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Output power control for hydro-viscous transmission based continuously variable speed wind turbine

Xiu-xing Yin*, Yong-gang Lin, Wei Li, Hong-wei Liu, Ya-jing Gu

The State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Zheda Rd.38, 310027 Hangzhou, PR China

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ABSTRACT

A hydro-viscous transmission based continuously variable speed wind turbine is proposed in this paper to smooth the output power fluctuations in the full-load region. The hydro-viscous transmission concept is based upon mature technology and is characterized by low production cost and high reliability. Torque characteristics and transmission efficiency of this type of wind turbine are analyzed. A particle swarm optimization algorithm based multi-objective optimization method is employed to optimally design the hydro-viscous transmission. Major components of the wind power system have been mathematically modeled and analyzed in detail. Furthermore, a hybrid output power control strategy is proposed and implemented to precisely control the generated power and torque for this system. This wind power system has been validated by a theoretical analysis and a comparative simulation study. The simulation results by using an actual detailed model show the achievement of quite satisfactory performances of smoothing power and torque fluctuations despite the varying wind speed.
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1. Introduction

Nowadays, wind turbines represent a prominent facility for converting kinetic energy from the wind into electric energy via the generator. Wind turbines are also becoming the fastest growing energy source and receiving worldwide attentions due to the technological advancements in harnessing wind power [1]. However, since the wind velocity is highly stochastic, wind energy is not constant and aerodynamic power is proportional to the cube of wind speed, which causes the output power to fluctuate. The power fluctuations cause frequency fluctuation and voltage flicker inside the utility grid. Frequency fluctuation and voltage flicker deliver a poor power quality and create instability problems in the power system, especially when there are loads sensitive to high voltage and frequency variations. In order to reduce the power fluctuations, various approaches have been proposed in the literature. Among these approaches, pitch angle control is the most common method for limiting output power during above rated wind incidents [2]. Another important proposal is to use the variable speed wind turbine which can utilize the wind energy proficiently and is advantageous in the reduction of mechanical stress and improvement of power system reliability. Variable speed operation also enables wind turbines to keep the generator torque and frequency nearly constant. Current variable speed wind turbines typically utilize the power electronics to achieve the variable speed control. However, only indirect speed and torque control of the main shaft can be achieved by using the power electronics.

A potential approach to accomplishing variable speed operation would be to incorporate the continuously variable transmission between a wind turbine and an electric generator. In Ref. [3], an electrically controlled power splitting transmission for variable speed wind turbines was presented. This transmission consisted of wind rotor, three-shafted planetary gear set, generator and servo motor. By controlling the electromagnetic torque or speed of the servo motor, the variable speed operation of the wind rotor and the constant speed operation of the generator would be achieved, therefore, the generator would be coupled with the grid directly. In Ref. [4], a type of rolling traction transmission that uses balls to vary the transmission ratio was proposed. This transmission type allows smooth, continuous transition between an infinite number of gear ratios. The balls in this transmission transmit power from an input plate to an output plate using elasto-hydrodynamic lubrication. The transmission ratio is changed by varying the angle of the balls' rotational axes. Andrew H. Rex and Kathryn E. Johnson [5] developed a model that combined continuously variable transmission and induction generator dynamics with the FAST wind turbine simulator to create a high fidelity continuously variable transmission wind turbine model for

* Corresponding author. The State Key Laboratory of Fluid Power Transmission and Control, Yuquan Campus, Zhejiang University, No.38, Zheda Rd. Hangzhou, 310027, P.R. China. Tel./fax: +86 182 5049 2053.
E-mail address: lixingfile@163.com (X.-x. Yin).

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simulating the system's performance in MATLAB/Simulink. In their simulation, a proportional-integral (PI) controller provided the transmission with an input for the rate-of-change of the speed ratio, and available outputs included the FAST-measured torque loads, electric power, and line currents created by the transient induction generator model. In Ref. [6], a variable-ratio gearbox (VRG) based upon the automotive industry was integrated into the fixed-speed wind turbine to facilitate operation with a discrete set of variable speeds that boost efficiency. In that paper, a model-based design methodology was used to study the performance gain of integrating a VRG into a fixed-speed stall-regulated wind turbine system. Its results demonstrated how the VRG could improve the efficiency of the fixed-speed turbine in the partial-load region and the potential to use the VRG to limit power in the full-load region. In Ref. [7], the gain in efficiency for a VRG-enabled 100 KW wind turbine was quantified based on wind data from representing all seven wind classifications. A method was also presented to identify turbine sites that provided the VRG with the greatest opportunities to increase production. The overall findings suggested that the VRG could benefit all wind turbines, irrespective of wind class, with some wind profiles in the study experiencing gains greater than 10%. Even though the mechanical continuously variable transmission has advantages of higher improvement on efficiency, comparatively lower cost and higher torque load mitigation, the lower reliability, higher maintenance and limited amount of power that can be transferred in this transmission have impeded its production and implementation. Furthermore, the application of automobile automated transmission such as VRG in wind turbine is highly questionable, because such transmission generally has complex gearshift mechanisms, too many planetary sets and transferred power limitation which may cause high maintenance cost, limited durability and cannot be utilized in megawatt-scale wind turbine.

