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Current-based direct power control of a DFIG under unbalanced grid voltage

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ABSTRACT

A novel current-based direct power control (CB-DPC) strategy for a grid-connected doubly-fed induction generator (DFIG) is proposed. The reported control scheme is applicable to DFIG-based variable-speed wind turbines that operate under unbalanced network voltages. The required DFIG rotor voltage for precise regulation of the stator active and reactive output powers and accurate elimination of their inherent pulsations are directly obtained using a nonlinear integral sliding-mode control (ISMC) scheme. Compared with other control methods, the proposed strategy is simpler since it is not based on the symmetrical components theory, does not need multiple synchronous coordinate transformations, and only requires DFIG voltage and current values as its inputs. Constant switching frequency of the rotor-side converter (RSC) is achieved by means of space vector pulse-width modulation (SVPWM) technique. Uncertainties in the parameters of the generator are included in the design. A compensation strategy is also proposed for tracking error mitigation of the powers that occur due to elimination of the chattering phenomena in the ISMC scheme. Simulation results on a 2MW DFIG under different operating conditions are presented to validate the effectiveness and robustness of the proposed method.

Introduction

Among the existing renewable energy sources wind energy is the fastest growing sector such that by the end of 2010 it accounted for more than 63% of the total installed renewable energy capacity of the world [1]. In the modern wind turbine topologies those which employ doubly-fed induction generators (DFIGs) are the most popular due to their numerous advantages including independent control of both active and reactive powers, variable speed operation, lower converter size and cost, and higher efficiency. These advantages are achieved through controlling the rotor voltage or current by a converter while the stator is directly connected to the grid [2]. Fig. 1 illustrates a schematic diagram of the most widely used DFIG-based topology that utilizes a back-to-back power electronic converter. In such topologies the stator is directly connected to the grid, hence, network disturbances such as unbalanced grid voltages have strong adverse effects on the behavior of the DFIG [3,4]. Therefore, due to the rapidly growing penetration of DFIG-based wind turbines into the grid, accurate and robust control of the machine under various grid disturbances has been the subject of many researches during the past few years.

In most of the conventional control schemes of DFIGs the grid voltage is assumed to be balanced [5–10]; however, the focus has shifted to unbalanced networks in the past few years and researchers have tried to propose control schemes to address the associated issues to such conditions [11–25]. It is well understood that if the unbalanced grid voltage is not considered in the design process of the DFIG controllers, intense pulsations at twice the grid frequency will occur in the generator torque and output active and reactive powers [11]. This would lead to adverse effects on the stability of the grid. Moreover, the stator output current will become highly unbalanced, leading to unequal heating in the stator windings. Therefore it is necessary to have a well-designed control system to prevent form such hazards. Such control system enables elimination of the pulsations in the output instantaneous torque/active power and reactive power. It is not possible to simultaneously eliminate both the pulsations in the output instantaneous active power and electromagnetic torque using only the rotor-side converter (RSC) [12]. Therefore, control systems only aim for one of these objectives at a time.

In general, DFIG control techniques under unbalanced grid voltage are divided into two categories: Doubly vector control (DVC) [13–18] which is the most popular approach, and direct torque/power control (DTC/DPC) [19–25].

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Nomenclature

f	variable representing voltage, current and flux
$\mathbf{v}_s$, $\mathbf{v}_r$	stator and rotor voltage vector
$\mathbf{i}_s$, $\mathbf{i}_r$	stator and rotor current vector
$\boldsymbol{\lambda}_s$, $\boldsymbol{\lambda}_r$	stator and rotor flux vector
r_s, r_r	stator and rotor resistance
L_{ls}, L_{lr}	stator and rotor leakage inductance
L_{ms}	magnetizing inductance
ω_s, ω_r	stator and rotor angular speed
P, Q	instantaneous active and reactive powers

Subscripts

s, r	stator and rotor
$+$, $-$	positive- and negative-sequence components
d, q	synchronous dq axis
α, β	stationary $\alpha\beta$ axis
ref, $meas$	reference and measured values

In DVC-based approaches symmetrical components theory [26] is mainly employed to decompose machine variables into the positive-sequence and negative-sequence components. In these techniques the three-phase symmetrical components of the machine variables are transformed into positive and negative d–q reference frames, either aligned to the stator flux axis [14,15] or stator voltage axis [16–18]. Depending on the control strategy at least two transformations between different reference frames are needed for each sequence in order to decouple the active power (or electromagnetic torque) and reactive power control loops. The required rotor signals, i.e. voltage or current, are then calculated and generated using the rotor-side converter (RSC) to control the output characteristics of the machine. These methods require precise tuning of the control gains and are highly dependent on the DFIG parameters [8]. The decomposition of the unbalanced three-phase quantities into positive and negative components and multiple transformations of variables between different reference frames could intensely increase the complexity of DVC-based methods and demolish the transient response of these approaches. The symmetrical components extraction procedure itself could also introduce significant time-delay and contain some errors in the amplitude and phase. This will have a negative impact on the overall system's dynamic response and stability, even in presence of balanced three-phase voltages [27,28].

