

WIND TURBINE MODELING IN MATLAB SIMULINK

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Abstract

Accurate modeling of wind turbine systems has received a lot of concern for controls engineers, seeking to reduce loads and optimize energy capture of operating turbines. When designing wind turbine systems, engineers often employ a series of models.

This paper investigates the wind turbine systems modeling in Matlab Simulink environment. The model can be further used to study the parameters that affect the electrical power generated by the wind turbines, allowing optimizing the wind turbine.

Key words: Wind turbine, Wind energy, Modeling, Simulation.

INTRODUCTION

Modeling wind turbine systems require knowledge from a range of engineering and atmospheric science disciplines. The models approached in this paper are used in the design of the wind turbine systems, allowing to identify the loads and power for a given turbine design.

Often the models use some simplification assumptions. More accurate models such as computational fluid dynamics or finite element analysis are available but these models require high computational costs and are difficult to use.

This paper will focus mainly on the models implemented in Matlab Simulink.

The model of the overall wind turbine system integrates several building blocks.

Figure 1 shows a diagram representing the basic structure of the model.

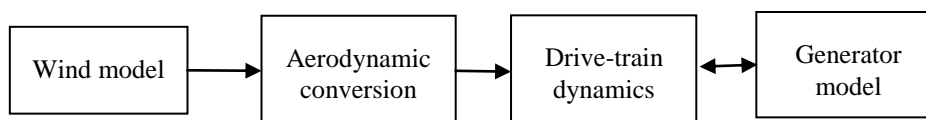


Fig. 1. The basic structure of the overall wind turbine system

This paper is organized as follows: section 2 approaches aspects related to wind simulation, section 3 presents the wind energy, section 4 focuses on wind turbine simulation. Section 5 concludes this paper.

MATERIAL AND METHOD

Wind simulation

Continuous changes in wind speed are the main reason for power fluctuations in turbine output.

The wind speed consists of two parts: the first part is a mean wind speed and the second part is turbulences added to the mean wind speed [Thri96].

The observations are based on the wind analysis data measured in the hillside area of Oradea in the period 2008-2011.

The wind speed model is very important in the wind turbine modeling process. Generally, the wind is modeled as a stochastic process. However, the wind variation can be modeled in different manners.

In [Nish02] the wind speed is modeled as a sum of harmonics as presented in relation (1):

$$v(t) = v_m(1 + \sum_{i=1}^N A_i \sin(\omega_i t)) \quad (1)$$

Where the wind speed at time t is $v(t)$, v_m is the mean wind speed, ω_i is the harmonic frequency and A_i is the harmonic amplitude.

The harmonic amplitude at angular frequency can be expressed as [Lei06]

$$A_i = \frac{2}{\pi} \sqrt{\frac{1}{2} [\Phi_u(\omega_i) + \Phi_u(\omega_{i+1})][\omega_i - \omega_{i+1}]} \quad (2)$$

where Φ_u are the Dryden spectrum. For engineering purposes it is assumed that the power spectra of atmospheric turbulence can be approximated by the Dryden spectra. The longitudinal Dryden power spectrum is defined by [Lei06]

$$\Phi_u(\omega) = \frac{L_u}{v_m} \frac{2\sigma^2}{\pi} \frac{1}{1 + (L_u \frac{\omega}{v_m})^2} \quad (3)$$

where σ is the turbulence intensity, L_u is the turbulence length and ω is the harmonic frequency. The harmonic samples N are assumed equal to 15 and the frequency in the range 0.1-10 Hz.

In [Martem03] the wind speed distribution is modeled with a statistical distribution of the wind speed named Weibull distribution. The wind speed probability function is given by:

$$H(v \geq v_p) = 8760 \exp[-(\frac{v_p}{c})^k] \quad (4)$$

This is the probability that the wind speed is equal or larger than wind speed v_p in hours per year. In this equation the parameters 'c' and 'k' are used for fitting the distribution to a certain wind field.

The wind speed distribution density is given by relation (5):

$$H(v < v_p < v + dv) = 8760 \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] dv \quad (5)$$

This is the probability that the wind speed is actually between v and $v + dv$ in hours per year.

The relation with the annual average wind speed \bar{v} is given by (6):

$$\bar{v} = c \Gamma\left[1 + \frac{1}{k}\right] \quad (6)$$

where

$$\bar{v} = \Gamma\left[1 + \frac{1}{k}\right] \text{ is the gamma function with the argument } \left[1 + \frac{1}{k}\right]$$

All time variations in wind speed and direction with a period smaller than 0.1 hour are considered as turbulence. The true efficiency of a wind turbine depends on its behavior in a turbulent wind flow field. These parameters are difficult to measure and their values are prescribed as standard recommendations or are obtained using assumptions based on site geography.

