A Review on Wind Power Simulation Models

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***Abstract*—Wind energy has emerged as a prominent source of renewable energy due to its sustainability and low environmental impact. Efficient utilization of wind resources requires accurate prediction and modeling of wind behavior.**

This paper presents an overview of the most commonly adopted mathematical models employed in simulating the electrical power production of renewable wind generators.

In addition, some indication of the best application is provided for each category of simulation model.

***Index Terms*—modeling, renewables, review, simulation, wind.**

I. Introduction

Wind energy is a vital component of the global effort to transition to clean and sustainable energy sources. Wind turbines convert the kinetic energy of moving air masses into electrical power. To harness this energy efficiently, it is essential to understand and model the complex dynamics of wind flows. Mathematical models play a crucial role in simulating wind energy systems, aiding in design, optimization, and operational decision-making. Nevertheless, a simplified estimation of the power production from wind energy is required in some kinds of studies, such as the development of control algorithms, economic optimization models, or preliminary energy resource assessments. The reason is usually to reduce the computational burden of the simulation with details that are out of the main focus of the study.

This paper provides a review of the mathematical models usually adopted in literature to simulate the electricity pro- duction of wind generators. In detail, the main correlations are illustrated and categorized according to the generator operating principle (constant vs. variable speed, high vs. low rated power), in order to help software developers to identify the most proper correlation to the specific application.

II. Background

A. *Power coefficient*

The power coefficient of a wind turbine, also known as the performance coefficient, is a dimensionless variable indicating the amount of power extracted from the wind flow, as illustrated in (1) [1]:

$$P_{el,WT} = P_w \; C_p = \frac{\rho}{2} \; A_{WT} \; v_w^3 \; C_p \qquad (1)$$

In this equation, $P_{el,WT}$ is the electricity production of the wind turbine, P_w is the wind power, C_p is the power coefficient, ρ is the air density, A_{WT} is the wind turbine swept area, and v_w is the air (wind) speed. Generally, the power coefficient of a wind turbine is a variable and it depends on the wind speed, on the turbine technology, and on the turbine regulation system.

In order to quantify the power coefficient of a wind genera- tor, many theories were developed, all of them being based on mass conservation and energy conservation principles. The most ideal theory, known as the actuator disc theory, shows that the maximum theoretical power extraction of a horizontal-axis wind turbine is equal to 16/27 ≅ 0.593 (Betz limit) [2]. Taking into account the three-dimensional airflow, the creation of vortexes, the airfoil varying along the blade and the finite number of blades allows for obtaining more accurate relations [3]. These power coefficient formulas depend on other dimensionless parameters, the most important one being the tip speed ratio, *i.e.* the ratio between the blade tip speed and the average wind speed, as in (2) [4]:

$$\lambda = \frac{\omega_{WT}\ R_{WT}}{v_w} \tag{2}$$

where λ is the tip speed ratio, ω_{WT} is the wind turbine angular speed and R_{WT} is the wind turbine radius. This quantity can link the power coefficient and the torque coefficient C_t of a wind turbine (*i.e.* the dimensionless torque applied to the shaft of the turbine) as in (3) [5]:

$$C_p = \lambda\ C_t \tag{3}$$

Thus, using (3), the correlations for the power coefficient C_p shown in this review might also be used to calculate the torque coefficient.

B. *Mathematical models*

Mathematical models for the simulation of wind generator power production can be divided into two main categories: power coefficient models and power output models.

Power coefficient models are used to simulate the influence of the main regulation variables (usually the tip speed ratio and the pitch angle) on power production. In detail, these algorithms are employed to evaluate the power coefficient C_p and are usually adopted for the base equation of wind power shown in (1).

The main reason to adopt this kind of correlation is to decouple the influence of regulation variables from other variables as the air density, which may vary with the local temperature and pressure. They do not require the knowledge of specific details on the wind generator model and are based on empirical parameters.

Power output models are simplified models that neglect some details as the wind generator swept area or the air density while relying on the following specific data, usually available on wind generator data sheets: rated power, cut-in wind speed, rated wind speed, and cut-off wind speed. The general form of the power output models is illustrated in (4).

$$P_{el,WT} = \begin{cases} 0 & \text{if } v_w < v_{c,i} \text{ or } v_w \geq v_{c,o} \\ P_r\ q(v) & \text{if } v_{c,i} \leq v_w < v_r \\ P_r & \text{if } v_r \leq v_w < v_{c,o} \end{cases} \tag{4}$$

where $v_{c,i}$ is the cut-in wind speed, v_r is the rated wind speed, $v_{c,o}$ is the cut-off wind speed, and v_r is the rated power of the wind turbine. The term $q(v)$ is a function of the quantities listed above and of the wind speed and can be expressed in different ways, as shown in Section III.B.

