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Model Predictive Direct Power Control of Doubly Fed Induction Generator with Dead-Time Compensation

Van Quang Binh Ngo, Pedro Rodriguez-Ayerb, Sorin Olaru *
and Silviu-Iulian Niculescu **

* Laboratory of Signals and Systems,
CentraleSupélec-CNRS-UPS-Paris Saclay University, Gif-sur-Yvette
91192, France (e-mail: Binhvanquang.Ngo@supelec.fr,
Pedro.Rodriguez@centralesupelec.fr, Sorin.Olaru@centralesupelec.fr)
** Laboratory of Signals and Systems,
CNRS-CentraleSupélec-UPS-Paris Saclay University, Gif-sur-Yvette
91192, France (e-mail: Silviu.Niculescu@l2s.centralesupelec.fr.

Abstract: The paper presents the control of a doubly fed induction generator connected with a three-level neutral point clamped inverter with compensation of dead-time effects. The principle of the proposed control scheme is to use the dynamical model to compute predictions of the future values of the stator flux, rotor current and DC-link capacitor voltages for all possible configurations of voltage vectors. However, the dead-time to avoid the short circuit in the inverter also causes the modeling errors. Thus, by taking into account the dead-time in the model, it is possible compensate the dead-time effect of the switching devices. The active and reactive powers can be estimated based on the stator flux and the rotor current. The cost function considers the error between the active, reactive powers and their references, balance the DC-link capacitor voltage and reduce the switching frequency and common-mode voltage. The optimal switching state that minimizes the cost function is selected and applied to the inverter. The simulation results were carried out with Matlab under different conditions of wind speed and verifying the effectiveness of the proposed method.

Keywords: Power Plants and Power Systems, Control of renewable energy resources, Application of power electronics.

1. INTRODUCTION

Nowadays, the global wind energy capacity has increased rapidly and became one of the fastest developing renewable technologies. For such an application, doubly fed induction generator (DFIG) represents an attractive solution due to its advantages: for instance, it allows the power converter to deal with approximately 30% of the generator power, reduces converter cost and power lost (Fig. 1) (Abad et al. (2011)). By using this configuration, it is possible to allow both bidirectional active and reactive power flow from the rotor side to grid through the rotor side converter (RSC) and grid side converter (GSC). Furthermore, from the technological point of view, the three-level neutral point-clamped (3L-NPC) inverter structure represents a good solution for high power due to its advantages: reduction of the total harmonic distortion (THD) and increasing the capacity of the inverter due to a decreased voltage applied to each component.

Several approaches have been proposed to control DFIG for wind energy generation. Most of the existing control methods use the classical vector control based on the orientation of the flux stator (stator flux oriented) or stator voltage (stator voltage oriented). This method allows controlling independently the electromagnetic torque or active power and reactive power by means the components of the rotor current (Abad et al. (2011)). However, one drawback of this method is that its performance depends on accurate machine parameters such as stator and rotor resistance and mutual inductance. Next, another drawback of using PI controller is the necessity of tuning of the gains in the whole operating range of wind speed.

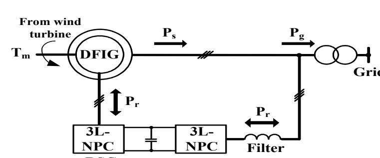

Fig. 1. Schematic diagram of DFIG based wind generation systems (Abad et al. (2011))

Recently, direct torque control (DTC) or direct power control (DPC) (Xu and Cartwright (2006)) have been proposed to improve the controller performance. These methods used the hysteresis control and the inverter switching states, selected from a look-up table (LUT) based on the errors between the reference and estimated values, and rotor or stator flux position. Therefore, these methods do not require the current control loops and space vector modulation. Nevertheless, the drawback of LUT

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is that it has large active and reactive power ripple and switching frequency variation. Moreover, the dead-time effect will distort the output voltage, neutral-point voltage and current. Thus, a dead-time compensation is necessary to be added into the control scheme (Irnura et al. (2012); Sprenger et al. (2013)). In this context, model predictive control is an alternative control technique that has been recently applied to DFIG due to its advantages, such as easy inclusion of non-linearities in the model, delay and dead-time compensation (Sun and Wang (2016)).

The present paper proposes the model predictive direct power control (MPDPC) to control the active and reactive power for DFIG connected to a 3L-NPC inverter while maintaining the balance between the DC link capacitor voltage, reducing the switching frequency and the common-mode voltage. These objectives are accomplished through the cost function in a predictive control strategy. In this paper, we focus on the modelling of errors caused by dead-time induced by the physical switching mechanism. With this approach, the model to predict the inverter ouput voltage and neutral-point voltage takes into account the dead-time take of the conveter to compensate its effects. No current loops are considered and the inverter switches are directly obtained from the cost function minimization. This control allows improving the quality of the power regulation and minimizing the switching losses. In order to reduce the computational effort, a control horizon of two is used for the prediction, where only combination of inputs having a difference of one switch in the inverter is considered.