However, for describing a turbulent airflow a number of different models are available, having different complexity, and the quality of the calculations depends on the turbulence model.

The spectral model of continuous turbulence by Kaimal [Ros03] is based on a wind speed average per hour \bar{v} with a standard deviation. The frequency behavior of the wind speed fluctuations is described by a model of the spectral power density $S(n)$, where n is the frequency.

$$nS(n) = \frac{\left(\frac{n}{\bar{v}}\right)^2 \sigma^2}{f_m \left(1 + \frac{1.5}{f_m} \left(\frac{n}{\bar{v}}\right)\right)^{\frac{5}{3}}} \quad (7)$$

with z the height above ground level and the coefficient f , equal to 0.06 for the longitudinal component of the wind and equal to 0.2 for the lateral component of the wind.

Lateral v_x and longitudinal v_y components of the wind speed fluctuations are obtained by relation (8), as presented in [Martem03]:

$$v_i(t) = \sqrt{2} \sum_{k=1}^m [S_i(n_k) \Delta n]^{1/2} \cos(2\pi t + \beta) \quad (8)$$

with $i=x,y$ (lateral, longitudinal direction), m is the number of frequencies, Δn the frequency spacing and β a random phase angle.

In [Matlab] Dryden Wind Turbulence, Von Karman Wind Turbulence Models, continuous and discrete Wind Gust Models are implemented.

Wind gusts

Wind patterns are considered to be wind gusts when their speed grows 1.5 times their average speed in maximum time span of 3 seconds.

A commonly used shape function is the so-called 'one minus cosine' shape function (9):

$$v(t) = v + 0,5\Delta v \left[1 - \cos\left(\frac{2\pi}{\tau} t\right)\right] \quad (9)$$

With Δv the amplitude of the wind gust, τ the period and t the time since the beginning of the wind gust.

The wind energy

The energy in the wind is given by relation (1).

$$E_w = \frac{1}{2}mv^2 = \frac{1}{2}(\rho A)v^2 [W] \quad (1)$$

where

A- is the rotor surface [m^2],

v- is the wind speed [m/s],

ρ - is the air density [kg/m^3].

The total power available to a wind turbine is the rate of the incoming kinetic energy of a wind stream. In meteorological wind speed calculations the mean speed is used. This speed cannot be applied in energy computations and, in this case, the cube of wind speed is to be used and thus, the total power in the wind is directly proportional to the cube of wind velocity.

Based on the law of Betz, the maximum quantity of the kinetic energy of the wind that can be converted in mechanical energy is 59%.

This leads to the relation (1) related to the maximum power generated by a wind turbine system.

$$P_w = \frac{16}{27} \frac{1}{2} (\rho A)v^3 [W] \quad (1)$$

where P_w is the theoretical power generated by a wind turbine and 16/27 is the Betz's constant. It can be seen that the power in the wind is a cubic function of the wind speed and it is important, therefore, to create a correct wind model if realistic results are to be obtained.

RESULTS AND DISCUSSIONS

The model is implemented in [Matlab] and is based on the steady-state power characteristics of the turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine. The output power of the turbine is given by the following equation (10).

$$P_m = c_p(\lambda, \beta) \frac{\rho A}{2} v_{wind}^3 \quad (10)$$

where : P_m is the mechanical output power of the turbine (W), c_p is the performance coefficient of the turbine, ρ is the air density, A is the turbine swept area, v_{wind} is the wind speed, λ is the ratio of the rotor blade speed by the wind speed, β is the blade pitch angle, Equation (10) can be normalized, thus obtaining $P_{m,pu}$, the power in per unit (pu) system, that is the nominal power for particular values of ρ and A. A generic equation is used to model

$c_p(\lambda, \beta)$. This equation, based on the modeling turbine characteristics of [Sieg98] is (11).

$$c_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{-c_5}{\lambda_i}} + c_6 \lambda \quad (11)$$

$$\text{With } \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^2 + 1} \quad (12)$$

The coefficients c_1 to c_6 are: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$. The c_p - λ characteristics, for different values of the pitch angle β , are illustrated in Figure 2. The maximum value of c_p ($c_{p\max} = 0.48$) is achieved for $\beta = 0$ degree and for $\lambda = 8.1$. This particular value of λ is defined as the nominal value λ_{nom} .

