Electrical Power and Energy Systems 75 (2016) 8–18

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Analysis and compensation of voltage unbalance of a DFIG using predictive rotor current control

Van-Tung Phan [a,*], Thillainathan Logenthiran [a], Wai Lok Woo [a], Dave Atkinson [b], Volker Pickert [b]

[a] School of Electrical and Electronic Engineering, Newcastle University (Singapore campus), 172A Ang Mo Kio Avenue 8, #05-01, Singapore 567739, Singapore
[b] School of Electrical and Electronic Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, UK

ARTICLE INFO

Article history:
Received 27 July 2014
Received in revised form 30 April 2015
Accepted 28 August 2015
Available online 8 September 2015

Keywords:
Doubly fed induction generator
Predictive current control
Wind turbine
Unbalanced load
Stand-alone DFIG
Voltage unbalance

ABSTRACT

This paper analyzes the unbalance problem of a stand-alone doubly-fed induction generator (DFIG) under unbalanced loads and proposes a compensation method to balance the stator output voltage. The proposed compensation method is developed based on a predictive current control (PCC) method implemented in the rotor current controller. The development of the PCC is based on the discrete model of the DFIG to predict an appropriate average rotor voltage vector to eliminate the rotor current error in the following switching period. The identified rotor voltage vector is then applied to the rotor-side converter (RSC) by using space-vector modulation (SVM) with constant switching frequency. To improve the control performance, a compensation method for time delay based on the prediction of the future rotor current at the end of current sampling period also is investigated. The proposed control scheme was tested by experiments with 2.2 kW DFIG to demonstrate its excellent steady-state performance as well as extremely fast dynamic response.

Introduction

Doubly fed induction generators (DFIGs) have been commonly used in variable-speed wind turbines [1–25] due to its advantages such as converters with slip rating, ease of implementation, and four-quadrant active and reactive power control. The control and operation of the DFIG have been focused on generator modeling [1–3], direct power control [3–10], fault ride-through capability [11–14], unbalanced grid voltage [6–10,15–16], and unbalanced load in case of stand-alone mode [17–25]. In these studies, the majority of current control systems for DFIG systems have been mainly developed based on the traditional vector control scheme using a conventional proportional-integral (PI) controller to regulate the current. However, it has major disadvantages such as steady-state errors, difficult tuning process of control parameters, and sensitivity to system parameters when reference control variables are not dc components. Consequently, this considerably reduces the control bandwidth and seriously causes oscillations on the control system in either the steady state or the transient behavior. Especially, the DFIG-based wind turbines working under unbalanced grid or unbalanced load conditions requires more accurate control due to the effect of the negative sequence component. Under such condition, control quantities are composed of the negative component with twice synchronous frequency that a conventional PI controller cannot regulate precisely. In order to increase the control accuracy, the analysis and operation of grid-connected DFIG systems under unbalanced network [6–10] or unbalanced stand-alone systems [17–25] have been widely investigated based on a dual rotating reference frame, called positive and negative frames. In this control approach, the positive and negative sequence components of the current are controlled in the positive and negative reference frames, respectively. However, these control schemes are too complicated to implement due to decomposition processes and frame transformations, which significantly increase the control time delay. To tackle this problem, an improved control approach for an unbalanced stand-alone DFIG system, implemented in a single positive reference frame with a PI plus a resonant controller (PIR), was introduced in [23,38]. The complexity in calculations of the control algorithm was greatly reduced, but the design of controller parameters was not a straightforward task. Furthermore, the transient performance of the proposed method was not taken into account in that research. As such, it is necessary to offer an optimal controller that gives faster transient response than PI and PIR controllers under unbalanced operating conditions for the DFIG system.

* Corresponding author. Tel.: +65 6908 6068.
E-mail addresses: vantung.phan@ncl.ac.uk (V.-T. Phan), t.logenthiran@ncl.ac.uk (T. Logenthiran), lok.woo@ncl.ac.uk (W.L. Woo), dave.atkinson@ncl.ac.uk (D. Atkinson), volker.pickert@ncl.ac.uk (V. Pickert).

http://dx.doi.org/10.1016/j.ijepes.2015.08.020
0142-0615/

Nomenclature

v_s, v_r	stator and rotor voltages
v_P	voltage at the point of common stator (PCS)
i_s, i_r, i_{ms}	stator current, rotor current and stator magnetizing current
λ_r	rotor flux
L_m	mutual inductance
R_r, L_r, L_s	rotor resistance, rotor inductance and stator inductance
ω_s, ω_r, ω_{sl}	synchronous, rotational rotor, and slip speeds
θ_s, θ_r, θ_{sl}	synchronous, rotational rotor, and slip angles
σ	total leakage factor
d/dt, Δ	differential operators in time domain and discrete time domain, respectively
ε	error values

Superscripts

+, −	synchronous positive and negative reference frames
$\wedge$, *	predicted and reference values

Subscripts

+, −	positive and negative sequence component
s, *r*	stator, rotor
dq	synchronous *dq* axes

Many developments of predictive current control (PCC) approach in the literature have shown very good performance for control of power converters and motor drives, offering the potential for obtaining fast transient response, null steady state errors, high control bandwidth, and accurate control. An overview of basic concepts, operating principles, and control diagrams of model predictive control for the traditional 3-phase voltage-source inverter was presented in [26]. For current controllers, the authors in [27] proposed a PCC method in which the future current values in the stationary reference frame were predicted with all possible switching states and then an optimal one that gave the minimum current error was chosen. The advantage of this PCC was no coupling effects between current responses when one of these reference currents was changed. However, the method to choose an optimal quality function utilizing constraints is difficult and sensitive. In [28], an enhanced predictive current control technique with fixed switching frequency was developed for an asymmetrical dual three-phase ac drive in which fast torque and current responses were achieved. The predictive control scheme helps avoid the use of PI controllers and pulse width modulation (PWM) schemes which are not easy to regulate controller gains in multiphase drives. A discrete-time PCC for a PMSM was proposed in [29], where a delay compensation method was employed by adopting a predictive observer for the current. However, the control algorithm is sensitive to machine parameters. In [30], a robust PCC method combining two-sample deadbeat control with a Luenberger observer was developed to estimate the future value of the grid current. However, the control algorithm requires more computational complexity. One of important characteristics of PCC method is the accuracy of estimated parameters of system models that significantly improve control performances. In [31], an online parameter estimation method with respect to PCC approach for a phase-controlled rectifier was outlined. A robust high bandwidth discrete-time PCC scheme for voltage-source PWM converters was developed in [32], where the time delay compensation method utilized a predictive current observer with an adaptive internal model for system uncertainties and disturbances. In addition, the PCC strategy has been proposed for microgrid applications [33], induction motor drives [34], inverters of uninterruptible power supply applications [35], active power filters [36], etc. However, it has been rare to see the PCC approach in DFIG applications.

The purpose of this paper is to develop an improved predictive rotor current control scheme for a stand-alone DFIG system connected to an unbalanced three-phase load. Under this working condition, the stator output voltage will be unbalanced due to the load effect and can be compensated by generating a proper reference rotor current for the rotor current controller. Due to the requirement for controlling the ac terms of both positive and negative sequence components in the reference rotor current during voltage unbalance, the proposed predictive rotor current control scheme was developed to improve the current control accuracy and to increase the control bandwidth and system stability. The principle of the proposed PCC method is to predict the appropriate average rotor voltage vector in the next sampling period in order to remove the rotor current error in the next sampling period. To enhance the control accuracy and improve control performance, a conceptual analysis of PCC with the control time delay compensation for such a DFIG system is clearly analyzed and effectively implemented. The control time delay compensation method in which the sampling frequency is set as two times of PWM switching frequency is developed to accurately predict the actual instantaneous values of the rotor current, which greatly enhance the control performance. The whole control scheme is based on the positive reference frame where there is no need sequential decomposition of the measured rotor current. The paper is organized as follows. Section 'Unbalance problem in an unbalanced stand-alone DFIG' analyzes the unbalance problems in an unbalanced stand-alone DFIG system. The proposed PCC algorithm under unbalanced operation conditions is discussed in Section 'The proposed PCC algorithm of DFIG control scheme'. Next, Section 'Experimental results' will show experimental results to demonstrate the advanced features of the proposed PCC control scheme. The conclusions are drawn in Section 'Conclusions'.

Unbalance problem in an unbalanced stand-alone DFIG

Analysis of unbalanced stator voltage of DFIG

Fig. 1 shows the general configuration of a stand-alone DFIG supplying an unbalanced three-phase load. The system is composed of a rotor-side converter and a load-side converter (LSC),

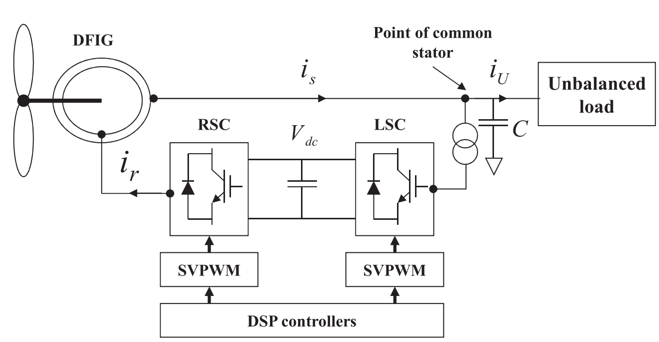

Fig. 1. Back-to-back converters based DFIG configuration with an unbalanced load.