THE INPUT-OUTPUT LINEARIZING CONTROL SCHEME OF THE DOUBLY-FED INDUCTION MACHINE AS A WIND POWER GENERATION

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Abstract: *The non-linear state-feedback input-output linearizing control with tracking controllers for a doubly fed induction generator connected to utility grid and driven by a wind turbine is presented. A space vector modulation back-to-back PWM three-level converter is used. The paper discusses the operating principles of the power generation scheme. Simulation results show that the input-output linearizing control provides decoupled control and perfect tracking of the generated active and reactive powers.*

Key words: *Doubly fed induction machine, wind turbine, input-output feedback linearization, space vector modulation, back-to-back three-level converters.*

1. Introduction

The wind power generation using a variable-speed constant-frequency scheme (VSCF) produces electricity for a wide range of wind speeds. One commonly used VSCF is the well-known Sherbius drive, employs a doubly fed wound-rotor induction generator (DFIG) using an AC-DC-AC converter in rotor circuit, [1][2][3]. Such a scheme requires a low rating as it only handles the rotor sleep power, [4]. Moreover, the configuration generates low distortion current to the grid and enables flexible control of the active and reactive power components of the generated power. Thus increasing transmission efficiency and enhancing voltage stability, [5].

To achieve a decoupled control of the DFIG active and reactive powers, the so-called vector control is generally used; this is realized by regulating the rotor current components in the magnetizing stator flux reference frame, [6][7][8]. The main difference between various control realizations is the way of determining the stator flux vector. If the stator flux is regulated to a constant value, the discussed vector control assures asymptotic decoupled control of the DFIG's active and reactive powers, as well as linear relation-ship between the inputs and the outputs, [9][10][11]. But when the stator flux varies, this control is no longer decoupled, and the performances of the drive are affected.

In attempt to achieve a high performances decoupled control of the DFIG's active and reactive powers in the steady state as well as during the transients of the start flux, a different non-linear control structure must be used. In [12][13][14], the control design method based on the input-output linearization induction motor model is described. The proposed control structure includes two essential parts: the non-linear state feedback and the non-linear state variables transformation. It assures decoupled control of the DFIG's active and reactive powers and linear relationship between the inputs and the outputs in the steady state as well as during stator flux transients.

The focus of this paper is to show that the input-output linearzing control, in contrast to the vector control, assures decoupled control of the doubly fed active and reactive powers even during the stator flux transients, and that perfect tracking of reference trajectories can be achieved.

2. System configuration

Two voltage source converters VSC control the DFIG system used in wind turbines as shown in Figue 1. The converter on the rotor side, controls the torque and the field in the machine. The converter on the grid side controls the DC-link voltage and the reactive power to the grid from the converter. The active power transmitted to the grid is the sum of stator power P_s and rotor power P_r , assuming the power converter is loss less, $P_r = P_g$, P_g is the active power from the grid side converter.

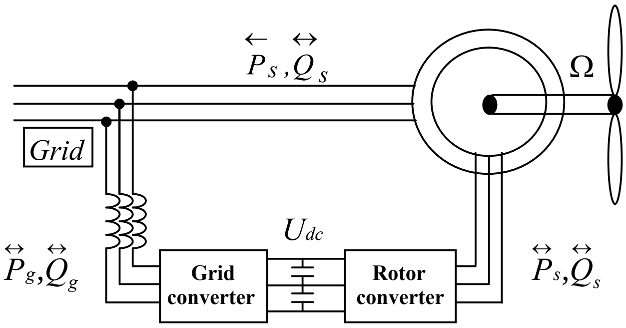

Fig. 1. DFIG system used.

Depending on the DFIG operating modes P_r may be either drawn from the grid to compensate the rotor losses or supplied to the grid. For sub-synchronous mode when rotor angular speed ω is less than the mains angular frequency ω_g , the power flows from the grid to the rotor; otherwise the rotor power is supplied to the grid. Hence the net DFIG generated power is $P_s \pm P_r$. The reactive power Q_s is determined by the machine excitation requirement and the desired grid power factor.

The control objective is to ensure that the phase shift between the grid voltage and machine supplied current is at the desired value for a given power developed by the turbine that is determined by the wind speed.

As is known for wind speeds within the range from cut-in to rated level, the mechanical power generated by the wind turbine varies according to the turbine shaft speed [3]. Figure 2 shows a typical set of wind turbine output-power/shaft speed characteristics for a 3kW machine.

