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Hydro-viscous transmission based maximum power extraction control for continuously variable speed wind turbine with enhanced efficiency

Xiu-xing Yin, Yong-gang Lin*, Wei Li, Hai-gang Gu

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

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A B S T R A C T

The hydro-viscous transmission is potentially attractive for large scale wind turbines and is capable of significantly improving the turbine controllability and reliability due to the direct drive-train speed control. The hydro-viscous transmission based maximum power extraction control is presented in this paper. The system design, basic dynamic characteristics, thermal losses and management are presented and thoroughly analysed. The system model and the maximum power extraction control loop are also presented and designed. By using the designed control loop and controlling the hydro-viscous transmission, the turbine rotating speed can be continuously adapted to the incoming wind speed to maintain the optimum power points. Simulation results of a 2.0 MW wind turbine demonstrate that the hydro-viscous transmission based wind turbine has increased power capture due to the continuously variable speed feature as compared to a variable speed wind turbine with merely converter control. The hydro-viscous transmission works well enough and has an enhanced overall efficiency than the conventional system with fixed gear ratio.

1. Introduction

Variable-speed wind turbines generally achieve a higher energy yield than their fixed-speed counterparts in the partial load region [1]. The variable-speed operation and generator power regulation for these turbines can be typically fulfilled by means of the generator-side frequency converters. However, it is not really possible to achieve satisfactory power regulation through the converters since only indirect turbine speed control can be achieved by using the converters [2]. Therefore, the turbine rotating speed and the aerodynamically captured power cannot be regulated within a relatively wide range. Furthermore, the limited overload capability and voltage support capability of the converters will inevitably undermine the overall stability of the turbine system during grid faults.

As an alternative, continuously variable-speed wind turbines with an infinitely variable transmission between the turbine rotor and the electric generator would be desirable for the further improvement of overall power conversion efficiency over a wide range of operating conditions [2]. In addition, the surge-like dynamic torque and speed variations of the turbine rotor can also be isolated by the continuously variable-speed transmissions, which are mainly based on the use of continuously variable-speed mechanical or hydraulic transmissions. The mechanical transmission may be occasionally used in small wind turbines even though their frictional losses are relatively high [3]. However, they are not suitable for large scale wind turbines due to the limited power capability. Additionally, the so-called variable-speed power-splitting transmission with electric servo-motors is relatively complex and always requires a lot of servicing [4]. The hydrostatic transmission can also be employed to split the transferred wind power into a mechanical flow and a hydrostatic flow. The continuously variable-speed operations can be achieved by regulating the volumetric displacement of the hydraulic devices [5]. However, the experiences gained from test operations indicated that this transmission was neither convincing in efficiency nor in reliability, let alone in production cost [6]. Further, the hydraulic devices with high power/volume ratio have hitherto not been economically viable in large scale wind turbines due to the relatively low transmission efficiency and high cost [7,8].

Unlike the aforementioned transmission types, the continuously

* Corresponding author.
E-mail address: Calminder@126.com (Y.-g. Lin).

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Nomenclature

A_p the area of the hydraulic piston
c the specific heat coefficient
c_0, c_1, c_2 and c_3 the constant coefficients
d the thickness of each rotating disc
dT_h the torque transmitted by the infinitesimal circumferential area
dr the local radius increment of the rotating disc
h the oil film thickness
h_i ($i = 1, 2, \ldots, N$) the oil film thickness of the ith rotating disc
i_h the transmission ratio of the hydro-viscous element
J_t the turbine inertia
k_1, k_w, k_a and k_b the constant coefficients that are directly related to the construction of the hydro-viscous element
k_c the valve flow-pressure coefficient
k_{h1} and k_{h2} the constant torque coefficients of the hydro-viscous element
k_q the valve flow gain
k_t the constant torque-speed gain
k_v the constant control gain of the servo valve
L the position of the Nth oil film
m_d the mass of each rotating disc
m_p the mass of the hydraulic piston
N the number of the rotating discs
P_h the power losses or the thermal energy
Q the flow rate of the lubricant oil
q_L the hydraulic oil flow through the servo valve
r the local radius the rotating disc
r_1 the internal radius of the rotating discs
r_2 the external radius of the rotating disc
T_h the total transmitted torque of the hydro-viscous element
x_i ($i = 1, 2, \ldots, N$) the initial positions of the ith rotating disc
Δh_i ($i = 1, 2, \ldots, N$) the variations of the ith oil film thickness
ΔP_L the chamber pressure variations of the hydraulic actuator
ΔP_g the generator power variation during a sampling interval
ΔT the temperature increment of the lubricant oil
ΔT_h the variations of the transmitted torque
Δu the control command increment
Δx_i ($i = 1, 2, \ldots, N$) the displacement of the ith rotating disc with respect to the operating points
Δx_v the valve displacement with respect to the operating points
$\Delta \omega_r$ the variations of the turbine rotating speed
$\Delta \omega_{ropt}$ the optimum turbine rotating speed variation during a sampling interval
μ the dynamic viscosity
ρ the density of the lubricant oil
τ the shear stress of the rotating disc
ω_h the output speed of the hydro-viscous element
ω_r the turbine rotating speed

hydro-viscous transmission can also be highly integrated into the wind turbine drive train to re-construct an automatic gearbox and hence to boost the overall transmission efficiency [2]. This transmission can directly link the turbine rotor to the electric generator through a controllable hydro-viscous element that is utilized to achieve continuously variable-speed operations by regulating the oil film thickness of the element (Fig. 1). The hydro-viscous transmission can also be used to simplify the conventional fixed-ratio gearbox and reduce exogenous loads, thereby enhancing the overall stability and reliability of the wind power system.

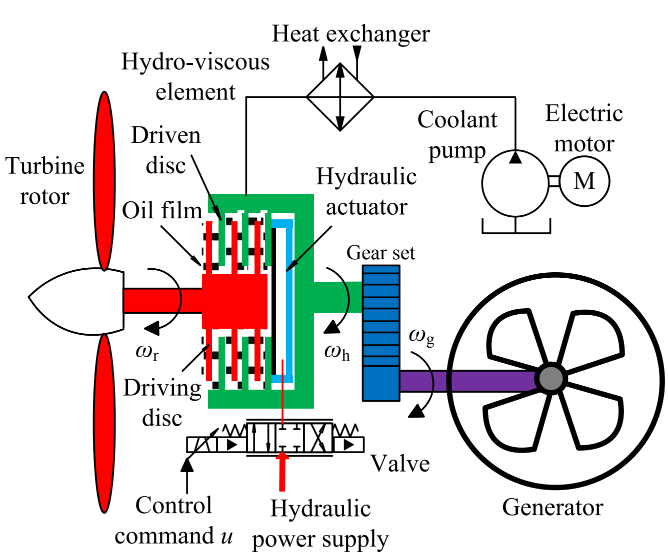

Fig. 1. Schematic of the hydro-viscous transmission based wind turbine.

In this paper, the hydro-viscous transmission based maximum power extraction control is presented to maximize the energy capture for the variable-speed wind turbines. The system design, dynamic characteristics, thermal losses and management are presented in detail. The hydro-viscous transmission system is also modelled from the control perspective to thoroughly illustrate how the output power and torque can be continuously regulated by using the maximum power extraction control loop. Simulations are conducted to evaluate the proposed turbine system in the control accuracy and the maximum power extraction. Realistic test results are also obtained to validate the feasibility and efficacy of the hydro-viscous transmission in improving the overall power conversion efficiency.

2. System design and characteristics

2.1. System description

As shown in Fig. 1, the hydro-viscous transmission-based wind turbine system mainly consists of the turbine rotor, the hydro-viscous element, gear set and an electric generator. The turbine rotor converts the harvested wind power into mechanical energy that can then be transferred into electric energy through the hydro-viscous element, gear set and the generator. The power transmission ratio and efficiency can be continuously regulated by controlling the hydro-viscous element to achieve the maximum aerodynamic efficiency over a wide range of wind speeds.

This hydro-viscous element is typically comprised of a set of driving and driven discs that are arranged in parallel to transmit the captured mechanical power in series from the turbine rotor to the generator. The turbine torque and power transmission can be achieved through the fluid shear forces from the hydraulic oil film between the discs in the hydro-viscous element [9]. The oil film