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Modeling and improvement of direct power control of DFIG under unbalanced grid voltage condition

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ABSTRACT

This paper presents analysis and control of a doubly-fed induction generator (DFIG)-based wind generation system operating under unbalanced grid voltage condition. The DFIG system is modeled in synchronous positive reference frame. System behavior and operation of both the generator and the grid side converter (GSC) under unbalanced condition is illustrated by definition of oscillating power terms in the synchronous reference frame. This analysis makes it possible to control both the active and reactive power generation by means of direct power control (DPC) technique. It is shown that considering the DFIG model in synchronous reference frame simplifies the power terms extraction. Moreover, alternative DFIG control targets such as reducing unbalanced stator current, torque and power pulsations minimization, are considered. In addition, by the proposed method, the oscillation of the stator output power is compensated by the GSC, to ensure constant power output from the overall DFIG generation system. The validation of results has been performed through simulation results on a 2 MW DFIG wind generation system.

1. Introduction

Nowadays wind turbines based on doubly fed induction generators (DFIG) are the most employed structures for wind energy application. These generators provide four-quadrant active and reactive power control achieved via rotor side converter rated at about 30% of generator rating power (Fig. 1). So the converter power loss and price is lower than generators in which the converter is connected in stator circuit.

Most of wind turbines are installed in rural areas, where there are many sources of unbalanced voltage such as heavy unsymmetrical loads, voltage dips and unsymmetrical transformer windings or transmission impedances. If unbalanced voltage in a small grid is not considered by the DFIG control system, it will lead to large torque and stator power oscillating which are harmful to mechanical components of wind turbine and stability of connected power grid [1]. In addition unbalanced stator and rotor currents and DC link voltage pulsation could increase machine losses and temperature and decrease DC link capacitor life time [2].

As a result, the DFIG-based wind turbines with no unbalancing control system might have to be disconnected from the grid during such conditions [3]. This is in conflict with the requirement of wind farms to withstand a maximum value of 2% steady-state unbalanced voltage without tripping [4].

One conventional technique to control the rotor side converter (RSC) and the grid side converter (GSC) is vector control (VC), in which active and reactive powers are controlled using two current control loops. Many studies based on VC have focused on effect of voltage unbalance on DFIG and enhancement of its performance under such condition.

In [5,6] by separate control of positive and negative rotor currents, with an additional negative sequence current control loop, various strategies are applied to control the DFIG under unbalanced condition. Some authors use PI-R controller to control positive and negative sequence currents without any necessity of the positive and negative component decomposition which lead to less computation [8–9]. In [11,11] the resonance controllers tuned at the fundamental and double grid frequency and put in the direct power control loops. The GSC dynamic is considered in [7–10] and the oscillation of the stator active power is compensated by the GSC to ensure constant total output active power. Some authors applied additional resonance controllers to eliminate distortion effects besides unbalanced grid voltage problems [13–14]. A vector proportional–integral controller is proposed in [16] and employed in the rotor side converter of the DFIG to eliminate torque and stator power oscillations. The unbalanced VC based method may face to some defects such as slow dynamic response and low bandwidth of current control loops [10].

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Nomenclature

V_s, V_r	stator, rotor voltage vector
I_s, I_r	stator, rotor current vector
ψ_s, ψ_r	stator, rotor linkage flux vector
P_s, Q_s	stator active and reactive power
P_g, Q_g	GSC active and reactive power
P_r, P_e	rotor and electromagnetic active power
V_{dc}	DC link voltage
L_s, L_r	stator, rotor self inductance
L_{ls}, L_{lr}	stator, rotor leakage inductance
L_m	mutual inductance
T_{em}	electromagnetic torque
R_s, R_r	stator, rotor resistance
ω_s, ω_r	synchronous and rotor angular frequency

Superscripts

+, −	positive, negative reference frame
*	reference value for controller

Subscripts

+, −	positive, negative sequence component
α, β	stationary $\alpha\beta axis$
d, q	synchronous dq axis
$\sim$	oscillating term of variable
DC	constant term of power

On the other hand, the direct power control (DPC) have been applied for DFIG and proved to have several advantages in compared with the conventional VC strategy, such as fast dynamic response, robustness against system parameter variation and simple implementation [17]. Major improvements have also been made in the DPC in order to tackle the unbalanced operation. A new reference generator for the DPC is proposed in [18,18] in order to eliminate power, torque oscillations, or current unbalances applying a factor that prioritizes the variable to be compensated (torque, current, or power). In [20] both RSC and GSC control strategies are developed based on the appropriate active and reactive power reference generation strategy for the DPC control by extracting power components. But as demonstrated in [18] for a DPC based control DFIG system, under unbalanced condition the stator current will be no longer sinusoidal. The current contains odd harmonics so extracting power components requires to extraction of fundamental component of stator current which leads to complicated calculations.

In this paper a DPC strategy based on power definition in synchronous reference frame is proposed. This is the main contribution of this paper to ease the DPC process and reduce the required calculations that is explained in Section 6. The active and reactive power components of both the stator and the GSC are extracted in synchronous (positive) reference frame and performance of the generator and the GSC is studied under unbalanced grid voltage condition. Several control targets for enhancement of DFIG operation such as stator balanced and sinusoidal current, constant stator power and constant electromagnetic torque is analyzed and the most proper target is proposed. Finally simulation results validate the theoretical study.

2. Direct power control system

As depicted in Fig. 2, the control system of the DFIG can be divided into two different general parts. The first part generates reference powers according to selected unbalanced target (highlighted blocks). This subsystem is enabled in unbalanced condition defined in following sections. It is clear that under normal condition the reference powers will be:

$$P_s^* = P_{s\_required} Q_s^* = Q_{s\_required}$$

$$P_g^* = P_{g\_required} Q_g^* = Q_{g\_required}$$

which "required" subscript shows the constant required power determined by power management or GSC controller system.

The second part is a DPC technique controlling the active and reactive power directly. The DPC strategy for controlling the RSC is depicted in Fig. 3a. The stator active and reactive power references are determined according to wind speed condition and grid demand respectively. Two three-level hysteresis comparators are used to generate the active and reactive power states S_p and S_q. The optimum switching table selects suitable voltage vector for applying to rotor circuit according to stator flux position and stator active and reactive power states. The same DPC strategy with some differences is used to control the GSC in which the active power reference is determined by DC link voltage regulator, and the optimum switching table operates based on grid voltage position and two level hysteresis comparators (Fig. 3b).

3. Power definition under unbalanced condition

Under unbalanced condition each three phase variable can be decomposed into three separate and balanced systems: positive, negative, and zero-sequence. Whereas the machine terminals are usually connected to $\Delta - y$ ungrounded transformers, zero

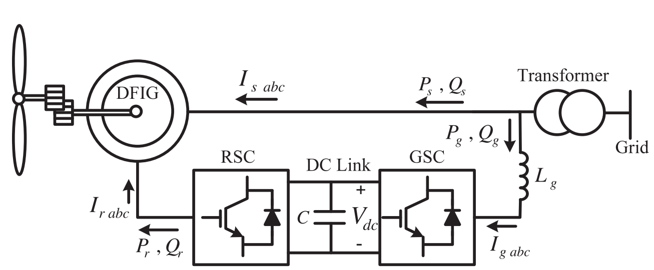

Fig. 1. Schematic diagram of the DFIG-based wind energy generation system.

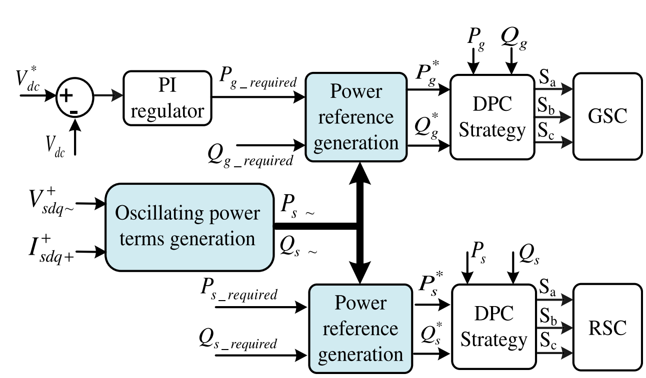

Fig. 2. Unbalanced direct power control diagram.