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Site-specific design optimization of horizontal-axis wind turbine systems using PSO algorithm

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Abstract: Due to the complexity of wind turbine systems (WTSs) containing multiple components, design parameters of a WTS must match each other in order to produce electrical energy at a lower cost and a higher efficiency. In this study, a framework for site-specific design optimization of a horizontal-axis WTS is proposed. It is based on cost reduction and the objective function is the produced energy cost. The cost of energy model proposed by the National Renewable Energy Laboratory is utilized. In order to compute turbine output power that results in annual energy production, a new approach is proposed to model the power coefficient of rotor for fixed-speed WTSs. Design optimizations are performed by using a particle swarm optimization algorithm, which appears to be efficient for this type of problem. WTSs in northern Europe and the Mediterranean were studied. Results show that optimized WTSs for these sites have high profitability in terms of cost and amount of energy when compared with reference WTSs installed in these sites. Parametric analyses are also undertaken in order to evaluate the effect of wind characteristics on the produced energy cost for both types of WTSs and the effects of rotor tip-speed ratio and turbine-rated power on the design parameters and produced energy cost for fixed-speed WTSs. It is concluded that rotor tip-speed ratio has strong effects on design wind speed for fixed-speed WTSs and on the cost of kWh.

Key words: Cost of energy, particle swarm optimization, rotor power coefficient, Weibull distribution, wind turbine systems

1. Introduction

Wind energy is a favored energy resource in electrical energy production. There are a great number of reasons to utilize wind energy. Some of these are:

- the quantity of fossil fuel resources is limited,
- wind is potentially available,
- wind is a free energy resource.

Additionally, the burning of fossil fuels contributes to global warming. Given all of these reasons, wind energy is preferable to other available resources [1]. For these reasons, the use of wind turbine systems (WTSs), and especially horizontal-axis wind turbine systems (HAWTSs), for electrical energy production has increased. Accordingly, several studies and applications in terms of modeling and control methods have been demonstrated for WTSs in the literature [2–8]. Modeling of a wind turbine generator and its integration into grid systems were

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performed in [2,3]. In [4], the authors investigated the effect of system voltage level on the power characteristics of both fixed- and variable-speed WTSs. Variation of frequency in the power output characteristics of WTSs were also analyzed in that study. Cost models in terms of algebraic equations for all components of WTSs, taking into account design parameters (generator power, hub height, the radius of rotor, etc.), were developed in [5]. Modeling of the rotor power coefficient resulting in power characteristics of WTSs and a comparison of produced energy for both types of wind turbines were given in [6]. Stability analyses and generator output voltage-power control strategies were demonstrated in [7,8].

There have been various ways to reduce the capital cost of WTSs. One of them is optimal wind farm planning and predictive maintenance. The main objective of optimal wind farm planning includes site selection of wind farms and layout design to minimize the cost of energy (COE) and/or to maximize the net energy production. Layout design of a WTS involves multiple factors, such as aerodynamic performance, economics, and site requirements. Previous optimization approaches generally tried to maximize power for only a single design operation point [9]. Then the whole wind speed regime was considered in design optimization approaches as explained in detail in [5]. The amount of produced energy by a WTS changes according to the site, because different sites have different wind characteristics in terms of mean wind speed, frequency, and direction. Accordingly, there have been a number of studies on performing site-specific design optimization of WTSs in the literature [5,10–18]. A basic model for COE was given in [5]. In the model, COE is a function of the turbine design parameters and the annual energy production (AEP). An improved model, for which the total cost of a WTS is a function of rotor loads, was developed in [10]. In that study, the blade element momentum theory given in [11] was used to compute the amount of energy production. In [12–15,18], site-specific methods for optimizing WTSs based on cost reduction, for which the objective function was per cost of energy, were proposed. Design optimization was performed to maximize produced energy at minimum cost and site wind characteristics were incorporated into the design process. Additionally, special parametric analyses, i.e. of effects of wind characteristics on the maximum energy production and rotor tip-speed ratio [15] and of effects of turbine rated power and rotational speed on turbine design parameters and COE [18], were also carried out.

The difficulties in the decision-making phase for a complex system in which many simultaneous competing works and procedures need to be considered can be overcome by a superior multilevel system design approach. Applications of a multilevel design configuration for WTS can also be found in the literature [16,17]. Fuglsang et al. minimized the energy cost by varying the rotor parameters and the blade shape in [16]. In the cases of determining the constraints via gradient-based optimizers, a multidisciplinary optimization study was performed, taking into account power production, structural loading, noise emission, lifetime, and reliability. In [17], a similar multilevel approach was used for optimal rotor configuration in WTSs. This multilevel approach constitutes two procedures. The first one is optimal blade geometry design to maximize AEP, and the second one is structural blade design to minimize the bending moment at the blade root.

It is well known that the amount of energy produced by a WTS increases with the rotor size, but this will increase the size of many other components, such as the generator, which will increase the COE. Similarly, wind speed increases with hub height, which increases the tower cost. Design parameters of a wind turbine must match each other and the wind characteristics of the site have to be incorporated into the design process to produce energy at a higher efficiency and a lower cost. In this study, a new model is proposed to calculate rotor efficiency results in power output and energy production for fixed-speed WTSs. The model is only a function of turbine cut-in wind speed and design wind speed where the rotor efficiency is maximized. It enables the user to obtain the power output characteristics and net energy production of a fixed-speed WTS under variable wind speed conditions. The proposed model is used in an optimization procedure that implements an algorithm, namely particle swarm optimization (PSO), to determine the design parameters of variable-speed WTSs yielding minimum COE. The results clearly indicate that the proposed model is well suited for design optimization of this type of WTS. The rest of the paper is organized as follows: aeroturbine mathematic models for both types of wind turbines are presented in Section 2. Then relations between the design parameters of a WTS are detailed by approximate formulations. In order to calculate the rotor power coefficient for fixed-speed wind turbines, a new model is proposed in this section. Section 3 starts with a description of the COE model. The PSO algorithm is then detailed. Finally, optimization variables and constraints are defined, and a brief description of the optimization algorithm is given. In Section 4, the optimization algorithm is applied to different sites with different wind characteristics, and the design parameters (rotor radius, hub height, generator power, optimal tip-speed ratio) and performances (per cost of energy, AEP, turbine capacity factor, etc.) of optimized WTSs are given and compared with those of reference WTSs located in these sites. In this section, parametric analyses are also carried out for evaluating the effect of wind characteristics on the produced energy cost for both types of wind turbines. The effects of design parameters, i.e. rotor tip-speed ratio and turbine-rated power, on the design wind speed, as well as produced energy cost for fixed-speed WTSs, are analyzed and results are presented.