C. *Wind turbines technologies*

Wind turbines evolved in the last decades in many aspects, including the rated power, the control strategy, and the technology used for electrical energy production. The designers are continuously announcing even bigger turbines. The biggest commercially deployed wind turbine has a rated power of over 15 MW (for example, the Vestas model V236 [6]).

The common approaches to control the power output are:

- Pitch regulation;
- Stall regulation.

The first approach involves the modulation of the pitch angle of each rotor blade. This procedure requires the activation of actuators and is typically adopted in high-power machines and recent devices. For turbines with small sizes, stall regulation is preferred, designing blades to promote the stall condition and reducing the lift force. As shown in Fig. 1, turbines with pitch regulation exhibit a constant power output in the range between the rated speed and the cut-off speed. On the other hand, a stall-regulated turbine is affected by a decreasing trend of the power output in this range. This suggests that (4) usually refers to pitch-regulated turbines and that it should be modified in order to properly model the stall-regulated turbines in the third region.

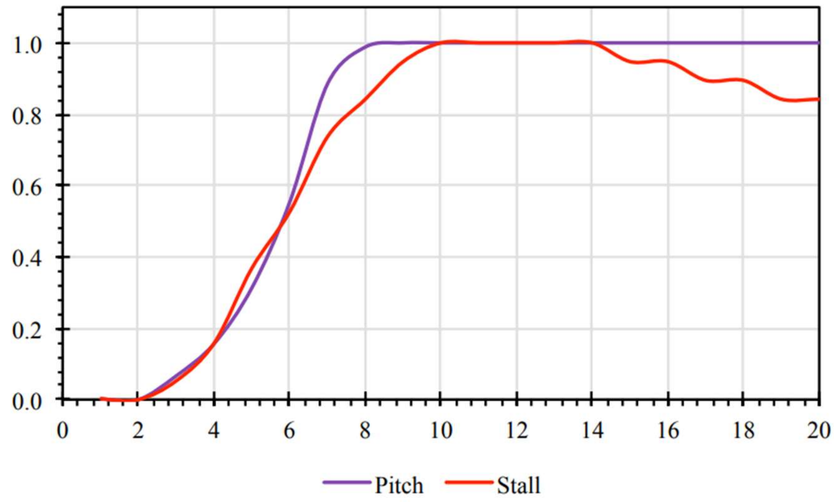

Fig. 1. Comparison of the power output of two wind turbines regulated by pitch or stall

Relevant progress was made also in the electrical generator. The first machines were equipped with asynchronous generators, operating practically at a fixed speed (linearly proportional to the frequency of the electrical grid). The slip speed, defined in (5), is below 0.02.

$$s = \frac{\omega_s - \omega_r}{\omega_s} \quad (5)$$

In (5), ω_s is the angular speed of the induced magnetic field, and ω_r is the mechanical angular speed of the rotor. As demonstrated in advanced models on wind turbines (Blade Element Momentum), wind turbines work with a higher efficiency if the tip speed ratio is maintained inside a limited range. This means that the angular speed of the rotor should be increased linearly with the wind speed. For this reason, designers introduced many solutions in order to allow a significant variation of the angular speed of blades:

- Asynchronous generator with a variable resistor on the rotor (slip below 0.10).
- Asynchronous generator in doubly fed configuration (DFIG, slip below 0.30).
- Asynchronous or synchronous generator in full converter configuration.

The last solution allows a complete disconnection between the angular speed of blades and the frequency of the electrical grid. However, the entire power production must be converted by an electronic power converter.

Fig. (2) shows qualitatively the different strategies of fixed speed and variable speed turbines:

- For fixed-speed turbines, blades always rotate at a fixed speed independently of wind speed and the power coefficient assumes sub-optimal values in many conditions
- For variable-speed turbines, blades rotate at different an- gular speeds in order to keep the tip speed ratio

constant and the power coefficient is always kept at the optimal condition.

