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Improved control strategies for a DFIG-based wind-power generation system with SGSC under unbalanced and distorted grid voltage conditions ☆

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ABSTRACT

This paper investigates an improved control strategy for a doubly-fed induction generator (DFIG) based wind-power generation system with series grid-side converter (SGSC) under network unbalance and harmonic grid voltage distortion conditions. The integrated mathematical modeling of the DFIG system with SGSC is established by taking both the negative-sequence and harmonic components of the grid voltages into consideration with multiple synchronous rotating reference frames. Under network unbalance and harmonic distortion situations, stator voltage can be kept symmetrical and sinusoidal by the control of SGSC, which indicates that the rotor-side converter (RSC) can be still controlled with the traditional vector control strategy without modifications. Meanwhile, for the parallel grid-side converter (PGSC), three sets of selectable control targets are identified and their corresponding current references are calculated. In addition, the allocation principles for the PGSC's current references are proposed by taking into account the PGSC's current rating limit. The impact of PGSC's current limit on the proposed control strategies have been investigated in detail. Furthermore, a PI regulator with a dual-frequency resonant (PI-DFR) controller in the positive synchronous reference frame for PGSC and SGSC are designed to achieve the rapid and precise regulation of the corresponding components simultaneously. Simulation studies on a DFIG system with SGSC under network unbalance and harmonic distorted voltage situation validate the proposed control strategies and allocation principles for PGSC's current reference.

Introduction

As a renewable and environmental-friendly energy, wind energy has gain global attentions in recent years. Recently, with the increasing proportion of wind power generation in power system, doubly-fed induction generators (DFIGs) have been generally used in numerous wind power generation systems due to its many excellent advantages, i.e., independent power regulating capability, variable speed constant frequency operation and low rating converter [1–6]. However, the DFIG system is more sensitive to grid disturbances and faults, due to the back-to-back converter's power rating limited and the stator windings directly connecting to power grid [7–10]. Thus, how to further enhance the DFIG operational performance under non-ideal grid voltage conditions has attracted more and more attentions nowadays.

Due to the widespread use of power electronic facilities, asymmetrical loads and nonlinear loads in the power system simultaneously, the coexisting phenomenon of unbalanced and harmonically distorted grid voltages is more likely to happen in the transmission line and distributed power grid, as mentioned in [11]. As a result, the unbalanced and distorted currents may exist in the whole system when DFIG operates under network unbalance and harmonic grid voltage distortion situations, which will lead to oscillations in the output powers and the electromagnetic torque of generator, degrading the safe and stable operation performance of the generator. Besides, the oscillations of DFIG output active power might influent the stability of grid frequency, while the oscillations of output reactive power could have an adverse effect on the grid voltage stability, degrading the grid-connected power quality.

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Nomenclature

$\boldsymbol{u}_s$ and $\boldsymbol{u}_g$ stator and grid voltage vectors
$\boldsymbol{u}_{seires}$ series injected voltage vector of SGSC referred to stator-side
$\boldsymbol{i}_s$, $\boldsymbol{i}_r$ stator and rotor current vectors
$\boldsymbol{i}_{series}$ SGSC current vector referred to stator-side
$\boldsymbol{i}_{total}$ total current vector of the DFIG system
P_s and Q_s stator output active and reactive powers
P_r and Q_r rotor output active and reactive powers
P_g and Q_g PGSC output active and reactive powers
P_{series} and Q_{series} active and reactive powers through SGSC
P_{total} and Q_{total} total output active and reactive powers of the DFIG system with SGSC
T_e electromagnetic torque
u_{dc} common dc-link voltage
ω synchronous angular speed
θ_g grid voltage angle
s slip
C common dc-link capacitance

Subscripts
α,β stationary α- and β-axis
av average component
sin and cos sine and cosine oscillating components
abc stationary abc-axis
dq synchronous dq-axis
s and r stator and rotor
g and series PGSC and SGSC
+, −, 5− and 7+ fundamental, negative-sequence, fifth-order and seventh-order components

Superscripts
+, -, 5− and 7+ positive $(dq)^+$, negative $(dq)^-$, harmonic $(dq)^{5-}$ and $(dq)^{7+}$ reference frames
$'*$ and $*$ reference value without and with current limit respectively

Furthermore, if the impact of unbalanced and distorted grid voltage isn't taken into account in its excitation control strategy, the generation system may disconnect from the power grid due to over voltage/current [12–15], which cannot meet the requirements of modern power system for wind power integration.

