Electric Power Systems Research 81 (2011) 254–262

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A novel control scheme for DFIG-based wind energy systems under unbalanced grid conditions

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ARTICLE INFO

Article history:
Received 16 May 2010
Received in revised form 25 August 2010
Accepted 31 August 2010
Available online 8 October 2010

Keywords:
DFIG
Unbalance grid voltage
Rotor side converter (RSC)
Grid side converter (GSC)
dc-Link voltage
Torque ripple

ABSTRACT

This paper presents an analysis and a novel control scheme for a doubly fed induction generator (DFIG) based wind energy generation under unbalanced grid voltage conditions. The control objectives are: (i) to limit the rotor currents, (ii) to suppress ripples in the torque and (iii) to suppress the dc-link voltage fluctuation through converter controls. Negative sequence compensation techniques by one of the converters, namely, the rotor side converter (RSC) or the grid side converter (GSC) in a DFIG are discussed and their limitations are presented. A coordinated control scheme with a concise structure compared to the conventional dual sequence control structure is proposed in this paper. The RSC is controlled to suppress ripples in the torque and the rotor currents while the GSC is controlled to suppress ripples in the dc-link voltage by considering the rotor power effect. The major contributions of the paper include: (i) the presentation of the limitation of negative sequence compensation using one converter; (ii) development of a concise coordination control scheme which is free of low pass filters and uses a reduced number of reference frame transformation. Matlab/Simulink tests for a 2MW DFIG demonstrate the effectiveness of the control scheme.

1. Introduction

Doubly fed induction generator (DFIG)-based wind generation (Fig. 1) is the state-of-the-art wind generator technology. The stator of a DFIG is connected directly to the grid while the rotor of a DFIG is connected through the rotor side converter (RSC), the dc-link and the grid side converter (GSC) to the grid.

Unbalanced stator conditions in DFIGs give rise to high frequency components in rotor currents and torque pulsations which can cause excessive shaft stress and winding losses [1]. Existing control techniques in literature to minimize the torque pulsations include: (i) rotor-side converter (RSC) compensation by supplying negative sequence voltages to the rotor circuits [2–4] to suppress the negative sequence components in the rotor currents and ripples in the electromagnetic torque, or (ii) grid-side converter (GSC) compensation by compensating negative sequence currents to the grid [5] to keep the stator currents free of negative sequence components and thus eliminate the negative sequence components in the rotor currents.

In the above mentioned references, dc-link voltage ripples are not in the modeling consideration. Large ripple in the dc-link voltage ripple is however another concern under unbalanced grid conditions. To suppress the dc-link voltage ripples and at the same time to suppress the pulsations in the rotor currents and the torque, coordinated control schemes for both the RSC and GSC are proposed in [6–9].

Negative sequence compensation have been adopted in the above mentioned references. Negative sequence compensation can be realized through current control loops [3,5–10], or through direct power control [11,12]. The cascaded control structure with inner fast current control and outer slower power/voltage control is widely used in converter control and is also used in the commercial DFIG technology [13]. Hence, this control structure is also widely adopted in the existing research. In our research, the cascaded control structure will be adopted as well. In cascaded control structure, the coordination scheme is to use the RSC to limit the torque and rotor current fluctuations and to use the GSC to suppress ripples in the dc-link voltage [6–9]. Dual sequence control is adopted applied in dealing with issues that arise due to unbalanced grid conditions. In dual sequence control, positive and negative sequence components are firstly separated and then controlled via proportional integral (PI) controllers. The negative sequence loops are the supplementary control loops specifically dealing with negative sequence components.

The major disadvantages of dual sequence control include its extensive measurements, complicated computation for the reference current values and the usage of low pass filters for sequence component separation. These filters contribute

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doi:10.1016/j.epsr.2010.08.011

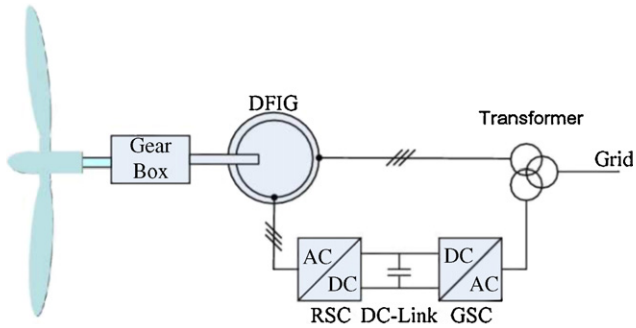

Fig. 1. Schematic diagram of a DFIG-based wind generation system.

excessive time delays and can deteriorate the control performance.

The purpose of this paper is to develop an easy to implement control scheme that can overcome the major shortcomings of the dual sequence control while realizing the same control objectives. In our previous work [14], comparison of negative sequence compensation through either RSC or GSC was made. [14] found that negative sequence compensation through GSC is more effective to suppress the ripples in torque. However, ripples in dc-link voltage are not in consideration. This paper will take into consideration of pulsations in the rotor currents and the torque and the ripples in the dc-link voltage.