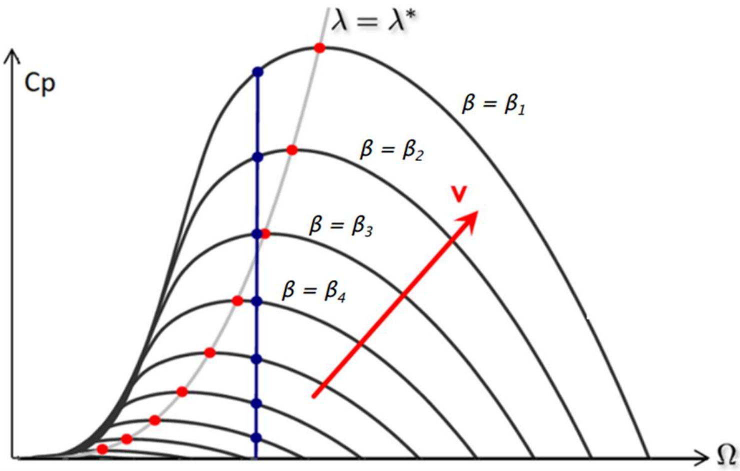

Fig. 2. Comparison of Power Coefficient trend against the angular speed of fixed speed (vertical blue line) and variable speed wind turbines (red dots) for several pitch angle values

III. Mathematical models review

A. Power coefficient models

Power coefficient models are usually employed for wind turbine control studies or maximum power point tracking studies.

This kind of model can be further divided into three categories: exponential functions, polynomial functions, and sinusoidal functions [5], [7].

1) Exponential functions: Exponential functions models for power coefficient are among the oldest and most reliable mathematical models developed for the approximation of wind turbines' power coefficients, with the first example dating back to 1981 and being related to a 2.5 MW wind turbine equipped with a fixed-speed synchronous generator [8]. This formula depends on the blade pitch angle (in degrees) and on the ratio between the wind speed (in mph) and the rotor angular speed (in rad/s). This formula was later used replacing the latter ratio with the non-dimensional tip speed ratio and applied to almost every kind of horizontal-axis wind turbine. The general form of the exponential function models is shown in (6):

$$C_p(\lambda,\beta) = a_0\left(\frac{a_1}{\lambda_i} + a_2\beta + a_3\beta\lambda_i + a_4\beta^{a_5} + a_6\right)\dots$$
$$\dots e^{\left(\frac{a_7}{\lambda_i}+a_8\right)} + a_9\lambda \quad (6)$$

where

$$\frac{1}{\lambda_i} = \frac{1}{a_{10}\lambda + a_{11}\beta + a_{12}} + \frac{a_{13}}{1 + a_{14}\beta^3} \quad (7)$$

and a_i are the correlation coefficients of the exponential function models.

This model is by far the most used in literature, being shown in at least 40 international literature studies or books between 1981 and 2023 with at least 13 different sets of correlation coefficients [5], [7]–[18]. These studies are focused on a wide range of rated sizes, ranging from 300 W [11] up to 5 MW [12].

Due to this wide employment, this function can be considered a reference for the wind power generators simulation to the extent that it was also implemented in the library of the simulation software MATLAB/Simulink for the wind turbine model [19]. The set of coefficients available in the Simulink model is also the most commonly found in the literature investigated for the present work.

It is not easy to identify a specific range of size or a specific turbine technology to model with this function family. Nevertheless, the parameters recapped in TABLE I might be adopted for the most common turbine technologies, although a non- linear regression on each specific wind turbine performance is highly recommended. In detail, the set of parameters for the variable speed wind turbine might be adopted for different electrical generator technologies such as DFIG, permanent magnet synchronous generators, or wound rotor synchronous generators, as the author states in [20].

TABLE I – Correlation Coefficients Suggested For Selected Wind Turbine Technologies Using The Exponential Function Models

Coefficient	*Constant-speed turbine [21]*	*Variable-speed turbine [21]*	*Small size [18]*	*DFIG (Multi-MW size) [15]*
a_0	0.44	0.73	1	0.22
a_1	125	151	1.12 λ^c	116
a_2	0	-0.58	0	-0.4
a_3	0	0	0	0
a_4	0	-0.002	0	0
a_5	0	2.14	0	0
a_6	-6.94	-13.2	-2.8	-5
a_7	-16.5	-18.4	-0.38 λ^c	-12.5
a_8	0	0	0	0
a_9	0	0	0	0
a_{10}	1	1	1	1
a_{11}	0	-0.02	0	0.08
a_{12}	0	0	0	0
a_{13}	-0.002	-0.003	0	-0.035
a_{14}	1	1	0	1