Basic DTC/DPC-based methods that take the voltage unbalance into account select voltage vectors from a predefined lookup table in order to control the output quantities of the generator [9,19]. Compared with DVC-based techniques, these methods are simper, do not need multiple reference frame transformations, have a better dynamic response and are less parameter dependent. However, because of the variable switching frequency, these methods could introduce a wide range of harmonics in the output which are difficult to filter; thus, will cause power quality issues [19]. To solve the variable switching frequency problem of the basic DTC and DPC schemes, some new reference signal generators are proposed in [20–25]. These methods employ a constant switching technique for the RSC to control the DFIG. The design procedure of these new DPC and DTC schemes are complex and usually based on the symmetrical components theory [20–22]; the shortcomings of which were discussed. To eliminate the need for symmetrical components extraction, some novel control schemes were proposed in [23–25]. In [23] two separate SMC controllers are designed for the RSC and grid-side converter (GSC) to account for the unbalanced voltage condition. The RSC is responsible for regulating the generated torque and reactive power by the DFIG while the GSC has the duty of maintaining the DC-link voltage and a steady active power output. A fast dynamic response and good robustness against parameter uncertainty was observed by this method. However, a constant switching frequency could not be achieved. Another SMC-based method was proposed in [25] in the stationary reference frame that did not need the extraction of symmetrical components and used a flux estimator to generate the rotor voltage references. Simultaneous elimination of the pulsations in both the reactive power and electromagnetic torque was achieved in this method. The authors in [24] have proposed a direct power control approach based on SMC that does not need the extraction of the negative-sequence component of the stator current. Three selective control targets were achieved: symmetrical sinusoidal stator currents, elimination of reactive power ripples and elimination of active power oscillations. It was shown that one of these objectives could be achieved at a time.

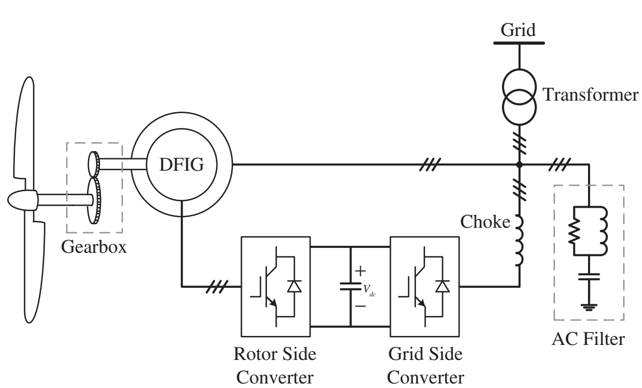

Fig. 1. Schematic diagram of the most widely used DFIG-based wind turbine.

With regard to the above discussion, the main contribution of this paper is to propose a new current-based direct power control (CB-DPC) scheme for unbalanced grid conditions. This method is relatively simple, needs no flux estimator, does not need symmetrical components extraction, and does not require multiple transformations of variables between different reference frames. The control objectives of the proposed method are simultaneous elimination of the pulsations in the active and reactive powers while a fairly symmetrical sinusoidal stator current is achieved. Since the powerful variable structure sliding mode control (SMC) theory is used, the proposed method is robust against parameter uncertainty and provides fast and accurate dynamic responses. An effective solution for minimizing the inaccuracy caused by elimination of the chattering phenomena in the SMC is also proposed. Furthermore, using the space vector pulse-width modulation (SVPWM) technique for the RSC, constant switching frequency is achieved. Simulations on a 2MW DFIG-based wind turbine that operates in an unbalanced network are presented to validate the effectiveness of the proposed approach.

DFIG modeling and analysis under unbalanced grid voltage

DFIG modeling

The equivalent circuit of a DFIG in a three-phase three-wire system expressed in the synchronous rotating reference frame is illustrated in Fig. 2. The mathematical model of a DFIG can be expressed as follows [29]: