in the literature [12]-[17], [20]. It is characterized by two parameters as given in following equation.

$$W(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^k\right] \quad (5)$$

Here, u represents the steady wind speed, k and c denotes the shape and scale parameter, respectively, and is defined in terms of height and ground surface friction [12-17]. For a WTS, the Annual Energy Production (AEP) is necessary for determination of energy cost, and it is computed by using the annual mean power of the WTS. The value of mean power for a WTS is determined depending on the turbines' power output and probability density function of wind speed (Generally Weibull distribution) as follow:

$$P_o(u_o) = \int_{u_{min}}^{u_{max}} P(u)W(u)du \quad (6)$$

Here, the wind speed varies between cut-in and cut-out wind speed of the WTS, (u_{min} and u_{max}), respectively [12]. It is used for determination of turbine capacity factor and the amount of energy produced. Capacity factor (C_f) is an important performance parameter in terms of energy efficiency, and defined as given in below.

$$C_f = \frac{P_o(u_o)}{P_{rated}} \quad (7)$$

It is used for determining Annual Energy Production (AEP). The AEP is the quantity of annual total energy generated by a WTS. It is used for determining the cost of energy and evaluation the performance of wind turbines for different wind conditions, and defined as:

$$AEP = 8760 \times P_o(u_o) \times \mu \times Availability\,\% \quad (8\text{-a})$$

$$AEP = 8760 \times P_{rated} \times C_f \times \mu \times Availability\,\% \quad (8\text{-b})$$

where, μ denotes the efficiency of the turbine including soiling and array losses, the number 8760 refers to the annual hours and the Availability% is the annual operating hours of a WTS in percentage [12]. For estimating the cost of *kWh*, the Cost of Energy Model (CEO) model reported by National Renewable Energy Laboratory (NREL) in [12] is commonly used in studies dealing with the optimization of the design and analysis [12, 14, 16-18]. In this model, the cost of energy is defined as given in below.

$$COE = \frac{FCR \times ICC + AOE}{AEP} \quad (9)$$

where, *ICC* denotes initial investment cost (*$*), *FCR* stands for fixed charge rate for one year. *AOE* stands for the operating expenses for one year ($/year). The model consists of all components of WTSs, namely rotor, drive train, tower, land lease and etc., and is detailed in [12].

3. Design methodology and software descriptios

3.1 Design methodology for WTS

In order to configure of a WTS with the ideal size/value of design parameters, the size/value of these parameters has to be optimized undertaking the wind potential of the region into the design process. For this purpose, design optimization algorithms have been developed for both fixed- and variable-speed WTS. In these algorithms, Particle Swarm Optimization (PSO) method [24] and Differential Evolution Algorithm (DEA) [25] are utilized, since they need less user input, easy and simple to use. Additionally, they are effective for obtaining the best solution for every kind of optimization problems by converging and commonly used for this type of problems [14], [16]-[17]. The algorithm developed for designing of variable-speed WTSs optimizes the size of the rotor, the tower height, the generator rating, and the value of the rated wind speed. It also determines the value of capacity factor for optimized wind turbine depending on the wind potential of a given site. The cost of energy in $/kWh is taken as the objective function. The algorithm can be summarized as follows. The rotor radius and the rated wind speed are chosen as independent parameters for the optimized WTS. The optimized parameters and their limits are given in Table 1. As given in table, the rated wind speed and the hub height are arbitrarily selected in the range of their lower and upper bounds. The rotor radius is then computed with respect to *h*. Using computed R_{min} and R_{max}, a range is defined and the value of *R* is arbitrarily selected from this range for each value of *h*. Similar to the computation of *R*, for each value of *R* and u_r, the range of rated power is defined for random value of $C_{p\text{-}max}$ between 0.3 and 0.4 which is defined by observing a number of practical wind turbine data collected from product brochures and company website. Rated power, P_r, is then arbitrarily selected from that range. The value of capacity factor is determined numerically by utilizing power curve model given in Eq. (4) and Weibull distribution at the selected hub height and u_r as given in following equation.

$$C_f = \frac{P_o(u_o)}{P_r} = \int_{u_{ci}}^{u_{co}} (1 - e^{-\left(\frac{u}{0.70335986\ x\, u_r - 0.00049995}\right)^5}) \\ x\left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^k\right] du \tag{10}$$

Where, *k* and *c* parameters are determined using selected hub height (h), surface friction coefficient and Weibull's parameters (k_o and c_o) or mean wind speed and standard deviation at the reference height (h_o) for the region. It is repeated to create candidate solution sets for the design parameters (h, u_r, R, P_r, C_f), the amount of energy which will be produced by the WTS and the cost of energy are then computed for each set by using Eq. (8) and Eq. (9), respectively. The selection and mutation process are then performed with PSO [24] and DEA [25] algorithms and it is repeated until maximum number of iterations is met. It must be stated that At last, the solution set which has the lowest cost of energy is identified as the best (optimum) solution. It must be stated that The geographical features (altitude and mean temperature) are used for determining the value of air density which is used for computation of rated power (P_r).

Table 1. Design parameters and their range for variable-speed WTs

Design Parameters		Its range	Step
Independent Parameters	Hub height (*h*)	h_{min}-h_{max} (input parameters) 20-100 (m)	DEA-PSO
	Rated wind speed (u_r)	u_{r_min}- u_{r_max} (input parameters) 11-17 (ms^{-1})	DEA-PSO
Dependent Parameters	Rotor radius (*R*)	$\left(\frac{h}{7.711}\right)^{\frac{1}{0.6713}} \le R \le \left(\frac{h}{4.56}\right)^{\frac{1}{0.7385}}$	Random
	Rated power (P_r)	$0.195 \times \left(\frac{R}{0.5927}\right)^{\frac{1}{0.4639}} - 0.5\rho\, A u_r^{\,3}\, C_{p\_max}$	Random
	Capacity factor (C_f)	Eq. (10)	[*k=k(h)* and *c=c(h)*]

For a fixed-speed WTS, the size of components and the value of parameters namely generator rating, wing length, tower height, the rotor speed, tip-speed ratio and design wind speed comprise the set of optimization variables by considering constrains defined in [14]. Geographical features of the region such as; altitude and average temperature are also considered as equality constrains. The Weibull distribution, characterized shape and scale parameters (*k*, *c*), are used for computation of turbine mean power for one year by using Eq. (6). The maximum value of rotor efficiency is determined depending on the aero dynamical variables (lift to drag ratio) and the number of blades by Eq. (3). In the design process, the velocity and position of all particles (the value of design parameters) are randomly updated by taking into account the range of design parameters. After updating, all particles are checked and limited according to constrains. This process is continued until the number of iterations that are the stopping criterion is completed. The algorithm could be examined in [14], in detail.

3.2 Software description

Because of the user-friendliness that is the one of most apparent advantages of a graphical user interface, a package called *A&DOP* (**A**nalysis & **D**esign **O**ptimization **P**ackage) was developed. It has one main window that allows users to carry out energy and cost analyses, and to optimize design parameters undertaking wind potential of the site into the design process. C# is used for all program routines of the package, since it is inexpensive and supports cross-platform applications for a lot of operating system as well as 64-bit compilation on Windows [23]. Figure 1 shows main window of the package. As can be seen from the figure, the main window is divided into two main sections called *Analysis* and *Design Optimization*, on which an input and output data for considering WTS is entered and seen, respectively. The first section of the package consists of energy and its cost analyses for fixed-and variable-speed WTS, separately. This section enables the user to analyse the performance of WTS such as; mean power, resulting in AEP, turbine capacity factor and the cost of kWh, total cost of WTS and project for both types of WTS. For the variable type, however, the tip-speed ratio is not to be required with the proposed model; the parameter is used as an input parameter to compute design wind speed for which rotor efficiency is in maximum and the maximum value of rotor efficiency using Eq. (1-d) and Eq. (3), respectively. Besides geographical features of the region i.e., altitude, mean temperature and surface friction coefficient, the wind potential is entered either mean wind speed with its standard deviation or Weibull shape and scale parameters at reference height. Input data in terms of design parameters of WTS, geographical and wind features are typed in using the *Analysis and Design Optimization* windows. In addition to performance analyses in terms of energy and cost, it is also possible to analyse the power curve and Weibull distribution of the wind site graphically by clicking related button on *Graphical Analysis* Section as shown in Figure 2. In the figure Data input and performance analysis of a variable-speed WTS on the *Analysis Window* is examined. It enables to user determining power-energy and cost analysis of a WTS for a specified wind site with its geographical and wind features.

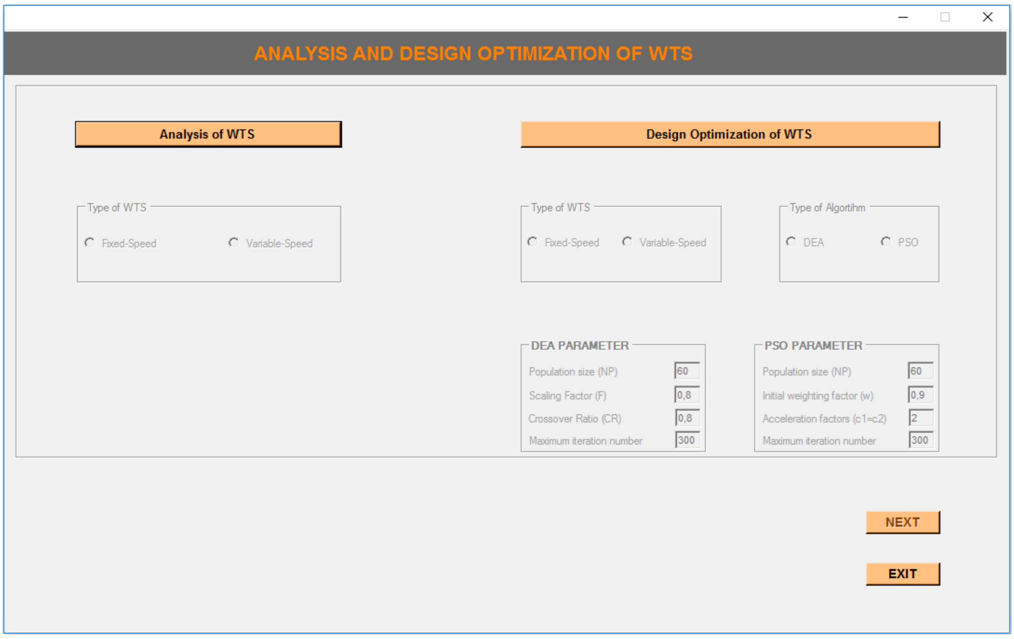

Figure 1. Main window of the package

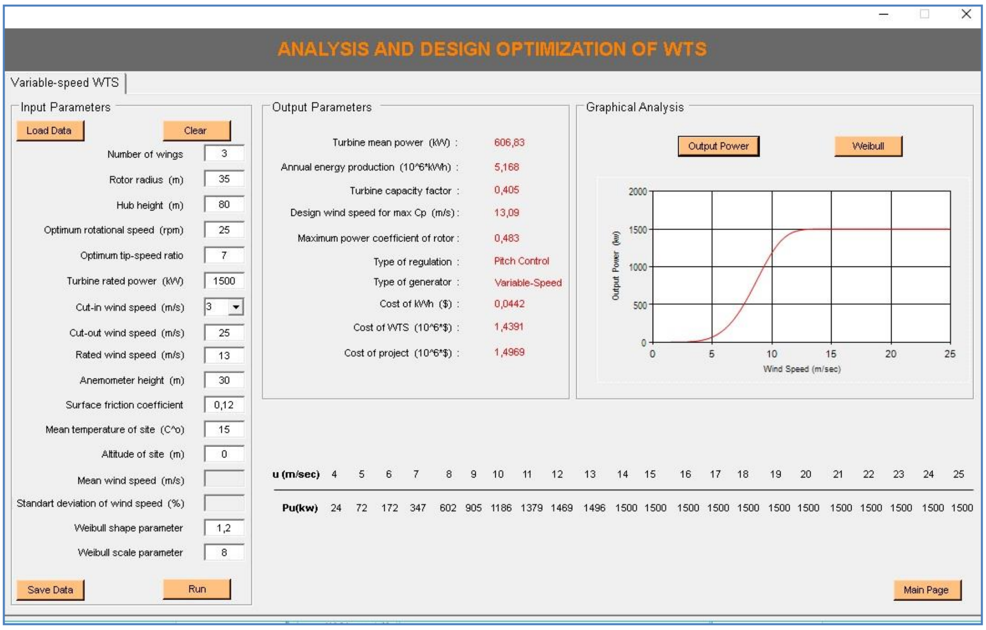

Figure 2. Data input and performance analysis of variable-speed WTS on the *Analysis* window

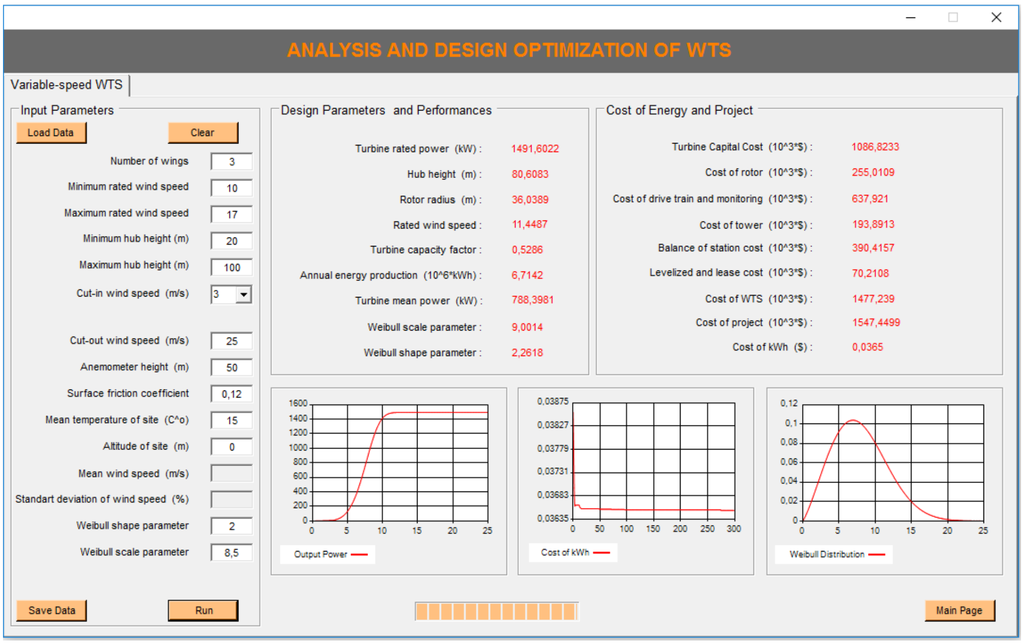

Figure 3. Data input and design optimization of variable-speed WTS on *Optimization* window

The second section of the package, called *Design Optimization of WTS*, facilitates optimal design of both fixed- and variable-speed WTS. In this section maximum iteration number of the optimization algorithm, the value of PSO and DEA parameters could be changed by the user as can be viewed in Figure 1. The *Design Optimization* section of the package consists of three sections for both types of WTS. The first section is called *Input Parameters*, and wind and geographical data of the related site, the range of some design parameters given in Table 1 are entered in this section as it can be viewed in Figure 3. In the figure data input and design optimization of a variable-speed WTS on *Optimization Window* is examined. The first section, called *Input Parameters*, includes the range of independent parameters, geographical features and wind characteristics of the site. The second section, called *Design Parameters & Performances*, provides the optimal size or value of design parameters for variable-speed WTS i.e. rated power, hub height, rotor radius, rated wind speed, and resulting in AEP applying optimization algorithm with the our power curve model as can be seen in Figure 3. The final section, called *Cost of Energy & Project*, allows user to perform cost analyses containing cost of kWh, the cost of all components of the turbine, total cost of WTS and project by using cost of energy model [12]. It also provides turbine power curve and Weibull distribution of the site, graphically.

Recently, even though variable-speed WTSs based on Double Fed Induction Generator or Permanent Magnet Synchronous Generator is the most favorite type of the WTSs, the fixed-speed WTSs are still used in rural areas. Therefore, power curve modeling and analysis of this type of WTS is still an important task. The package is also consisted of analysis and design optimization sections for fixed-speed WTSs. Similarly, the performance of the related WTS; mean power for one year, annual energy production, tip-speed ratio, maximum value of rotor efficiency, and cost of kWh and project could be analysed by using *Analysis* section of the package clicking *Fixed-Speed WTS* button. Our rotor efficiency model presented in [14] is used for power curve characterization in COE model for both *Analyses and Design Optimization* Sections. In *Analysis* section, it is also possible to perform graphical analyses i.e. power curve of the considered WTS as can be seen in Figure 4. In the figure, data input and design optimization of fixed-speed WTS on *Optimization* window is examined. As can be seen from the figure, it is similar to variable-speed type of WTS. The site specified design optimization of fixed-speed WTS could be carried out on *Design Optimization* section of the package. In the optimization algorithm, generator rating, rotor size, tower height, optimum value of rotor speed, tip-speed ratio and design wind speed comprise the set of optimization variables by considering inequality constrains as given in [14], in detail. Geographical and aero dynamical variables namely lift to drag ratio and number of wings are also used as equality constrains. It facilitates to user determining the optimal value or size of design parameters, and its performances in terms of energy and cost undertaking equality and inequality constraints as can be seen in Figure 4. Moreover, the entered data can be saved and reloaded by the Save Data and Load Data buttons in the Analysis and Design Optimization sections of the package. With the Save Data button, information is recorded in the Microsoft Access Database (.accdb) file type. The most suitable WTSs used in the practice can be selected with the *Select Wind Turbine* tab, based on the installed power for the designed WTSs and in particular the nominal wind speed as can be seen in Figure 5. As shown in Figures 1-4, the main window of the package is returned by the *Main Page* button, the screen is cleared with the *Clear* button and the program is closed by using the *Exit* button.

