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Novel fuzzy logic based sensorless maximum power point tracking strategy for wind turbine systems driven DFIG (doubly-fed induction generator)

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ABSTRACT

This paper presents a novel FLC MPPT (fuzzy logic sensorless maximum power point tracking) method for WECS (wind energy conversion systems). The proposed method greatly reduces the speed variation range of the wind generator which leads to the downsizing the PWM (pulse width modulation) back-to-back converters by approximately 40% in comparison with conventional techniques. The method also increases the system's reliability by reducing the converter losses. Firstly, a MRAS (model reference adaptive system) based on fuzzy logic technique is used to estimate the DFIG (doubly-fed induction generator) rotor's speed. Then, a FLC MPPT (Fuzzy Logic Maximum Power Point Tracking) method is applied to provide the reference electromagnetic torque. Subsequently, in order to achieve the overall sensorless MPPT technique, the wind power is approximated from estimated generator speed and the reference of electromagnetic torque. Finally, the wind speed is estimated from the mechanical power using a fuzzy logic technique. The proposed control method has been applied to a WTG (wind turbine generator) driving a 3.7 kW DFIG in variable speed mode. In order to validate the simulation results, experimental tests have been performed on a 3.7 kW test bench, consisting of a DFIG and DC motor drive.

1. Introduction

Rising cost of fossil fuels and the need to reduce CO_2 emissions, especially in industrialized countries [1], have led to search for alternative energy sources such as wind energy which is considered as one of the most cost-effective renewable sources [2–6]. Wind turbines generated about 1.5% of global electricity consumption, with an installed capacity of 121 GW by the end of 2008 in more than 70 countries [7].

There are many major issues facing the design of WECS (wind energy conversion system). The first one is the significant wind speed variations at different points over the blades swept area which makes difficult any direct measurement of effective wind speed [8,9]. Furthermore, using mechanical sensors increases the cost of both equipment and maintenance, and reduces the reliability of the wind system [9–11]. To overcome these issues, some studies [8] have proposed to estimate the effective wind speed indirectly by using other signals, such as output power, electric torque, generator rotor's speed which are easy to measure [11], and combined with a dynamic model of wind turbine [12–14]. This approach has some drawback, since the wind turbine model is nonlinear and its parameters are difficult to find. Moreover, the wind speed can be estimated through system identification, state observer, data mining, and fuzzy techniques [8,10]. In Ref. [14], the wind speed estimation method based on the linearized model using a filter and a Newton's search algorithm. Nevertheless, the simulation result has not proved the stability or the convergence of the estimator.

In Ref. [10], Gaussian radial basis functions network dependent on the knowledge of the mechanical power, the turbine speed and the blade pitch angle have been proposed. However, this method which relies on the output power measurement and the power losses estimation, does not take into account the case where the output power is limited if the wind speed is above its rated power by pitch control system. A Neuro-fuzzy method to find wind speed profiles up to the height of 100 m based on the knowledge of wind speed at heights 10, 20, 30, 40 m is reported in Ref. [15], but the use of sensors increases the cost of the system.

This work presents a new strategy to compute the wind speed based on the estimation of the DFIG (doubly fed-induction

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generator) rotor's speed and its electromagnetic torque given by the fuzzy logic technique. The method allows the computation of wind speed even if it is above its rated value as reported by Ref. [10], which is due to limitation of output power at the rated value with pitch control system.

The rotor speed signal can be obtained by a number of methods such as speed sensor or using simple open loop speed estimator. Both of these methods have some drawbacks. The first method has a mechanical coupling problem and it is costly due to the use of a sensor and a connection cable. For the second method, the accuracy of speed estimation depends strongly on the machine parameters [16]. Sensorless speed and position estimation of the DFIG, based on the rotor or air gap flux linkage with integration calculation, have some drawbacks. Indeed, if the generator operates around synchronous speed, its rotor is excited with low frequency voltages, and the integrator cannot give an accurate output value. Then, it causes the failure of flux-linkage based control strategies [17,18]. In this paper, we propose a MRAS (model reference adaptive system) speed estimation observer based on the fuzzy logic controller which can take into account the errors from machine parameters variation [19]. To achieve the sensorless maximization of output power, a MRAS (model reference adaptive system) observer is used to estimate the rotor speed of the DFIG [20–23]. As reported in Ref. [24], many techniques have been developed for sensorless control of induction machines and for PMSG (permanent magnet synchronous generator)applications [24]. In Refs. [25], a MRAS using PI (proportional-integral) controller to estimate the DFIG rotor speed with low transient speed tracking is presented. In Ref. [26], a speed estimator based on adaptive fuzzy logic control technique is proposed. The drawback of this method is that the initial error of the starting period leads to a large percentage of error on the rotor speed value [27]. In Ref. [14] a nonlinear static state feedback with PI controller is proposed for a wind turbine driving a DFIG. However, this approach shows large errors between actual and estimated values. In order to improve the performance of the closed loop MRAS observe, a fuzzy logic controller is proposed in this paper.

