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A direct power control of the doubly-fed induction generator based on the SVM Strategy

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Abstract. This paper proposes a direct power control scheme for the doubly-fed induction generator (DFIG) for variable speed wind-power generation. The machine is connected as a generator. Its rotor is fed by a two-level inverter. We propose to control the DFIG with a technique based on the direct power control (DPC) performances.

A combination of a space-vector modulation (SVM) technique and active and reactive power controllers is made to replace hysteresis controllers used in the classic DPC drive resulting in a fixed switching frequency of the power converter.

The performances obtained by using this control strategy are shown under MATLAB Simulink.

Keywords: DPC, SVM, DFIG, Wind turbine

Neposreden nadzor moči pri dvojno napajanem asinhronskem generatorju na podlagi strategije SVM

V prispevku je predstavljen neposreden nadzor moči pri dvojno napajanem asinhronskem generatorju pri vetrnih elektrarnah. Pri nadzoru moči smo uporabili kombinacijo prostorsko-vektorske modulacije in aktivnih ter reaktivnih močnostnih krmilnikov za zamenjavo krmilnikov s histerezo, ki se uporabljajo pri klasičnem neposrednem nadzoru moči. Zmogljivost predlaganega pristopa smo preverili v okolju MATLAB Simulink.

1 INTRODUCTION

In the Direct Torque Control (DTC) of an induction machine, the control strategy is based on the selection of appropriate stator voltage vectors in order to maintain the torque and the stator flux within their hysteresis bands [1]. The direct power control (DPC) is based on the well know a DTC for induction machines.

The recent advances in the power semiconductor and microprocessor technology have made possible to use advanced control techniques for the Doubly Fed Induction Generator (DFIG). The basic idea of the DPC approach is a direct control of the active and reactive power without any internal control loop or PWM modulator. The switching states are selected via a switching table and the states are chosen based on the instantaneous error between the estimated and the desired active and reactive-power of the DFIG drive systems [2]. In this paper, a DPC strategy is proposed to control the doubly fed induction generator using a two-level inverter. The DPC performances can be ensured by using a Switching Table (ST) to select the switching voltage vector. The inverter connected to the DFIG must provide the necessary complementary frequency in order to maintain a constant stator frequency

2 WIND TURBINE CHARACTERISTIC

The wind Electric Conversion System (WECS) is a good solution to electrify isolated locations which are far from the power distribution network. Due to the increasing concern about the clean environment and the depletion of natural resources, such as fossil fuels and nuclear fusion materials, much of the novel research is mainly focused on obtaining electricity from nonconventional energy sources. The WECSs are recently getting a lot of attention, for being cost-viable, inexhaustible, environmentally clean and safe renewable energy sources compared to the thermal and nuclear power generation systems [3].

A wind turbine can be characterized by a nondimensional curve of power coefficient C_p as a function of Tip-Speed Ratio (TSR) λ, where, λ is given in terms of rotor speed, ω_m (rad/s), wind speed, V (m/s), and rotor radius, R (m) as [3]:

$$\lambda = \frac{R\omega_m}{V}$$

The wind turbine power coefficient, C_p is dependent upon λ. If the pitch angle, β is incorporated, C_p becomes a function of λ and β, i.e. $C_p = f(\lambda, \beta)$. The power

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coefficient as a function of λ and β can be expressed as [2]:

$$C_p(\lambda,\beta)=0.518\left(\frac{16}{\lambda_i}-0.4\beta-5\right)e^{\left(\frac{-21}{\lambda_i}\right)} \quad (1)$$
$$+0.0068\lambda$$

Where:

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1}$$

Figure 1 shows simulation results in MATLAB/Simulink of evolution of power coefficient C_p a function of relative speed λ for different pitch angles β.

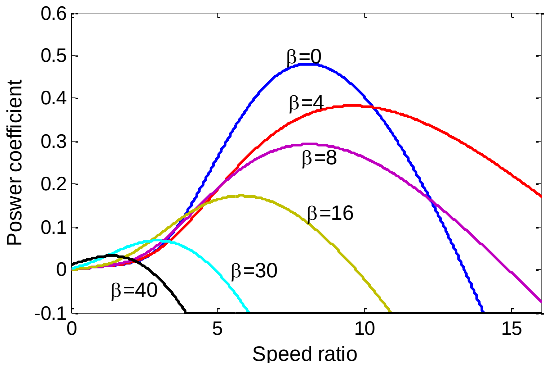

Figure1. Power coefficient.