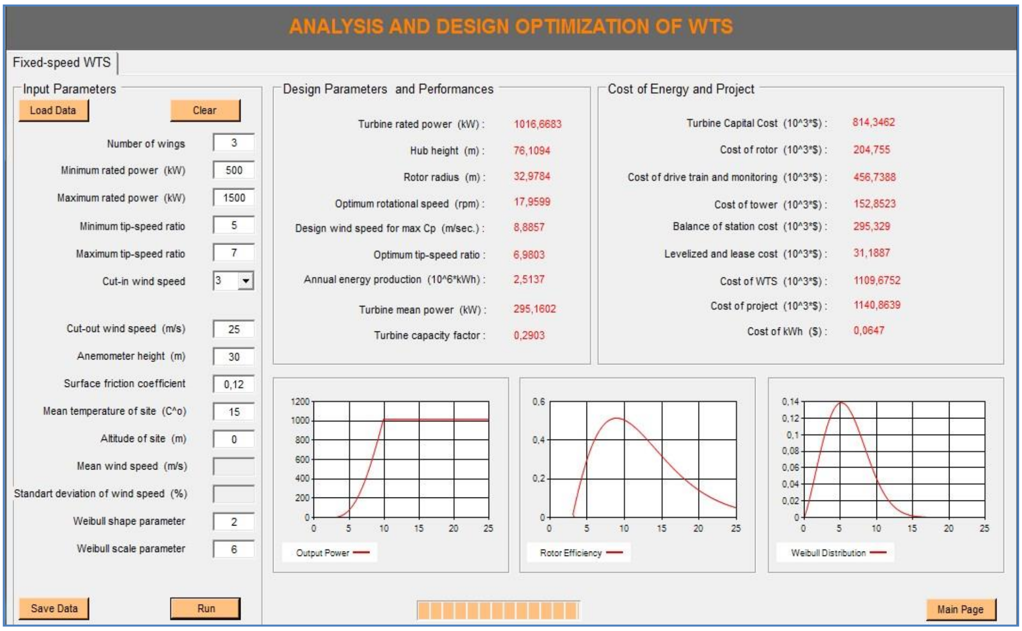

Figure 4. Data input and design optimization of fixed-speed WTS on *Optimization* window

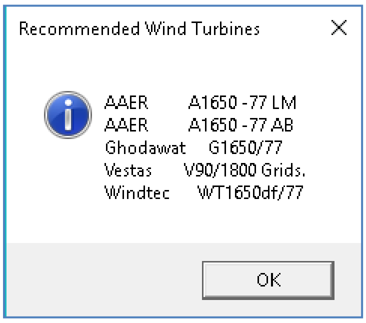

Figure 5. Optimal commercial WTS selection

3 Software testing

In this case of the study, three wind sites are considered in order to evaluate the reliability of the developed package. The size/value of design components/parameters of the WTS that should be installed are obtained by using *Design Optimization* section of the package for both types of WTS. Firstly, the design optimization is performed for variable-speed type and Mediterranean site of Europe whose Weibull parameters are k=1.2 and c=8 m.s^{-1} at the reference height of h=30 m [13]. The wind friction coefficient of the region is taken as α =0.12 [13]. The reason for this is that there is a bigger wind potential in the Mediterranean countries than in the Northern Europe. In addition, some of the Environmental Policies of the Mediterranean countries have been amended for the purpose of increasing the wind parks. A PC, which has the following characteristics, has been used for the simulations; Core™ i5-4590 CPU, 3.3-GHz processor and 8 GB/3.3-GHz memory. The design parameters for the WTS to be installed in this site are determined. Optimization results are presented in Table 2 with the ones of WTSs optimized in [13] and in [16] for this site. One can see from the table that the WTSs designed by using two different optimization methods of the package are in agreement in terms of design parameters and energy cost. Moreover, they are more advantageous in terms of the energy cost and/or the amount of energy production rather than the reference WTS given in [13]. However, both of them produces electrical energy nearly at the same cost, the capacity factor of the optimized WTSs is greater than that of the reference WTS and it generates more energy. On the other hand, when the wind turbines designed are compared with the other wind turbine that is designed for the same area given as in [16], one can see that the wind turbine designed as in [16] is slightly more advantageous in terms of energy amount and its cost. But, in the study, the value of rotor efficiency at the nominal wind speed was taken greater than 0.4, however; the rotor efficiency decreases as the wind speed increases. When the real power curves of the WTSs used in practice are examined, it is observed that taking the rotor efficiency value lower than 0.4 at the nominal wind speed in Eq. (1) is a more accurate approach. For this reason, although it has a slightly lower performance, it is possible to claim that the designed wind turbines are more realistic in terms of the power curve model, constraints and design methodology.

Secondly, the design parameters for a WTS optimized by NREL as in [12] for k=2 and c=8.5 m.s^{-1} at the reference height of h_o=50 m are considered in comparison. For this site, designed wind turbines with the value of its parameters are given in Table 3. As it may be observed in the table, the parameters of WTSs designed by using two different methods of the package and the design parameters for the reference WTS (h, u_r, R, P_r) are consistent at a great rate. On the other hand, it is observed that the designed WTSs by using the developed package are slightly more advantageous in terms of turbine capacity factors; and as a result of annual energy production. For design algorithm given in [12], here, it must be stated that the turbine power output has been determined with the classical method given in Equation (1) by using the change between the rotor efficiency according to wind speed. Since a great number of WTSs with various power rates are evaluated in design process, especially in design optimizations performed with a population-based optimization algorithm, it is not possible to use rotor efficiency in a realistic manner in forming the power curve for each WTS. For this reason, in addition the realistic results, it is possible to claim that the algorithm is also advantageous in terms of implementation.

Table 2. Optimized parameters of the variable-speed WTSs for Mediterranean site of Europe

Parameter	p	D (m)	H_{hub} (m)	U_r (m.s^{-1})	P_{rated} (kW)	AEP (kWh)	Cost of kWh ($cent)	Capacity Factor	Mean power (kw/yr)
Optimized WTS with PSO	3	68.1	79	12.17	1606	5.98×10^6	0.039	0.437	702
Optimized WTS with DEA	3	69.2	79	12.09	1624	6.09×10^6	0.039	0.440	715
WTS [13]	3	30	30	14.00	1000	2.97×10^6	0.038	0.349	349
WTS [16]	3	64.26	73.5	12.40	1705	6.57×10^6	0.0366	0.488	771

Table 3. Optimized variables of the variable-speed WTSs for k=2, c=8.5 m.s^{-1} at h=50 m.

Design Parameters	p	D (m)	h (m)	u_r (ms^{-1})	P_r (kW)	Capacity Factor	Mean power (kw/year)	AEP (kWh)	Cost of kWh ($)
Optimized WTS with DEA	3	72	80	11.44	1491	0.528	797	6.78×10^6	0.036
Optimized WTS with PSO	3	71.6	81	11.42	1460	0.531	775	6.60×10^6	0.036
WTS in Ref. [12]	3	70	65	11.39	1500	0.511	767	6.53×10^6	0.036

As can be seen from the results of both design optimization processes given in Table 2 and Table 3, different wind site has significant influence on the size of the turbine components and the value of other design parameters; rated wind speed and capacity factor. For this reason, the effect of the wind speed on these parameters is analyzed parametrically, and the results are given in Figure 6. As can be seen from the figure, it is obvious that different wind speed and its standard deviation cause different rated wind speed values for the designed wind turbines. From this analysis, we also observed similar situation for the variation of the turbine capacity factor and the amount of energy produced. They are also significantly affected with the variation of the wind speed. Consequently, it can be stated that the rated wind speed of a WTS is a very important parameters in terms of energy production and its cost; hence it must be selected as a design parameter as design in design optimization processes.