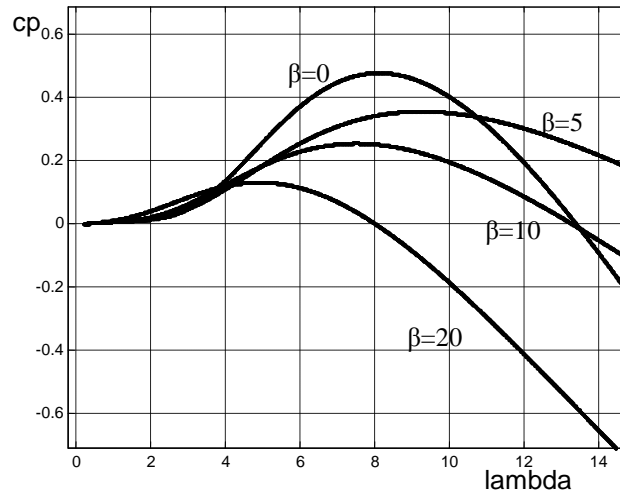


Fig. 2. The c_p - λ characteristics

The Simulink model of the turbine is illustrated in the Figure 3. The three inputs are the generator speed, the pitch angle and the wind speed [Matlab]. The ratio λ is obtained by the relation (13)

$$\lambda = \frac{R\omega}{v} \quad (13)$$

Relation (13) is normalized giving λ in per unit (pu) system. The output is the torque applied to the generator T_m .

Wind turbine induction generator (WTIG)

In [Matlab] is implemented the phasor model of squirrel-cage induction generator driven by variable pitch wind turbine. Figure 4 presents the block diagram of the WTIG.

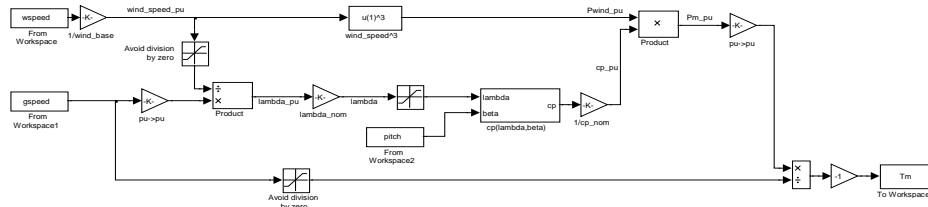


Fig. 3. The Simulink model of the turbine

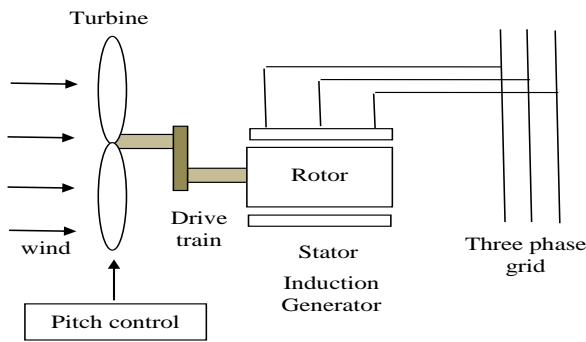


Fig. 4. The block diagram of the WTIG

The stator winding is connected directly to the grid and the rotor is driven by the wind turbine. The power captured by the wind turbine is converted into electrical power by the induction generator and is transmitted to the grid by the stator winding. The asynchronous machine has been used as generator for many years in wind turbines. This type of machine has high reliability, low price, and low maintenance.

The speed flexibility, when compared to the synchronous machines reduces the current spikes due to wind gusts. The main disadvantage is that asynchronous machine consumes reactive power, which influences the wind turbine/grid integration in normal and transient conditions.

The pitch angle is controlled in order to limit the generator output power to its nominal value for high wind speeds. In order to generate power the induction generator speed must be slightly above the synchronous speed. The speed variation is typically so small that the wind turbine induction generator is considered to be a fixed-speed type.

The blade pitch angle is controlled by a PI controller in order to limit the electric output power to the nominal mechanical power. If the measured electric output power is under its nominal value the pitch angle is kept equal to zero degree. If it increases above its nominal value the PI controller

increases the pitch angle to bring back the measured power to its nominal value.

Figure 5 presents the Simulink block for the WTIG.

The inputs are:

- A B C, the three terminals of the WTIG;
- Trip, input to implement a simplified version of the protection system, by applying there a logical signal equal to 0;
- Wind, input of the wind speed;
- T_m , input of the mechanical torque;

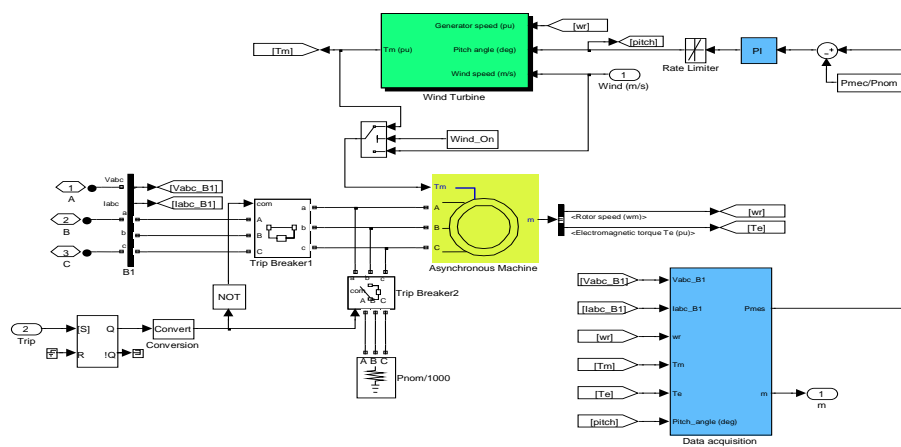


Fig. 5. The Simulink block for the WTIG

The output is m , a Simulink vector containing 8 internal signals. They are: Phasor voltages, Phasor currents, output power, output reactive power, Generator rotor speed, Mechanical torque applied to the generator, Electromagnetic torque, and Pitch angle.

In [Joh04] wind turbines are developed on the basis of the so-called “Danish concept” for wind turbines, which features a fixed-speed wind turbine with an asynchronous machine as wind turbine generator.

[Matlab] implement also the wind turbine and the doubly-fed induction generator (WTDFIG). Comparing to the WTIG it contains an AC/DC/AC converter divided into two components: the rotor-side converter and the grid-side converter.

In [Iov04] a Matlab/Simulink Toolbox for wind turbine applications is presented. In order to analyze the dynamic and/or steady state behaviour of a wind turbine, the basic components of a wind turbine have been modelled and structured in seven libraries: Mechanical Components, Electrical Machinery, Power Converters, Common Models, Transformations, Measurements and Control. Some simulation results using the developed models are shown.

CONCLUSIONS

The utilization of wind energy for power generation is becoming increasingly attractive. Modeling and simulation of wind turbine systems allow researchers to study the parameters which lead to enhanced power generation capabilities. It can be concluded that many factors have to be considered in designing wind turbines.

The Simulink model can be further used in optimization tasks related to reduce loads and increase energy capture.

REFERENCES

1. T. Thiringer, "Power quality measurements performed on a low-voltage grid equipped with two wind turbines", *IEEE Trans. Energy Conv.*, vol. 11, pp. 601-606, Sep. 1996.
2. C. Nishita, D. Luca, B. Dakyo, and E. Ceanga, "Large band simulation of wind speed real time wind turbine simulator," *IEEE Trans. Energy Conv.*, vol. 17, no. 4, pp. 523-529, Dec. 2002.
3. Y. Lei, A. Mullane, G. Lightbody, and R. Yacamini, "Modeling of the wind turbine with a doubly fed induction generator for grid integration studies," *IEEE Trans. Energy Conv.*, vol. 21, no. 1, March 2006, pp. 257 – 264.
4. Martem A., Albers P., Wind Turbine Study Investigation into CVT application in wind turbines, Reportnumber: DCT 2003.90, Eindhoven, 2003.
5. P. Rosas, "Dynamic influences of wind power on the power system", Risø -R-1408 (EN), 2003.
6. MATLAB/Simulink SimPowerSystems Documentation. <http://www.mathworks.com>.
7. Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems," John Wiley & Sons Ltd, 1998, ISBN 0-471-97143-X.
8. Florin Iov, Anca Daniela Hansen, Poul Sørensen, Frede Blaabjerg, Wind Turbine Blockset in Matlab/Simulink. General Overview and Description of the Models. Technical report. Aalborg University 2004.
9. Johnsen K., Eliasson B, SIMULINK Implementation of Wind Farm Model for use in Power System Studies, Nordic Wind Power Conference, 2004, Chalmers University Of Technology.