Renewable Energy 48 (2012) 333–343

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

DFIG equivalent circuit and mismatch assessment between manufacturer and experimental power-wind speed curves

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ARTICLE INFO

Article history:
Received 1 August 2011
Accepted 4 January 2012
Available online 13 June 2012

Keywords:
Correction method
Doubly-fed induction generator
Equivalent circuit
Power-wind speed curve
Wind system

ABSTRACT

The modelling of wind turbines with doubly-fed induction generator (DFIG) requires consideration of overall aerodynamic, mechanic, electromagnetic and control aspects, even in the case of DFIG representation in steady-state conditions for energy production assessment. This paper firstly summarizes the background concepts for interpreting the characteristic curves of the DFIG. Then, it considers and illustrates the structure and use of a dedicated equivalent circuit based on the incorporation of an apparent resistance in the model. Furthermore, a new method for correcting the experimental data gathered from wind turbines in practical applications is proposed, in order to make these data comparable with the quantities indicated by the manufacturers in the power-wind speed curve of the wind turbines. Application examples are provided by using data of real DFIG machines.

1. Introduction

For a wind power generator, the transposition from wind speed to electrical quantities at the grid connection interface depends on the integrated view of complex aerodynamic, mechanic, electromagnetic and control aspects [1,2]. The specific models used to represent wind generators are then generally different from the conventional ones used in power system analysis [3]. In particular, the DFIG with bidirectional electronic converter (BEC) on the wound-rotor side [4] is widely used in wind system installations. The DFIG modelling requires the representation of further details referred to the BEC control [5–7].

For the purpose of energy production studies, the link between the wind speed and the power produced by a wind generator is given by the so-called *power curve* [2,8], typically provided by the wind turbine (WT) manufacturer. The wind speed indicated in the power curve is the one corresponding to the hub height with measurement point located *in front* of the hub. However, wind generators could be equipped with wind speed sensors (anemometers) located on the back of the nacelle, thus measuring the wind speed and direction in a section located behind the blades [9]. This creates a discrepancy between the wind speed indicated on the manufacturer power curve and the wind speed data measured in operational conditions on the field. In fact, the characteristics of the air stream change during the air passage through the blades [8,10]. In particular, the air stream behind the blades exhibits a slight expansion and the wind speed at the anemometer becomes lower than the wind speed in front of the blades. In order to enable comparison of the experimental data with the ones indicated in the manufacturer power curve, a procedure for correcting the experimental data is needed [11]. In this procedure, the experimental data are gathered with sampling rate around one sample per second, but are stored in the form of 10 min mean values of electric power at the wind generator terminals and wind speed from nacelle anemometers. Calculation of the mean values makes the information concerning transient phenomena no longer explicitly available. As such, methods addressing short-term wind system operation cannot be used directly with these data.

This paper provides a set of dedicated contributions referred to the aforementioned aspects of DFIG application in energy production studies. Section 2 summarizes the background concepts by providing a structured view of the DFIG characteristics, with an organic and synthetic illustration of blade design principles, DFIG control modes and their representation on the power-wind speed curve. Section 3 deals with the construction of an enhanced steady-state model of the DFIG, proposed to embed the presence of the BEC and thus allowing to interpret the effects of control actions with reference to the manufacturer power-wind speed curve. Section 4 addresses the correction of the experimental wind speed data obtained from data acquisition systems when the anemometer is located on nacelle, in order to make these measured points consistent with the ones given in the manufacturer power curve. The proposed correction method is based on the principles used for

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doi:10.1016/j.renene.2012.01.002

measurement instruments calibration. The analysis uses nominal and measured data of real DFIG machines.

2. Blade design and control modes for doubly-fed induction generators

The blade aerodynamics is complex because of variable point-by-point contributions along the airfoil associated to the drag and lift components ([1], chapter 3). The aerodynamic effects also depend on air flow viscosity, and on the transition between laminar and turbulent flow that may occur in some points and can be explained by resorting to the boundary layer concept [1]. In this paper, a synthetic approach is followed, taking into account global vector quantities without entering into the details of laminar and turbulent flows.

Fig. 1 shows the global vector quantities applied to the centre of pressure, in terms of kinematics and dynamics of the blade (close to the tip) [1], by considering:

- U unperturbed wind speed;
- $V_x = \omega_{\text{rot}} \cdot R_x$ tangential speed at distance R_x from the hub;
- W_x relative wind speed at distance R_x from the hub;
- F_L lift component of the resulting force F_R;
- F_D drag component of the resulting force F_R;
- F_T torque component of the resulting force F_R;
- F_H thrust component of the resulting force F_R.

The *inclination* angle γ of the local blade chord to the rotor, variable along the blade length, is considered during blade design to optimize the blade performance. For a given angle of attack α, the *flow* angle $\varphi = \alpha + \gamma$ of resultant velocity W_x to rotor plane is linked to the *tip speed ratio* $\lambda = \cot\varphi$. The tip speed ratio is inversely related to the wind speed, according to the relation $\lambda = \omega_{\text{rot}} \cdot R/U$, where ω_{rot} is the rotational speed and R is the WT rotor radius. Furthermore, the *pitch angle* β is a control parameter defined as the angle *deviation* with respect to the reference angle γ. Positive values of β correspond to pitch angle control towards feather, while negative values of β stand for pitch angle control towards stall. The stall condition corresponds to $\beta = -\gamma$.