2. Modeling and design of WTS

A WTS power output is affected by several criteria, such as wind speed, rotor power coefficient, rotor diameter, hub height, etc. Energy conversion from the wind by a WTS is defined as follows:

$$P_m = \frac{1}{2}\rho\pi R^2 C_p(\beta,\lambda)u^3, \tag{1a}$$

$$\lambda = \frac{w_r R}{u}, \tag{1b}$$

where u denotes the wind speed (m/s), R is the radius of the rotor (m), ρ is the air density (kg/m^3), and w_r denotes the angular velocity of the rotor (rpm). C_p is the rotor power coefficient that defines the aerodynamic efficiency of the rotor. It varies with the pitch angle of blade (β) and rotor tip-speed ratio (λ). The tip-speed ratio is described as given in Eq. (1b) [1]. The value of the power coefficient depends on the aerodynamic design of rotor, but it is lower than 0.593, which is called the Betz limit. For a wind turbine with a fixed pitch angle of blades, the tip-speed ratio has an optimum value (λ_{opt}) for which the power coefficient is at a maximum ($C_{p\_\max}$). It is specified that the optimal tip-speed ratio ranges from 6 to 8 and that the maximum power coefficient varies between 0.4 and 0.5 for large WTSs [18]. The analytic expression for the maximum value of power coefficient with the optimum tip-speed ratio is given as follows:

$$C_{p\_max} = 0.593\left(\frac{\lambda_{opt}p^{0.67}}{1.48+\lambda_{opt}(p^{0.67}-0.04)+0.0025\lambda_{opt}^2} - \frac{1.92\lambda_{opt}^2 p}{1+2\lambda_{opt}p}\frac{C_d}{C_L}\right), \tag{2}$$

where C_L/C_d is the lift-to-drag ratio, λ is the amount of lift generated by a wing divided by the drag, and p is the number of blades [12].

2.1. Modeling of a variable-speed WTS

The speed of early wind energy conversion systems was constant, because their generators were directly connected to the grid. This drawback was overcome by power semiconductors that contributed significantly to variable-speed WTSs. In this type of WTS, the rotor speed is controlled by a control unit to maximize power output and decrease torque loads. In order to maximize energy production, the most appropriate operation is to change the turbine speed with the wind speed, yielding a continuously maintained tip-speed ratio to keep the power coefficient at a maximum. If wind speed is less than the rated speed for the maximum power point, the rotor speed is adjusted and maintained. When the wind speed is greater than the nominal speed, the power output is decreased by controlling the pitch angle of blades. For various wind speeds, the produced power can be found by using the following equation [12]:

$$P_m = \frac{1}{2}\rho\pi R^2 u^3 C_{p\_max}. \tag{3}$$

The main advantage over the fixed-speed wind turbine is the energy production. A fixed-speed turbine is most productive at a single wind velocity, whereas a variable-speed wind turbine has the ability to adjust the speed to different wind velocities. This means that it is at peak performance nearly all of the time [15].

2.2. Modeling of a fixed (constant)-speed WTS

The second operation type for WTSs is fixed-speed power generation. In this type of WTS, the generator is connected directly to the distribution grid through a transformer and the rotor speed is kept constant by using the stall principle or pitch control. The tip-speed ratio changes with the variation of wind speed, which leads to changes in the rotor power coefficient as well as the power output [15].

For a fixed-speed WTS, the calculation of rotor efficiency (power coefficient) is difficult, because it requires a lot of data, such as the geometry of the blades. In such a model [1], the power coefficient is defined as a function of the rotor tip-speed ratio and pitch angle of the blades. In this type of WTS, the angle of the blades is not constant, because of the variable wind speed. Additionally, the power coefficient calculations require a field test or data from the wind turbine manufacturer. For these reasons, different numerical approximations have been developed and used for this type of WTS. One of them is the Wilson equation, in which the power coefficient is described by a cubic function of wind speed [19]. In this model, the power coefficient strongly depends on the cut-in wind speed instead of turbine design wind speed (u_{des}) for which the tip-speed ratio is optimal and the rotor power coefficient is maximized. A new model was proposed by Diveux et al. in [12] to compute the rotor power coefficient. In that model, the cut-in wind speed is closely related to u_{des}; that is not the case in practice. In [6,15], a powerful model in which the rotor power coefficient is a function of rotor tip-speed ratio by a third-degree polynomial was given. Although the model can be useful for computing the approximate maximum value of the power coefficient, it is most sensitive to the rotational speed and rotor diameter of the selected wind turbine. A small difference in the rotational speed and/or rotor diameter may cause great variation in the value of the power coefficient as well as in the turbine power output. In other words, it requires exact values for the rotor diameter and the rotational speed. In order to overcome these difficulties, a functional model developed from the Weibull probability density function is presented to calculate the power coefficient for fixed-speed WTSs. The Weibull probability density function is commonly used for computation of AEP for wind turbines and is described as:

$$W(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right], \tag{4}$$

where u denotes wind speed, k is the shape parameter, and c is scale parameter of distribution. The maximum value of the function and the corresponding wind speed changes with the shape and scale parameters. In addition, this distribution has different maximum values at the same wind speed for different combinations of shape and scale parameters. The Weibull distribution and the variation of rotor efficiency of a constant-speed WTS with wind speed have similar characteristics. Therefore, the Weibull density function is utilized to model rotor efficiency to compute power output. For this purpose, Eq. (4) is enhanced by adding a term including turbine cut-in wind speed (u_{ci}) as follows:

$$w(u) = \left(\frac{u}{u_{ci}} - 1\right)\left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right]. \tag{5}$$

