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Back-to-back converter state-feedback control of DFIG (doubly-fed induction generator)-based wind turbines

F.E.V. Taveiros*, L.S. Barros, F.B. Costa

Federal University of Rio Grande do Norte (UFRN), Natal, Brazil

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ABSTRACT

Control of DFIG (doubly-fed induction generator) is traditionally based on PI (proportional-integral) controllers and recently many papers have proposed sliding-mode based controllers. However, such controllers may excite unmodeled high-frequency system transients due to chattering, resulting in oscillations or even in unforeseen instability. In order to overcome these drawbacks, this paper proposes a internal model state-feedback control strategy for regulation of rotor direct and quadrature currents for wind driven DFIG, which can keep the smooth control signal of the classical PI controller and, at the same time, provides robustness to external disturbances. The currents are controlled in order to accomplish reactive power support to the grid and MPPT (maximum power point tracking). The proposed state-feedback control strategy as well as the classical PI and the VS-MRAC (variable-structure model reference adaptive control) sliding-mode strategy were discretized and implemented in a digital signal processor in order to interact with a real-time digital simulation of the DFIG-based wind energy conversion system. The proposed control structure achieved the fastest and the most robust dynamic response without stressing the converters or deteriorating the power quality.

1. Introduction

Nowadays, there is an effort to minimize the environmental impact of electricity generation and, therefore, the search for a clean and renewable energy has received much attention throughout the world. The main advantages of renewable energy sources are neutrality with respect to greenhouse gas emissions and the infinite availability of the input energy that is converted into electricity. Among the renewable energy, wind energy presents the highest growth and technological development in installed capacity and penetration in modern power systems [1]. Wind power generation already compete economically with traditional sources of generation in many sites, comparing with coal, fuel or gas-based plants, and in many other, it is likely to be competitive in the short term. Therefore, reliability and efficiency of wind turbines become important topics in research and industry. Accordingly, reliable and powerful control strategies are needed for wind energy conversion systems to achieve maximum performance.

Power control of wind turbines allows the MPPT (maximum power point tracking), which seeks to extract maximum power from the wind energy source [2,3]. The wind turbine harnessing is highly influenced by the rotor speed, therefore, modern wind turbines operate in the variable-speed mode, whose benefits include maximum power extraction and mechanical stress reduction [4]. Appropriate control of back-to-back converter scheme allows DFIG (doubly-fed induction generator)-based wind turbines to operate in the variable-speed mode [5,6]. The control schemes for DFIG are generally based on vector control concept associated with classical PI (proportional-integral) controllers [7]. This control technique has the limitations that its performance largely depends on the tuning of the PI parameters, the accuracy in machine parameters and the connected grid voltage conditions [8–10]. One of the main issues in any realistic control system is its robustness with respect to perturbations and variations of its parameters. Therefore, aiming to reduce parametric dependence and disturbance rejection, papers have presented different control schemes for DFIG such as smart control or adaptive algorithms [8–16]. As advantages, these control strategies do not require the knowledge of the parameters of the system to be controlled, which reduce parametric dependence and remove cross-coupling compensation. These control structures achieve fast and robust dynamic response and are not sensitive to

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* Corresponding author.
E-mail addresses: filipe.taveiros@ect.ufrn.br (F.E.V. Taveiros), lsalesbarros@dee.ufrn.br (L.S. Barros), flaviocosta@ect.ufrn.br (F.B. Costa).

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parametric uncertainties. However, many of these strategies produce high frequency control signal which may increase harmonic distortion, mechanical stresses and high heat losses in power circuits due to chattering.

Considerable amount of work has been done on chattering issues in past and researchers are still working in this domain to get a chattering free controller. One effective technique to alleviate chattering is to introduce a boundary layer around the sliding surface. As a result, a continuous function around the sliding surface neighborhood is obtained as used in Ref. [10]. One algorithm that uses this technique is the VS-MRAC (variable-structure model reference adaptive control) sliding-mode strategy, originally proposed by Ref. [17]. It allows to reduce switching in the control signal, however, the controller performance is still limited by the power converters in medium–high power turbines, where the device switching frequency is normally below 1 kHz [18]. The above difficulties have been motivating the search for a robust control strategy that does not produce control signals of high frequency.

