Energy Conversion and Management 174 (2018) 378–387

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Using a new wind turbine emulator to analyze tower shadow and yaw error effects

Ebrahim Mohammadi, Roohollah Fadaeinedjad*, Hamid Reza Naji

Department of Electrical and Computer Engineering, Graduate University of Advanced Technology, Kerman, Iran

ARTICLE INFO

Keywords:
Wind turbine emulator
Tower shadow effect
Yaw error
FAST
AeroDyn

ABSTRACT

The majority of the available wind turbine emulators (WTEs) utilize the detailed electrical sub-systems, whereas the simplified models are considered for the other aspects. However, wind turbines (WTs) are complicated systems with different aspects that should be appropriately modeled for a realistic assessment. This paper presents a new wind turbine emulator which considers aerodynamic, mechanical, and electrical aspects of the WTs. Some tests are performed to evaluate the capabilities and limitations of the emulator; then, the proposed emulator is used to analyze the tower shadow and yaw error effects which can produce power fluctuations and fatigue loads. In addition to tower shadow effect, the yaw error which has a more severe effect is studied in this paper considering the mechanical dynamics of the WT which were not considered in literature. The proposed emulator utilizes the AeroDyn and FAST software tools to model the aerodynamic and mechanical aspects of a WT considering the real electrical sub-systems. Moreover, the tower shadow and yaw error effects are modeled in simulation and the results are compared with the emulation results. The electrical sub-systems are modeled in the MATLAB/Simulink for simulation, whereas the real mechanically coupled induction motor-induction generator set is used for the emulator.

1. Introduction

Wind energy is one of the fast-growing renewable resources due to its advantages including being sustainable, cost-effective, and pollution-free. These benefits have motivated countries to use this energy and highly invest in the technology related to the wind energy conversion systems (WECSs) in both research and industry sections. A new WECS's technology can be developed during different steps including design, simulation, and emulation. Simulation is a good tool to analyze the performance of the designed WECSs if appropriate software packages are used, as discussed in [1,2]. However, another tool is required to evaluate the performance of wind turbines in more realistic environment and develop different parts experimentally. In so doing, wind turbine emulators (WTEs) as appropriate, cost-effective, and safe tools were developed. The available WTEs mainly use a mechanically coupled motor-generator sets which are connected to the grid without or with power electronics interfaces. The motor is controlled via power electronic devices or commercial variable speed drives to reproduce the mechanical torque or rotation speed of the actual wind turbine. The studies related to the WTEs can be classified into different groups including:

1. modeling of the wind turbines to reproduce the behavior of the real wind turbines,
2. using different hardware and equipment to implement the WTEs and analyze their performances,
3. other studies consisting of implementation of new control methods, maximum power point tracking (MPPT) strategies, and grid connection studies.

Most of the available papers concentrate on the electrical sub-systems and simple models were considered for aerodynamic and mechanical aspects. In these studies, the WTEs mainly divided based on the type of the utilized electric motor and the associated drive as a prime mover. Generally, the utilized motors in WTEs are divided into DC motors [3–6], permanent magnet synchronous motors (PMSMs) [7–9], and induction motors (IMs) [10–13]. Although DC motors have been utilized in literature to develop the WTEs, some disadvantages of these motors including large size for a given power rating, being relatively expensive, and requiring the frequent maintenance make them less attractive [14]. On the other hand, the PMSMs have good power density and efficiency but they are expensive machines. The induction machines are widely used as prime-movers in the WTEs due to their high robustness and reliability, being inexpensive, and requiring low

* Corresponding author.
E-mail addresses: e.mohamadi66@gmail.com (E. Mohammadi), rfadaein@kgut.ac.ir (R. Fadaeinedjad), hamidnaji@ieee.org (H.R. Naji).

https://doi.org/10.1016/j.enconman.2018.08.049
Received 18 May 2018; Received in revised form 18 July 2018; Accepted 13 August 2018

maintenance. Hence, in the present study a mechanically coupled induction motor-induction generator set is utilized.

Modeling of a wind turbine is the most important part for WTE development and availability of a comprehensive model can be helpful for the other studies. The utilized model should be capable of considering the static and dynamic behavior of a real wind turbine. Wind turbines are complicated systems consisting of different aspect including aerodynamic, mechanical, and electrical aspects. A WT always faces with different aerodynamic and mechanical phenomena including tower shadow, yaw error, wind shear, and mechanical dynamics of the turbine which affect its behavior in terms of power production, power quality, fatigue loads, and mechanical stress. Therefore, to reproduce the realistic behavior of a WT in laboratory environment, these issues should be taken into consideration. A number of studies used a simple power curve as a model of wind turbine [14–17], whereas some dynamics of wind turbines were considered in various papers including inertia of the turbine [3]. Tower shadow and wind shear effects were considered in [18], where these effects added as sinusoidal terms to the mechanical torque. The tower shadow effect was modeled in [12,13], where the aerodynamic of the blades and gearbox were modeled in MATLAB/Simulink. The dynamic characteristic of pitch mechanism [11] and load torque dynamic compensation [8] were also studied in literature. In [4], the WTEs were equipped with different sensors and components including blades and gearbox to develop a more comprehensive system; however, adding different sensors and components increases the cost of the emulator. The WTE, proposed in [7], utilizes a direct-drive prime-mover concept in combination with non-torque units to apply dynamic force and moments in 5 degrees of freedom (DOFs) for stress analysis at the rotor hub and power electronics. A heterogeneous WTE was implemented on an embedded NVIDIA Jetson TK1 board for a 5 MW WT as a case study [19], where a linear parameter varying model was extracted considering different DOFs. In this study, the authors tried to consider some DOFs similar to those modeled by the FAST software tool. However, implementation of the electrical parts was not included in this study. A simple technique was proposed in [20] to emulate the fast dynamics of mechanical systems based on the compensator development and the proposed method was used for emulation of aero gas engine dynamics.

