Renewable Energy 85 (2016) 273–280

Contents lists available at ScienceDirect

Renewable Energy

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

Displacement of the maximum power point caused by losses in wind turbine systems

Jeroen D.M. De Kooning*, Tine L. Vandoorn, Jan Van de Vyver, Bart Meersman,
Lieven Vandevelde

Electrical Energy Laboratory (EELAB), Department of Electrical Energy, Systems and Automation (EESA), Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

ARTICLE INFO

Article history:
Received 7 July 2014
Received in revised form
8 May 2015
Accepted 21 June 2015
Available online xxx

Keywords:
Wind energy
Maximum power point tracking
Modeling of losses
Power coefficient
Energy yield

ABSTRACT

The energy yield of wind turbines is to a large extent determined by the performance of the Maximum Power Point Tracking (MPPT) algorithm. Conventionally, they are programmed to maximize the turbines power coefficient. However, due to losses in the generator and converter, the true optimal operating point of the system shifts. This effect is often overlooked, which results in a decreased energy yield. Therefore, in this paper, the wind turbine system is modeled including the dominant loss components to investigate this effect in detail. By simulations and experiments on a wind turbine emulator, it is shown that the location of the maximum power point is significantly affected for low wind speeds. For high wind speeds, the effect is less pronounced. The parameter of interest is the increase in yearly energy output with respect to the classical MPPT method, which is calculated in this paper by including a Rayleigh wind speed distribution. For typical average wind speeds, the energy yield can increase with 1−2%. There is no cost associated with operating the turbine in the overall MPP, making it worthwhile to include this effect. The findings are implemented in an MPPT algorithm to validate the increased performance in a dynamic situation.

1. Introduction

Wind turbines play an important role in the production of renewable energy. The global installed capacity of wind power reached 318 GW at the end of 2013 [1], growing 35 GW during the last year. The majority of these wind turbines have a rated power of several MW. However, small and medium wind turbines with a rated power below 300 kW can also have a valuable contribution in the production of renewable energy. They have less visual impact and can be installed close to the consumer in a decentralized manner, for example, in rural, urban or industrial areas.

Although small and medium wind turbines undeniably have a positive impact on the environment [2], they often have a disappointing energy yield and economical profitability. This can be caused by many aspects, such as a mismatch between the wind speed range for which the turbine was designed and the actual wind speed at the location. Also, the performance of the Maximum Power Point Tracker (MPPT) determines the efficiency of the wind turbine system to a large extent. The goal of classical MPPT algorithms is to regulate the turbine to its maximum power coefficient by controlling the rotational speed to the optimal value for each wind speed. An inaccurate or slow MPPT results in a reduced power coefficient of the turbine and less capture of renewable energy.

In recent years, much research has been done to improve the performance of MPPT algorithms [3]. Several advanced methods have been proposed, such as adaptive fuzzy logic [4,5], neural networks [6], Perturb & Observe [7,8] or alternative converter topologies [9–11]. The main focus of these methods is to bring the turbine to the Maximum Power Point (MPP) as fast and efficiently as possible whenever a change in the wind speed occurs.

In the design of MPPT algorithms, it is often assumed that the controller must maximize the power coefficient of the turbine. Although this is the maximum power point of the turbine, abbreviated as TMPP here, it is not necessarily the overall maximum power point, including the generator and power electronics. The latter will be abbreviated as OMPP here. For example, since mechanical losses increase with rotational speed, it is beneficial for these losses to operate at a speed slightly below the value

---

* Corresponding author.
E-mail address: Jeroen.DeKooning@UGent.be (J.D.M. De Kooning).

http://dx.doi.org/10.1016/j.renene.2015.06.052
0960-1481/© 2015 Elsevier Ltd. All rights reserved.

corresponding with the TMPP. Moreover, the iron and copper losses of the generator differ for each mechanical operating point, again resulting in a difference between the OMPP and the TMPP. Finally, the switching and conduction losses of the converter have a similar effect.

It is crucial to know the location of the OMPP of the turbine system, such that the controller can be programmed to regulate the turbine to this OMPP instead of the TMPP. This will reduce losses and, thus, increase the total energy yield of the turbine system. In Ref. [12], it was shown how the generator losses can affect the optimal rectified dc voltage, and thus the MPP. In this paper, the converter losses, i.e., switching and conduction losses, are included in the analysis and the mechanical loss model is extended, including friction in the radial shaft seals and windage losses. This allows to calculate the OMPP by taking into account the complete system, up to the grid connection. Since the complete system is modeled in this paper, the potential increase in yearly energy yield can be calculated which is the main parameter of interest.

