Overview of Wind Turbine Modeling in Modelica Language

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Abstract—**The wind turbine, being one of the longest developed alternatives to conventional power plant, has attracted considerable attention at many. The system needs to be developed in quick and efficient manners with low resources based on modeling and simulation method. With the development of wind turbine library in open source Modelica language, it could be used as a base for further advancement of wind turbine technology. This paper focusing on providing summary of models of wind turbine performance characteristics such as power output and shaft torque among others. Models presented could simplify and reduce time in modeling process related to wind turbine application.**

Index Terms—**Modelica language, wind turbine model.**

I. Introduction

Many papers shown very detail derivation of the wind turbine (WT) model whereas some of the models can be presented but at some application does not need very complicated models to be applied. At the application level, simplified and final equations are preferable for the calculation and dimensioning of a certain system. This paper targets to achieve a compilation of most basic but important for WT performance characteristic modeling specifically for modeling in Modelica language. With the provided models, one can apply directly in their own simulation software accordingly. Take note that all equations here are presented with horizontal axis wind turbine (HAWT) in mind and not considering the dynamic load effect to the tower..

II. Modeling Approach

Modeling process of a component in the WT library of this reported work is modeled according to the flow chart shown in Fig. 1. WT system is first decomposed and analyzed. At this stage detail information about its structure and components are obtained. Then the initial modeling phase started where all equations, assumptions, variables and parameters as well as characteristics of the model are documented. A new Modelica library is then defined considering the structure and classes available in the Modelica Standard Library (MSL) [1] and using Modelica modeling and simulation environment which in this case is referred to Dynasim [2]. Several models will then be sorted out from the Modelica library and continued by further works in modeling wind turbine components using the sub-models available in the library and followed by parameterization of the specific application's models. The library structure design follow the guidelines provided as in [3].

The free Modelica language is developed by the non-profit Modelica Association. The Modelica Association also develops the free Modelica Standard Library that contains about 780 generic model components and 550 functions in various domains, as of version 3.0 [4].

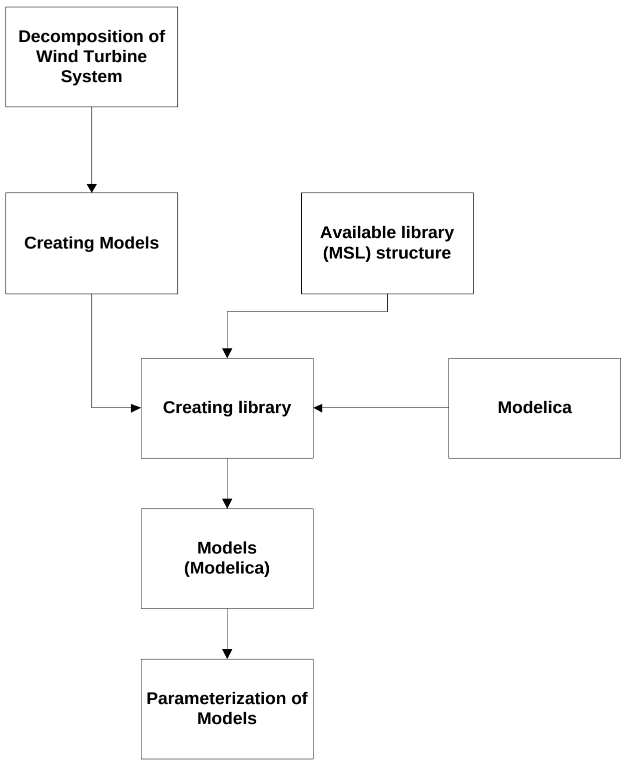

Fig. 1. Approach in modeling of wind turbine components.

III. Library Structure

Models are group according to its hierarchy and purpose as in Fig. 2. Modelica has the capability of physical modeling and that can simplified the structure of a model library and the models developed physically classed into the corresponding packages. The advantage of this library design is that it can be modularly expanded without affecting the existing models. Proper guidelines of model development in Modelica library can be referred in [3].

