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Predictive control strategies for wind turbine system based on permanent magnet synchronous generator

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A B S T R A C T

In this paper, Model Predictive Control and Dead-beat predictive control strategies are proposed for the control of a PMSG based wind energy system. The proposed MPC considers the model of the converter-based system to forecast the possible future behavior of the controlled variables. It allows selecting the voltage vector to be applied that leads to a minimum error by minimizing a predefined cost function. The main features of the MPC are low current THD and robustness against parameters variations. The Dead-beat predictive control is based on the system model to compute the optimum voltage vector that ensures zero-steady state error. The optimum voltage vector is then applied through Space Vector Modulation (SVM) technique. The main advantages of the Dead-beat predictive control are low current THD and constant switching frequency. The proposed control techniques are presented and detailed for the control of back-to-back converter in a wind turbine system based on PMSG. Simulation results (under Matlab-Simulink software environment tool) and experimental results (under developed prototyping platform) are presented in order to show the performances of the considered control strategies.

1. Introduction

Nowadays and for the near future, the electricity networks of the world are likely to change as a result of the penetration of distributed generation (DG) based on renewable energy sources into their structure [1]. This is mainly due to the increasing costs of electricity from non-renewable sources. In this trend towards the diversification of the energy market and the satisfaction of the global energy demands, wind energy systems are the most promising and growing renewable energy sources [2]. The commonly used wind energy systems are made with the use of Doubly Fed Induction Generator (DFIG) [3], squirrel cage induction generator [4] and Permanent Magnet Synchronous Generator (PMSG) [5]. For the future, the use of PMSG appears to be the most promising and successful configuration of wind energy systems since it has many advantages such as high power density, high precision, variable speed operation, reduced maintenance, and increased reliability thanks to the absence of gearboxes.

The PMSG wind energy system is connected to the grid trough a bidirectional power flow back-to-back converter, which is composed of two parts connected through a dc-link capacitor as depicted on Fig. 1. The first part is based on the Synchronous Generator Side Converter (SGSC), while the second one is based on the Grid Side Converter (GSC). Several control methods have been proposed in the literature for the control of the back-to-back converter used to connect the PMSG to the grid [6,7]. The commonly used control methods are based linear controllers (Field Oriented Control (FOC) [8] and Voltage Oriented Control (VOC) [9]) and hysteresis controllers (Direct Torque Control (DTC) [10] and Direct Power Control (DPC) [11,12]), Predictive control methods can also be considered as an appropriate solution to control the PMSG energy system and to meet required control performances. The main characteristic of predictive control methods is the use of system model for the prediction of the controlled variables [13]. A well known type of predictive controller is the Model Predictive Control (MPC) [14,15]. It uses the system model to predict the behavior of the controlled variables and a cost function is used as a criterion to select the voltage vector that minimizes the error between the controlled variable and its reference. The main advantages of the MPC algorithm are robustness against parameters variations and low current THD. Another type of predictive controller is the Dead-beat predictive controller [16,17]. It uses the system model to compute the optimum voltage vector, in order to set the controlled variable error to zero within one sampling period. Then, the obtained voltage vector is applied by means of SVM technique. The main features of the Dead-beat predictive algorithm

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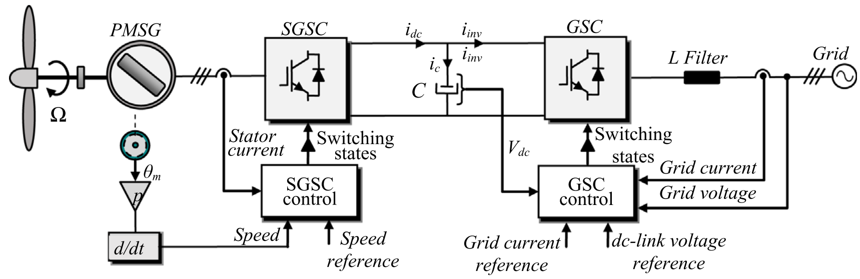

Fig. 1. PMSG Wind turbine power system.

are constant switching frequency and low current THD. However, Dead-beat predictive control is sensitive to parameters variations.

This work is aimed to present an MPC-based algorithm and Dead-beat predictive-based algorithm used for the control of SGSC and the GSC of the PMSG wind energy system.

This paper is organized as follows. In section II, the model of the wind power system based on PMSG is firstly presented. Then, MPC and Dead-beat predictive controls for SGSC and GSC are detailed. Finally, section III presents numerous simulation results in order to compare and discuss performances of the considered predictive algorithms.