The values of parameters k and c at which the distribution function will have its maximum desired u_{des} could be easily determined using Eq. (5). In order to have a larger set of data for k and c, u_{des} was increased from 6 m s^{-1} to 15 m s^{-1} by incremental steps of 0.2 and u_{ci} was increased from 2 m s^{-1} to 3.5 m s^{-1} by incremental steps of 0.5. For each pair of u_{des} and u_{ci} in the given ranges, k, c, and the corresponding maximum value of the distribution function w_m were computed using Eq. (5). In these cases, the final value of the distribution at which the wind speed is the turbine cut-out wind speed was kept at approximately 0.1 and its maximum value was kept around 1.0 to simulate the variation of power coefficients for fixed-speed WTSs. After determining the values of k, c, and w_m for each value of u_{des}, they were modeled using an exponential form of u_{des} as given in Eq. (6). The coefficients of each parameter (k, c, and w_m) were determined for different cut-in wind speeds using a curve-fitting method, namely the Gauss–Newton method of [20]. The coefficients of these parameters for each cut-in wind speed are given in Table 1.

$$k = k_1 e^{(k_2 u_{des})} + k_3 e^{(k_4 u_{des})} \tag{6a}$$

$$c = c_1 e^{(c_2 u_{des})} + c_3 e^{(c_4 u_{des})} \tag{6b}$$

$$w_m = w_1 e^{(w_2 u_{des})} + w_3 e^{(w_4 u_{des})} \tag{6c}$$

Thus, the generalized function given in Eq. (5) can be used for computing the rotor power coefficient after dividing w_m and multiplying the C_{p_max}, as given in following equation.

$$C_p(u) = \frac{C_{p\_\max}}{w_m}\left(\frac{u}{u_{ci}} - 1\right)\left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right] \tag{7}$$

The last equation enables users to compute the rotor power coefficient with respect to wind speed and cut-in wind speed of the wind turbine, which results in obtaining power output characteristics and computing the AEP for a fixed-speed WTS. The model was validated on an installed 1500-kW Denmark WTS with a cut-in wind speed of 3.5 m s^{-1}, u_{des} = 9 m s^{-1}, and a maximum rotor efficiency of approximately 0.44. Variation of the rotor efficiency with the wind speed is given in Figure 1. By using these data in Eqs. (6) and (7), variation of the rotor efficiency is also given in Figure 1. As seen in Figure 1, the values of the power coefficient obtained by the proposed model are in close agreement with the exact data. However, though the absolute error is slightly bigger for wind speeds higher than nominal wind speed, it will not affect the power characteristics because the power is controlled around the turbine rated power for this site. The model characterizes the variation of the rotor efficiency with respect to wind speed under variable tip-speed ratio properly. Therefore, it can be used in Eq. (1) to compute power output and AEP for this type of WTS and also in design optimization studies. It must be stated that the power extracted from the wind is influenced by the aerodynamics of the rotor blades. The aerodynamic design of optimum rotor blades from a known airfoil type means determining the geometric parameters, such as chord length and twist angle distribution along the blade span, for a certain tip-speed ratio where the power coefficient of the rotor is maximized. In the model, the effect of the aerodynamic structure of the blades on the power output is included in terms of lift and drag forces characterized by the coefficients of C_l and C_d in computing the maximum value of power coefficient by Eq. (2).

Table 1. Coefficients of Eq. (6) for different cut-in wind speeds (u_{ci} = 2–3.5 m s^{-1}).

Coefficients of Eq. (6)	Cut-in wind speed (u_{ci})			
	2.0 m s^{-1}	2.5 m s^{-1}	3.0 m s^{-1}	3.5 m s^{-1}
k_1	0.496573	0.455796	0.425054	0.413269
k_2	0.121922	0.125928	0.130272	0.131543
k_3	–27.63697	–22.50087	–20.92655	–10.67648
k_4	–0.917701	–0.812986	–0.713853	–0.534774
c_1	6.235108	5.641625	5.325033	14.47420
c_2	0.061462	0.067054	0.070120	0.019127
c_3	–18.20245	–25.48576	–37.45718	–34.92125
c_4	–0.207992	–0.250126	–0.286448	–0.131397
w_1	0.063406	0.042473	0.031896	0.037743
w_2	0.137188	0.144883	0.148747	0.126524
w_3	–0.807930	–0.737211	–0.539682	–0.222403
w_4	–0.491432	–0.457384	–0.375764	–0.179157

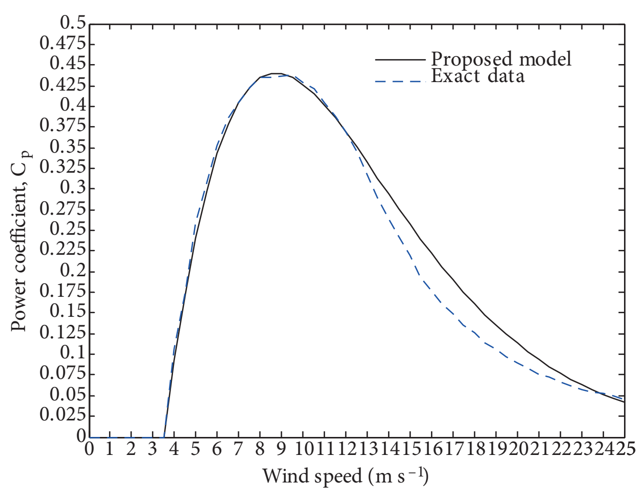

Figure 1. Variation of the rotor power coefficient of a Denmark WTS versus wind speed.

2.3. Design methodology of WTS

For a WTS, if a large rotor with a small generator is used, the WTS will convert only a small part of the wind energy into electrical energy at higher values of wind speed. On the other hand, if a large generator with a small rotor is used, the generator will operate at a low efficiency for all wind speeds. Accordingly, the rotor-to-generator ratio has to be optimized to determine the ideal size of these components. In order to compute the approximate value of rotor diameter, an empirical formula given in the following equation is commonly used:

$$D = \left(\frac{P_{rated}}{0.195}\right)^{\frac{1}{2.155}}, \tag{8}$$

where D is the rotor diameter and P $_{rated}$ is the turbine-rated power in kW. The rated power is the capacity of the WTS to convert mechanical (shaft) power to electrical power and it is called generator rating power. To utilize wind power efficiently, the rotor has to have a suitable rotational speed. The rotational speed is related to rotor size and wind speed. In [21], a trend for rated tip speed with respect to rotor diameter was demonstrated. It can be converted to an approximate formula for rotational speed (N) by a linear form of rotor diameter using a curve-fitting method [20] as given in following equation:

$$N = 30\frac{0.5945 \times D/2 + 49.19}{\pi D/2}. \tag{9}$$

It is a well-known fact that wind speed increases with hub height and that a larger rotor captures more energy, but the tower mass is related to hub height and rotor size as well. Moreover, rotor cost increases with size. A larger rotor turbine at a higher hub height may produce more energy, but it increases the energy cost. To produce energy with a WTS at higher efficiency, rotor diameter and hub height have to be compatible. An approximate formula was developed in [21] by using the trend of hub height with the rotor diameter as follows:

$$h = 2.7936 \times D^{0.7663}. \tag{10}$$

For a site, the wind is not steady. In order to determine the AEP, a probability distribution of the wind speed has to be used. The Weibull probability density function given in Eq. (4) is commonly used for calculating AEP because of its comprehensive nature and its ability to illustrate the random variation of wind speed. Since the site environment affects the wind speed, the scale parameter (c) varies with tower height. It is determined using the power law given in Eq. (13). The shape parameter (k) is also defined as a function of hub height as follows:

$$c = c_o(\frac{h}{h_o})^{\alpha}, \tag{11a}$$

$$k(h) = k_o + \Delta k(h), \tag{11b}$$

$$\Delta k(h) = \begin{cases} 0.008h - 0.08 for h < 20m \\ 0.003h + 0.02 for h \geq 20m \end{cases}, \tag{11c}$$

where $h$denotes the hub height (m), c_o is the value of shape parameter at the reference height (h_o), and α is the coefficient of the ground surface friction [12].

Due to the nonlinear variation of power with steady wind speed, the mean power obtained over time in a variable wind with a mean speed is not the same as the power obtained in a steady wind of the same speed. The mean power at a mean speed is computed by using the steady power and Weibull distribution as follows [5]:

$$P_o(u_o) = \int_{u_{ci}}^{u_{co}} P(u)W(u)du. \tag{12}$$

The ratio of mean power to rated power is called turbine capacity factor (C_f). In other words, the capacity factor of a WTS is the amount of actual annual energy output divided by the theoretical energy output computed by using rating power. It can be defined as:

$$C_f = \frac{P_o(u_o)}{P_{rated}}. \quad (13)$$

In practice, the capacity factor usually varies from 20% to 50% [5]. AEP is the amount of energy produced by a WTS for 1 year. It depends on the wind characteristics of the site and the design parameters of the WTS and is defined as:

$$AEP = 8760 \times P_o(u_o) \times \mu \times Availability\%, \quad (14a)$$

$$\mu = (1 - SoilingLosses\%)(1 - ArrayLosses\%) \quad (14b)$$

where the efficiency of the turbine (μ) is defined as a function of soiling and array losses as in Eq. (14b). Soiling losses are taken as 3.5%. The aerodynamic interference between wind turbines in a wind farm causes array losses, usually around 5%. The coefficient 8760 is the total amount of operating hours in a year and the availability coefficient characterizes the percentage of operating hours of the turbine in a year; this is taken as 98% in this study as in [5].

3. Site-specific design optimization of WTS

3.1. COE model

In order to estimate the per cost of energy produced by a WTS, the model developed by the National Renewable Energy Laboratory and proposed in [5] is utilized. The model is based on the economy and the performance of a WTS and COE is calculated by using the following equation:

$$COE = \frac{FCR \times ICC + AOE}{AEP}, \quad (15)$$

where ICC is initial capital cost of the rotor components, drive train, tower cost, expenses of manufacturer services, etc. FCR is a fixed charge rate (1/year). AOE is annual operating expenses (cost/year) and consists of land lease cost and replacement costs. For this model, an algebraic equation of all components is given in [5] in detail.

3.2. PSO algorithm

In order to design a WTS for a specific site, a well-known population-based optimization algorithm, the PSO algorithm [22], was used because it is simple and requires small computational time. Moreover, it is capable of converging to a global optimum for all types of complex optimization problems [22]. The algorithm uses the procedures of moving particles around a multidimensional search space for approaching an optimal point. First, a particle group is created randomly and put into motion. By considering its own experience and that of neighboring particles, each particle sets its movement by regulating its position. After each optimization, the fitness value of all particles is calculated and they change their position towards a better one. Since the speed of each particle is a random variable, they can be updated depending on the distance from the best location. The velocity (u) and position (s) of each particle i is updated as follows:

$$u_i^{t+1} = wu_i^t + c_1 rand_1(pbest_i^t - s_i^t) + c_2 rand_2(gbest^t - s_i^t), \quad (16a)$$

$$s_i^{t+1} = s_i^t + u_i^{t+1}, \tag{16b}$$

where c_1 and c_2 are acceleration factors and w is the weighting factor. The convergence of the algorithm is formed based on the difference between the fitness values of two successive iterations or maximum number of iterations.

3.3. Constraints and optimization algorithm

In order to increase reliability and computational efficiency, the approximate formulas given in Eqs. (8)–(10) describing the relationship between design parameters are taken into account in the design optimization procedure. First, the reliability of these formulas was tested on different sizes of HAWTs, which were 350 kW in [18], 600 kW in [12], and 1500 kW in [5]. It was observed that the value of design parameters (rotor diameter, rotational speed, and hub height) obtained by using these approximate formulas were in good agreement with their exact data for each WTS. The maximum error was in the range of 10%, which occurred in the rotor radius of the 1500-kW WTS. Therefore, these formulas could be used for design optimization as inequality constraints between design parameters, with tolerances defined by the test results as follows:

- The relation between the rotor and generator size given in Eq. (8) is defined as an inequality constraint with ±10% tolerances as follows:

$$0.9 \times \left(\frac{P_{rated}}{0.195}\right)^{\frac{1}{2.155}} \leq D \leq 1.1 \times \left(\frac{P_{rated}}{0.195}\right)^{\frac{1}{2.155}}. \tag{17}$$