Some enhanced operation and control strategies have been studied for DFIG system under grid voltage unbalance or distortions. In [16], a PI regulator with a dual-frequency resonant (PI-DFR) compensator for rotor current control were designed to tune at 2ω and 6ω in the positive $(dq)^+$ reference frame, which aims to eliminate pulsations and distorted current in the DFIG system. However, such method couldn't mitigate the power/torque pulsations and balance the stator/rotor currents simultaneously, owing to RSC control variables limitation. In [17], by the coordinated control of parallel grid-side converter (PGSC) and rotor-side converter (RSC), it was achieved that suppressing the oscillation of the total active power and the electromagnetic torque. However, due to the currents of the stator and rotor still asymmetrical and distorted, there are still uneven heating and harmonic current losses in the DFIG's windings. On the other hand, the influence of converter ratings' limitation to the system control under only unbalanced network was researched in [18,5]. But, under both network unbalance and harmonic distortions, detailed research about the influence of converter ratings' limitation to system control of DFIG during has not been reported.

Unbalanced and harmonically distorted stator voltages are the key to cause the asymmetrical and distorted currents of stator and rotor and power/electromagnetic torque pulsations in the DFIG. Thus, the adverse effects of asymmetric and harmonic grid voltage upon the generator can be diminished, by controlling the stator voltage balance and undistorted. In [19–22], a series grid-side converter (SGSC) was applied to improve the DFIG's operation performance during grid faults or grid voltage unbalance or harmonic distortions. However, such control scheme in [22] was only developed under grid voltage distortions but not both grid voltage unbalanced and distorted conditions. In fact, the coexisting phenomenon of the grid voltage unbalanced and harmonically distorted is more likely to happen in a power grid. It is necessary to analysis the dynamic behavior and improved control strategy of the DFIG system with SGSC under the coexisting situations of network unbalance and harmonic voltage distortion.

The main contribution of this paper is to propose an improved control strategy for DFIG systems with SGSC under both the network unbalance and harmonic voltage distortion conditions. First, the detailed mathematical models of the PGSC and SGSC under network unbalance and 5th and 7th harmonic distortions are analyzed in multiple synchronous rotating reference frames. The control goal for the SGSC under network unbalance and harmonic voltage distortions are identified, while three selectable control targets for the PGSC under such condition as well as the calculated reference current values of the PGSC with the three targets are also detailed investigated. In addition, by taking into account the limited PGSC current rating, the allocation principles for PGSC's calculated current references and the modified PGSC's calculated current references are proposed. Furthermore, a PI-DFR compensator for PGSC current control and SGSC voltage control are designed to tune at 2ω and 6ω in the positive synchronous reference frame, and a coordinated control strategy of PGSC, RSC and SGSC are presented. Finally, the simulation results on a 2 MW DFIG system with SGSC are demonstrated to assess the feasibility of the proposed control strategy.

Analysis of DFIG system with SGSC under network unbalance and distorted voltage conditions

As shown in Fig. 1, the DFIG stator voltage is equivalent to the sum of the grid voltage and the SGSC output voltage. Therefore, when the grid voltages are unbalanced and distorted, the stator voltage can be still symmetrical and sinusoidal by flexibly regulating the SGSC series injected voltage, enhancing the operation performance of the DFIG system. The stator voltage can be expressed as

$$\boldsymbol{u}_s = \boldsymbol{u}_{series} + \boldsymbol{u}_g \tag{1}$$

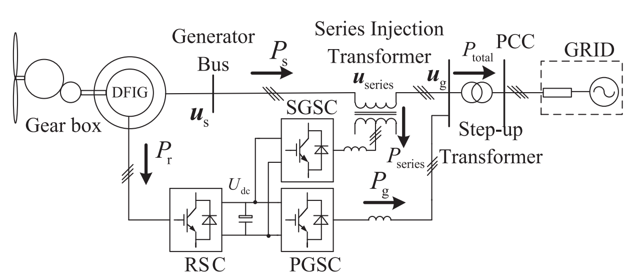

Fig. 1. Configuration of DFIG system with SGSC.