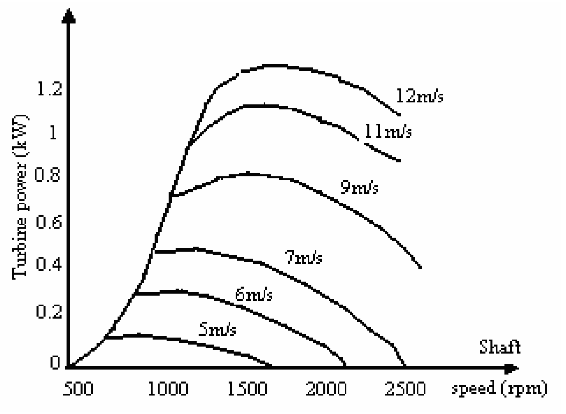

Fig. 2 Wind turbine output power to shaft speed characteristic curves

3. Input-output linearizing control of the DFIG

As shown in [15][16] the doubly fed induction machine can be expressed in a stator-flux oriented reference frame by the flowing equations:

$$\frac{di_{ims}}{dt} = \frac{R_s M}{L_s}\left(i_{rd} - i_{ms}\right) + \frac{u_{sd}}{M} \qquad (1)$$

$$\omega_{ms} = \frac{u_{sq}}{M i_{ms}} + \frac{R_s M}{L_s}\frac{i_{rq}}{i_{ms}} = \frac{d\rho}{dt} \qquad (2)$$

$$\frac{d\omega_m}{dt} = -\frac{p^2 M^2}{J L_s} i_{ms} i_{rq} - \frac{p}{J} T_l \qquad (3)$$

$$u_{rd} - \left(\frac{M}{L_s}\right) u_{sd} = \left[R_r + R_s\left(\frac{M}{L_s}\right)^2\right] i_{rd} + \sigma L_r \frac{di_{rd}}{dt} - $$
$$ - \left(\omega_{ms} - \omega_m\right)\sigma L_r i_{rq} - R_s\left(\frac{M}{L_s}\right)^2 i_{ms} \qquad (4)$$

$$u_{rq} - \left(\frac{M}{L_s}\right) u_{sq} = \left[R_r + R_s\left(\frac{M}{L_s}\right)^2\right] i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + $$
$$ + \left(\omega_{ms} - \omega_m\right)\sigma L_r i_{rd} - \left(\frac{M}{L_s}\right)^2 \omega_m i_{ms} \qquad (5)$$

T_l is the load torque and T_e is machine torque on the shaft:

$$T_e = -\frac{pM^2}{L_s} i_{ms} i_{rq}$$
(6)

J is the inertia of the rotating parts of the machine, σ is the total leakage factor.

Before applying the non-linear control to the DFIG active and reactive power control, a feedback linearization theory for multivariable systems is described, which is referred to in [17][18].

Consider a multi-input multi-output (MIMO) system as:

$$\begin{cases} \dot{x} = f(x) + g.u \\ y = h(x) \end{cases} \qquad (7)$$

Where: x state vector ; u control inputs ;
y outputs ; f, g smooth vector fields ;
h smooth scalar function.

An approach to obtain the input-output linearization of the MIMO system is to differentiate the output y of the system until the inputs appear. By differentiating (7):

$$\dot{y}_i = L_f h_i + \sum_{j=1}^{m} \left(L_{gj} h_i\right) u_j \tag{8}$$

Where $L_f h$ and $L_g h$ represent Lie derivatives of $h(x)$ with respect to $f(x)$ and $g(x)$ respectively. If $L_{gj} h_i(x) = 0$ for all j, then the inputs u do not appear and we have to differentiate respectively as:

$$y_i^{(r_i)} = L_j^{r_i} h_i + \sum_{j=1}^{m} \left(L_{gj} L_f^{r_i - 1} h_i\right) u_j \tag{9}$$

With $L_{gj} L_f^{r_i-1} h_i \neq 0$ for all least one j.