- The rotational speed of the rotor is related to the rotor diameter and wind speed. The relation between rotor size and rotational speed described in Eq. (8) can be used as an inequality constraint with ±10% tolerances, as follows:

$$0.9 \times 30\frac{0.5945 \times D/2 + 49.19}{\pi D/2} \leq N \leq 1.1 \times 30\frac{0.5945 \times D/2 + 49.19}{\pi D/2}. \tag{18}$$

- The approximate formula given in Eq. (10) describing the relation between rotor diameter and hub height can be defined as an inequality constraint, as follows:

$$2.7936 \times D^{0.7663} \leq h_{hub} \leq 1.2 \times 2.7936 \times D^{0.7663}. \tag{19}$$

- To produce energy at a higher efficiency, the capacity factor of a WTS must be taken into account in the design optimization process. Accordingly, it is also defined as an inequality constraint as follows:

$$0.2 \leq C_f. \tag{20}$$

In order to design a WTS for a specific site, an optimization algorithm is proposed. It is based on cost reduction and the objective function is per cost of energy in US$/kWh. The flow chart of the design optimization algorithm is presented in Figure 2. The turbine-rated power, rotor diameter, hub height, rotational speed, tip-speed ratio, and design wind speed constitute the overall set of the design variables by undertaking the inequality constraints given above for both types of WTSs. Geographic and aerodynamic variables are also used as equality constraints. The air density (ρ) of the site is computed by using average temperature (T_o), altitude (H) of the site, anemometer height (h_o), and air density for atmospheric air pressure (ρ_o). Aerodynamic variables (C_d,

C_l), the number of blades (p), and the tip-speed ratio are used in Eq. (2) to compute the maximum value of the power coefficient. In the optimization process, as indicated in Table 2, the rated power and tip-speed ratio are randomly chosen between 50 and 2500 kW and 6 and 8, respectively, as in the NPx1 column vector where NP is the population size of the PSO algorithm. For each value of P_{rated} in the selected range, the rotor diameter is computed by Eq. (8). Then a range is defined in terms of computed D as given in Eq. (17) and D is randomly chosen from this range. For each value of rotor diameter, the same process is repeated for computing hub height by using Eqs. (10) and (19) and rotational speed by using Eqs. (9) and (18). For each λ and computed N_{rotor} and D values, the design wind speed is calculated by using Eq. (1b). These values are used in Eqs. (6) and (7) to obtain the power output of fixed-speed WTSs, which is used for computing turbine mean power by using Eq. (12). These results are used in Eq. (14) to compute the amount of energy produced in a year. The λ value is also used for computing the maximum rotor efficiency in Eq. (2). At each iteration, P_{rated} and λ values are randomly updated by using Eq. (16) and checked for their limits. The remaining ones are determined based on these updated values of parameters as given in Table 2. This process repeats until the maximum number of iterations or tolerance of fitness values are met. The implementation of the algorithm for solving the WTS design problem is given step-by-step as follows:

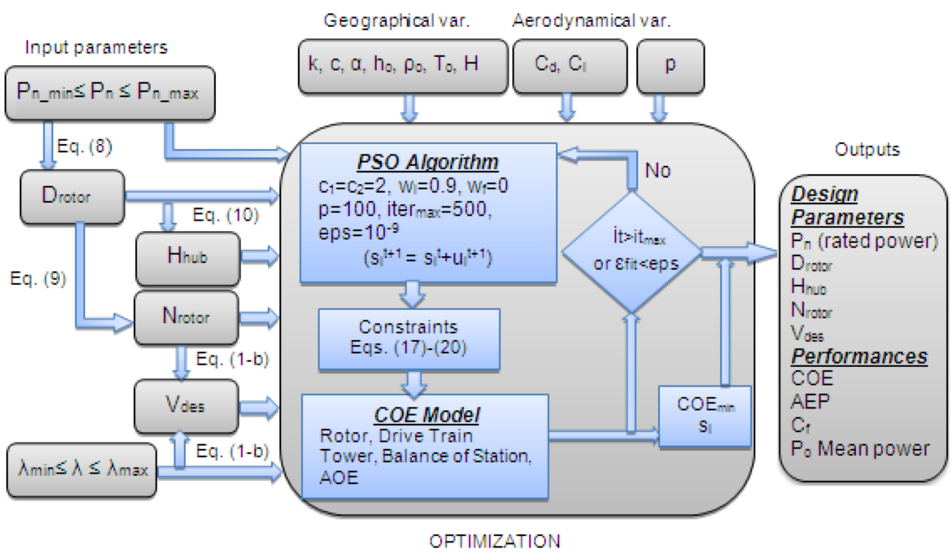

Figure 2. Flow chart of WTS's design optimization algorithm.

Table 2. Variation range of design parameters.

Parameter	Range of parameter	Step
Rated power (P_{rated})	50–2500 (kW)	Random
Tip-speed ratio (λ)	6–8	Random
Hub height (h)	Eqs. (12) and (**??**) (m)	Random
Rotor diameter (D)	Eqs. (10) and (19) (m)	Random
Rotational speed (N_{rotor})	Eqs. (11) and (20) (m)	Random
Design wind speed (u_{des})	Eq. (1b) (m s^{-1})	-

Step 1. Input geographical, turbine aerodynamic variables, wind data of the region, and number of blades (T_o, H, α, k_o, c_o, h_o, C_d, C_l, p).

Step 2. Set the maximum number of iterations and the tolerance of fitness values.

Step 3. Create a population of agents (particles) as given in Table 2.

Step 4. Evaluate each particle's position according to the objective function (cost of per energy) by using Eq. (15).

Step 5. If a particle's current position is better than its previous best position, update it.

Step 6. Determine the best particle (according to the particle's best positions) and the value of objective function.

Step 7. Update particles' velocities for P_{rated} and λ, and move these particles to their new positions using Eq. (16) and check their limits. Then compute the new values of remaining elements of each particle (D, h, N_{rotor}, u_{des}) as given in Table 2.

Step 8. Go to step 4 until the stopping criteria (maximum number of iteration or fitness error) is satisfied.

