Energy Conversion and Management 52 (2011) 1244–1251

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Hybrid intelligent control of PMSG wind generation system using pitch angle control with RBFN

Whei-Min Lin [a], Chih-Ming Hong [a,*], Ting-Chia Ou [b], Tai-Ming Chiu [b]

[a] Department of Electrical Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan, ROC
[b] Institute of Nuclear Energy Research, Atomic Energy Council, Taoyuan 325, Taiwan, ROC

ARTICLE INFO

Article history:
Received 29 November 2009
Received in revised form 1 September 2010
Accepted 19 September 2010
Available online 13 October 2010

Keywords:
Fuzzy sliding mode control
Radial basis function network (RBFN)
Wind turbine generator (WTG)
Permanent magnet synchronous generator (PMSG)

ABSTRACT

This paper presents the design of a fuzzy sliding mode loss-minimization control for the speed of a permanent magnet synchronous generator (PMSG) and a high-performance on-line training radial basis function network (RBFN) for the turbine pitch angle control. The back-propagation learning algorithm is used to regulate the RBFN controller. The PMSG speed uses maximum power point tracking below the rated speed, which corresponds to low and high wind speed, and the maximum energy can be captured from the wind. A sliding mode controller with an integral-operation switching surface is designed, in which a fuzzy inference mechanism is utilized to estimate the upper bound of uncertainties. Furthermore, the fuzzy inference mechanism with center adaptation is investigated to estimate the optimal bound of uncertainties.

1. Introduction

Recently, wind generation systems are attracting great attentions as clean and safe renewable power sources. Wind generation can be operated by constant speed and variable-speed operations using power electronic converters. The variable-speed generation system is more attractive than the fixed-speed system because of the improvement in wind energy production and the reduction of the flicker problem. And the wind turbine can be operated at the maximum power operating point for various wind speeds by adjusting the shaft speed optimally to achieve maximum efficiency at all wind velocities [1,2]. All these characteristics are advantages of the variable-speed wind energy conversion systems (WECS). In order to achieve the maximum power control, some control schemes have been studied.

Many generators of research interests and for practical use in wind generation are induction machines with wound-rotor or cage-type rotor [3,4]. Recently, the interest in PM synchronous generators is increasing. The desirable features of the PMSG are its compact structure, high air–gap flux density, high power density, high torque-to-inertia ratio, and high torque capability. Moreover, compared with an induction generator, a PMSG has the advantage of a higher efficiency, due to the absence of rotor losses and lower no-load current below the rated speed; and its decoupling control performance is much less sensitive to the parameter variations of the generator [5]. Therefore, a high-performance variable-speed generation including high efficiency and high controllability is expected by using an PMSG for a wind generation system [6].

Hui et al. proposed a small wind generation system with neural network principles applied for wind speed estimation and PI control for maximum wind power extraction [7]. The mechanical power of the wind turbine can be well tracked for both dynamic and steady state, but the power deviation and speed tracking errors are large with transient response for almost 20 s [7]. Boukhezzar and Signerdidjane developed a cascaded nonlinear controller for a variable-speed wind turbine equipped with a DFIG [8], but the rotor speed errors are large with efficiency around 70%. Wang and Chang proposed an advanced hill-climb searching method taking into account the wind-turbine inertia. However, it required an additional intelligent memory method with an on-line training process [9], and maximum error of power coefficient is about 23%. Shigeo et al. proposed an output maximization control without mechanical sensors such as the wind speed sensor and position sensor [10], but the ac power output efficiency is only around 80%. Wai et al. proposed a novel MPEA including a MPED mechanism and a MPDS control for a wind generation system with a PMSG, but the power coefficient deviation is too large [11]. Tan and Islam presented three sensorless control methods: the wind prediction, fixed voltage scheme for inverter, and current-controlled inverter [12]. However, the fixed voltage scheme does not vary with the load to match the maximum power line of the wind turbine

* Corresponding author. Tel.: +886 7 5252000x4115; fax: +886 7 5254199.
E-mail address: d943010014@student.nsysu.edu.tw (C.-M. Hong).

0196-8904/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2010.09.020

generator, and results in low conversion efficiency when the wind speed is above or below the given range attained by Weibull distribution for the wind speed [12]. Muljadi and Butterfield developed two methods to adjust the aerodynamic power: pitch and generator load control, both of which are employed to regulate the operation of the wind turbine [13], but power coefficient deviation is too large.

