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Control of Torque and Unity Stator Side Power Factor of the Doubly-Fed Induction Generator

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Abstract: In this study, a control of totque and unity stator side power factor of the Doubly-Fed Induction Generator (DFIG) is proposed. First, a mathematical model of the doubly-fed induction generator written in an appropriate d-q reference frame is established to investigate simulations. In order to control the rotor currents of DFIG, a control law is synthesized using PI controllers; under conditions of the stator side power factor is controlled at unity level. Results obtained in Matlab/Simulink environment, are presented illustrating a good control system performance.

Key words: Doubly-Fed Induction Generator (DFIG), modelling, control of torque, power factor

INTRODUCTION

A doubly-fed induction generator is an electrical asynchronous three-phase machine with open rotor windings which can be fed by external voltages. The typical connection scheme of this generator is reported in Fig. 1. The stator windings are directly connected to the line grid, while the rotor windings are controlled by means of an PWM inverter, (Peterson, 2003; Bose, 1996). This solution is very attractive for all the applications where limited speed variations around the synchronous velocity are present, since the power handled by the converter at rotor side will be a small fraction (depending on the slip) of the overall system power. In particular, for electric energy generation applications, it is important to note that the asynchronous nature of the DFIG allows to produce constant-frequency electric power with a variable mechanical speed and to reduce copper losses, (Bose, 1996).

Different strategies were proposed in the study to solve the DFIG control problem. A vector controlled doubly fed induction generator is an attractive solution for high performance and energy generation application (Peterson, 2003; Bose, 1996; Leonhard, 1995).

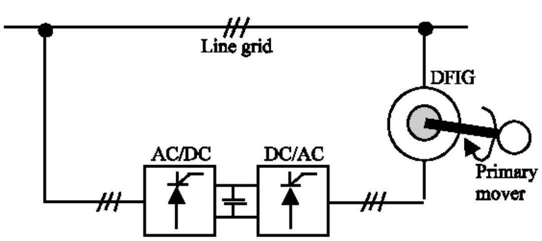

Fig. 1: The tipical connection scheme of DFIG

In this study, control of torque strategy is achieved by adjusting rotor currents and using stator voltage vector oriented reference frame. Simulation is investigated with PI regulators, under condition of unity stator side power factor. Simulation results present a high dynamic performance vector controlled doubly-fed induction generator.

MATHEMATICAL MODEL OF THE DFIG

The equivalent two-phase model of the symmetrical DFIG is represented in stator voltage-vector oriented frame (d-q) is Peresada *et al.* (1998) and Tapia *et al.* (2003):

$$J\frac{d\omega}{dt} = [p\mu(\Psi_{qs}\cdot i_{dr} - \Psi_{ds}\cdot i_{qr}) - T_L - f\omega] \tag{1}$$

$$\frac{d\Psi_{ds}}{dt} = -\alpha_s\Psi_{ds} + \omega_s\Psi_{qs} + \alpha_s M i_{dr} + V_{ds} \tag{2}$$

$$\frac{d\Psi_{qs}}{dt} = -\alpha_s\Psi_{qs} - \omega_s\Psi_{ds} + \alpha_s M i_{qr} + V_{qs} \tag{3}$$

$$\begin{aligned}\frac{di_{dr}}{dt} &= -\gamma_r i_{dr} + \omega_r i_{qr} + \alpha_s\beta\Psi_{ds} \\ &-\beta p\omega\Psi_{qs} - \beta V_{ds} + \frac{1}{\sigma_r}V_{dr}\end{aligned} \tag{4}$$

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$$\frac{di_{qr}}{dt} = -\gamma_r i_{qr} - \omega_r i_{dr} + \alpha_s \beta \Psi_{qs} + \beta p \omega \Psi_{ds} - \beta V_{qs} + \frac{1}{\sigma_r} V_{qr} \quad (5)$$

$$\dot{\theta} = \omega \quad (6)$$

Where: V_{dr}, V_{qr}, i_{dr}, i_{dr}, Ψ_{dr}, Ψ_{qr} are rotor voltages, rotor currents and stator fluxes, T_L is a moving torque generated by the primary mover, U_m and ω_s are stator (line) voltage amplitude and angular frequency, θ and ω are angular position and rotor speed, $\omega_r = \omega_s - \omega$ is sleep angular frequency, p is number of pole pairs.

Positive constants related to DFIG electrical parameters are defined as:

$\alpha_s = R_s/L_s$;
$\sigma_r = L_r(1-M^2/L_sL_r)$;
$\beta = M/(L_s.\sigma_r)$;
$\mu = 3M/2L_s$;
$\gamma_r = R_r/\sigma_r + (R_sM^2)/L_s^2\sigma_r$

Where R_s, R_r, S_s, R_r: Resistance and inductance of stator and rotor, respectively, M: Mutual inductance (Appendix 1).

Appendix 1: Doubly fed induction generator parameters (Persada *et al*., 1998)

Rotor resistance	$R_r = 5.3\ \Omega$
Rated current	5.2 A
Stator inductance	$L_s = 0.161$ H
Rated voltage	220/380 V
Rotor inductance	$L_r = 0.161$ H
Rated torque	15 Nm
Mutual inductance	$M = 0.138$ H
Rated speed	880 rev/min
Number of pole pair	$p = 3$
Stator resistance	$R_s = 4.7\ \Omega$
Friction coefficient	$f = 0.45$

VECTOR CONTROL ALGORITHM FOR DFIG

Conditions of stator flux field orientation and line voltage orientation are equivalent if the stator side power factor is controlled at unity level (Tapia *et al*., 2003; Pena *et al*., 1996). Under such condition the stator flux modulus is not a free output variable but it is a function of the produced electromagnetic torque.

The reactive component of the stator current is practically equal to zero as it is the given working condition of DFIG control algorithm. Figure 2 shows the diagram control of power factor.

The setting of different vectors and transformation angles is represented in Fig. 3.

Under using this reference frame, the flux errors defined as:

$$\tilde{\Psi}_{ds} = \Psi_{ds}, \tilde{\Psi}_{qs} = \Psi_{qs} - \Psi^*, i_{qs} = 0.$$

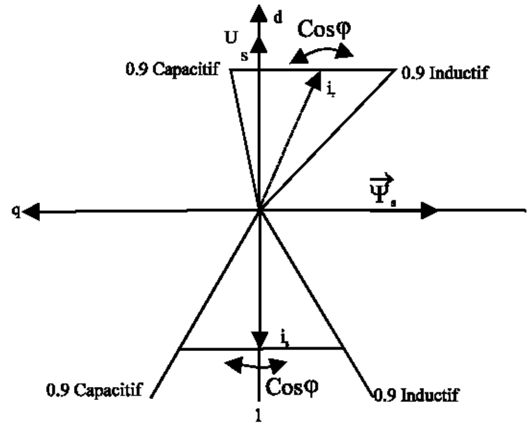

Fig. 2: Diagram control of power factor

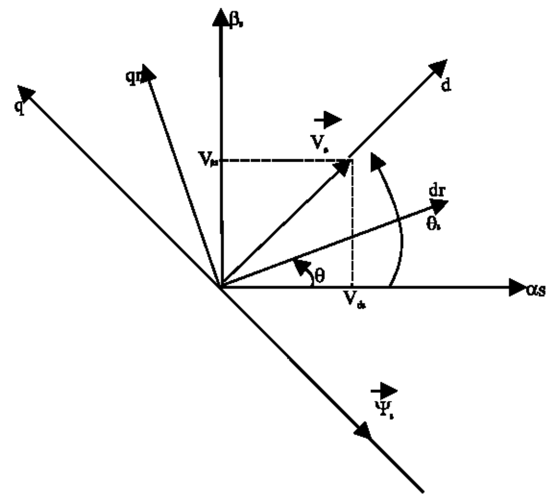

Fig. 3: Setting of vectors oriented and transformation angles

Where: Ψ^* is the flux level reference trajectory.

The complete equations of the vector control of the doubly-fed induction generator are given by:

Stator flux vector controller:

$$i^*_{qr} = \frac{1}{\alpha_s M}\left(\alpha_s \Psi^* + \dot{\Psi}^*\right) \quad (7)$$

$$\Psi^* = \frac{-U_m - \left(U_m^2 - 4(2/3)\omega_s R_s T_g^*\right)}{2\omega_s} \quad (8)$$

Torque controller:

$$i^*_{dr} = \frac{T_g^*}{\mu \Psi^*_{qs}} \quad (9)$$

Rotor current controller:

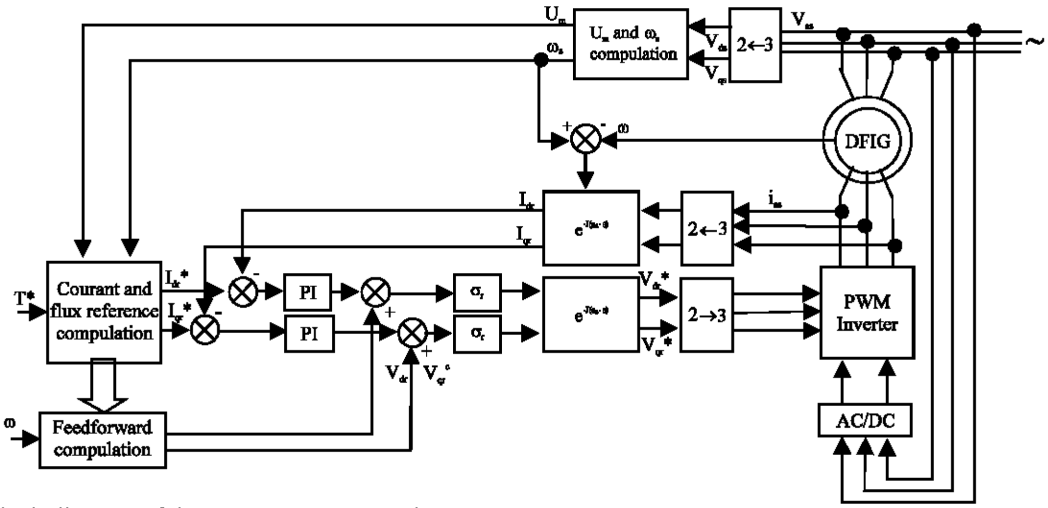

Fig. 4: Block diagram of the DFIG vector control

$$U_{dr} = \sigma_r[\gamma_r i^*_{dr} - \omega_r i^*_{qr} + \beta\omega\Psi^* + \beta U_m + \frac{di^*_{dr}}{dt} + kp\tilde{i}_{dr} + x_d]$$

$$U_{qr} = \sigma_r[\gamma_r i^*_{qr} + \omega_r i^*_{dr} - \beta\alpha_s\Psi^* + \frac{di^*_{qr}}{dt} - kp\tilde{i}_{qr} + x_q] \quad (10)$$

$$\dot{x}_d = -ki \cdot \tilde{i}_{dr} \quad (11)$$

$$\dot{x}_q = -ki \cdot \tilde{i}_{qr} \quad (12)$$

$$\tilde{i}_{dr} = i_{dr} - i^*_{dr} \quad (13)$$

$$\tilde{i}_{qr} = i_{qr} - i^*_{qr} \quad (14)$$

Where i^*_{dr}, i^*_{qr} are rotor currents reference in (d-q) reference frame; k_p and k_i are positive proportional and integral gains of rotor current controllers; **Ψ*** is stator flux reference; x_d, x_q are integral components of current controllers.

Under such condition, the stator side active and reactive powers are given by:

$$P = -\frac{3}{2}U_m i_{ds} \quad (15)$$

$$Q = \frac{3}{2}U_m i_{qs} \quad (16)$$

The study, that we present, consists in using a generator where the rotor is supplied through a converter. This converter is based on PWM control algorithm (Zhang and Watthanasam, 1998) operating at 2 KHz switching frequency.

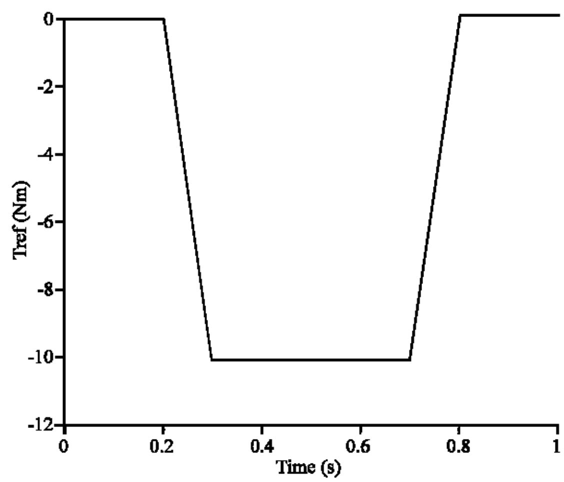

Fig. 5: Torque reference

The proportional and integral gains of the rotor current controllers have been set at k_p=500, k_i=62040. All programs for controller implementation have been written using Matlab/simulink environment. The bloc diagram of the proposed controller is shown in Fig. 4.

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SIMULATION RESULTS

The results reported in Fig. 5-14. was performed to investigate system behaviour during torque tracking. The sequence of operation during this test is shown in Fig. 5. The DFIG, already connected to the line grid, is required to track a trapezoidal torque reference, which starts at t = 0.2s from zero initial value and reaches the rated value of -10 Nm at t = 0.3 s.

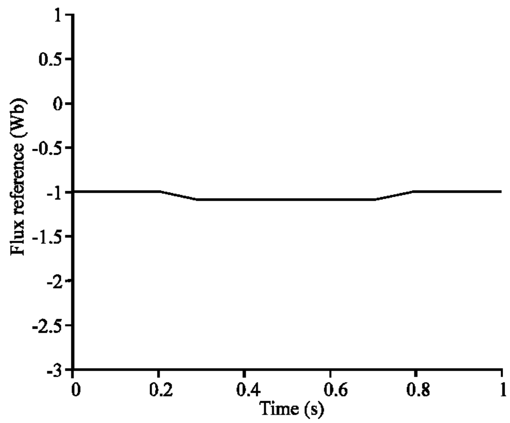

Fig. 6: Flux reference

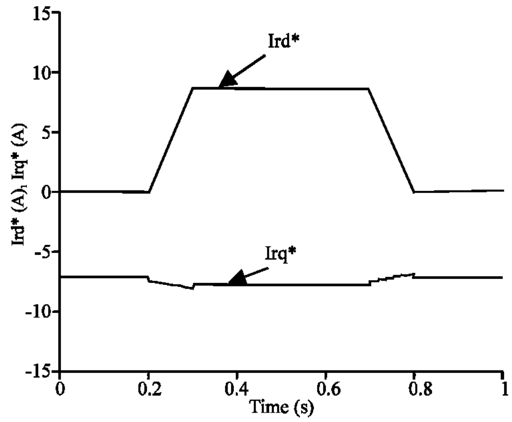

Fig. 7: Rotor reference currents Ird* and Irq*

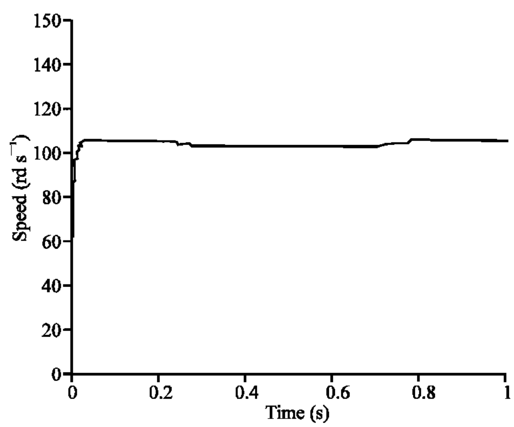

Fig. 8: Speed

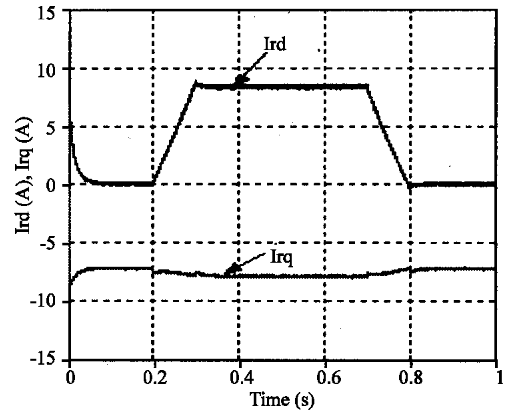

Fig. 9: Rotor currents responses Ird and Irq

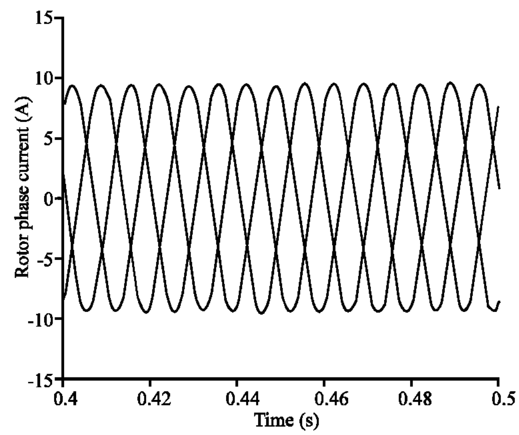

Fig. 10: Rotor phases currents

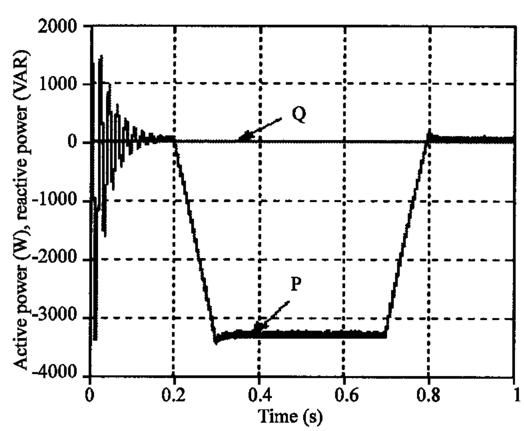

Fig. 11: Stator active power P and reactive power Q

Note that flux value, required to track torque trajectory with unity power factor at stator side is not a constant. The rotor current is sinusoidal as shown in Fig. 10. Waveforms of the rotor reference currents and are shown in Fig. 7. The stator power follows the current as