The effect of the losses is inherently taken into account by a Perturb & Observe (P&O) MPPT algorithm, given that the power injected into the grid is tracked, instead of the electric output power of the generator. However, in practice, Power Signal Feedback (PSF) controllers are more popular due to their simplicity and effectiveness. P&O controllers are known to be slow and suffer from oscillations [7]. Therefore, this paper presents a method to alter the PSF controller so that the effect of the losses is taken into account, combining the speed of a PSF controller with the theoretical accuracy of a P&O algorithm.

In section 2, it is explained how the losses are modeled and implemented in a simulation model for a typical wind turbine system. In section 3, the efficiency maps of the different components in the system are calculated to gain more understanding of their behavior. In section 4, the location of the OMPP is calculated for different wind speed values. It is shown that there is a considerable difference between the location of the OMPP and the TMPP for low and medium wind speed values. For high wind speeds, the effect is less pronounced. Since the complete system is simulated, the potential improvement in the yearly energy yield is calculated by using a Rayleigh wind speed distribution. Experimental validation of these results is given in section 5 with measurements on a lab-scale wind turbine emulator. Finally, the findings of section 4 are implemented in an improved PSF controller and compared with classical algorithms, such as P&O, in 6, in order to validate the increased energy yield for a varying wind speed pattern.

2. Modeling of the turbine system

The simulation models of the different components, i.e., turbine, generator and power electronics are explained in this section. Special attention is given to the modeling of the losses, as this will determine the location of the OMPP.

2.1. Overview of the wind turbine system

Fig. 1 gives an overview of the most common wind turbine system based on a Permanent Magnet Synchronous Generator (PMSG). The turbine (a) drives the PMSG (b). Since the shaft speed is variable, the PMSG produces an ac with a variable frequency and amplitude, i.e., ‘wild ac’. The wild ac is converted to a dc voltage proportional to the turbine's rotational speed by the diode rectifier (c). A boost dc/dc chopper (d) converts this variable dc voltage to a constant dc voltage while performing the MPPT. An inverter (e) then injects an ac current with a constant frequency into the grid (f).

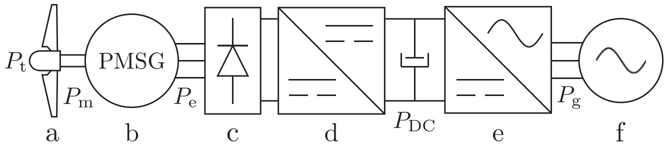

Fig. 1. Overview of a wind turbine system.

2.2. Turbine blades

The mechanical power of the turbine P_t is given by:

$$P_t = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda) \tag{1}$$

where ρ is the air density, R is the turbine radius and v is the wind speed. The factor $C_p(\lambda)$ is the power coefficient of the turbine, which is determined by the Tip-Speed Ratio (TSR) λ. The pitch system is not considered here. The TSR characterizes the air flow around the blades and is defined by:

$$\lambda = \frac{R\Omega}{v} \tag{2}$$

where Ω is the rotational speed of the turbine. The relation between the power coefficient C_p and the TSR λ is determined by the shape of the blade. Here, an empiric $C_p(\lambda)$ relation from Refs. [13,14] is used to model the blades:

$$C_p(\lambda) = \left(\frac{116.46}{\lambda} - 10.53\right)e^{-18.4/\lambda} \tag{3}$$

This power coefficient $C_p(\lambda)$ is shown graphically in Fig. 2. The power coefficient reaches a maximum value of 0.44 for a TSR of 6.91, which is the TMPP. The TMPP is the most favorable operating point of the turbine as the power output is maximized here.

2.3. Mechanical losses

Mechanical losses are present as friction in bearings and radial shaft seals and windage losses due to friction of the rotor with the surrounding air. They can be approximated by:

$$P_f = \mu M_r \frac{d}{2}\Omega + 0.442\, S\,\Omega + 0.0017\, D^3\, L\Omega^3 \tag{4}$$

The first term represents the friction losses in the bearings where μ is the friction coefficient and d is the pitch circle. The total radial force M_r can be calculated from the weight of the turbine m_T and roughly half of the generator weight $m_G/2$, since only the rotor should be taken into account. The second term represents the friction losses in radial shaft seals and is an empiric first-order approximation on manufacturer data, where S is the amount of seals in the drivetrain. The third term models the windage losses for an outer rotor machine [15] where D is the outside rotor diameter

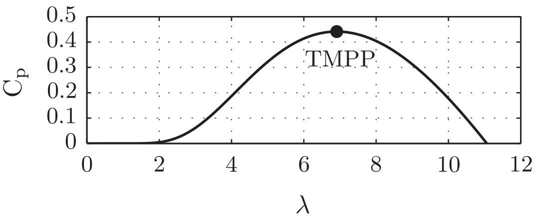

Fig. 2. Empiric $C_p(\lambda)$ curve [13,14].