In this study, a sliding mode controller combined with fuzzy inference mechanism and adaptive algorithm is proposed for PMSG speed control [14]. In the sliding mode controller, a switching surface with an integral operation is designed. When the sliding mode occurs, the system dynamic behaves as a robust state feedback control system. In a general sliding mode control, the upper bound of uncertainties, including parameter variations and external mechanical disturbance, must be available [15,16]. However, the bound of the uncertainties is difficult to obtain in advance for practical applications. A fuzzy sliding mode position controller is investigated to resolve the above difficulty, in which a simple fuzzy inference mechanism is utilized to estimate the upper bound of uncertainties. Furthermore, to reduce the control effort of the sliding mode controller, the fuzzy inference mechanism is improved by adapting the center of the membership functions to estimate the optimal bound of uncertainties [17]. The operating principle and control objects for variable speed, pitch-regulated wind turbine were also introduced. Pitch controller was designed based on RBFN algorithm to cope with the nonlinear system. Experimental results are provided to show the effectiveness of the proposed overall PMSG control system.

2. Analysis of wind generator system

2.1. Composition of wind generation system

The wind power generation system studied in this paper is shown in Fig. 1. The wind turbine is coupled to the shaft of an PMSG through a gear box, where the converter loss of the speedup gear is ignored in this study. The PMSG is connected with the power converter and inverter circuit. Wind power (P_w) is converted into mechanical (P_m), there after into ac electrical power (P_e), then to dc output power (P_{dc}), and the power is directly fed to the power system.

2.2. Wind turbine characteristics

In order to capture the maximal wind energy, it is necessary to install the power electronic devices between the wind turbine generator (WTG) and the grid where the frequency is constant. The input of a wind turbine is the wind and the output is the mechanical power turning the generator rotor [7,8]. For a variable-speed wind turbine, the output mechanical power available from a wind turbine could be expressed as

$$P_m = \frac{1}{2}\rho A C_p(\lambda,\beta)V_\omega^3 \tag{1}$$

where ρ and A are air density and the area swept by blades, respectively. V_ω is the wind velocity (m/s), and C_p is called the power coefficient, and is given as a nonlinear function of the tip speed ratio (TSR) λ with

$$\lambda = \frac{\omega_r r}{V_\omega} \tag{2}$$

where r is the wind turbine blade radius, ω_r is the turbine speed. C_p is a function of the TSR λ and the blade pitch angle β, and is general defined with

$$\begin{aligned} C_p &= 0.73\left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{\frac{-18.4}{\lambda_i}} \\ \lambda_i &= \frac{1}{\frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3+1}} \end{aligned} \tag{3}$$

By using (3), the typical C_P versus λ curve is shown in Fig. 2. In a wind turbine, there is an optimum value of tip speed ratio λ_{opt} that leads to maximum power coefficient $C_{p\max}$. When $\beta = 0$, the TSR in (2) can be adjusted to its optimum value with $\lambda_{opt} = 6.9$, and with the power coefficient reaching $C_{p\max} = 0.4412$, the control objective of the maximum power extraction is arrived. From (1) and (2), we get

$$P_{\max} = \frac{1}{2\lambda_{opt}^3}\pi\rho C_{p\max} r^5 \omega_{opt}^3 \tag{4}$$

This equation shows the relationship between the turbine power and turbine speed at maximum power output. When regulating the system under the specification of maximum power, it must be taken into account that turbine power must never be higher than generator rated power. Once generator rated power is reached at rated wind velocity, output power must be limited. For variable-speed wind turbine, a mechanical actuator is usually employed to change the pitch angle of the blades in order to reduce power coefficient and maintain the power at its rated value. For some wind turbines, when working with the maximum power coefficient, rated speed is obtained at a wind velocity lower than that of generator rated power.

2.3. PMSG

The wind generator chosen for this study is a three-phase PMSG, where the mechanical torque (T_m) and electrical torque (T_e) can be expressed as [6]

$$T_m = \frac{P_m}{\omega_r} \tag{5}$$

$$T_e = \frac{P_e}{\omega_e} = \frac{2}{n_p}\frac{P_e}{\omega_r} \tag{6}$$

In general, the mechanical dynamic equation of a PMSG is given by

$$J\frac{d\omega_r}{dt} = T_m - B\omega_r - T_e \tag{7}$$

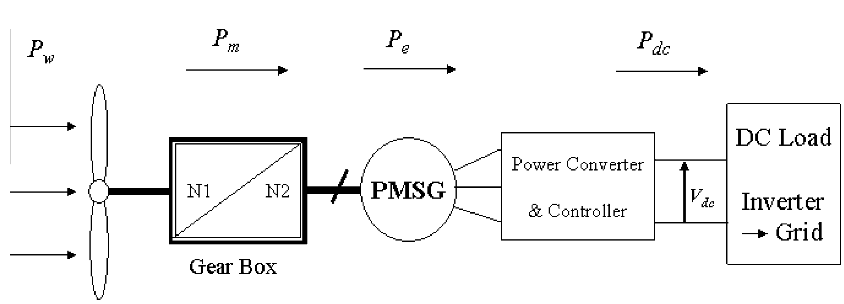

Fig. 1. Wind generation system configuration.