4. Design optimization of WTS

Optimal site selection and layout design of wind turbines could not only reduce energy production cost but also extend the life time of turbines, which results in increased energy production. WTSs at a site in northern Europe and another in the Mediterranean were optimized. That is due to the fact that Mediterranean sites have a greater wind potential than northern Europe and that in these countries, environmental policies have been changed in order to increase their wind turbine parks. The Weibull probability density function was used to characterize the wind characteristics of these sites. As indicated in [12], the shape parameter ranged between 1.0 and 2.0 and the scale parameter was around 8.0 m s^{-1} for Mediterranean sites. On the other hand, k is usually around 2.0 and c ranges between 5 m s^{-1} and 7 m s^{-1} in northern Europe [12]. A personal computer with a 2.4 GHz Core 2 Duo processor T6600 and 2 GB memory was used for simulations and algorithms were coded in MATLAB. The performance of the PSO algorithm was evaluated to determine the proper algorithm performing a number of simulations. For simulations, only population size (number of particles) and iteration numbers were investigated to see the changes in optimal solutions. For the PSO algorithm, upon simulation results, both acceleration factors (c_1 and c_2) were set to 2.0 as in [22], while the weighting factor had an initial weight of 0.9 and a final weight of 0. The population size varied from 10 to 100 and it should be 80. The maximum number of iterations was set to 500 and the tolerance of fitness value was set to 10^{-9} as in [15].

First, a site in northern Europe was considered and its wind potential was characterized as k = 2, c = 6 m s^{-1} at h = 30 m, and α = 0.12. Design parameters of the constant-speed WTS were determined by using an optimization algorithm whose flow chart is given in Figure 2. Since the COE model requires the computation of turbine mean power as a result of AEP, the developed model given in Eq. (7) was used in Eq. (1a) in order to compute turbine power output with wind speed. Turbine mean power for 1 year was computed with respect to wind speeds ranging from u_{ci} = 3 m s^{-1} to u_{co} = 25 m s^{-1} using Eq. (12). C_{p_max} was determined by Eq. (2) for the number of blades p = 2–3 and for the lift to drag ratio C_L/C_d = 120 as in [12]. Results are given in Table 3. The parameters of the reference wind turbine and its performances, mean power, energy production for 1 year, capacity factor, and COE were recomputed by using Eqs. (12)–(15), respectively, and are given in the first column of Table 3. It is seen from Table 3 that rotor size, hub height, and rated power for the optimized wind turbine were higher than those of the reference wind turbine, whereas parameters related to rotor diameter, i.e. rotational speed and optimum tip speed, were lower than those of the reference wind turbine. Both have nearly the same capacity factors, but the COE for the optimized wind turbine is lower than that of the reference wind turbine while it produces more energy. Thus, the optimized WTS is more advantageous than the reference wind turbine for this site; however, its total cost is more than that of the reference wind turbine. Design optimization was also performed by fixing rated power to that of a reference wind turbine (P_n = 660 kW), and the results are also given in Table 3 in the third column. Design parameters and the performance of the optimized WTS are in close agreement with those of the reference wind turbine. Therefore, it can be said that the parameters of the reference WTS are well-designed for generators around 600 kW of rated power. Additionally, Figure 3 shows initial (o) and final (x) conditions of PSO particles. From the optimization results, it could be said that the PSO algorithm is efficient for this type of problem; however, the computational time increases as the population size and/or maximum number of iterations increases.

Table 3. Optimized parameters and performances of a fixed-speed WTS compared with those of a reference WTS for northern Europe (k = 2, c = 6 m s^{-1} at h = 30 m, and α = 0.12).

Parameters	Reference WTS, WT2 in ref. [12]	Optimized WTS	Optimized WTS (P_n =660 kW)
p	3	3	3
D (m)	47	54.6	47.5
H_{hub} (m)	60	69	63
N (rpm)	26	20.9	24
u_{des} (m s^{-1})	8	8.02	7.84
P_n (kW)	660	906	660
Type of regulation	Pitch	Pitch	Pitch
Type of generation	Constant speed	Constant speed	Constant speed
AEP (kWh)	1.30×10^6	1.84×10^6	1.34×10^6
Cost of kWh (US cents)	7.12	6.89	7.02
Capacity factor	0.23	0.24	0.24
Opt. tip-speed (rad/s)	2.72	2.19	2.51
Mean power (kW/year)	153.4	216.8	158.2

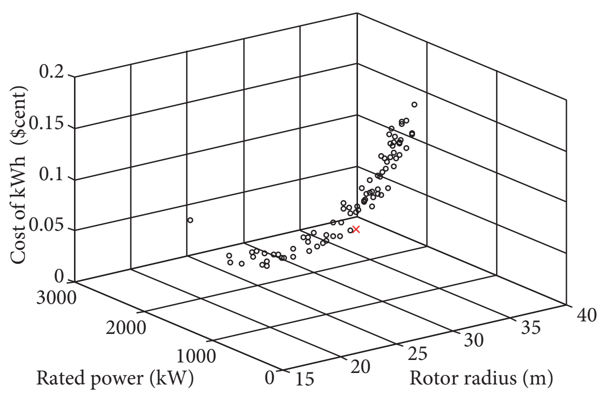

Figure 3. Initial (o) and final (x) conditions of PSO particles.

It is seen from Table 3 and Figure 4 that the design wind speed is around 8.0 m s^{-1} for this site. The figure shows the influence of the design wind speed on the per cost of energy for constant-speed WTSs designed for a northern European (a) and a Mediterranean site (b). For the Mediterranean site, the wind characteristic is characterized by Weibull parameters of k = 1.2, c = 8 m s^{-1} at h = 30 m, and wind shear coefficient α = 0.12. Optimizations were performed for different values of design wind speed ranging from 6 m s^{-1} to 14 m s^{-1} with incremental step of 0.2 for the number of blades p = 3. From Figure 4, it is clearly seen that the energy can be produced at minimum cost when the design wind speed is approximately 8.0 m s^{-1} for the northern European site and the cost of energy is \$0.069/kWh, whereas optimal design wind speed is approximately 8.6 m s^{-1} for the Mediterranean site, where the cost of energy is \$0.043/kWh. The COE for the Mediterranean wind turbine is much smaller than for the northern European wind turbine and it increases as the design wind speed increases, $u_{des} > u_{des\_opt}$, for both sites. It was also observed from analyses that the performances of optimized wind turbines (capacity factor, mean power, and energy production for one year) were greater for the Mediterranean site than for the northern Europe site.