2) Sinusoidal functions: Sinusoidal function models are usually adopted for variable-pitch wind turbines since these relations depend on both tip speed ratio and pitch angle, as well as exponential function models. The first developed model dates back to 1983 and was applied to a 6.2 MW wind turbine equipped with a synchronous generator. The general form of the sinusoidal function models is shown in (8):

$$C_p(\lambda,\beta) = [b_0 + b_1(\beta - b_2)]\, sin\left[\frac{\pi(\lambda + b_3)}{b_4 + b_5(\beta - b_6)}\right] + \dots$$
$$\dots + b_7(\lambda + b_8)(b_9\beta - b_{10}) \quad (8)$$

where b_i are the correlation coefficients of the sinusoidal function models. In detail, the coefficient b_0 is the maximum value of the power coefficient while the values b_2, b_6, and b_{10} are the value of pitch angle that allow the maximum where b_i are the correlation coefficients of the sinusoidal function models. In detail, the coefficient b_0 is the maximum value of the power coefficient while the values b_2, b_6, and b_{10} are the value of pitch angle that allow the maximum where b_i are the correlation coefficients of the sinusoidal function models. In detail, the coefficient b_0 is the maximum value of the power coefficient while the values b_2, b_6, and b_{10} are the value of pitch angle that allow the maximum value of the power coefficient.

This model was used in at least seventeen international literature studies between 1983 and 2023, with six sets of correlation coefficients available [5], [13], [22]–[36]. These functions were used to simulate a wide range of wind turbine sizes, ranging between 3 kW [26] and 6.2 MW [22]. Nevertheless, no study mentions how these correlations were obtained. A thorough inspection of the parameters and the references provided in the literature showing the six sets of coefficients available was performed for this study. This work allows to state that the original correlation was obtained in [22]. In the subsequent literature, this correlation was simplified in [24] for a stall-regulated wind turbine (no dependency on pitch angle) and then updated in 2004 in [36] for modern turbines. The other three sets of correlations found in the literature appear as the result of typing errors.

3) Polynomial functions: Polynomial functions are usually adopted for fixed-pitch wind turbines since these relations do not take into account the dependency of the power coefficient from the pitch angle. The general form of the power coefficient polynomial function models depending on the tip speed ratio is shown in (9):

$$C_p(\lambda) = \sum_{i=0}^{N} c_i \, \lambda^i \qquad (9)$$

where c_i are the correlation coefficients of the polynomial function models.

This model was first proposed in [37] and used in at least twelve international literature studies between 2006 and 2022, with four sets of correlation coefficients available. All of these studies focus on wind turbines with small rated-sizes (0.2 kW - 8 kW). Most of these studies aim was to develop a wind turbine emulator or to develop a maximum power point tracking algorithm [5], [29], [38]–[48]. Only one study provides details on the power coefficient trend reference and on the method for obtaining the correlation coefficients [38]. The maximum polynomial degree used in literature for these functions is seven, in contrast to what is reported in the review study in [5], where the authors state that the maximum degree in literature is six. In detail, the study in [39], reviewed in [5], actually used a sixth-degree polynomial to model C_t. Nevertheless, if one applies (3), this function becomes a seventh-degree polynomial to describe C_p.

Thus, TABLE II shows a recap of the correlation coefficients used in the polynomial function models in the international literature, where some misprints were corrected with respect to the analogous table in [5].

Another formula, proposed in [49], can be considered as an extended version of (9) and is illustrated in (10) [7]:

$$C_p(\lambda, \beta) = \sum_{i=0}^{n} \sum_{j=0}^{m} d_{i,j} \, \beta^i \, \lambda^j \qquad (10)$$

where $d_{i,j}$ are the correlation coefficients of this model. This model is much more detailed with respect to the previous one, although it requires many more coefficients (25 in [49]–[51] or 16 in [9]) and was employed to simulate the behavior of wind turbines with larger size (1.5 MW - 3.6 MW).

TABLE II - Correlation Coefficients Employed In The Polynomial Function Models Available In Literature

Coefficient	***Third order correlation***	***Fourth order correlation***	***Fifth order correlation***	***Seventh order correlation***
c_0	-0.02086	0.11	0.043	0
c_1	0.1063	-0.2	-0.108	0.0015
c_2	-0.004834	0.097	0.146	-0.0022
c_3	3.7×10^{-5}	-0.012	-0.0605	0.0052
c_4	0	4.4×10^{-4}	0.0104	-5.1425×10^{-4}
c_5	0	0	-6.0×10^{-4}	-2.795×10^{-5}
c_6	0	0	0	4.6313×10^{-6}
c_7	0	0	0	-1.331×10^{-7}

B. Power output models

Recalling (1), many terms influence the evaluation of the power output for a turbine: first, the wind speed; secondarily, the power coefficient and finally the air density.