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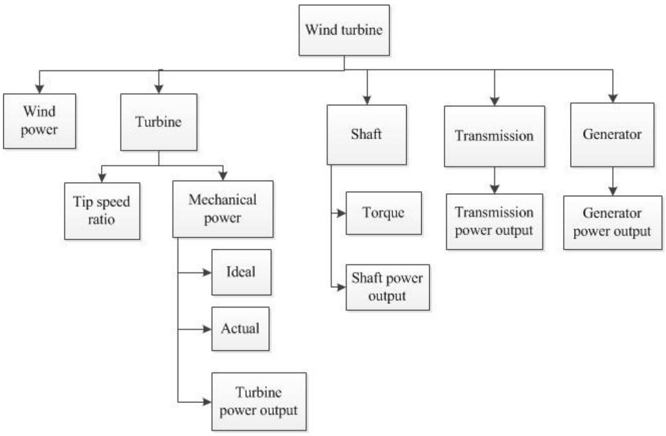

Fig. 2. Modular wind turbine library structure

IV. Model of Wind Turbine Characteristics

A. Energy in the Wind

Power in the wind be determined using kinetic energy (E_w) equation and derivation of it will lead to power in the wind, P_w.

$$E_w = \frac{1}{2} m u^2 \tag{1}$$

$$P_w = \frac{1}{2} \frac{dm}{dt} u^2 \tag{2}$$

and

$$\frac{dm}{dt} = \rho A u \tag{3}$$

which lead to

$$P_w = \frac{1}{2} \rho A u^2 \tag{4}$$

with

$$\rho = 3.485 \frac{p}{T} \tag{5}$$

then finally

$$P_w = 1.742 \frac{p}{T} A u^2 \tag{6}$$

where

m = parcel air mass [kg]

u = speed of wind [m/s]

A = turbine blade swept area [m^2]

ρ = air density [kg/m^2]

p = air pressure (kPa)

T = air temperature (K)

P_w can be determined with ρ, p, T and A held constant while data for u is supplied to the model. An extra caution must be given when selecting the value for air pressure and temperature as these two properties strongly varies according to the elevation from ground. For air at standard condition, with p = 101.3 kPa and T = 273 K, equation (6) is reduced to

$$P_w = 0.647 A u^2 \tag{7}$$

B. Mechanical Power Extracted by Turbine

Mechanical power extracted by wind turbine can be found using the concept of circular tube of air flowing through ideal wind turbine from Fig 3. Circular tube concept or more commonly known as actuator-disk analysis is an idealized concept and efforts continue to be made to refine it to provide more exact answers [5].

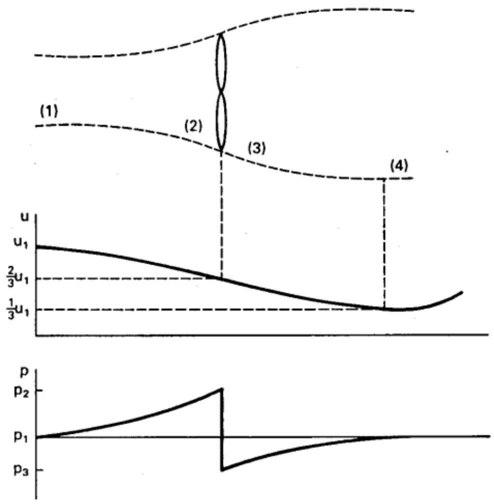

Fig. 3. Circular tube of air through ideal turbine [6]

At point 1 undisturbed tube of moving air flows approaching the turbine at point 2 causing the air pressure increase to maximum and drop significantly after the turbine at point 3. Portion of the kinetic energy in the moving air tube is transferred to the turbine (turbine blade rotation). This phenomenon strongly relates with change of diameter and air speed at the respective points. For summary, the mechanical power extracted from the undisturbed moving air is the variance between input and output power in the wind, in this case, power at point 1 and 2. Applying (4) will deliver a general equation of:

$$P_{mech,ideai} = P_1 - P_4 = \frac{1}{2} \rho \left(A_1 u_1^3 - A_4 u_4^3 \right) \tag{8}$$

By considering undisturbed wind speed u_1 and wind turbine area of A_2, (7) is reduced to

$$P_{mech,ideai} = \frac{1}{2} \rho \left(\frac{16}{27} A_2 u_1^3 \right) \tag{9}$$

where 16/27 = 0.593 is the well-known Betz coefficient.