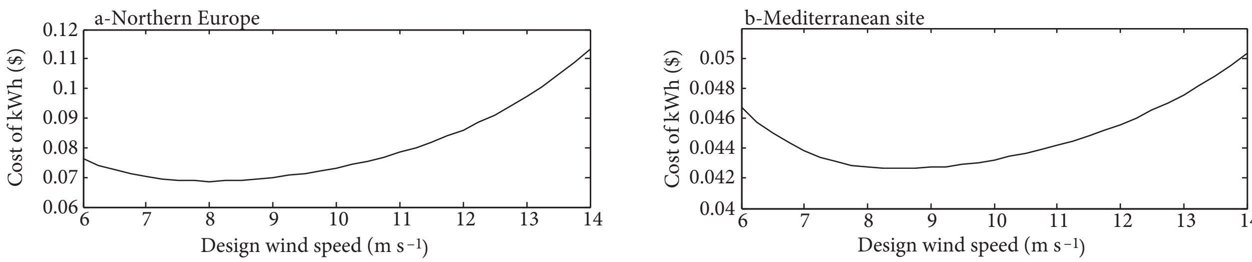

Figure 4. Variation of produced energy cost of optimized wind turbines with design wind speed (u_{des} = 6–14 m s^{-1}) for sites in northern Europe (a) and the Mediterranean.

For a WTS, there exists an optimum tip-speed ratio at which the power coefficient is maximized. The corresponding wind speed is called design wind speed, as mentioned above. It is evident from Eq. (1b) that the tip-speed ratio is related to the design wind speed and rotor diameter, resulting in turbine-rated power. Accordingly, the effect of rotor tip-speed ratio on design wind speed and on produced energy cost for a fixed-speed wind turbine was analyzed. Various combinations of rated power and tip-speed ratio were analyzed, and the results obtained for the Mediterranean site are given in Figures 5 and 6. Parametric analyses were applied where the rated power was changed from 0.5 MW to 2.5 MW in incremental steps of 0.25 while the tip-speed ratio increased from 5.0 to 9.0 in incremental steps of 0.5. It is seen in Figure 5 that rotor tip-speed ratio has a strong effect on design wind speed. For a given rated power, the design wind speed decreases as the tip-speed ratio increases in order to keep rotor diameter and rotational speed constant, which are strongly related to rated power. On the other hand, for a given tip-speed ratio, rated power has a low influence on the design wind speed for optimized WTSs. The speed slightly increases as the rated power increases, due to increasing turbine rotor size (rotor diameter) that decreases the rotational speed. Similar observations could be made from the variation of per cost of energy given in Figure 6. For a given rated power, the variation of tip-speed ratio has a strong effect on the produced energy cost, whereas rated power has a low effect on the cost of kWh for a fixed tip-speed ratio. Both parameters have an optimal value where COE is minimal. An optimal match appears to be a tip-speed ratio of approximately $\lambda_{opt} = 7$ with the generator rating power around 1500 kW for this site. Note that a similar variation was also observed in the optimization results of simulations performed for the site in northern Europe.

Due to the number of advantages over fixed-speed WTSs, variable-speed WTSs are available today in the market. In this work, a design optimization algorithm was also applied in order to optimize these types of WTSs. A Mediterranean site was considered and the optimum values of design parameters were determined using an optimization algorithm whose flow chart is given in Figure 2. Power output and performances of the optimized WTS were computed by using Eq. (3) and Eqs. (12)–(14), respectively. Results are given in Table 4 with the parameters and performances of the reference WTS and those of the WTS optimized in [12] for this

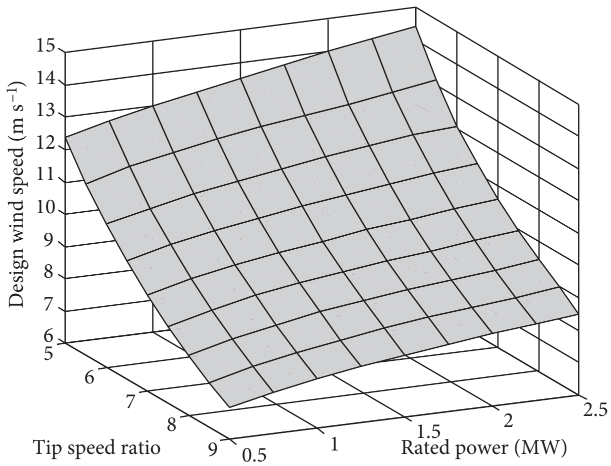

Figure 5. Design wind speed of optimized wind turbines with respect to tip-speed ratio and generator-rated power for the Mediterranean site (k = 1.2, c = 8 m s^{-1} at h = 30 m, and α = 0.12).

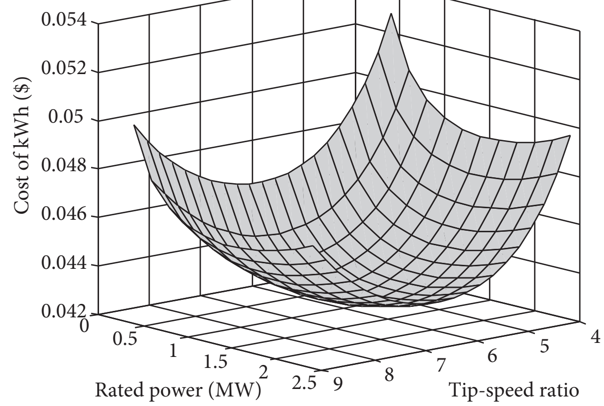

Figure 6. Cost of kWh for optimized wind turbines with respect to tip-speed ratio and generator-rated power for the Mediterranean site (k = 1.2, c = 8 m s^{-1} at h = 30 m, and α = 0.12).