The most specific result of the blade design for a wind generator is represented by the curve $C_p(\lambda,\beta)$ which links the *power coefficient* C_p to the tip speed ratio λ and to the pitch angle β [1,12]. The $C_p(\lambda,\beta)$ function can be expressed through approximate numerical relations [13–16]. For instance, this paper uses the model introduced in [15], for non-negative β values:

$$C_p(\lambda,\ \beta) = 0.22\left(\frac{116}{\tilde{\lambda}} - 0.4\,\beta - 5\right) e^{-\frac{12.5}{\tilde{\lambda}}} \tag{1}$$

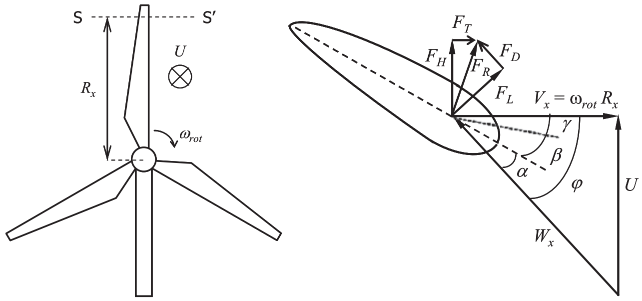

Fig. 1. Front view and top view with representation of the vector quantities applied to the centre of pressure of the blade section S–S′ for a horizontal-axis WT.

with $\tilde{\lambda} = \left(\dfrac{1}{\lambda + 0.08\beta} - \dfrac{0.035}{1+\beta^3}\right)^{-1}$.

The coefficient C_p can be explained as the aerodynamic or blade efficiency in function of the wind speed, by maintaining constant in the blade both the rotational speed ω_{rot} and the angle β. Thus, high tip speed ratios mean low wind speed ranges, whereas low tip speed ratios are assigned to high wind speed ranges.

At constant pitch angle β, the $C_p(\lambda)$ function shows an absolute maximum corresponding to the right value of angle of attack α which permits to harness the lift for torque generation. The best angle of attack depends on the aerodynamic profile, as defined by using for instance the classification introduced by NACA (the U.S. National Advisory Committee for Aeronautics), with indicative values falling around 10° [1]. Low values of α lead to scarce lift, as with high values of λ, whereas high values of α may conduct to the stall phenomenon, in turn reducing the coefficient C_p.

Fig. 2 summarizes all these considerations for a wind generator with $R = 26$ m and four different values of pitch angle β, starting from the design condition with $\beta = 0$ and increasing β towards the feather condition.

Another situation may occur for cut-in conditions, in which the WT needs high torque to achieve fast start-up. In other words, at or below the cut-in wind speed, maximization of the coefficient C_p is not the paramount target, and the torque increase can be obtained by making the angle β slightly negative [1].

If the blade speed is changed according to the wind speed variation (constant λ), it is possible to keep C_p constant and equal to its maximum value. Usually, this task is called *maximum power point tracking* [17], and the locus of maximum power points is a cubic function of the rotor speed (Fig. 3). Within the low-mid range of wind speeds (4–9 m/s) the pitch angle is maintained constant at $\beta = 0$ in order to achieve this goal (Fig. 4). The rotor speed can be increased by taking into account the blade loadings in terms of bending moment (torque), thrust and centrifugal force. The material which constitutes the blades must withstand these loadings. Fatigue limit has to be included as well. Therefore, glass-fibre provides worse performance than carbon-fibre; the latter permits better closeness to the maximum $C_p(\lambda)$, yet at higher cost.

A gearbox permits to interface the blades rotating at relatively low speed (because of the centrifugal limit) with the electrical generator rotating at relatively high speed (constrained by the grid frequency for a given number of poles) [18]. The gearbox efficiency (mechanical power to blade power ratio) can be significantly high (about 95–97%) if no more than three stages are used (i.e. with ratios of $5 \times 5 \times 2$) [19,20]. This makes the mechanical power P_{mec} slightly lower than the blade power P_{blade} (Fig. 4).

On the other hand, when the wind speed is close to the value corresponding to the rated power, a reduction of the efficiency C_p, consequent to the pitch regulation towards the feather, is accepted in order to limit the power increase. The centrifugal force imposes a threshold in the angular speed of the blades (Fig. 4), which can only be increased in transient conditions (e.g. wind gusts). The way by which the task of reaching the rated power can be achieved is twofold:

1. with *steep variation* between high derivative in power before the rated value and zero derivative after the rated value (this implies higher loading and noise in the structure); the related conditions are indicated with the superscript 1 in Fig. 5;
2. with *smooth variation* between the power derivatives before and after reaching the rated value (more used due to reduced loading), indicated with the superscript 2 in Fig. 5.

The existence of different ways to reach the rated power conditions is one of the reasons according to which the manufacturer