The remaining paper is organized as follow: Section 2 presents the mathematical model of direct power control with dead-time compensation for a DFIG connected to a 3L-NPC. Next, section 3 details the proposed control method. In section 4, simulation results are represented and analyzed and, finally, section 5 draws the conclusion.

2. MODEL OF DFIG CONNECTED 3L-NPC INVERTER

The doubly fed induction generator (DFIG) can be modelled by the equivalent circuit in dq coordinate (see Abad et al. (2011)) based on stator fluxed orientation. The stator and rotor voltage vectors can be described from Fig. 2 as follows:

$$u_s^{dq} = R_s i_s^{dq} + \frac{d\psi_s^{dq}}{dt} + j\omega_s \psi_s^{dq} \tag{1}$$

$$u_r^{dq} = R_r i_r^{dq} + \frac{d\psi_r^{dq}}{dt} + j\omega_r \psi_r^{dq}. \tag{2}$$

where u_s^{dq}, i_s^{dq}, ψ_s^{dq} are the stator voltage, current and flux vector in dq reference frame while u_r^{dq}, i_r^{dq}, ψ_r^{dq} are the rotor counterparts with respect to the stator. R_s, R_r are the stator resistance and the rotor resistance referred to the stator, ω_s, ω_m are the synchronous speed of stator flux and angular rotor speed (rad/s), $\omega_r = \omega_s - \omega_m = s\omega_s$ is the rotor angular frequency, with the coefficient s denoting the slip.

The relationship between fluxes and currents is:

$$\psi_s^{dq} = L_s i_s^{dq} + L_m i_r^{dq}, \tag{3}$$

$$\psi_r^{dq} = L_r i_r^{dq} + L_m i_s^{dq}, \tag{4}$$

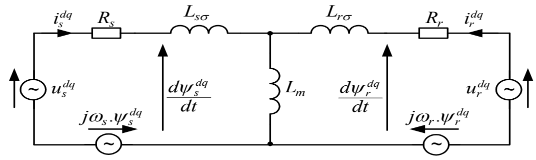

Fig. 2. Equivalent circuit of the DFIG in dq reference frame

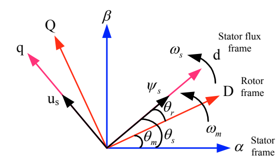

Fig. 3. Vector representation in different reference frame

with L_s and L_r are the stator and rotor inductances and L_m the magnetizing inductance.

By substituting the stator current i_s^{dq} from equation (3) into equation (1), the stator flux dynamics can be expressed as follows:

$$\frac{d\psi_s^{dq}}{dt} = \frac{1}{T_s}\left(-\left(1 + j\omega_s T_s\right)\psi_s^{dq} + L_m i_r^{dq} + T_s u_s^{dq}\right), \tag{5}$$

where $T_s = \frac{L_s}{R_s}$ is the time constant of the stator.

By substituting equation (5) and the rotor flux ψ_r^{dq} from equations (3) and (4) into equation (2), the dynamics of the rotor currents are represented as follows:

$$\frac{di_r^{dq}}{dt} = \frac{1}{\sigma L_r}\left(\psi_s^{dq}\left(\frac{L_m}{L_s T_s} + j\omega_m \frac{L_m}{L_s}\right) + u_r^{dq}\right) - \frac{1}{\sigma L_r}\left(i_r^{dq}\left(R_\sigma + j\omega_r \sigma L_r\right) + \frac{L_m}{L_s} u_s^{dq}\right), \tag{6}$$

where $R_\sigma = R_r + L_m^2/L_s T_s$, $\sigma = 1 - {L_m}^2/L_s L_r$ is the leakage coefficient.

Based on equations (5) and (6), the dynamical model of DFIG can be expressed in matrix form as below:

$$\dot{x} = A(\omega_s, \omega_m)x + Bu, \tag{7}$$

where $x = \begin{bmatrix} \psi_{ds} \\ \psi_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix}$, $u = \begin{bmatrix} u_{ds} \\ u_{qs} \\ u_{dr} \\ u_{qr} \end{bmatrix}$,

$$A(\omega_s, \omega_m) = \begin{bmatrix} -\frac{1}{T_s} & \omega_s & \frac{L_m}{T_s} & 0 \\ -\omega_s & -\frac{1}{T_s} & 0 & \frac{L_m}{T_s} \\ \frac{L_m}{L_s T_s \sigma L_r} & -\frac{\omega_m L_m}{L_s \sigma L_r} & -\frac{R_\sigma}{\sigma L_r} & \omega_r \\ \frac{\omega_m L_m}{\sigma L_s L_r} & \frac{L_m}{L_s T_s \sigma L_r} & -\omega_r & -\frac{R_\sigma}{\sigma L_r} \end{bmatrix}, \tag{8}$$

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\frac{L_m}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} & 0 \\ 0 & -\frac{L_m}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} \end{bmatrix}.$$

Since the stator is connected to the grid, the stator flux is a function of the grid voltage in steady state (with