The $Cp=f(\lambda,\beta)$ curves for some β values are shown in Figure 1. It can be seen that as β increases, C_p decreases too, thus reducing the power generated by the wind turbine, knowing the speed of the turbine the aerodynamic torque is determined by:

$$C_t=\frac{P_t}{\Omega_t}=\left(\frac{\left(C_p(\rho S V_v^3)\right)}{2}\right)\left(\frac{1}{\Omega_{turb}}\right) \quad (2)$$

The multiplier is mathematically modelled using the following equations:

$$G_g=\frac{G_t}{G} \quad (3)$$

$$\Omega_t=\frac{G_g}{G} \quad (4)$$

The connection between the turbine and the electric part of the wind is represented here by the equation of the shaft:

$$J=\frac{J_t}{G^2}+J_g \quad (5)$$

The mechanical torque applied to the rotor:

$$J\frac{d\Omega}{dt}=C_{mec}=C_g-C_{em}-C_f \quad (6)$$

And we have that:

$$C_f=f_f\Omega_g \quad (7)$$

3 A DFIG Dynamic Model

In order to investigate the DFIG behavior, a dynamic equation needs to be considered. From the point of view of the control, the *d-q* representation of an induction machine leads to control flexibility. The DFIG dynamic behavior in a synchronous reference frame can be represented by the Park's equations, provided all the rotor quantities are referred to the stator side. The stator and rotor voltages are expressed as follows [3][4][5]:

$$\begin{aligned}
V_{ds}&=R_sI_{ds}+\frac{d\Phi_{ds}}{dt}-\theta_s\Phi_{qs}\\
V_{qs}&=R_sI_{qs}+\frac{d\Phi_{qs}}{dt}-\theta_s\Phi_{ds}\\
V_{dr}&=R_rI_{dr}+\frac{d\Phi_{dr}}{dt}-\theta_r\Phi_{qr}\\
V_{qr}&=R_rI_{qr}+\frac{d\Phi_{qr}}{dt}-\theta_r\Phi_{dr}
\end{aligned} \quad (8)$$

$$\begin{aligned}
\Phi_{ds}&=L_sI_{ds}+MI_{dr}\\
\Phi_{qs}&=L_sI_{qs}+MI_{qr}\\
\Phi_{dr}&=L_rI_{dr}+MI_{ds}\\
\Phi_{qr}&=L_rI_{qr}+MI_{qs}
\end{aligned} \quad (9)$$

The electromagnetic torque, the active and reactive power equations for DFIG may be written as:

$$C_{em}=C_r+f\Omega+J\frac{d\Omega}{dt} \quad (10)$$

This can be expressed as a function of stator fluxes and rotor currents:

$$C_{em}=\frac{M}{L_s}\left(\Phi_{qs}I_{dr}-\Phi_{ds}I_{dr}\right) \quad (11)$$

4 Control Strategy of the Doubly-Fed Induction Generator

The doubly-fed electric machines are electric motors or electric generators with windings on both the stationary and rotating parts, where both windings transfer a significant power between the shaft and the electric system. The doubly-fed machines are useful in applications that require a variable speed of the machine shaft for a fixed power system frequency. As the penetration of large-scale wind turbines into electric-power grids continue to increase, electric system operators are placing greater demands on the wind turbine power plants.

For obvious reasons of simplifications, the *d-q* reference frame related to the stator spinning-field pattern and the stator flux aligned on the *d*-axis are adopted. Moreover, the stator resistance can be neglected since it is a realistic assumption for the generators used in the wind turbine [3][4]

DFIG is controlled by the rotor voltages via an inverter. It is an independent control of the active and reactive power. In the d-q reference frame, in an asynchronous generator stator, the active power *Ps* and reactive power *Qs* are:

$$Q_s = -V_s \frac{M}{L_s} I_{qr} + \frac{V_S^2}{L_s \omega_s} \tag{12}$$

Adaptation of these equations to the simplified assumptions gives

$$\begin{aligned} V_{dr} &= R_r I_{dr} + \left(L_r - \left(\frac{M_2}{L_s}\right)\right)\frac{dI_{dr}}{dt} \\ &- g\left(L_r - \left(\frac{M_2}{L_s}\right)\right)\omega_s I_{qr} \end{aligned} \tag{13}$$

$$\begin{aligned} V_{qr} &= R_r I_{qr} + \left(L_r - \left(\frac{M_2}{L_s}\right)\right)\frac{dI_{dr}}{dt} \\ &- g\left(L_r - \left(\frac{M_2}{L_s}\right)\right)\omega_s I_{qr} + g\left(\frac{MV_s}{L_s}\right) \end{aligned} \tag{14}$$