Chap-Drive [8] developed and tested an integrated hydraulic drive train for wind turbines. The integrated hydraulic drive train consisted of a low speed hydraulic pump, a high speed hydraulic motor with variable displacement volume and a high voltage, synchronous generator. The variable displacement volume of the motor was used to control the rotational speed of the pump and rotor when the generator was connected to the grid. The motor was operated at a constant speed, and any changes in the displacement volume would cause a proportional change in the flow rate of the hydraulic oil from the pump, thus the motor displacement control would control the rotor speed. In Ref. [9], a techno-economic feasibility study for a proposed 1.5 MW wind turbine utilizing a continuously variable ratio hydrostatic transmission (HST) was presented. The estimated cost of energy was compared to that of a conventional wind turbine of equivalent rated power. The annual energy production was estimated for the hydrostatic turbine using an assumed wind speed distribution and a turbine power curve resulting from a steady state performance model of the turbine. In Ref. [10], a complete mathematical model of a hydraulic transmission concept for use in wind turbines was presented. The hydraulic system transferred the power from the nacelle to ground level. The main focus had been to develop a model that takes into account the dynamics affecting the wind turbine and the hydraulic transmission system involved. J. H. Shao et al. [11] designed a fluid driven variable speed transmission system for wind turbine by using the torque converter with adjustable guide blades. This hydrodynamic transmission system could be operated at maximum power point by controlling the torque directly in the drive train. However, the hydrodynamic transmission is characterized by constant power transmission and limited power rating, and hence cannot be used in wind turbine since the transmitted wind power is proportional to the cube of wind speed, which can cause the output power to fluctuate above its rated value. Wang, F. et al. [12] proposed a hydro-mechanical transmission (HMT), combining the high efficiency of gearbox and variable ratio function of hydrostatic transmission (HST) to increase the energy capture for mid-sized turbines. A dynamic simulation model of the HMT wind turbine was built and simulation results showed that an HMT turbine had higher drive train efficiency and generator output power than an HST turbine and a fixed speed turbine. Although the HST and HMT hold the advantages of comparatively lower cost and higher torque load mitigation capability compared with the mechanical transmission, they still suffer from the problems of higher energy losses and limited wind generation which are important issues with large-scale wind turbines.

An alternative to the aforementioned transmission types would be to use the hydro-viscous transmission. This transmission transmits captured power using fluid shear force between multiple sets of rotating parallel plate pairs and continuously regulates the transmission angular velocity by precisely controlling the clearance between such parallel plates [13,14]. Hence, the direct torque and continuously variable speed control of the wind turbine can be achieved. As a mature and reliable technology, the hydro-viscous transmission is particularly suitable for high power and heavy duty machines such as metallurgy, electric power, and megawatt-scale power device [15]. Therefore, this transmission is attractive and promising for large and medium-sized wind turbines, which is lacking in the aforementioned transmission types. Furthermore, this transmission can also achieve the synchronous drive and drive interruption, which allows the possibility of extracting the maximum wind power and active stall to stop the wind turbine for emergency braking.

In this paper, a proposal of hydro-viscous transmission based continuously variable speed wind turbine is presented. Characteristics of the transmitted torque and transmission efficiency of this type wind turbine are analyzed. This transmission is optimally designed by using a multi-objective optimization method to enhance its performances and improve the transmission efficiency. Furthermore, this type of wind turbine has been mathematically modeled and a hybrid output power control strategy is proposed to smooth power and torque fluctuations. Simulation results have validated the capability and effectiveness of the proposed control strategy for power regulation and torque mitigation.

The remainder of this paper is organized as follows. In Section 2, a brief description of the hydro-viscous transmission based wind power system is presented. Characteristics of the transmitted torque and transmission efficiency are then analyzed. A multi-objective optimization method is employed to design this transmission system. In Section 3, major components of this type of wind turbine including the aerodynamic system, the drive-train, the generator, and the electrohydraulic servomechanism have been mathematically modeled. In Section 4, a hybrid output power control strategy is proposed and implemented to smooth power and torque fluctuations for this system. In Section 5, the capability and effectiveness of the proposed control strategy for power regulation and torque mitigation are evaluated by using Matlab/simulink package and the FAST aero-elastic simulator. The final section makes conclusion upon this study and provides an outline of future work.

2. Hydro-viscous transmission for wind turbine

As described in Fig. 1, this wind power system includes the wind rotor, a hydro-viscous transmission based automatic gearbox (HTAG), magnet synchronous generator (PMSG), pulse-width modulation (PWM) controlled converter or inverter and control system. This system converts kinetic energy of the wind to mechanical energy by means of wind rotor and automatic gearbox, and then the generator converts the mechanical power to electrical power that is being fed to the grid through power electronic converters. Generator side converter is connected to the grid side

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