Electric Power Systems Research 81 (2011) 228–236

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Operation and control of a grid-connected DFIG-based wind turbine with series grid-side converter during network unbalance

Yong Liao, Hui Li*, Jun Yao, Kai Zhuang

State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, 400044 Chongqing, China

ARTICLE INFO

Article history:
Received 7 May 2010
Received in revised form 9 August 2010
Accepted 3 September 2010

Keywords:
Doubly-fed induction generator (DFIG)
Unbalance
Series grid-side converter (SGSC)
Wind-power generation
Resonant controller
Wind turbine

ABSTRACT

This paper proposes a control scheme of a grid-connected doubly-fed induction generator (DFIG) wind turbine with series grid-side converter (SGSC) to improve the control and operation performance of DFIG system during network unbalance. The behaviors of DFIG system with SGSC under unbalanced grid voltage conditions are described. The SGSC is controlled to inject voltage in series to balance the stator voltage. Therefore, the adverse effects of voltage unbalance upon the DFIG such as large stator and rotor current unbalances, electromagnetic torque and power pulsations are removed and the conventional vector control strategy for the rotor-side converter (RSC) remains in full force under unbalanced conditions. Meanwhile, three selective control targets for the parallel grid-side converter (PGSC), such as eliminating the oscillations in total active or reactive power, or no negative-sequence current injected to the grid are identified and compared. Besides, the proportional resonant controllers in the stationary reference frame are designed for both the SGSC and PGSC to further improve the dynamic performance of the whole system. Finally, the ratings and losses of the SGSC and the injected transformer are discussed and the effectiveness of the proposed control scheme is verified by the simulation results of a 2 MW DFIG-based wind turbine with SGSC under steady state and small transient grid voltage unbalance.

1. Introduction

Large wind farms are mostly located in remote rural areas where a stiff grid is not available and unbalanced voltage is a common feature [1,2]. Asymmetrical loads, transformer windings, or asymmetrical transmission impedances and grid faults can lead to grid voltage unbalance [3]. The DFIG, as the most popular generator for wind energy application, is very sensitive to unbalanced operation. If the voltage unbalance is not taken into account in the DFIG control system, the stator and rotor currents could be highly unbalanced even with a small unbalanced grid voltage due to the low negative-sequence impedance of the DFIG [4]. The unbalanced currents will create unequal heating on the stator and rotor windings which may degrade the insulation of the windings. The unbalanced currents will also create torque and power pulsations at double the line frequency in the generator. The periodic torque pulsation may cause the acoustic noise and the fatigue on the mechanical components [4,5]. Accordingly, in order to protect the machines, DFIGs may have to be disconnected from the grid beyond a certain amount of unbalance (e.g. 6%) [6]. However, with the increased penetration of wind power into power grids, its impact on the power grids cannot be neglected as before. A large number of trips may compromise the stability of the connected weak grids.

In recent years, many research efforts have been devoted to improve the performance of DFIG system under unbalanced grid voltage conditions [1,5–12]. With most of them [5,7–10] were focused on how to effectively control the negative-sequence current of the rotor-side converter (RSC) and/or grid-side converter (GSC) to eliminate or suppress the torque and/or power pulsations, and dual current proportional integral (PI) controllers were usually employed in these control strategies to provide the required system responses. However, due to the considerable time delay and certain errors in the amplitude and phase introduced by decomposing the positive- and negative-sequence feedback components, the transient performance and stability of the DFIG system will be degraded naturally. In [1,11,12], enhanced control and operation by using a proportional resonant (PR) controller [1,11] or a proportional integral and resonant (PIR) controller [12] were implemented without involving sequential decomposition to improve the transient performance of the whole system. But the main disadvantage of these methods mentioned above is that the stator and rotor current unbalances still exist during network unbalance. Therefore, unequal heating on the stator and rotor windings is inevitable and the lifetimes of the windings insulation materials will be decreased

* Corresponding author at: State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Room 209, Building 6, Chongqing University, Shapingba District, Chongqing 400044, China.
E-mail address: lihui4219@sina.com.cn (H. Li).

0378-7796/$ – see front matter
doi:10.1016/j.epsr.2010.09.002

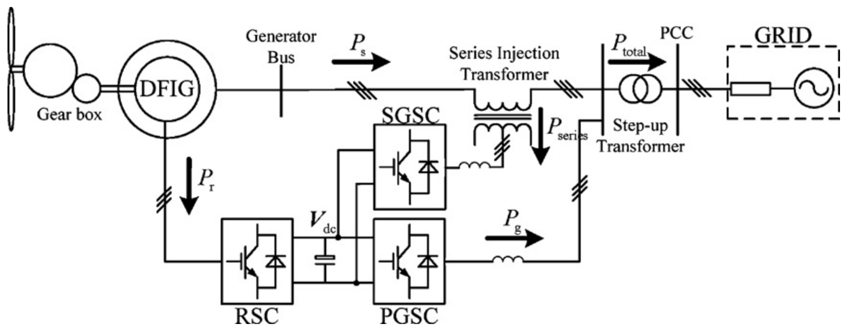

Fig. 1. Configuration of DFIG system with SGSC.

greatly, as wind farms connected to distribution networks periodically experience higher voltage unbalance of greater than 2% [13].