The rest of the paper is organized as follows. In Section 2, the limitation of compensation using one converter will be identified. A coordinated control of RSC and GSC will be developed in Section 3. Comparison of the proposed scheme and the dual sequence control scheme is also presented in this section. Matlab/Simulink tests for a 2MW DFIG to demonstrate the effectiveness of the control scheme and compare the proposed scheme with the dual sequence scheme are presented in Section 4. Section 5 concludes the paper.

2. Negative sequence compensation techniques and their limitations

The transients in rotor voltages due to stator voltage dip are analyzed in [15]. Under unbalanced grid voltage, the most severe operation problems are the torque ripple due to the negative sequence components in the stator and rotor currents and the dc-link voltage ripple [9]. The steady state components in the rotor currents and electromagnetic torque are analyzed in [16]. In this section, negative sequence compensation techniques via one converter and their limitations are presented.

2.1. Negative sequence compensation via GSC

Negative sequence compensation via GSC is presented in [5]. The philosophy is to let the GSCs compensate the negative sequence currents required in the network during any unbalanced operation. The circuit model is shown in Fig. 4. The GSCs will supply the negative sequence current components to the grid. Hence the stator currents will remain balanced. This method is documented in [5].

For negative sequence compensation via GSC, the current controllers of the GSC will measure the network currents, extract the negative sequence components and generate the required negative sequence currents for compensation. The reference values of the negative sequence currents come from the measurements of the currents to the grid $i_{e,abc}$. The negative sequence components of $i_{e,abc}$ are then extracted through abc/qd^- transformation and low pass filters.

Since the GSC compensates a negative sequence current to the grid, the three-phase voltage from the GSC should provide the negative sequence component as well. The instantaneous power through the GSC will have pulsating components. The dynamic equation of dc-ink voltage is given by:

$$CV_{dc}\frac{dV_{dc}}{dt} = P_g - P_r \quad (1)$$

where P_g and P_r are the GSC and RSC instantaneous powers. The detailed analysis of the dc-link voltage due to unbalanced grid voltages can be found in [17]. If there is only negative sequence compensation from the GSC, and assume that the rotor power P_r has only dc component, the dc-link voltage will have ripples with two pulsating components at frequencies of $2\omega_e$ and $4\omega_e$ [17]. The more unbalanced the grid voltage, the higher the magnitude of the pulsating power, and hence the higher the magnitude of the dc-link voltage ripple.

2.2. Negative sequence compensation via RSC

Torque pulsation can also be eliminated via negative sequence compensation via the RSC [3,4]. The steady-state negative sequence circuit model with the RSC compensation can be derived using qd^- reference frame and then relating q-axis and d-axis variables to phasors. The main reason for using qd^- reference frame is that for negative sequence components (currents, voltages), they are "seen" as dc variables at steady-state. And it is easy to relate them to phasors [18]. The circuit model is developed in [16] and is shown in Fig. 5.

From the circuit model, it can be seen that injecting a negative sequence voltage from the RSC can eliminate the negative sequence rotor current ($\bar{I}_{ar}^- = 0$) or the negative sequence stator current ($\bar{I}_{as}^- = 0$) or the torque pulsation. The derivation of the rotor current reference values to eliminate the torque pulsation can be found in [3].

Without losing the generality, the RSC needs to inject a negative sequence voltage. Similar as the consequence of negative sequence compensation via GSC, the dc-link voltage will have ripples with pulsating components. Therefore using RSC negative sequence compensation alone leads to dc-link voltage ripples.

2.3. Summary

Analysis in Section 2 presents the limitations of using one converter. Two control objectives, namely torque ripple suppression and dc-link voltage ripple suppression, cannot be achieved simultaneously using either RSC compensation or GSC compensation. Therefore both RSC and GSC controls are used in [6–9]. In Section 3, a concise coordination control structure will be proposed.

3. Proposed coordination technique under unbalanced grid condition

Unbalanced grid conditions cause high frequency pulsations in the torque and the rotor currents and ripples in the dc-link voltages. Torque ripples increase the stress of the mechanical components of DFIGs. Constant dc-link voltages are preferred for voltage source converters. Meanwhile the converters have limited capability and the magnitudes of the high frequency rotor current components should be limited. The control objective is three-fold: (1) to suppress torque ripples, (2) to reduce the ripples in the dc-link voltages, and (3) to reduce the magnitude of the rotor currents.

The analysis in Section 2 has identified the conflicting nature of negative sequence compensation via RSC or GSC alone. Various control techniques based on RSC-GSC coordination have been proposed in literature. In [6,7], the RSC is controlled to eliminate the torque oscillations at double supplying frequency while the GSC is controlled to cancel the stator power pulsation. The overall output