$L\ \omega$ is the stator reactance. Equations showing the relationship between the rotor currents and voltages are established and will be applied to control the generator.

5 DPC PRINCIPLE

The DTC method is basically a performance-enhanced scalar control method. The main features of a DTC are direct control of the flux and torque by the selecting an optimal inverter switching vector.

The basic principle of DPC was proposed by Noguchi and is based on the well-know a DTC for induction machines. In DPC, the active and reactive powers replace the torque and flux amplitude used as a controlled output in DTC. The basic concept consists of selecting the appropriate switching states from a switching table based on the errors, which are limited by a hysteresis band, present in the active and reactive powers [6][7][8][9].

The measured values of powers P_s and Q_s are estimated from the following relations where powers can be written in terms of the two rotor flux components in the (α_r-β_r) frame.

$$\begin{cases} P_s = -\dfrac{M}{\sigma L_s L_r} V_s \Phi_{r\beta} \\ Q_s = \left(\dfrac{V_s}{\sigma L_s}\Phi_s - \dfrac{V_s M}{\sigma L_s L_r}\Phi_{r\alpha}\right) \end{cases} \tag{15}$$

Where:

$$\begin{cases} \Phi_{r\alpha} = \sigma L_r i_{r\alpha} + \dfrac{M}{L_s}\Phi_s \\ \Phi_{r\beta} = \sigma L_r i_{r\beta} \\ \left|\overline{\Phi}_s\right| = \dfrac{\left|\overline{V}_s\right|}{\omega_s} \\ \sigma = 1 - \dfrac{M^2}{L_s L_r} \end{cases} \tag{16}$$

Ps and Qs can be reformulated by inducing angle δ between the stator and rotor vectors as follows:

$$\begin{cases} P_s = -\dfrac{M}{\sigma L_s L_r}\omega_s |\Phi_s||\Phi_r|\sin\delta \\ Q_s = \dfrac{\omega_s}{\sigma L_s}|\Psi_s|\left(\dfrac{M}{L_r}|\Phi_r|\cos\delta - |\Phi_s|\right) \end{cases} \tag{17}$$

The derivation of the two equations in (10) gives:

$$\begin{cases} \dfrac{dP_s}{dt} = -\dfrac{L_m\omega_s}{\sigma L_s L_r}|\Phi_s|\dfrac{d\left(|\Phi_r|\sin\Phi_r\right)}{dt} \\ \dfrac{dQ_s}{dt} = \dfrac{M\omega_s}{\sigma L_s L_r}|\Phi_s|\dfrac{d\left(|\Phi_r|\cos\delta\right)}{dt} \end{cases} \tag{18}$$

The stator active and reactive powers can then be varied by changing the angle between the rotor and stator vectors:

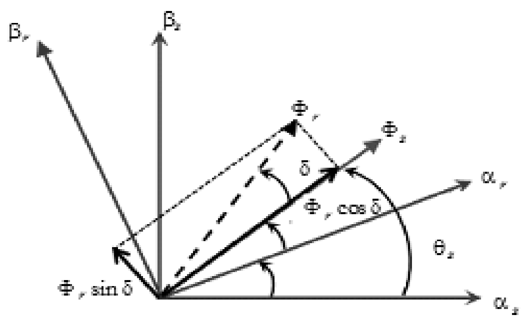

Figure 2. Rotor flux vector (α-β).

6 DPC BASED ON THE SVM STRATEGY

The space vector modulation (SVM) is an algorithm to control the pulse width modulation (PWM). It is used to create of alternating current (AC) waveform. It is most commonly used in inverters and three-phase ac-powered motors. There are various types of SVM that result in different quality and computational requirements. One active area of development is in the reduction of the total harmonic distortion (THD) created by the rapid switching inherent to these algorithms [10].