If we perform the above procedure for each input y_i, we can obtain a total of m equations in the above form, which can be written completely as:

$$\begin{bmatrix} y_1^{(r_1)} \\ \cdots \\ \cdots \\ y_m^{(r_m)} \end{bmatrix} = \begin{bmatrix} L_f^{r_1} h_1(x) \\ \cdots \\ \cdots \\ L_f^{r_m} h_m(x) \end{bmatrix} + E(x) \begin{bmatrix} u_1 \\ \cdots \\ \cdots \\ u_m \end{bmatrix} \tag{10}$$

Where the $m \times m$ matrix $E(x)$ is defined as:

$$E(x) = \begin{bmatrix} L_{g1} L_f^{r_1-1} h_1 & \cdots & \cdots & L_{gm} L_f^{r_1-1} h_1 \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ L_{gm} L_f^{r_m-1} h_m & \cdots & \cdots & L_{gm} L_f^{r_m-1} h_m \end{bmatrix} \tag{11}$$

The matrix $E(x)$ is called the decoupling matrix for the MIMO system. If $E(x)$ is non-singular, then the input transformation can be obtained as:

$$u = -E^{-1}(x) \begin{bmatrix} L_f^{r_1} h_1(x) \\ \cdots \\ \cdots \\ L_f^{r_m} h_m(x) \end{bmatrix} + E^{-1}(x) \begin{bmatrix} v_1 \\ \cdots \\ \cdots \\ v_m \end{bmatrix} \tag{12}$$

Substituting (12) into (10) results in a linear differential relation between the output y and the new input v :

$$\begin{bmatrix} y_1^{(r_1)} \\ \cdots \\ \cdots \\ y_m^{(r_m)} \end{bmatrix} = \begin{bmatrix} v_1 \\ \cdots \\ \cdots \\ v_m \end{bmatrix} \tag{13}$$

Note that the above input-output relation is decoupled, in addition to being linear.

4. Non-linear control of the DFIG

When the DFIG dynamic model of the equation (1) till equation (6) is expressed in the form of (12), we obtain:

$$f(x) = [f_1 \ f_2 \ f_3 \ f_4]^T \ ;$$

$$f_1 = \frac{1}{\sigma L_r}\left(-\left[R_r + R_s \left(\frac{M}{L_s}\right)^2\right] i_{rd} - \sigma L_r \omega_m i_{rq} + \right.$$
$$\left. + \frac{\sigma L_r}{M} u_{sq} \frac{i_{rq}}{i_{ms}} + \frac{\sigma L_r}{L_s} R_s \frac{i_{rq}^2}{i_{ms}} + R_s \left(\frac{M}{L_s}\right)^2 i_{ms}\right) \tag{14}$$

$$f_2 = \frac{1}{\sigma L_r}\left(-\left[R_r + R_s \left(\frac{M}{L_s}\right)^2\right] i_{rq} + \sigma L_r \omega_m i_{rd} - \right.$$
$$\left. - \frac{\sigma L_r}{M} u_{sq} \frac{i_{rd}}{i_{ms}} - \frac{\sigma L_r}{L_s} R_s \frac{i_{rd} i_{rq}}{i_{ms}} + \frac{M^2}{L_s} \omega_m i_{ms}\right) \tag{15}$$

$$f_3 = \frac{R_s M}{L_s}\left(i_{rd} - i_{ms}\right) + \frac{u_{sd}}{M} \tag{16}$$

$$f_4 = -\frac{p^2 M^2}{J L_s} i_{ms} i_{rq} - \frac{p}{J} Tl \quad (17)$$

$g = [g_1 \;\; g_2]$;

$$g_1 = \begin{bmatrix} \frac{1}{\sigma L_r} & 0 & 0 & 0 \end{bmatrix}^T ,$$

$$g_2 = \begin{bmatrix} 0 & \frac{1}{\sigma L_r} & 0 & 0 \end{bmatrix}^T \quad (18)$$

$$\begin{aligned} x &= [x_1 \quad x_2 \quad x_3 \quad x_4]^T \\ &= [i_{rd} \quad i_{rq} \quad i_{ms} \quad \omega_m]^T \end{aligned} \quad (19)$$

$$u = \begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} u_{rd} - \frac{M}{L_s} u_{sd} \\ u_{rq} - \frac{M}{L_s} u_{sq} \end{bmatrix} \quad (20)$$

Since there are two control inputs for the given system, we should have two outputs for input-output decoupling. We choose the two outputs as:

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} Q_s \\ P_s \end{bmatrix} \quad (21)$$