site. Even though the reference WTS is not located in the region of interest, this comparison is given because the region of interest and the location of the reference WTS have nearly the same wind characteristics [12]. As can be seen from Table 4, the optimized WTS produces more energy at a lower cost; however, its total cost is greater than that of the reference wind turbine. In addition, the optimal tip-speed ratio was determined to be λ = 7.11, which is more practical to keep the AEP at maximum for a three-bladed larger WTS [15,18]. Contrary to the conclusion of [12], the reference wind turbine had a lower COE and higher energy production than those of the wind turbine optimized in [12] when the COE model [5] was used for computing the performances of these WTSs. Design optimization was also performed by fixing rated power equal to that of the reference wind turbine and the results are given in the fourth column of Table 4. However, the parameters of the optimized WTS, except design wind speed, are smaller than those of the reference wind turbine. The performances (AEP, cost of energy, tip-speed ratio, and capacity factor) were very close to those of the reference WTS. Consequently, contrary to the specifications of [12], the parameters of the reference WTS are only well-designed for its generator rating power. On the other hand, it is seen from the second column of the table that the rotor diameter and the hub height of the WTS optimized in [12] are smaller and that the cost of kWh is much greater and energy production is smaller when compared with those of both the reference and proposed WTSs. In addition, its capacity factor is 22%, which is very small compared with that of both WTSs. Consequently, the optimized WTS was more favorable than these WTSs for this site. The reference wind turbine was also favorable for this site only for its rated power. On the other hand, the WTS proposed in [12] appears not to be favorable when its performance, determined by using the COE model [5], is compared with those of the reference and proposed WTSs.

Finally, in this work, the effects of wind characteristics on the performances of both types of WTSs were evaluated by applying parametric analyses where the Weibull scale parameter increased from 5.0 to 12 in incremental steps of 0.2 while the shape parameter increased from 1.0 to 3.0 in incremental steps of 0.25. Figure 7 depicts a three-dimensional representation in terms of cost of kWh for optimized three-bladed fixed- and variable-speed WTSs. It is seen from Figure 7 that for a given scale parameter, the shape parameter has a low

Table 4. Optimized parameters and performances of a variable-speed WTS compared with those of a reference WTS at a Mediterranean site (k = 1.2, c = 8 m s^{-1} at h = 30 m, and α = 0.12).

Parameters	Reference WTS, WT3 in [12]	Optimized WTS in [12]	Optimized WTS	Optimized WTS (P_n = 600 kW)
p	3	3	3	3
D (m)	48	35	67.6	45.6
H_{hub} (m)	70	35	79	52.9
N (rpm)	28	40	19.25	28.05
u_{des} (m s^{-1})	9	14	9.57	8.58
P_n (kW)	600	1000	1450	600
Type of regulation	Pitch	Pitch	Pitch	Pitch
Type of generation	Variable speed	Variable speed	Variable speed	Variable speed
AEP (kWh)	2.26×10^6	1.95×10^6	5.17×10^6	2.1×10^6
Cost of kWh (US cent)	4.42	5.44	4.24	4.42
Capacity factor	0.44	0.22	0.42	0.41
Opt. tip-speed ratio	7.8	5.23	7.11	7.81
Mean power (kw/year)	265.4	229.7	607.3	244.9

influence on the cost of kWh for optimized wind turbines; this influence decreases as scale parameter increases. On the other hand, the Weibull scale parameters have a strong effect on COE. It decreases with the increase of the scale parameter value and this variation becomes the highest as the shape parameter value increases. In other words, COE is more dependent on the mean wind speed than on distribution shape (frequency), and this dependency becomes the highest when the distribution shape increases for both types of WTSs. It is also seen from the figure that COE for the variable-speed wind turbine is smaller than that of the fixed-speed wind turbine for all wind conditions and the difference decreases as scale parameters increases.

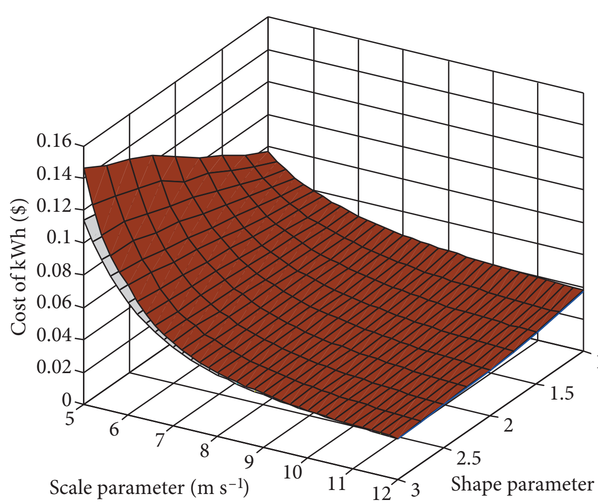

Figure 7. Cost of kWh for optimized WTSs (fixed speed, variable speed) with different combinations of Weibull shape and scale parameters.

5. Conclusions

In this study, a framework for design optimization of a WTS was proposed. It is based on the cost reduction by taking into account the wind characteristics and geographical features of the site. Various parameters that define the configuration of a WTS, such as rotor diameter, hub height, generator rating power, turbine design wind speed, and rotational speed of rotor, were used as design parameters. In order to increase reliability and computational efficiency, empirical formulas describing relations between these design parameters were incorporated into an optimization algorithm as inequality constraints. The geographic and aerodynamic variables were also used as equality constraints, and the design optimizations were performed by using a PSO algorithm that was efficient in solving such problems. Different sites (northern Europe and the Mediterranean) were evaluated and their wind potentials were characterized by Weibull parameters. The optimized values of design parameters and performances of WTSs were given by comparing them with values from reference wind turbines installed in these sites. It was found that optimized wind turbines have an excellent profitability when compared with the reference WTSs. Additionally, the reference wind turbines were also found to be well designed only for their generator size.

Moreover, a new method for calculating the rotor power coefficient was proposed in order to compute turbine power output and, as a result, AEP for a fixed-speed WTS. The model was developed by using a Weibull probability density function whose shape and scale parameters were defined as a function of the design wind speed of the WTS in exponential form. It was used for computing turbine power output, which resulted in the AEP for this type of WTS in design optimizations and was found to be reliable. Parametric analyses were carried out in order to evaluate the effect of tip-speed ratio on design parameters such as design wind speed and turbine performances for fixed-speed WTSs. Results showed that rotor tip-speed ratio has a strong effect on both design wind speed as well as COE for this type of WTS. Additionally, the effect of wind characteristics on the produced energy cost for both types of WTS was also examined. It was observed that the per cost of produced energy for optimized wind turbines strongly decreased with the increase of Weibull scale parameters, and this variation became the highest when the value of shape parameter increased for both types of WTS, as expected.

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