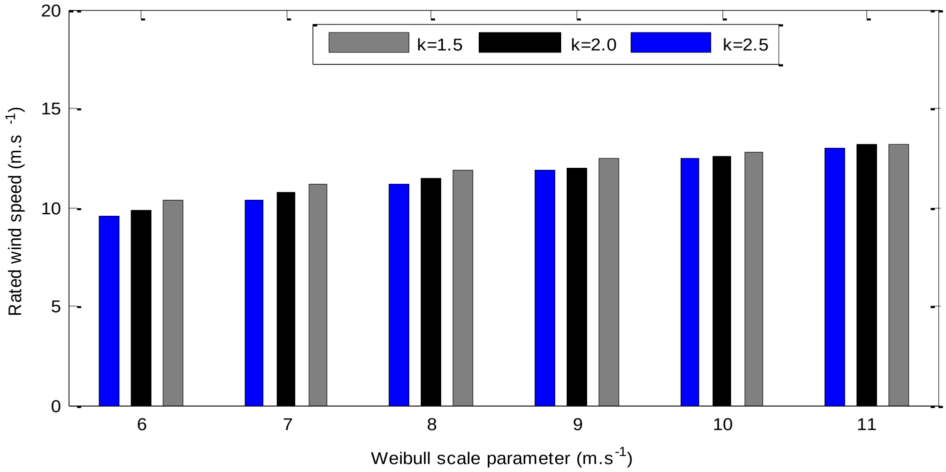

Figure 6. The value of rated wind speed of WTS designed for different wind site

In this case study, finally, Northern site of Europe which has k=2 and c=6 $m.s^{-1}$ at h=30 m, and α=0.12 is considered to validate the optimization section of the package for the fixed-speed WTSs. Table 4 shows the optimization results that can also be seen from Figure 4. The optimized value of design parameters for reference wind turbine given in [13] and its performances are also given. One can see from the table that the value/size of the design parameters, namely design wind speed, rotor diameter, hub height and generator rating power are greater, but the design parameters; rotor speed and optimum tip-speed are lower as compared with those of the suggested WTS in [13]. The values of capacity factor are the same for both wind turbines, but the amount of energy production is more advantageous. Additionally, the results obtained for the same region are given in the last columns of the table by taking the turbine power equal to the reference WTS's power (660 kW) to test the validity of the design algorithm and the identified constraints. One can see that the size of turbine components and the value of design parameters (such as; hub height, rotor radius, design wind speed, and etc.) are matched at a great rate. On the other hand, it is possible to say that the WTS designed is more advantageous in terms of energy cost and annual energy production amount compared to the reference WTS.

Table 4. Optimized variables of the fixed-speed WTS for Northern site of Europe

Parameters	Reference WTS in [13]	Optimized WTS with DEA	Optimized WTS with PSO	Optimized WTS with DEA *(P_n=660kW)*	Optimized WTS with PSO *P_n=660kW)*
p	3	3	3	3	3
D (m)	47	65.8	63.4	53.6	52.6
H_{hub} (m)	60	76	77	69	68
N (rpm)	26	17.9	18.5	21.3	21.9
U_{des} ($m.s^{-1}$)	8	8.88	8.83	8.0	8.29
P_{rated} (kW)	660	1016	943	660	660
AEP (kWh)x10^6	1.30	2.51	2.35	1.66	1.64
Cost of kWh ($cent)	7.12	6.47	6.46	6.44	6.49
Capacity Factor	0.23	0.29	0.29	0.29	0.29
Opt. tip-speed ratio	7.99	6.98	6.97	7.48	7.46
Mean power (kW/yr)	153.4	295	276	195	193

4. Conclusion

The installation of WTSs has been increased in recent times. Accordingly, to product electrical energy at higher efficiency with the lower cost, accurate mathematical methods and algorithms has to be used in analysis and design processes. In this paper, a software package called *A&DOP* (Analysis & Design Optimization Package) for energy system engineering was presented. It was composed by utilizing GUI environment of C#, and validated for both fixed- and variable-speed WTS at different wind sites. It enables the user to analyse and design of a WTS by using functional power curve method, mathematical models defined between the sizes of main components. It also permits the user to gain experience and knowledge in energy and cost analysis, and optimal design of fixed- and especially variable-speed WTSs by taking into account of geographical features of the region. In the optimization algorithm, population based methods; Differential Evolution Algorithm (DEA) and Particle Swarm Optimization (PSO) algorithm were used for solving such problem to determine the most appropriate size/value of design parameters. The parameters consist of the size of turbine main components (hub height, rotor diameter, rated power, and the value of the parameters that has effects on the produced energy and its cost (rated wind speed and turbine capacity factor). From results, it was concluded that the WTSs designed by using the developed package are more advantageous in terms of the energy amount that will be produced and its cost, and are more realistic as compared with those of WTSs given in the literature. Additionally, it was also observed that the DEA is more efficient to solve this type of problem, however; it requires slightly higher computation time as compared with the performance of PSO algorithm. The package is available at: https://muhendislik.gop.edu.tr/Icerik.aspx?d=tr-TR&mk=31052&m=tanitim&bidr=11151&bid=11557 and can be freely downloaded. The package will be continuously modified in terms of power computation methods, constraints defined between the design parameters and the design optimization processes. Additionally, realization of optimal hybrid system design for the regions is planned by including photovoltaic panels to the package.

Acknowledgment

This work has been supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under Grant No: EEEAG-114E961.

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