2. System modeling

2.1. PMSG model

The electric equations of the PMSG in the dq synchronous reference frame are expressed as follows.

$$V_{sd} = R_s i_{sd} + \frac{d\phi_{sd}}{dt} - \omega_{dq}\phi_{sq} \quad (1)$$

$$V_{sq} = R_s i_{sq} + \frac{d\phi_{sq}}{dt} + \omega_{dq}\phi_{sd} \quad (2)$$

$$\phi_{sd} = L_{sd} i_{sd} + \phi_{rd} \quad (3)$$

$$\phi_{sq} = L_{sq} i_{sq} \quad (4)$$

The mechanical equations of the PMSG are given by the following equations

$$T_e = \frac{3}{2} p(\phi_{sd} i_{sq} + \phi_{rd} i_{sq}) \quad (5)$$

$$J\frac{d\omega}{dt} = T_e - T_L - f\omega \quad (6)$$

where i_{sd} and i_{sq} are the dq components of the stator current vetcor, V_{sd} and V_{sq} are the dq components of the stator voltage vector, Φ_{sd} and Φ_{sq} the dq components of the stator flux linkage, Φ_{rd} the permanent magnet flux linkage, ω_{dq} the angular electrical rotor speed, ω is the rotational speed, p the number of pole pairs, L_{sd} and L_{sq} the dq stator inductances, R_s is the stator resistance, f is the friction coefficient, J is inertia coefficient and T_e is the electromagnetic torque applied to the PMSG rotor.

2.2. GSC model

The mathematical model of the GSC connected to the grid through an L filter in the dq synchronous reference frame is characterized by the following relations.

$$\frac{di_{gd}}{dt} = \frac{1}{L_g}(V_{gd} - R_g i_{gd} + \omega_g L_g i_{gq} - V_{convd}) \quad (7)$$

$$\frac{di_{gq}}{dt} = \frac{1}{L_g}(V_{gq} - R_g i_{gq} - \omega_g L_g i_{gd} - V_{convq}) \quad (8)$$

$$P = V_{gd} i_{gd} + V_{gq} i_{gq} \quad (9)$$

$$Q = V_{gq} i_{gd} - V_{gd} i_{gq} \quad (10)$$

where i_{gd} and i_{gq} (respectively V_{gd} and V_{gq}) are the d and q components of the grid current vector (respectively the grid voltage vector) and ω_g is the angular frequency of the grid voltage. V_{convd} and V_{convq} are the d and q components of the converter output voltage vector. L_g and R_g are respectively the resistor and inductor of the used L filters. di_{gd}/dt et di_{gq}/dt are the the instantaneous grid current time derivatives.

3. SGSC predictive control

3.1. MPC-based control

The MPC-based control for the SGSC is presented on Fig. 2. It is based on the computation of the required converter voltage vector, to be applied during the next sampling period in order to minimize the error between the stator current and its reference in the dq synchronous reference frame. The d axis stator current reference i_{sd}^* is set to zero in order to obtain the maximum torque at the minimum current, whereas the q axis stator current reference i_{sq}^* is computed via the external PI-based speed controller.

For the development of the digital predictive current controller algorithm, expressions (1) and (2) can be written as follows

$$\frac{di_{sd}}{dt} = \frac{1}{L_{sd}}(V_{sd} - R_s i_{sd} + \omega_{dq} L_{sq} i_{sq}) \quad (11)$$

$$\frac{di_{sq}}{dt} = \frac{1}{L_{sd}}(V_{sq} - R_s i_{sq} - \omega_{dq} L_{sq} i_{sd} + \omega_{dq}\phi_{rd}) \quad (12)$$

According to Eqs. (11) and (12), and using the forward Euler discretization method, the following digital prediction equations are obtained.

$$i_{sd}[k+1] = a_0(V_{sd}[k] - e_{sd}[k]) + a_1 i_{sd}[k] \quad (13)$$

$$i_{sq}[k+1] = a_2(V_{sq}[k] - e_{sq}[k]) + a_3 i_{sq}[k] \quad (14)$$

$$e_{sd}[k] = -L_{sq}\omega_{dq}[k] i_{sq}[k] \quad (15)$$

$$e_{sq}[k] = L_{sd}\omega_{dq}[k] i_{sd}[k] + \omega_{dq}[k]\phi_{rd}[k] \quad (16)$$

where $a_0 = T_s/L_{sd}$, $a_1 = (1 - R_s T_s/L_{sd})$, $a_2 = T_s/L_{sq}$, $a_3 = (1 - R_s T_s/L_{sq})$ and T_s is the sampling period. $i_{sd}[k+1]$ and $i_{sq}[k+1]$ (respectively $i_{sd}[k]$ and $i_{sq}[k]$) are the predicted d and q stator current components at the $(k+1)$th sampling period (respectively measured d and q stator current components during kth sampling period). The e_{sd} and e_{sq} refer respectively to the d and q induced EMF terms. During each sampling period, the evolution of the d *and* q stator current components depends on the applied stator voltage components