In order to obtain a smooth operation at a constant switching frequency, direct power control is combined with the SVM strategy based on the principles of the classical DPC method

Elaboration of the switching table of the control structure is based on the outputs of the Rp and Rq controllers and rotor-flux position δ.

Table 1 gives a clear idea of the switching sequences of all the states of the inverter.

Table 1. Switching table

Rq		**1**			**-1**		
Rp		**1**	**0**	**-1**	**1**	**0**	**-1**
Rotor Flux sector	1	V_5	V_7	V_3	V_6	V_0	V_2
	2	V_6	V_0	V_4	V_1	V_7	V_3
	3	V_1	V_7	V_5	V_2	V_0	V_4
	4	V_2	V_0	V_6	V_3	V_7	V_5
	5	V_3	V_7	V_1	V_4	V_0	V_6
	6	V_4	V_0	V_2	V_5	V_7	V_1

A schematic diagram of the proposed DPC for a DFIG system is shown in Fig. 3. The controller contains two PI controllers, one for the active power and one for the reactive power, as well as SVM unit.

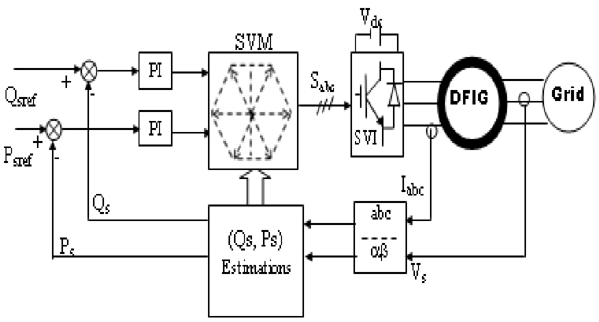

Figure 3. Conventional switching table based on DPC for DFIG.

7 SIMULATION RESULTS

The proposed DPC scheme is implemented with Matlab/Simulink in order to evaluate its performances. DFIG used for the simulations has the following parameters:

$$P = 2kw, V_n = 230V, f = 50Hz, R_s = 0.455\Omega,$$
$$R_r = 0.19\Omega, L_s = 0.07H, L_r = 0{,}213\Omega, M = 0{,}034H,$$
$$J = 0.3125kg.m^2, K_f = 0.001Nm.s/rad, p = 2$$

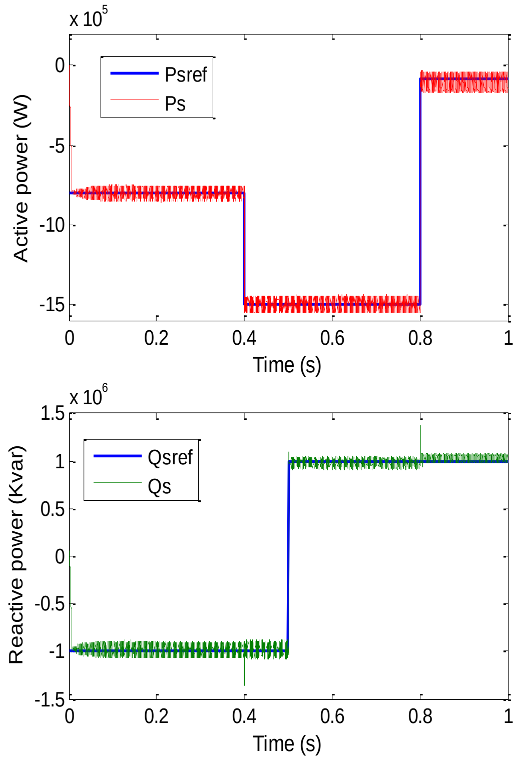

Figure 4. Active and reactive power (DPC).