Some effects including tower shadow and wind shear were modeled in literature. However, the utilized wind turbine models were simple and in some cases, limited parts and dynamics were included. A comprehensive model which can model different parts, dynamics, and some more phenomena was not presented in literature and this study fills this gap. The contributions of this work are as follows:

1. A new wind turbine emulator is developed which is capable of modeling the aerodynamic and the mechanical aspects of a WT using AeroDyn [21] and FAST [22] software tools, implemented in the master software LABVIEW. The electrical parts are implemented in laboratory environment.
2. The proposed WTE is used to model and investigate the tower shadow and yaw error effects in a downwind wind turbine considering the mechanical dynamics. The yaw error effect was not modeled in literature due to the limitation of the WTEs; however, the impact of this phenomena may be more sever than the tower shadow effect as discussed in [23].
3. The simulation is carried out using the FAST software and the results are compared with the emulation results.

The tower shadow effect and yaw error are undesired phenomena that generate power pulsation with two or three times per revolution (2p or 3p) frequencies, depending on the number of the blades. Modeling these phenomena using a WTE helps to study the behavior of wind energy conversion systems in more realistic conditions. To implement the WTE, a coupled IM-IG set with a torque transducer was used considering the advantages of the induction machines. The paper is organized as follows:

Tower shadow effect and yaw error are discussed in Section 2. The proposed WTE and utilized software tools are presented in Section 3. The simulation and experimental results are given and discussed in Section 4. Finally, the concluding remarks are summarized in Section 5.

2. Tower shadow effect and yaw error

2.1. Tower shadow effect

Although wind turbines are widely used in the world to generate electricity, the power quality of these resources can be affected by some phenomena including tower shadow and yaw error effects [23]. The WTs can be divided into two categories considering the relative location of the rotor and the tower known as upwind and downwind. In upwind WTs, the rotor is in front of the tower and airflow reaches the rotor at first, whereas in the downwind turbines the rotor is behind of the tower and the airflow reaches the tower initially. The airflow direction is changed by the presence of the tower in both WT types. In upwind WTs, the airflow is redirected in front of the tower and thereby the torque is reduced at each blade when passing in front of the tower. Similarly, the wind velocity reduces behind the tower caused by the tower obstruction in downwind WTs. This phenomenon, which generate torque or power pulsations, is called tower shadow effect. This phenomenon has been modeled and studied in literature in both simulation [23,24] and experiment using WTEs [12,18]. The present study utilizes the AeroDyn software [21] to model the tower shadow effect based on the work of Bak et al. [25] and Powles [26] for upwind and downwind turbines. The Bak et al. model utilizes a potential flow solution around a cylinder as the base flow field along with a downwind wake model dependent on tower drag coefficient (based on diameter), *Cd*, and a tower dam model for upwind influence. In this model the influence of the tower on the local velocity field at all points around the tower are considered containing the increases in the airflow velocity around the tower sides and the cross-stream velocity component in the tower near flow field. However, this model uses a specified width that does not increase with downwind distance, which is not realistic for downwind WTs. Hence the tower wake (shadow) model based on the work of Powels [26] is used in AeroDyn for downwind turbines which copes with this deficiency. Considering this model, the tower wake factor (dimensionless wake velocity deficit) can be determined as follows [21]:

$$u_{wake} = \frac{C_d}{\sqrt{d}}\cos^2\left(\frac{\pi}{2}\frac{y}{\sqrt{d}}\right), \quad for\ |y| \leqslant \sqrt{d} \tag{1}$$

and

$$d = \sqrt{x^2 + y^2} \tag{2}$$

where C_d is the drag coefficient of the tower section, d is the normalized radial distance from the center of the tower to the point of interest, x and y are the normalized downwind and crosswind distances from the tower center. The local velocity for a point inside the wake effect can be calculated as follows:

$$U_{local} = (1-u_{wake})U_\infty \tag{3}$$

where U_∞ is the total wind speed. It should be noted that the tower wake or shadow effect reduces in strength and increases in width as the distance from the tower increases. There are some parameters in the input file of the AeroDyn software for modeling of tower shadow effect including TWRSHAD (a measure of the strength of the velocity deficit in the wake of the tower), SHADHWID (the half-width of the tower shadow, measured at a distance T_Shad_Refpt), and T_Shad_Refpt (a distance that indicates the point downstream of the tower centerline where the indicated tower shadow deficit strength is encountered). The schematic of tower shadow model is shown in Fig. 1.