shown in Fig. 11. This results in unity power factor on the grid as the stator reactive power is zero. Rotor current errors are controlled at zero level. The reactive component of the stator current is almost equal to zero during all the time. As result, the stator phase current, reported in Fig. 14, has an opposite phase angle to the line voltage one and shows a low content of high order harmonics.

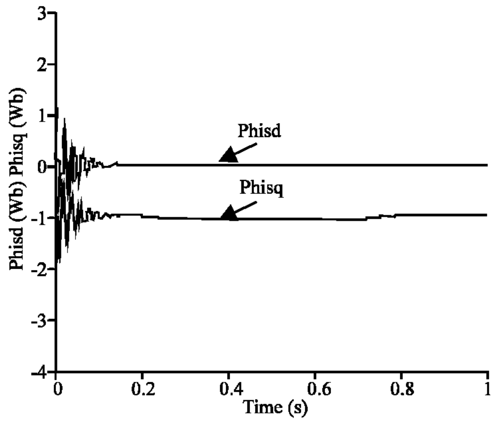

Fig. 12: Stator flux phisd and phisq

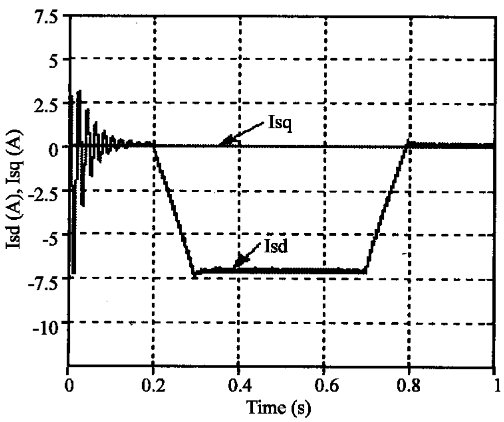

Fig. 13: Stator currents responses Isd and Isq

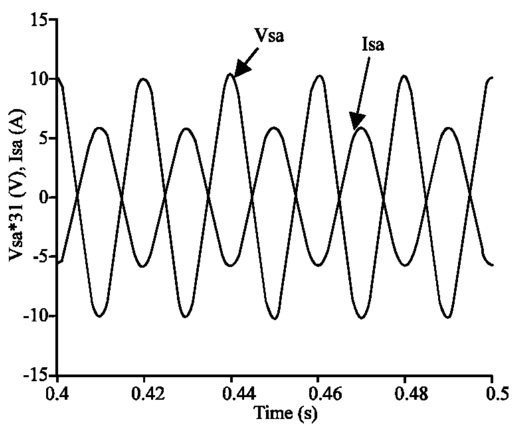

Fig. 14: Stator voltage and current

CONCLUSION

In this study, a control of torque of the doubly-fed induction generator has been proposed. Vector-control strategy has been achieved by adjusting rotor currents and using stator voltage vector oriented reference frame. Simulations have been investigated with PI regulators. Results show high performance torque tracking under condition of unity stator side power factor. Finally the proposed control is suitable for electric energy generation applications with DFIG.

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