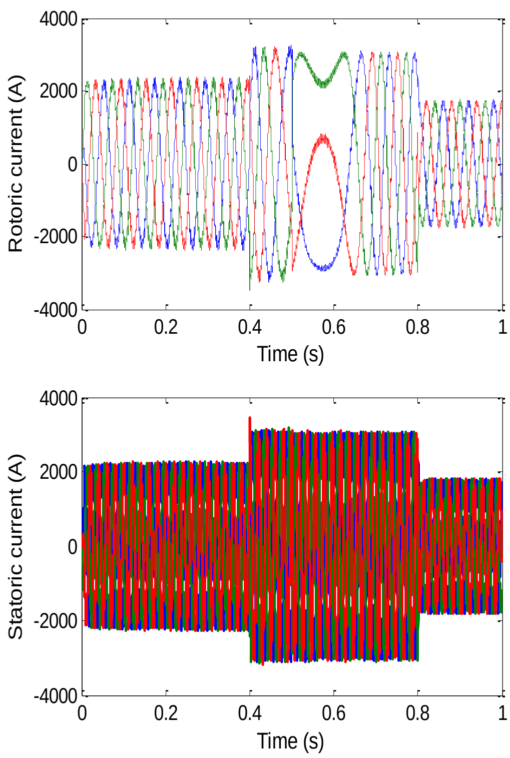

Figure 5. Rotor and stator currents (DPC).

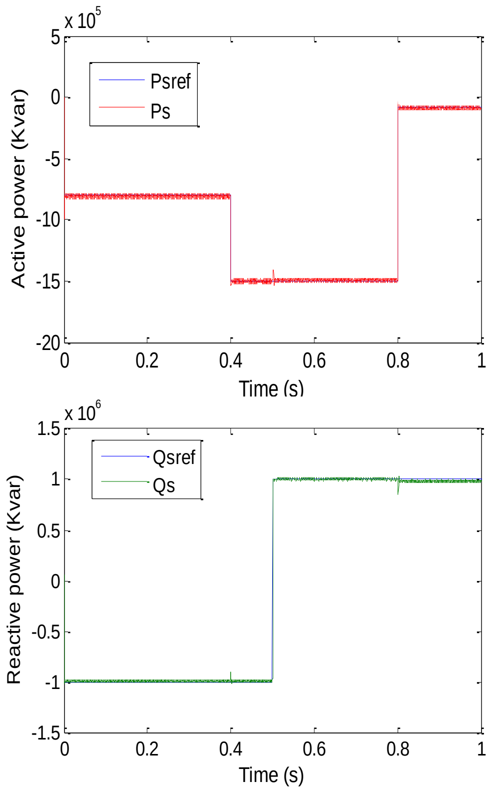

Figure 6. Active and reactive power (DPC-SVM).

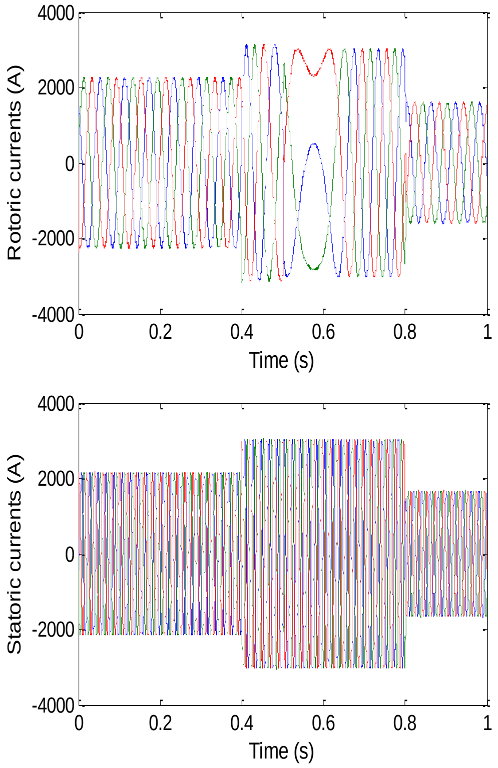

Figure 7. Rotor and stator currents (DPC-SVM).

Figure 4 shows that the active and reactive powers are decoupled from each other in the proposed DPC control process with a rapid time response, without overshoot and with a minimal static error, but with a significant chattering for all the parameters (Fig. 5).

The performance of the DTC-SVM can be seen in the maintaining of a perfect decoupling of the powers and a net reduction of chattering for the different parameters (Fig.6, Fig.7)

8 Conclusion

This paper presents a direct power control for a doubly fed induction generator that can achieve a high accuracy and fast dynamic power response. The direct power control scheme helps protecting the rotor-side converter because there is no overshoot in the rotor current.

The direct power control guarantees the active and the reactive power to reach their desired reference values and as satisfactory decoupling between the two stator powers.

The DTC-SVM gives a perfect decoupling of the powers and a net reduction of chattering for the different parameters of the machine parameters variations.

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