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Flicker emission, voltage fluctuations, and mechanical loads for small-scale stall- and yaw-controlled wind turbines

Ebrahim Mohammadi, Roohollah Fadaeinedjad*, Hamid Reza Naji

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

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ABSTRACT

This study analyzes and compares flicker emission, voltage fluctuations, and mechanical loads for two small-scale wind turbines (WTs), considering different control strategies. The investigated strategies are active yaw and stall control strategies for above rated wind speed operation to limit the captured power. The yaw controller is designed to limit the output power and rotation speed in high wind speeds by rotating the turbine out of the wind direction. On the other hand, the optimal blades are designed for the stall-controlled WT to have appropriate performance in all wind speed regions, especially in the stall region. In this WT, the captured power is regulated by controlling the rotor speed in relation to wind speed via power electronic interface in all wind speed regions without requiring the aerodynamic active devices. The maximum power point tracking (MPPT) algorithms are also implemented in low and moderate wind speeds. A simulation platform is used that considers aerodynamic, mechanical, electrical, and control aspects of the WTs. The MPPT, yaw and stall control, and simulation results are presented and discussed. Results demonstrate that flicker emission level, voltage fluctuation and mechanical loads for the stall-controlled WT are less than those in the yaw-controlled turbine.

1. Introduction

The renewable energy provided an estimated 19.3% of global final energy consumption by the end of 2015 [1]. Of this total share, wind, solar, biomass, and geothermal power are accounted for an estimated 1.6%. Renewable power generating capacity experienced its largest annual increase ever in 2016, with an estimated 161 GW of capacity added. Renewable energies provided about 24.5% of the global electricity with 4% the share of wind energy at the end of 2016. The global installed capacity of WTs was about 486 GW by the end of 2016 which demonstrates a growth of about 54 GW comparing to 2015. The most installed capacity was in China, USA, Germany, India, and Spain. Considering the highest wind energy penetration throughout 2016, wind power supplied 37.6% of electricity demand in Denmark, 27% in Ireland, 24% in Portugal, 19.7% in Cyprus, and 10.5% in Costa Rica [1]. Wind turbines can be installed in wind farms as large-scale generating units to provide the electricity of large demands or they can be installed as small-scale units. Small WTs have diverse applications including water pumping systems, rural and remote site electrification, and battery chargers, heating greenhouses and residential buildings, and hydrogen production for upgrading bitumen from oil fields [2,3]. Considering the wide application of these renewable energy resources, the performance and economic of the small wind turbines has been evaluated in different countries [4,5]. WTs can be divided into variable-speed and fixed-speed generating units. The variable speed wind turbines, equipped with the power electronic devices, can extract more energy from the wind comparing to the fixed speed ones. Variable speed WTs have different operating regions including region 1, 2 and 3. Wind speed in region 1 is below the cut-in wind speed and the WT is not capable of generating power. In region 2, the wind speed is below the rated wind speed and the turbine operates in the MPPT mode, whereas in region 3, where the wind speed is above the rated one the turbine should limit the output power. In region 2, different algorithms were utilized to implement the MPPT in variable speed WTs including direct- and indirect-based power control algorithms, fuzzy- and neural network-based algorithms, and adaptive algorithms [6]. In region 3, various control strategies are used to limit the output power of a WT. Most of these methods are mechanical which are used to limit the aerodynamic power. Blade pitch angle control is one of the commonly used method which is implemented as pitch to feather or pitch to stall mechanism for large- and moderate-scale WTs [7]. For small WTs, however, the pitch angle control is not usually used because of the inherent cost and complexities. In these turbines other methods such as furl control [8], active yaw [9], and soft-stall [10] are used. Stall is an aerodynamic phenomenon which occurs when the angle of attack exceeds a specified values. When it happens, the lift forces on the blades

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

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Nomenclature

Furl the tail vane is hinged, allowing the rotor to furl (turn) in high winds
Active yaw the nacelle is turned about the yaw axis using active devices such as motors
Stall airflow is separated from an airfoil at a high angle of attack which results in reduction in the lift forces
Pitch angle turning the wind turbine blades about their long axis into or out of the wind
Angle of attack (AoA) the angle between the chord line and relative wind speed
Chord line it refers to a straight line connecting the leading and trailing edges of an airfoil
Lift forces aerodynamic forces generated by the airflow which are perpendicular to the airflow direction
Drag forces aerodynamic forces generated by the airflow which are in the direction of the airflow
Twist angle the orientation of the chord of the local airfoil where a positive aerodynamic twist is the one that points the leading edge more upwind

are reduced and the drag forces are increased. Therefore, this phenomenon can be used to limit the output power and the rotor rotation speed. To control a WT by this method, the blades of the wind turbine should be designed to operate in the stall condition when the wind speed exceeds the rated one. In the furl and active yaw control strategies, the nacelle is turned out of the wind direction which results in capturing less energy in high wind speeds. Wind turbine components encounter different loads during the operation of the WT and the severity of the loads that the components experience can be related to the control strategies implemented in region 3. On the other hand, the flicker emission of the WTs can be different when various control strategies are utilized in region 3 to limit the power as it is discussed in the following section.

