Power Flow Control of a Doubly Fed Induction Generator (DFIG)

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Abstract: In this study a robust control of a Doubly-Fed Induction machine used in Generation mode (DFIG) is presented. It provides robust regulation of the primary side active and reactive power by the components of the stator currents. This strategy is suitable for both electric energy generation and drive applications. The mathematical model of the machine written in an appropriate d-q reference frame is established to investigate simulations. In order to control the power flowing between the stator of the DFIG and the power network, a decoupled control of active and reactive power is synthesized using PI controllers. Their respective performances are in terms of stator currents references tracking.

Key words: Active and reactive power, doubly fed induction generator, power flow control, robustness

INTRODUCTION

A vector controlled Doubly-Fed Induction Machine (DFIM) is an attractive solution for high performance restricted speed-range electric drives and energy generations applications (Leonhard, 1996; Aimani, 2003; Petersson, 2003). Figure1 reports the typical connection scheme of this machine. This solution is suitable for all of the applications where limited speed variations around the synchronous speed are present. Since the power handled by the rotor side (slip power) is proportional to slip, an energy conversion is possible using a rotor-side power converter, which handles only a small fraction of the overall system power.

An important feature of the vector controlled DFIG is the possibility to achieve de-coupled control of the stator-side active and reactive power in both motor and generator applications (Peresada *et al.*, 2003; Datta and Ranganathan, 2001). Moreover, if suitable controlled

Fig. 1: Typical connection scheme of a DFIG

AC/AC converter is used to supply the rotor side, the power components of the overall system can be controlled with low current harmonic distortion in the stator and rotor sides (Zhang and Watthanasarn, 1998).

The classical approach for DFIG vector control (Aimani, 2003) requires measurements of stator, rotor currents and rotor position. In order to achieve synchronization with line voltage vector for soft connection to the line-grid the information about line voltages is additionally needed. Exact knowledge of induction machine inductances (including saturation effect) is required to compute fluxes from currents. In this research, the approach for the design of DFIG active-reactive power control is proposed. Both controllers are developed in a line-voltage oriented reference frame (Pena *et al.*, 1996). Since the line voltage vector can be easily measured with negligible errors, this reference frame is DFIG parameter invariant in contrast to the field oriented one. Moreover, information about line voltage is typically needed in order to perform the soft connection of the DFIM to the line grid during preliminary excitation-synchronization stage.

The aim of this study is to introduce a new decoupled control algorithm of the DFIG active and reactive power. It is shown that direct closed loop control of active and reactive power guarantees global asymptotic regulation of output variables, under condition of measurable of the stator currents, voltages, rotor position and speed. In addition, owing to the closed loop structure with true-stator-current feedback signals, the controller compensates the non-linear of electric machine magnetic structure, delivering improved stator current waveforms.
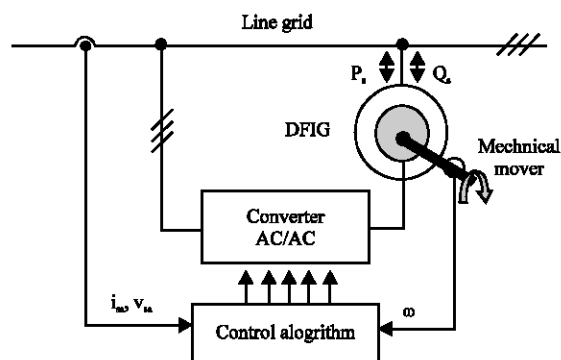
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MATHEMATICAL MODEL OF DFIG

Under assumption of linear magnetic circuits and balanced operating conditions, the equivalent two-phase model of the symmetrical DFIG, represented in an arbitrary rotating (d-q) reference frame is:

$$
\begin{cases}
v_{sd} = R_s i_{sd} + \dfrac{d\psi_{sd}}{dt} - \omega_s \psi_{sq} \\[2mm]
v_{sq} = R_s i_{sq} + \dfrac{d\psi_{sq}}{dt} + \omega_s \psi_{sd} \\[2mm]
v_{rd} = R_r i_{rd} + \dfrac{d\psi_{rd}}{dt} - (\omega_s - \omega)\psi_{rq} \\[2mm]
v_{rq} = R_r i_{rq} + \dfrac{d\psi_{rq}}{dt} + (\omega_s - \omega)_{rd} \\[2mm]
\dot{\omega} = \dfrac{1}{J}[C_e - C_r]
\end{cases}
\tag{1}
$$

where: i_{sd}, i_{sq}, $\bullet_{rd}$, $\bullet_{rq}$ are the components of the stator current and rotor flux vectors; v_{rd}, v_{rq} are the components of the rotor voltage vector, while v_{sd}, v_{sq} represent the line voltage components (stator windings are directly connected to the line grid) and R_r, R_s, L_s, L_r are stator/rotor resistances and inductances, respectively M_{sr} is magnetizing inductance; $\bullet$ is the rotor speed; C_e is the external torque applied to the mechanical system of the DFIG; C_r is the torque produced by the electrical machine; J is the total rotor inertia; $\bullet_s$ is the speed of the (d-q) reference frame with respect to the a-axis of the fixed stator reference frame (a-b).

The expressions of transformation of any vector at the rotating reference frame (d-q) are given in appendix.

CONTROL STRATEGY OBJECTIVES

The main control objective considered is the regulation of DFIM stator-side active and reactive powers, given by:

$$
\begin{aligned}
P_s &= \frac{3}{2}(v_{sd}i_{sd} - v_{sq}i_{sq}), \\[2mm]
Q_s &= \frac{3}{2}(v_{sq}i_{sd} - v_{sd}i_{sq})
\end{aligned}
\tag{2}
$$

In order to reduce the effet of the above inaccuracies in the reference frame generation and in vector transformation, a line (stator) voltage vector reference frame (d-q) has been adopted (the d-axis is aligned with the line voltage vector). This reference frame is independent of machine parameters and position sensor

resolution; only information from two voltage sensors and rotor position sensor are needed, instead of four current sensors.

Using the line voltage vector reference frame, a simple and smooth connection of the stator winding to the line grid can be performed during start-up procedure of the DFIM-based system.

Under the transformation of the stator voltage to the d-q reference frame according in the stator field the two component of the stator voltage in this reference can by replaced by: $v_{sd} = U$ and $v_{sq} = 0$ in DFIM model (1). In addition, currents i_{sd} and i_{sq}, in line-voltage oriented reference frame, represent the active and reactive components of the stator current vector. The expression of active and reactive powers (2) can be presented as:

$$
P_s = \frac{3}{2}U i_{sd}, \quad Q_s = -\frac{3}{2}U i_{sq}
\tag{3}
$$

From (3), it follows that active-reactive power control objective is equivalent to active-reactive stator currents control. Let P_s^* and Q_s^* are the references for the power components at stator side for the DFIM. Using (3), references for the components of the stator current, are given by

$$
i_{sd}^* = \frac{2}{3}\frac{P_s^*}{U}, \quad i_{sq}^* = -\frac{2}{3}\frac{Q_s^*}{U}
\tag{4}
$$

The control problem of DFIG is formulated in terms of stator active-reactive current regulation as to consider the DFIG model (1) under coordinate transformation. Let assume that:

- The stator voltage amplitude and frequency are constants (stator windings are directly connected to the line-grid).
- References for active and reactive stator currents are constant and bounded, or represent ramp signals with bounded first derivate and bounded amplitude.
- Under the assumption of a properly controlled primary mover the rotor speed is time varying, measurable and bounded together with its first time-derivate.
- Stator currents and voltages as well as rotor position and speed are available from measurements.

DESIGN OF THE CONTROL STRATEGY

The design procedure is performed in two steps: a flux control is designed first, to achieve flux regulation and then the current control algorithm is developed (Zhang and Wattanasarn, 1998).

Let define the flux regulation errors as:

$$e_{\psi_{rd}} = \psi_{rd} - \psi_{rd}^* , e_{\psi_{rq}} = \psi_{rq} - \psi_{rq}^* \tag{5}$$

where flux references, $\bullet_{rd}^*$ and $\bullet_{rq}^*$, will be defined later according to stator current control objectives.

Using definition (5) and the equations of the DFIM model (1) can be rewritten in 'error form' as

In order to deduce the derivative of the components of rotor flux starting from the model (1), the error can rewrite as:

$$\dot{e}_{\psi_{rd}} = -\frac{1}{T_r}(e_{\psi_{rd}} + \psi_{rd}^*) + \omega_r(e_{\psi_{rq}} + \psi_{rq}^*) +$$
$$+ \frac{1}{T_r}M_{sr}(e_{i_{sd}} + i_{sd}^*) + v_{rd} - \dot{\psi}_{sd}^* \tag{6}$$
$$\dot{e}_{\psi_q} = -\frac{1}{T_r}(e_{\psi_{sq}} + \psi_{sq}^*) - \omega_r(e_{\psi_{sd}} + \psi_{sd}^*) +$$
$$+ \frac{1}{T_r}M_{sr}(e_{i_{sq}} + i_{sq}^*) + v_{rq} - \dot{\psi}_{sq}^*$$

Where $\bullet_r = \bullet_s$ is the slip angular frequency.

Constructing the flux control algorithm as

$$v_{rd} = \frac{1}{T_r}\psi_{rd}^* - \omega_r\psi_{rq}^* - \frac{1}{T_r}M_{sr}i_{sd}^* + \dot{\psi}_{rd}^* + u_d$$
$$v_{rq} = -\frac{1}{T_r}\psi_{rq}^* + \omega_r\psi_{rq}^* - \frac{1}{T_r}M_{sr}i_{sq}^* + \dot{\psi}_{rq}^* + u_q \tag{7}$$

The flux error dynamics becomes

$$\dot{e}_{\psi_{rd}} = -\frac{1}{T_r}e_{\psi_{rd}} + \omega_r e_{\psi_{rq}} + \frac{1}{T_r}M_{sr}e_{i_{sd}} + u_d$$
$$\dot{e}_{\psi_{rq}} = -\frac{1}{T_r}e_{\psi_{rq}} - \omega_r e_{\psi_{rd}} + \frac{1}{T_r}M_{sr}e_{i_{sq}} + u_q \tag{8}$$

where u_d, u_q will be defined later. Applying the control algorithm (7), the current error dynamics from the Eq. 1 can be rewritten as

$$\dot{e}_{i_{sq}} = -\beta e_{i_{sq}} - \omega_s e_{i_{sd}} + \frac{\alpha}{T_r}e_{\psi_{rq}} - \alpha\omega e_{\psi_{rd}} - \alpha u_q$$
$$- i_{sq}^* - \alpha\dot{\psi}_{rq}^* - \frac{R_s}{\sigma}i_{sq}^* - \omega_s i_{sd}^* - \alpha\omega_s\psi_{rd}^*$$

$$\dot{e}_{i_{sd}} = -\beta e_{i_{sd}} + \omega_s e_{i_{sq}} + \frac{\alpha}{T_r}e_{\psi_{rd}} + \alpha\omega e_{\psi_{rq}} - \alpha u_d$$
$$- i_{sd}^* - \alpha\dot{\psi}_{rd}^* - \frac{R_s}{\sigma}i_{sd}^* + \omega_s i_{sq}^* + \frac{1}{\sigma}U + \alpha\omega_s\psi_{rq}^* \tag{9}$$

where,

$$T_r = \frac{L_r}{R_r}, \ \sigma = L_s\left(1 - \frac{M_{sr}^2}{L_sL_r}\right),$$
$$\alpha = \frac{M_{sr}}{\sigma L_r}, \ \beta = \left(\frac{R_s}{\sigma} + \frac{\alpha M_{sr}}{T_r}\right)$$

From Eq. 9 it follows that flux references should satisfy the following differential equations

$$\dot{\psi}_{rd}^* = \frac{1}{\alpha}\left(\alpha\omega_s\psi_{rq}^* + \frac{1}{\sigma}U - \frac{R_s}{\sigma}i_{sd}^* + \omega_s i_{sq}^* - i_{sd}^*\right)$$
$$\dot{\psi}_{rq}^* = \frac{1}{\alpha}\left(-\alpha\omega_s\psi_{rd}^* - \frac{R_s}{\sigma}i_{sq}^* - \omega_s i_{sd}^* - i_{sq}^*\right) \tag{10}$$

Substituting (10) into (9) the resulting current-flux error dynamics becomes

$$\dot{e}_{i_{sd}} = -\beta e_{i_{sd}} + \omega_s e_{i_{sq}} + \frac{\alpha}{T_r}e_{\psi_{rd}} + \alpha\omega e_{\psi_{rq}} - \alpha u_d$$
$$e_{i_{sq}} = -\beta e_{i_{sq}} - \omega_s e_{i_{sd}} + \frac{\alpha}{T_r}e_{\psi_{rq}} - \alpha\omega e_{\psi_{rd}} - \alpha u_q \tag{11}$$

A particular solution of (10), where oscillating terms are avoided, is given by

$$\begin{bmatrix}\psi_{rd}^* \\ \psi_{rq}^*\end{bmatrix} = \frac{1}{\sigma\alpha}\left\{\frac{1}{\omega_s}J\begin{bmatrix}U \\ 0\end{bmatrix} + \left(\sigma I - \frac{R_s}{\omega_s}J\right)\begin{bmatrix}i_{sd}^* \\ i_{sq}^*\end{bmatrix}\right.$$
$$\left. - R_s\sum_{k=1}^{\infty}\left[\left(\frac{1}{\omega_s}J\right)^{k+1}\frac{d^k}{dt^k}\begin{bmatrix}i_{sd}^* \\ i_{sq}^*\end{bmatrix}\right]\right\} \tag{12}$$

From (12) it follows that for arbitrary trajectories of current reference all of the time derivatives together with their initial conditions should be known. The following developments is based on the assumption that both current reference signals have bounded first time-derivate with all of the higher order ones equal to zero. Then the flux references are

$$\psi_{rd}^* = \frac{1}{\alpha\omega_s}\left(\frac{Rs}{\sigma}i_{sd}^* - \omega_s i_{sq}^* - \frac{1}{\sigma}U - \frac{1}{\sigma\omega_s}i_{sq}^*\right)$$
$$\psi_{rq}^* = \frac{1}{\alpha\omega_s}\left(-\frac{Rs}{\sigma}i_{sq}^* - \omega_s i_{sd}^* - \frac{1}{\sigma\omega_s}i_{sd}^*\right) \tag{13}$$

with

$$i_{sd}^* = i_{sq}^* = 0$$

In order to compensate, during steady-state conditions, for constant perturbation generated by DFIG parameter variations and error in rotor position measurement, the following two-dimensional proportional-integral current controller is designed

$$u_d = \frac{1}{\alpha}\left(k_p e_{i_{sd}} + \lambda e_{i_{sq}} - y_d\right),$$

$$\dot{y}_d = -k_i e_{i_{sd}} - \lambda \frac{R_s}{\sigma} e_{i_{sq}}$$

$$u_q = \frac{1}{\alpha}\left(k_p e_{i_{sq}} - \lambda e_{i_{sd}} - y_q\right),$$ (14)

$$\dot{y}_q = -k_i e_{i_{sq}} + \lambda \frac{R_s}{\sigma} e_{i_{sd}}$$

where $k_p > 0$ and $k_i > 0$ are the proportional and integral gains of the current controllers and $\lambda = k_i \omega_s^{-1}$ is the cross gain. The calculation of the PI parameters is according to Lyapunov stability analysis.

DIAGRAM OF THE CONTROL PROCESS

In this study some simulative resultants obtained to using the MATLAB/Simulink platform are presented in order to highlight the robustness of the proposed solution for decoupled stator active and reactive power control. A 5 kW DFIG, whose nominal parameters are reported in Table 1.

To guarantee stable operation and to enable independent control active and reactive power of the DFIG, a model based to using the PI controllers is developed using the dynamic model equations mentioned above.

A block diagram is shown in Fig. 2, In order to provide a decoupled control of the stator active power P_s and reactive power Q_s of the DFIG by means of the stator current regulation, the d-q components of the rotor currents are defined in the stator-flux oriented reference

Table 1: DFIG parameters

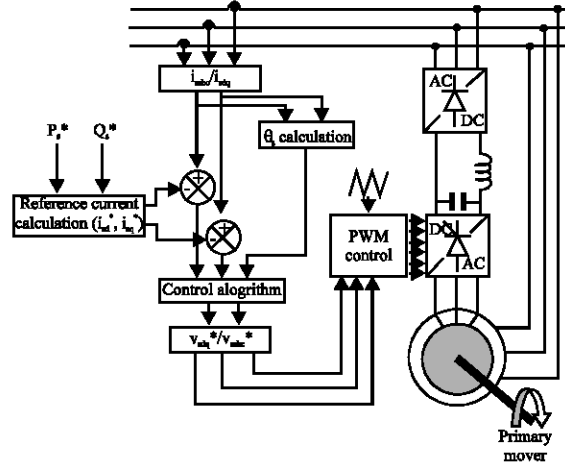| Parameters	Values
Power	5 kW
Voltage	380V (Y)
Frequency	50 Hz
Pole pairs	3
Speed	100 rad/s
Torque	50 N.m
Stator resistance	0.95 •
Rotor resistance	1.8 •
Stator inductance	0.094 H
Rotorique inductance	0.088 H
Magnetizing inductance	0.082 H

Fig. 2: Configuration of the power control of the DFIG

frame. The main is to represent P_s and Q_s as functions of the individual stator current components.

The desired P_s^* and Q_s^* can determine the reference stator currents, which us allows to calculate the components of the reference rotor voltage, as well as the control by technique PWM is realised for the inverter control which feeds the rotor through a converter.

For guarantee a drive of the DFIG around its speed of synchronism by carrying out a speed regulation.

RESULTS

The direct active and reactive power control algorithm is simulated on the MATLAB/SIMULINK platform. In this section the simulation results are presented in order to highlight the robustness of the proposed solution for stator active and reactive current control.

The active-reactive stator current and its reference are reported in Fig. 3 and 4. These figures represent a good pursuit, except that the presence of the oscillations during the transient mode. A very good decoupling between the two components of the stator currents is obtained, ensuring a decoupling between the active and reactive powers (Fig. 5), this leads to a good control of the power flow between the grid and the machine at all time.

The speed and torque of the DFIG are reported in Fig. 6. According to the latter, one notice that the motoring speed stays constant and the torque is depends directly on the direct component of the stator current.

The rotor phase voltage obtained on the output side of PWM inverter is represented by Fig. 7. The use of an inverter with PWM with a high switching frequency (5 kHz) makes it possible to improve the wave form of the stator current, as illustrated by the zoom of the Fig. 8 in Fig. 9.
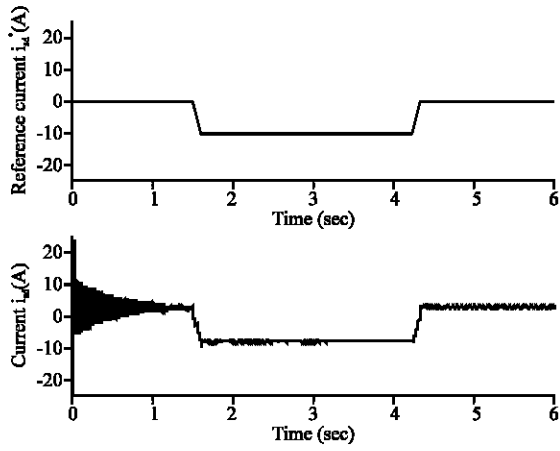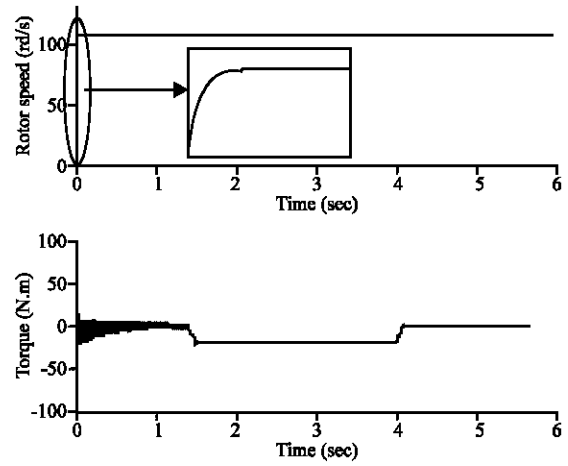
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Fig. 3: Current i_{sd} and its reference

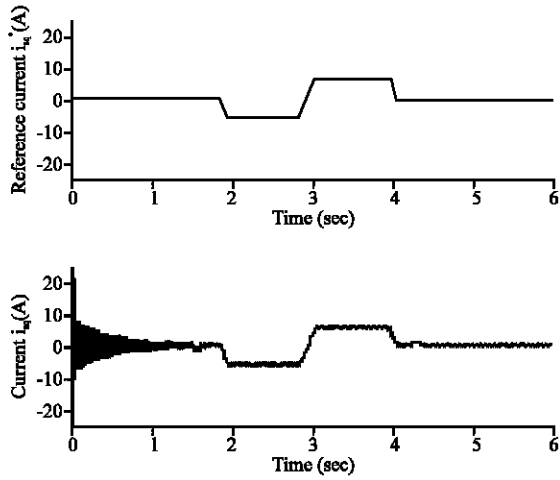Fig. 6: Speed and torque of DFIG
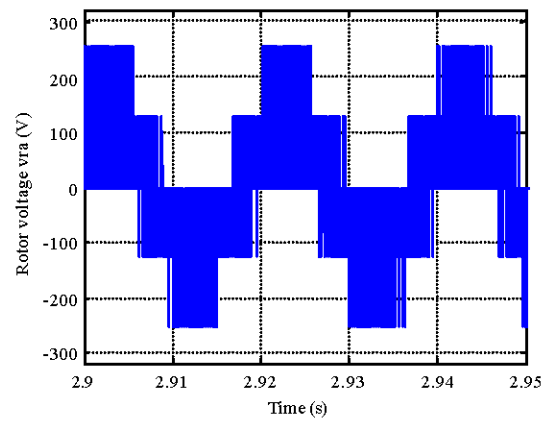
Fig. 4: Stator current i_{sq} and its reference
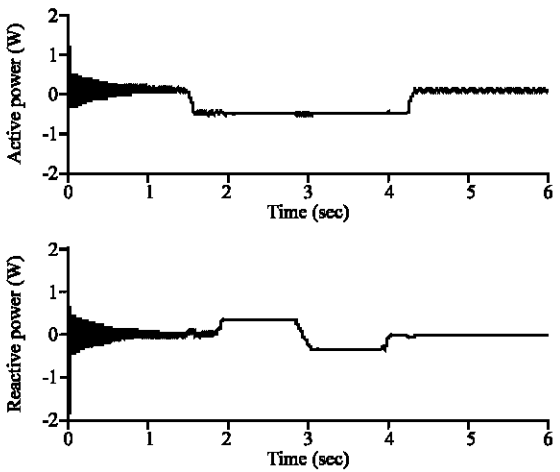
Fig. 7: Rotor phase voltage

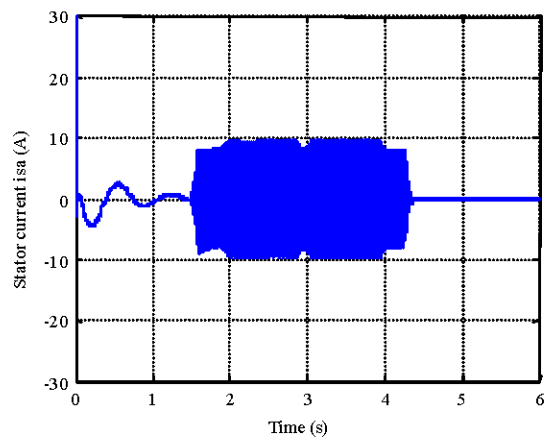Fig. 5: Stator active and reactive power
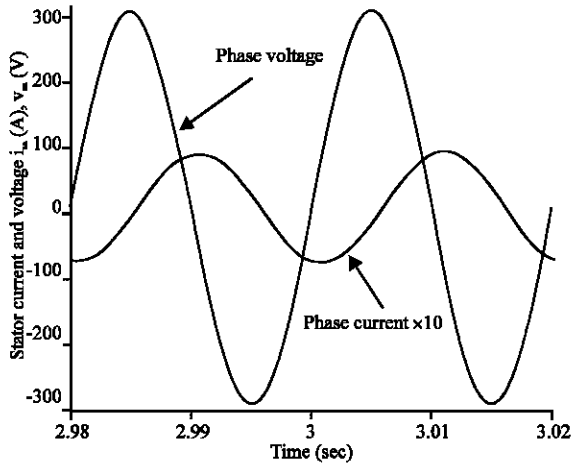
Fig. 8: Stator phase current

Fig. 9: Phase stator voltage and current

CONCLUSION

The direct control of the power flow of the DFIG by the stator current provides global asymptotic regulation in presence of the stator current reference variation. The simulation tests confirm the high dynamic performance and robustness of the proposed controller. The proposed controller is suitable for energy generation applications, where restricted variations of the speed around the synchronous velocity are present. The use of the PWM technique for drives inverter, allows it possible to obtain perfectly sinusoidal currents on the level of the stator, therefore the energy provided by the machine to the network is a clean energy without harmonics.

APPENDIX

Expressions of transformation: The transformation of the x vector related to the stator reference frame (a-b) at the rotating reference frame (d-q) is given by:

$$X_{sdq} = e^{-j\theta s} X_{sab}$$

$$X_{rdq} = e^{-j(\theta_s - \theta)} X_{ruv}$$

Where

$$e^{-j\delta} = \begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix}, \; j = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

where: x_{yz} stands for two dimensional vectors in the generic (y-z) reference frame; subscript 's' stands for stator variables while 'r' for rotor variables; (u-v) indicates rotor reference frame and • is the rotor angle position.

REFERENCES

Datta, R. and V.T. Ranganathan, 2001. Direct power control of grid-connected wound rotor induction machine without rotor position. IEEE. Trans., pp: 390-399.

El Aimani, S., 2003. Modelling of generated harmonics from a wind energy conversion system based on a doubly fed induction generator. Elec. Motion., pp: 629-634.

Leonhard, W., 1996. Control of Electrical Drives. New York: Springer-Verlag (2nd Edn).

Pena, R., J.C. Clare and G.M. Asher, 1996. Doubly fed induction generator using back-to-back PWM converters ands its application to variable-speed wind-energy generation. IEEE. Proc., pp: 231-241.

Petersson, A., 2003. Analyse, Modeling and control of doubly-fed induction generators for wind turbines, tutorial's thesis, Chalmers University of Technology, Göteborg, Sweden.

Peresada, S., A. Tilli and A. Tonielli, 2003. Indirect stator flux-oriented output feedback control of a doubly fed induction machine. IEEE. Trans. Control Sys. Tech., pp: 875-888.

Zhang, L. and C. Watthanasarn, 1998. A Matrix Converter Excited Doubly-Fed Induction Machine as A Wind Power Generator. IEEE. Conf. Pub., pp: 532-537.