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Adaptive fuzzy regulation of the DC-bus capacitor voltage in a wind energy conversion system (WECS)

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ABSTRACT

This paper proposes a new voltage regulator of the DC-bus capacitor of a variable speed wind power generation system based on adaptive fuzzy system. The change in the fuzzy rule base is done using a variable-structure direct adaptive control algorithm to achieve the pre-defined control objectives. This algorithm has two merits. First, it has a good performance in the training phase as it makes use of the initial rule base defined for the fuzzy logic controller. Second, it has a robust estimator since it depends on variable structure technique. The adaptive nature of the new controller significantly reduces the rule base size and improves its performance.

1. Introduction

Wind energy conversion systems (WECS) have enjoyed an increasing interest due both to the technological enhancement of wind turbines and to a significant decrease of the wind power costs. Control systems play a pivotal role in improving the performance of WECS. Typically, a WECS includes three control levels. The upper level is a supervisory controller that takes decisions related to start up, shut down, and braking. The middle level determines the operational set points for speed, power, and current. The lower level involves the feedback loops for speed, power, and current. The control strategy is to capture maximum energy as the long as the wind speed is greater than the start up speed and less than the normal speed of the specific wind turbine in use. Once the wind speed exceeds the normal speed but remains less than the maximum (shut down) speed, power regulation becomes the goal (Pao & Johnson, 2009). Here, we will focus on one of the low level control loops; namely the voltage regulation of the DC-bus capacitor in a WECS.

An important function of the bus voltage controller of voltage-source inverters (VSI) for WECS is to control the balance between ac and dc power. In WECS a ripple may exist in the bus voltage due to unbalance or harmonics present in the grid voltage or current or due to the randomness or the availability of the wind speed. This ripple may interact with the bus voltage controller leading to adverse consequences on the injected current. Hence, it results in negative impacts on the power converters (Meersman, Renders, & Degroote, 2009).

Fuzzy logic provides a convenient method for constructing non-linear controllers via the use of expert knowledge (Drainkov, Hellendoorn, & Reinfrank, 1993). The design of a fuzzy logic controller requires the selection of the size of the rule-base, the shape and parameters of the membership functions, and the rule inference mechanism. Increasing the number of rules to improve the performance corresponds to a substantial increase in memory requirements. That is known in the fuzzy literature as the rule explosion phenomenon (Kosko, 1997). Implementing a fuzzy system with a small rule base concerns many researchers (Guven & Passino, 2001; Trillas & Alsina, 2002; Wang, 1999). It is also noted that the conventional fuzzy logic controller lacks the ability of self tuning. Adaptive fuzzy controllers are attractive candidates that combine the merits of fuzzy control and self tuning (Hussein, Saad, Elshafei, & Bahgat, 2009; Mohagheghi, Venayagamoorthy, & Harely, 2008).

This paper proposes an adaptive fuzzy-logic controller for voltage regulation of the DC-bus capacitor of WECS. The proposed controller is initialized using the rule-base of the standard PI-like fuzzy-logic controller (Bollinger & Duffie, 1989; Elshafei, El-Metwally, & Shaltout, 2005) to ensure the acceptable performance during the learning stage. The rule-base is tuned on-line so that the controller can adapt to different operating conditions. The adaptive feature of the proposed controller (Chui, 1994; Hsu & Costa, 1994; Sastry & Bodson, 1989) results in a satisfactory performance using a significantly small rule-base as compared to standard PI-like fuzzy-logic controller with larger rule-base.

Section 2 describes the wind energy conversion system configuration. Section 3 describes the basis of the PI-like fuzzy logic controller. Section 4 describes the theoretical background of the variable structure adaptive fuzzy logic controller. Section 5 compares the performance of the adaptive fuzzy logic controller, the

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non-adaptive fuzzy logic controllers, and PI controller. The conclusions are given in Section 6.

2. System configuration

DFIGs are very popular in the wind energy conversion systems, since the power electronic equipment only has to handle a fraction (of about 20–30%) of the total system power. This leads to reductions in power losses and converter costs.

In this paper a power system consisting of a wind turbine with a doubly fed induction generator connected to a three-phase grid is considered (MATLAB, User's Guide Version, 2007), as shown in Fig. 1. The stator of the induction generator is directly connected to the grid, while the rotor winding is connected via slip rings to a converter.

The ac/dc/ac converter consists of the rotor-side converter (C_{rotor}) and the grid-side converter (C_{grid}). Both C_{rotor} and C_{grid} converters are voltage-sourced converters using forced commutated power electronic devices to synthesize an ac voltage from a dc voltage source. A capacitor connected on the dc side acts as a dc voltage source and a coupling inductor L is used to connect the grid-side converter to the grid.

The pitch angle command and the voltage command signals V_{r} and V_{gc} for C_{rotor} and C_{grid} converters, respectively, are generated by the control system driving the power of the wind turbine, the DC-bus voltage and the voltage at the grid terminals.

The control system for a *DFIG* is based on a flux-oriented control of the induction machine (Petersson, Harnefors, & Thiringer, 2005; Vas, 1990), in which the *dq* current and voltage values are referred to the reference frame aligned with the air-gap flux.