Partial power extracted from the total power in the wind by the practical WT correlate with coefficient of performance, C_p. As the real C_p will varies according to the specified value set by the turbine manufacturer and also with wind speed, equation (9) is reduced to

$$P_{mech,ideai} = C_p \left(\frac{1}{2} \rho A_2 u_1^3 \right) = C_p P_w \tag{10}$$

C. Tip Speed Ratio

Another important parameter in WT performance is tip speed ratio, λ

$$\lambda = \frac{r_m w_m}{u} \tag{11}$$

With

$$w_m = \frac{2\pi n}{60} \quad (12)$$

where,

r_m = maximum turbine radius [*m*]
w_m = mechanical angular velocity [*rad/s*]
u = undisturbed wind speed [*m/s*]
n = rotational speed [*r/min*]

The tip speed ratio has a strong influence on the efficiency of a wind energy converter. When tip speed ratio is small, the circumferential velocity is also small which results in an increase in the angle of attack. When the angle of attack increases past a critical angle, the wind flow breaks away from the blade profile and becomes turbulent, thus dramatically reducing the lift force. If the tip speed ratio is too large, the lift force will reach its maximum value and decrease afterwards, thus reducing the power efficiency of the converter [7].

By plotting C_p against λ, best operating point of a WT can be determined directly from the graph.

D. Torque at Constant Speed

The power in the wind is transmitted to the load through a rotating shaft and to make sure a WT works it has to be properly designed. The result of power transferred through a shaft, a torque, *T* will present.

$$T = \frac{P}{\omega} \quad (13)$$

where *P* is mechanical power [*W*] and ω is angular velocity of the shaft [*rad/sec*].

For any solid shaft, shearing stress, f_s will take place where the torque, *T*, distance from the axis of the shaft, *r* and the polar moment of inertia, *J*, of the shaft.

$$f_s = \frac{T_r}{J} \quad (14)$$

The expression of *J* is then further elaborated

$$J = \frac{\pi r_0^4}{2} \quad (15)$$

where r_o is the shaft radius.

$$D = 2r_0 = 2^3\sqrt{\frac{2T}{\pi f_s}} \quad (16)$$

There are equations for calculating the torque under variable speed, but for this paper, the application concentrated only on application at constant speed.

E. Generator Efficiencies

In WT system, from the turbine, the shaft power is transferred to the load (e.g. generator, pump etc.) by means of gearing/transmission system (Fig. 4).

Fig. 4. Energy conversion in wind turbine system.

Conversion process at the transmission will have some loss resulted from various causes for example friction. To obtain transmission output power, P_t, transmission efficiency η_m is multiplied by P_m.

$$P_t = \eta_m P_m \quad (17)$$

While generator output power, P_e, is the product of transmission output power, P_m and generator efficiency, η_g.

$$P_e = \eta_g P_t \quad (18)$$

From combination equations 10, 17 and 18, a final equation can be reached which relates power output from generator and wind power input.

$$P_e = C_p \eta_m \eta_g P_w \quad (19)$$

V. Conclusion

The mathematical equation summarized can be utilized to produce a usable wind turbine model and can be applied directly in simulation environment using equation-based modeling where in this case, Modelica language-based software. The equation is already simple as it is and ready to be applied into any engineering application involving wind turbine technology. One can make use the modular capability of Modelica model library to extend it with more complex models according to the needs of application.

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