2. Literature review

In this section, the flicker emission, voltage fluctuations, and mechanical loads in WTs are briefly reviewed and the contribution of the present study is discussed.

Connection of the renewable energy sources such as wind turbines to the grid is a challenge that can affect the system stability and power quality [11]. Flicker emissions, as the important factor of power quality, are produced by WTs due to continuous and switching operations [12]. Flicker emissions in continuous operations of WTs are produced by variation in the generated power due to wind speed variation, turbulence, tower shadow effect, wind shear, and mechanical properties of wind turbines. Voltage fluctuations and flicker emissions were studied in [13] for an island grid supplied by diesel generators with high wind energy penetration. The impact of rapid voltage changes in power system networks on flicker emissions was investigated in [14] and the correlation between short-term flicker sensation and rapid voltage changes was studied. The effect of digital differentiation to improve the measurement of flicker emissions from grid-connected wind turbines was analyzed in [15]. The maximum capacity of the wind farms for connecting to the distribution systems was studied in [16], where this capacity was limited and determined by flicker emission level and injected apparent power. In [17], different factors that affect the flicker emissions in wind power systems were recognized and analyzed. This study demonstrated that the aerodynamic phenomena such as wind shear, tower shadow, and mechanical failure such as gearbox tooth crashing, pitch control error and blade crashing are factors which lead to flicker emission in wind turbines. Different methods were used to reduce the flicker emissions by WTs including power factor angle control [18], and dynamic Volt/Var control [19]. Literature review shows the importance of flicker emission level and mitigation techniques in WTs.

On the other hand, the mechanical loads on the turbine structure are very important and they are main concerns in assessment of turbine structural requirement. These loads can be divided into different types including static (non-rotating), steady (rotating), cyclic, transient, impulsive, stochastic, and resonance-induced loads [7]. The sources of these loads can be aerodynamics, gravity, dynamic interactions, and mechanical control. The individual blade pitch control was used in [20] to reduce the fatigue loads of wind turbines. The PI-R controller was implemented in [21] to eliminate the balanced and unbalanced loads of a 1.5 MW WT. Internal model-based and individual blade pitch controls were utilized in [22] to reduce the WT fatigue loads and tower vibrations. Reviewing the previous studies shows that analysis of the mechanical loads and mitigation techniques in WTs are vital issues.

In literature, some comparative studies were carried out to analyze the performance of stall, furl and yaw control strategies. A study was carried out in [23] to investigate the output power of stall- and yaw-controlled WTs. The simulation results showed that the stall-controlled WT has a smoother output power. A comparative study was carried out for evaluating the performance of the furl and stall-controlled turbines in [24], where the results demonstrated that the stall control method has some advantages over the furl control or passive yaw. When the furl or passive yaw mechanism operate, the output power is rapidly reduced and the energy production is reduced in high wind speeds. Moreover, the thrust and furling noises are increased. In the yaw-controlled WT, the MPPT is controlled by power electronics but the mechanical yaw mechanism with two different operation modes is used to limit the captured power in region 3. On the other hand, in the stall-controlled WT both MPPT in region 2 and power control in region 3 are implemented using the power electronics interface. Hence, the control issues in yaw-controlled WT are more complicated and the controllers may interact with each other if they are not carefully designed. Flicker emission, voltage fluctuations, and mechanical loads were not compared in literature for the stall- and yaw-controlled WTs. The yaw error and mechanical control strategies can affect the flicker emission and mechanical loads in WTs. Therefore, the yaw-controlled WT may encounter with these problems that are discussed in the present paper.

Considering the importance of the flicker emission and mechanical loads in WTs, the present research evaluates and compares these issues in small-scale stall- and yaw-controlled WTs. The yaw and stall control strategies can be used in small-scale WTs to limit the captured power in region 3. The main contribution of our work is analyzing and comparing these control strategies in terms of flicker emission, voltage fluctuation, and mechanical loads. Although some studies have been carried out to analyze the performance of these two control strategies, their comparison in term of flicker emission, voltage fluctuation, and mechanical loads has not been presented in literature and this study fills this gap. All parts of two WTs are similar to each other except their aerodynamic or blade designs and their control methods. Improved yaw- and stall-controlled WTs are designed and their performances are evaluated in different wind conditions. The MPPT algorithms are also implemented for both WT in region 2. The blades of a stall-controlled WT are designed then utilized in simulations whereas, the available blades in FAST CertTest collection are utilized for the yaw-controlled WT. A simulation platform is used to analyze the aerodynamic, mechanical, electrical and control aspects of WTs.

The paper is organized as follows: In Section 3, the simulation platform is presented. Section 4 deals with the electrical controllers which are implemented in Simulink/MATLAB software environment.