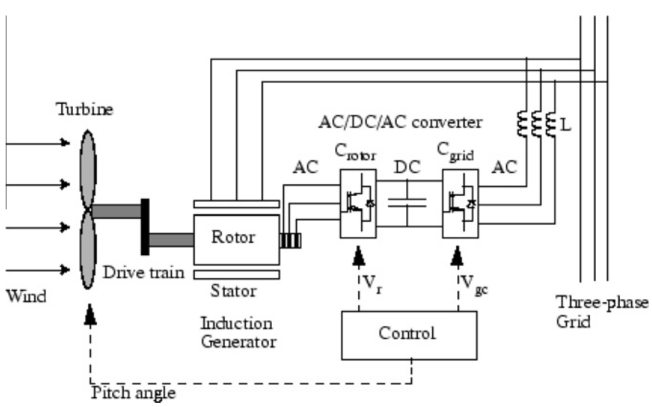

Fig. 1. Wind turbine and the doubly fed induction generator system (MATLAB, User's Guide Version, 2007).

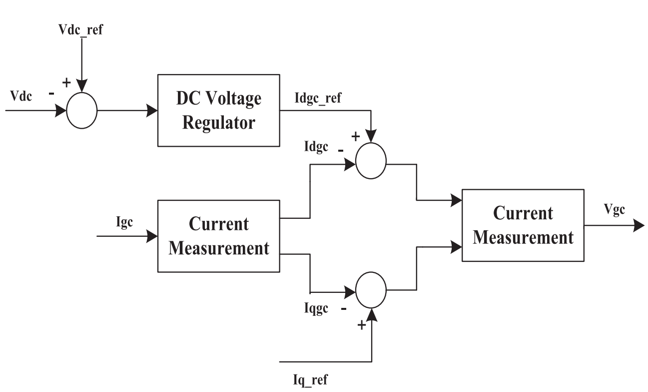

Fig. 2. C_{grid} control loop (MATLAB, User's Guide Version, 2007).

The control system is composed of two parts: in the first part the wind turbine output power and the voltage at the grid terminal are controlled by means of C_{rotor}; in the second part the voltage at DC-bus capacitor is controlled by means of C_{grid}.

The rotor-side converter controls both active and reactive power outputs through voltage components V_{qr} and V_{dr} obtained by separate proportional integral (PI) controllers.

Regarding the grid-side converter (C_{grid}), which is in our interest, the aim of its control is to keep the dc link voltage constant irrespective of the direction of the rotor power flow. The scheme of the control loop is shown in Fig. 2. A detailed description of the control system for both converters and pitch angle command can be found in MATLAB, User's Guide Version (2007).

3. PI-like fuzzy logic controller

The basic configuration of a fuzzy-logic controller is composed of four parts: the fuzzifier, the knowledge base, the inference engine and the defuzzifier; see Fig. 3.

Let the letter N, Z, and P stand for the linguistic values negative, zero, and positive, respectively. Also, let the letter B, M, and S stand for big, medium, and small, respectively.

Each of the input and output fuzzy variable is assigned seven linguistic values varying from, negative big (NB) to positive big (PB). Each linguistic value is associated with a membership function to form a set of seven normalized and symmetrical membership functions for each fuzzy variable as shown in Fig. 4.

The values X_{max} and X_{min} represent maximum and minimum variation of the input and output signals. This values are selected based on the simulation information. Let $X_{max} = -X_{\mathrm{min}}$, the range of each fuzzy variable is normalized between -1 and +1 by introducing a scaling factor ($k = 1/X_{\mathrm{max}}$) to represent the actual signal.

A symmetrical fuzzy rule set is used to describe the PI-like fuzzy controller, see Table 1 (Kosko, 1997). The PI-like fuzzy controller has two inputs (the error, e, and its change, Δe) and one output (the change of the control signal, Δu), see Fig. 5. The output of the fuzzy logic controller is then integrated to generate the control signal, u. Each entity in the table represents a rule of the form "if antecedent then consequent", e.g. the shaded rule in Table 1 is *if e is NB and* Δe *is PB then* Δu *is Z.*

Using the center of gravity defuzzification method the appropriate crisp control is then generated. Let $\theta_1, \ldots, \theta_M$ represent the centroids of Membership functions that are assigned to Δu. Thus, for M rules, the output of the controller is calculated as follow (Kosko, 1997):

$$\Delta u = \frac{\sum_{i=1}^{M}}{\sum_{i=1}^{M}} \frac{\omega_i \theta_i}{\omega_i} = \underline{\theta}^T \zeta, \tag{1}$$

where

$$\underline{\zeta} = [\,\zeta_1 \quad \cdots \quad \zeta_i \quad \cdots \quad \zeta_M\,]^T, \quad \zeta_i = \frac{\omega_i}{\sum_{k=1}^{M} \omega_k}, \quad \text{and}$$

$$\underline{\theta}^T = [\,\theta_1 \quad \cdots \quad \theta_i \quad \cdots \quad \theta_M\,].$$

The strength of the ith rule is ω_i. It is calculated based on the interpreting the 'and' conjunction as a product of the membership values corresponding to the measured values of e and Δe. Consider Table 1 and assume the range of the control signal Δu is normalized, i.e. $\Delta u \in [-1, 1]$. Let also the membership functions NB, NM, NS, Z, PS, PM, and PB will have their centroids at -1, $-\frac{2}{3}$, $-\frac{1}{3}$, 0, $\frac{1}{3}$, $\frac{2}{3}$ and 1, respectively.

The main contribution of this paper is to suggest a computationally efficient algorithm to tune $\theta_1, \ldots, \theta_M$ on-line, see Fig. 6, such that the PI-like voltage regulator of the DC-bus capacitor will have an improved performance and smaller rule base.