As reported above, the power coefficient depends on the wind speed and the type of turbine. The direct measurement of this parameter is quite complex. For this reason, instead of the power coefficient, in practical application designers provide the trend of the power output as a function of the wind speed. In literature, different power models are used to express the power output of a wind turbine:

- Discrete model: according to the IEC 61400-12 wind speeds should be discretized into 0.5 m/s bins, showing the corresponding power output for each bin. However, some catalogs report data by using 1 m/s bins;
- Deterministic and probabilistic models: a continuous function is often introduced in order to correlate the power output to the wind speed. Nevertheless, due to the different wind conditions inside a wind farm, the same turbine can produce different amounts of energy. For these reasons, a probabilistic model is often preferred;
- Parametric and non-parametric models: in the first case a mathematical equation is introduced, with a finite number of parameters. In the second case, no assumptions are made about the phenomenon behind the correlation be- tween the input and the output. This approach is typically used when it is difficult to define the theory behind the correlation.

Among these three categories, (4) belongs to the family of parametric models. Focusing attention on the wind speed range between the cut-in speed and the rated speed, the most common function models *q(v)* are thoroughly illustrated and discussed in [52]. Most of the parametric models in the literature adopt a polynomial approximation (linear or quadratic, as in (11), or cubic, as in (12)), especially for predicting the power output in the preliminary step of the energy assessment. The term polynomial refers to the exponent of the wind speed in the expression of *q(v)*. Although these functions could not properly fit the real trend of the power output function with good accuracy, they can be successfully adopted for a pre-sizing step or for economic evaluations.

$$q(v) = P_r \left(\frac{v - v_{c,i}}{v_r - v_{c,i}} \right)^n \qquad (11)$$

$$q(v) = av^3 - bP_r \qquad (12)$$

where n is a coefficient equal to 1 in linear models and 2 in quadratic models, and a and b are coefficients depending on the turbine parameters.

More advanced approaches exploit the shape parameter k extrapolated by the Weibull probability distribution function of the local wind conditions, in addition to the turbine-related parameters, or use logistic functions with four or five coefficients to model the power output instead of a piece- wise function, as in (13). These models are typically used to evaluate the forecasting of energy production with high accuracy for load flow analysis:

$$P = D + \frac{(A - D)}{\left(1 + \left(\frac{v}{C}\right)^B\right)^G} \qquad (13)$$

where A, B, C, D, and G are interpolation parameters obtained using evolutionary algorithms.

IV. Discussion

The main difference between the two models' main categories of mathematical models reviewed in this paper is the aim of the study where they are used: the power coefficient models are usually adopted for short-term simulations, while the power output models are often used in long-term studies, such as in yearly energy resource assessments, especially polynomial approximation models. On the other hand, logistic functions can efficiently model single wind turbines or wind farms for detailed applications such as business plans or energy trading, if reliable data on the local wind resource are also available. This aspect is crucial since most wind farms show turbulent phenomena that reduce power production and that can be hardly predicted with simple mathematical models.

In the power coefficient models category, the exponential functions are widely used, showing their ability to model a large variety of wind turbine performances. Furthermore, sinusoidal and polynomial functions might have negative values outside the fitting range, causing unexpected results. On the opposite, the computational burden of the polynomial function is clearly the smallest in this category of functions and might be used when simulation time is an important issue. Furthermore, the use of numerical parameters led numerous authors to error, misreading some coefficients.

In the power output models category, simpler polynomial models are preferred when the modeler has no data on the turbine performance and only the main working parameters are available. On the opposite, logistic functions can reliably model the performance curve in their details, such as the inflection point (when the curvature changes direction) or the hill slope [52].

Furthermore, it is essential to note that the three power coefficient model functions, as well as the logistic power output model function, share the mathematical property of being continuous and differentiable. This aspect is crucial in studies related to power control or maximum power point tracking. On the other hand, piece-wise power output models are not continuous functions since these models are mostly used in studies related to annual energy evaluation, thus concerning larger time steps and avoiding derivation operations.

Another interesting feature is that all the mathematical models illustrated in this review were used to simulate the behavior of horizontal-axis wind turbines, the most common model found on the market.

Nevertheless, the main recommendation for modelers is to employ reliable data on the wind resource and on the turbine performance in order to avoid gross mistakes. In this aspect, it is unpleasant to verify that most of the studies using the power coefficient models still rely on parameters obtained during the ’80s, when the technology of each turbine component was widely different with respect to modern wind generators.

V. CONCLUSION

Wind energy simulation plays a pivotal role in harnessing the full potential of wind resources for sustainable electricity generation. As wind energy continues to grow, ongoing re- search and innovation in modeling and simulation are essential to address emerging challenges and further optimize wind energy systems. This paper provided a review of the mathematical models available in the literature to simulate the power coefficient or the power output of a wind turbine, highlighting the technological models whereby they were developed and trying to suggest the best correlations to be employed in selected cases.

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