To overcome adaptive control limitations and still suppress disturbances, this paper proposes an internal model state-feedback approach to control the DFIG currents, which can keep the smooth control signal of the classical PI controller and, at the same time, provides robustness to external disturbances automatically, eliminating the need of disturbance compensation. Many studies have stated this technique presents better performance than classical PI, [19–23]. The proposed state-feedback control strategy as well as the classical PI and the VS-MRAC sliding-mode strategy were discretized and implemented in a digital signal processor, in order to interact with a real-time digital simulation of the DFIG-based wind energy conversion system. Real-time simulation can be used to get realistic behavior of the system and it is becoming an essential simulation environment for engineering design, especially in power systems. A wind speed profile measured in a high wind potential site was used to evaluate the control systems under various realistic conditions. The proposed control structure achieved the fastest and the most robust dynamic response without stressing the converters or deteriorating the power quality.

The paper is organized as follows: Section 2 presents an overview of the DFIG-based WECS (wind energy conversion system) and the basics of WECS power control. Section 3 presents the electrical models of the system, the classical control strategy and a sliding-mode control strategy. Section 4 presents the proposed state-feedback control technique. Section 5 presents the result assessment of the proposed control strategy in comparison with the classical control by means of real-time simulations. Section 6 concludes the paper.

2. DFIG-based wind energy conversion system

Nowadays, commercial WECS based on the DFIG are the most used for ratings equal or greater than 1 MW [1]. The topology of WECS under consideration in this paper is depicted in Fig. 1. The stator windings are connected direct to the grid bus, whereas the rotor windings are connected to the RSC (rotor side converter). The GSC (grid side converter) is connected to the grid bus trough a line filter to reduce harmonic content injection. The RSC and GSC are connected to each other by a DC link, forming the back-to-back scheme. The appropriate synthesizing of the RSC and GSC voltages allows control of many machine variables, such as active and reactive power injected into the grid or electromagnetic torque and speed. In this paper, the control is focused on tracking the maximum power point of the active power delivered to the grid and reactive power supply.

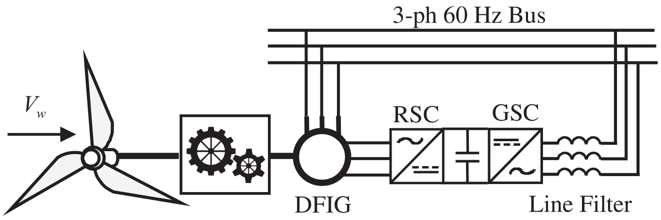

Fig. 1. Block diagram of conventional wind generator with a DFIG.

2.1. Power control

The fraction of power extracted from the wind by a wind turbine is usually referred by the symbol C_p, standing for the coefficient of performance or power coefficient. The actual mechanical power output P_m of a wind turbine is given by Ref. [6]

$$P_m = \frac{1}{2}\rho\pi R^2 V_w^3 C_p(\lambda,\beta), \tag{1}$$

where ρ is the air density, R is the blades length, V_w is the wind speed, β is the blade pitch angle and λ is the TSR (tip speed ratio), which is defined as

$$\lambda = \frac{\omega_T R}{V_w}, \tag{2}$$

where ω_T is the turbine rotational speed.

Theoretically, a maximum of 59.3% of the wind power can be harnessed and converted by a turbine. However, actual turbines have maximum power coefficient around 35–45% [24,25]. As stated in (1), the power coefficient is a parcel of the TSR and the pitch angle, which means that the harnessing of the turbine can be controlled by means of λ and β.

Variable-speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. However, this degree of freedom requires a power control scheme in order to track the maximum power available and to limit the captured power when the wind speed exceeds a certain level. All wind turbines are designed with some sort of power control. For variable-speed wind turbines, there are two types of power control: aerodynamic and generator control. Aerodynamic control aims to limit the power in very high winds in order to avoid damage to the wind turbine. The more commonly used form of aerodynamic power control is to adjust the attack angle of the turbine blades accordingly to the wind speed, often realized by pitch angle control. On the other hand, generator control is realized by adjusting its speed in order to capture the energy from the wind in an optimal way. Any change in the rotor speed induces change in the turbine power capture.

Fig. 2 depicts the ideal maximum power curve of a wind turbine with MPPT [26] in dependence of the wind speed V_w. The wind turbine operation is considered in four-speed bands. In the first band (I), which goes from zero to the minimum speed of generation (cut-in), the wind speed is usually below 3 m/s. Up to this limit, the power generation just supplies the friction losses. Therefore, the turbine is shut down. In band II, the turbine operates with fixed-pitch and variable-speed, which the generator speed is controlled in order to obtain the maximum power available from the wind (MPPT operation).

Ideally, aerodynamic control only starts to operate when the generated power achieves its rated value, which characterizes the beginning of band III. In the third band, i.e., for wind speeds above rated, the turbine speed and power must be limited to its rated