Considering that voltage unbalance will cause relatively large stator and rotor current unbalances, electromagnetic torque and power pulsations in the DFIG, if the negative-sequence voltage at the generator's stator terminal can be eliminated and only balanced positive-sequence voltage is left during network unbalance, the adverse effects of voltage unbalance upon the DFIG will be removed naturally. Recently, a new DFIG configuration with an additional grid-side converter in series with the generator's stator windings has been proposed by Flannery and Venkataramanan [14,15]. With this configuration (as shown in Fig. 1), the DFIG stator terminal voltage can be changed through the output voltage of series grid-side converter (SGSC). This feature provides the possibility for the secure operation of DFIG under unbalanced grid voltage conditions. In [15], excellent potential for various severe voltage dips tolerance has been demonstrated. However, it purely focuses on the control of the SGSC during deep unbalanced voltage dips and considers neither the small grid voltage unbalance nor the coordinated control of RSC, SGSC and parallel grid-side converter (PGSC) in order to provide DFIG system with enhanced performance to meet the overall operational targets, such as eliminating both electromagnetic torque pulsation and total active or reactive power oscillations of the DFIG system, etc.

The objectives of this paper are to extend the application area of the new DFIG configuration with SGSC to the case of small grid voltage unbalance (including both steady state and small transient grid voltage unbalance) and to propose a coordinated control scheme for the SGSC, PGSC and RSC to improve the DFIG system operation performance in such cases. The paper is organized as follows. Section 2 reviews the configuration of the DFIG wind turbine with SGSC. The behaviors of DFIG system with SGSC under unbalanced grid voltage conditions are analyzed in Section 3. In Section 4 the coordinated control of the SGSC, PGSC and RSC is proposed. Control schemes for SGSC and PGSC using PR controllers in the stationary reference frame are designed in Section 5. In Section 6 simulation results on a 2 MW DFIG system with SGSC are presented. Discussion and conclusions of the work are provided in Sections 7 and 8.

2. DFIG configuration with series grid-side converter

The overall configuration of the DFIG system with SGSC is depicted in Fig. 1. In contrast to the classical configuration of wind turbine based on the DFIG, a series grid-side converter and a three phase injection transformer are added in this configuration. Also, a RL filter is connected between the SGSC and the transformer to limit the voltage ripple at the injection transformer [15]. The SGSC, which shares the common dc-link voltage with the RSC and the PGSC, is connected via a three phase injection transformer in series with the main stator windings of the DFIG system. Neglecting the ohmic drop of the injection transformer, the stator terminal voltage of DFIG becomes the sum of the grid voltage and series injected voltage of SGSC which can be expressed in the stationary reference frame as follows:

$$\boldsymbol{u}_{\mathrm{s}} = \boldsymbol{u}_{\mathrm{series}} + \boldsymbol{u}_{\mathrm{g}} \tag{1}$$

which indicates that the DFIG stator terminal voltage can be changed through the output voltage of the SGSC.

3. Behaviors of DFIG system with SGSC under unbalanced grid voltage conditions

3.1. SGSC operation

Under unbalanced grid voltage supply, the unbalanced grid voltage can be expressed in terms of positive- and negative-sequence components in the stationary reference frame as follows:

$$\boldsymbol{u}_{\mathrm{g}\alpha\beta} = \boldsymbol{u}_{\mathrm{g}\alpha\beta+} + \boldsymbol{u}_{\mathrm{g}\alpha\beta-}. \tag{2}$$

If the negative-sequence grid voltage is eliminated and only balanced positive-sequence voltage is left at the generator's stator terminal with effective control of SGSC, the adverse effects of voltage unbalance upon DFIG such as large stator and rotor current unbalances, electromagnetic torque and power pulsations will be eliminated naturally, viz.:

$$\begin{aligned}
&\boldsymbol{i}_{\mathrm{s}-} = 0, \quad \boldsymbol{i}_{\mathrm{r}-} = 0, \quad T_{\mathrm{e\,sin\,2}} = T_{\mathrm{e\,cos\,2}} = 0,\\
&P_{\mathrm{s\,sin\,2}} = P_{\mathrm{s\,cos\,2}} = 0, \quad Q_{\mathrm{s\,sin\,2}} = Q_{\mathrm{s\,cos\,2}} = 0,\\
&P_{\mathrm{r\,sin\,2}} = P_{\mathrm{r\,cos\,2}} = 0, \quad Q_{\mathrm{r\,sin\,2}} = Q_{\mathrm{r\,cos\,2}} = 0.
\end{aligned} \tag{3}$$

The output voltage of the SGSC for canceling the negative-sequence grid voltage is

$$\boldsymbol{u}_{\mathrm{series}\alpha\beta} = -\boldsymbol{u}_{\mathrm{g}\alpha\beta-}. \tag{4}$$

On the other hand, while canceling the negative-sequence grid voltage, due to the presence of the injection transformer impedance, there is still a slight difference between the positive-sequence grid voltage and DFIG stator voltage. So, in this study, a small voltage vector is injected to eliminate the slight difference in order to make the stator voltage keep in line with the positive-sequence grid voltage.

Thus, the total output voltage of the SGSC under unbalanced grid voltage conditions can be expressed as follows:

$$\boldsymbol{u}_{\mathrm{series}} = \boldsymbol{u}_{\mathrm{com}+} - \boldsymbol{u}_{\mathrm{g}-} \tag{5}$$

where $\boldsymbol{u}_{com+}$ is the positive-sequence voltage error which needs to be compensated.

And the remaining voltage at the generator's stator terminal is

$$\boldsymbol{u}_{\mathrm{s}\alpha\beta} = \boldsymbol{u}_{\mathrm{g}\alpha\beta+}. \tag{6}$$