In the aim to capture the maximum electrical power, the speed of the WTG (Wind Turbine Generator) must be adjusted to reach the optimal value of the tip speed ratio [28]. In literature survey, a large number of MPPT (Maximum Power Point Tracking) algorithms are presented in order to extract a maximum output power, and it can be classified into four most control approaches [29,30]. The first one, is the TSR (tip speed ratio) control, which regulates the rotor speed, with keeping TSR at its optimum value with the aim to capture the maximum wind power [10,31–36]. This method requires an accurate knowledge of the wind turbine parameters and the measurement of the wind speed to provide the value of the generator's speed to extract a maximum power. In Refs. [31,32] the tip-speed ratio is fixed at its optimal value λ_{opt} to achieve the maximum output power extraction giving thus the maximum power coefficient. This method is faced to some drawbacks, such as the impossibility to adapt the speed of the wind generator in the case of fast variation of the wind speed, due to its inertia. In Ref. [10] another method is presented where λ_{opt} is calculated from the roots of the derivative of the power coefficient relation C_p. This method is mainly limited by time consumption and calculation complexity, especially when the mathematical representation of the C_p is a fourth-order polynomial. Many C_p relations are reported in the literature such as the Eq. (8) (used in the present study) where the roots of its derivatives are difficult to obtain. The second method is the Perturb and Observe (P&O) method which is mainly used in a PV array MPPT algorithm [37], is a simple strategy to implement and low cost [38], does not require prior knowledge of neither wind speed nor generator's parameters [4,39–44]. Nevertheless, this MPPT algorithm has not a good tracking performance, and then, some new methods based on fuzzy techniques, neural networks the optimum gradient method have been proposed which given a good accuracy [38]. A P&O method to extract a maximum power based on fuzzy logic technique is reported in Ref. [45]. In Ref. [46], fuzzy logic controller as used to measure the power and rotational speed and then perturbs the operating speed by an optimal increment/decrement of rotor speed, with regard on power turbine variation in positive or negative direction. The P&O method is suitable for wind turbines with small inertia, but not for medium and large inertia wind turbine systems, since the P&O method adds a delay to the system control [43], and some of them are still complex to implement [38].

The third method named PSF (power signal feedback), is based on the wind turbine maximum power curve (maximum power versus shaft speed) allowing the maximum power tracking by shaft speed control [47]. Wind speed measurement is not required with this method [47–50]. However, experimentally measurement of the power versus turbine speed curves, performed off-line is usually required. The last method called OTC (optimum torque control) consists of the adjusting of the generator torque to the optimum value to different wind speed [30,51–53]. This MPPT strategy needs a look-up table of optimum torque or as a function on speed rotor. Also, with this method, the estimation of the generator can be required [53]. This method is not appropriate in medium or large wind turbine, since its inertia makes its response slow during a sudden and rapid changes in wind speed [30].

In this paper, in order to overcome the drawbacks of the conventional MPPT algorithms, a novel sensorless FLC MPPT (fuzzy logic maximum power point tracking) is presented. The proposed sensorless MPPT strategy has been applied to a wind turbine driving a DFIG operating at variable speed in which stator is directly connected to the distribution grid while the rotor windings are connected via a Pulse Width Modulation (PWM) back-to-back converter (see Fig. 1). The paper is organized as follows. Section 2 presents the dynamics models of both DFIG and wind turbine system. Focus is given only on the RSC (rotor side converter). Section 3 presents the control of the DFIG. Section 4 detailed the proposed sensorless MPPT strategy based on fuzzy logic techniques. The proposed control scheme is investigated according to wind speed variations and simulation results are presented in Section 5. The experimental test of controlling DC motor as the wind turbine emulator is presented in Section 6. Finally, conclusions about the effectiveness and the performance of the proposed sensorless FLC MPPT algorithm are outlined.

2. DFIG wind turbine model

2.1. DFIG model

Application of Concordia and Park's transformations to the three-phase model of the DFIG allows to write the dynamic voltages and fluxes equations in an arbitrary d-q reference frame [54–56]:

$$\begin{cases} v_{ds} = r_s i_{ds} + \dfrac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \\ v_{qs} = r_s i_{qs} + \dfrac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} \\ v_{dr} = r_r i_{dr} + \dfrac{d\lambda_{dr}}{dt} - \omega_r \lambda_{qr} \\ v_{qr} = r_r i_{qr} + \dfrac{d\lambda_{qr}}{dt} + \omega_r \lambda_{dr} \end{cases} \tag{1}$$