With:

$$Q_s = -u_{sq} i_{sd} + u_{sd} i_{sq} \quad (22)$$

$$P_s = u_{sd} i_{sd} + u_{sq} i_{sq} \quad (23)$$

these powers can be expressed as

$$Q_s = -\frac{M}{L_s} \left[u_{sq} \left(i_{ms} - i_{rd} \right) + u_{sd} i_{rq} \right] \quad (24)$$

$$P_s = \frac{M}{L_s} \left[u_{sd} \left(i_{ms} - i_{rd} \right) - u_{sq} i_{rq} \right] \quad (25)$$

Differentiating y_1 and y_2 until a control input appears:

$$\dot{Q}_s = -\frac{M}{L_s} \Big[\dot{u}_{sq} \left(i_{ms} - i_{rd} \right) + u_{sq} \left(f_3 - f_1 \right) + \dot{u}_{sd} i_{rq} + u_{sd} f_2 - u_{sq} g_1 u_d + u_{sd} g_2 u_q \Big] \quad (26)$$

$$\dot{P}_s = \frac{M}{L_s} \Big[\dot{u}_{sd} \left(i_{ms} - i_{rd} \right) + u_{sd} \left(f_3 - f_1 \right) - \dot{u}_{sq} i_{rq} - u_{sq} f_2 - u_{sd} g_1 u_d - u_{sq} g_2 u_q \Big] \quad (27)$$

Arranging (26) and (27) in the form of (10):

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = A(x) + E(x) \begin{bmatrix} u_d \\ u_q \end{bmatrix} \quad (28)$$

Where:

$$A(x) = \begin{bmatrix} \frac{M}{L_s} \Big[-\dot{u}_{sq} \left(i_{ms} - i_{rd} \right) - u_{sq} \left(f_3 - f_1 \right) - \dot{u}_{sd} i_{rq} - u_{sd} f_2 \Big] \\ \frac{M}{L_s} \Big[\dot{u}_{sd} \left(i_{ms} - i_{rd} \right) + u_{sd} \left(f_3 - f_1 \right) - \dot{u}_{sq} i_{rq} - u_{sq} f_2 \Big] \end{bmatrix}$$

$$E(x) = \begin{bmatrix} \frac{M}{L_s} u_{sq} g_1 & -\frac{M}{L_s} u_{sd} g_2 \\ -\frac{M}{L_s} u_{sd} g_1 & -\frac{M}{L_s} u_{sq} g_2 \end{bmatrix}$$

Since $E(x)$ is non singular, the control law is given from (12) as:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = E^{-1}(x) \left[-A(x) + \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \right] \quad (29)$$

For tracking control, the new control inputs are given by

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_1^* - k_{11} e_1 \\ \dot{y}_2^* - k_{21} e_2 \end{bmatrix} \quad (30)$$

where $e_1 = y_1^* - y_1 = Q_s^* - Q_s$ and $e_2 = y_2^* - y_2 = P_s^* - P_s$, then the output errors are governed by

$$\dot{e}_1 + k_{11} e_1 = 0 \quad (31)$$

$$\dot{e}_2 + k_{21} e_1 = 0 \quad (32)$$

By locating the desired poles on the left-half plane, the gains k_{ij} are calculated and asymptotic tracking control to the reference is achieved.

Even though the non-linear system can be linearized by exact feedback linearization, there may exist a tracking error in the presence of parameter variations. To eliminate this tracking error, we add integral actions to (30) as:

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_1^* - k_{11} e_1 - k_{12} \int e_1 dt \\ \dot{y}_2^* - k_{21} e_2 - k_{22} \int e_2 dt \end{bmatrix} \quad (33)$$

From (33), then we obtained errors dynamics as :

$$\ddot{e}_1 + k_{11} \dot{e}_1 + k_{12} e_1 = 0 \quad (34)$$

$$\ddot{e}_2 + k_{21} \dot{e}_2 + k_{22} e_2 = 0 \quad (35)$$

Since $u_1 = u_d = u_{rd} - \frac{M}{L_s} u_{sd}$

And $u_2 = u_q = u_{rq} - \frac{M}{L_s} u_{sq}$, the resultant rotor voltage references to be modulated by SVMPWM rotor converter are given by:

$$u_{rd}^* = u_d^* + \frac{M}{L_s} u_{sd} \quad (36)$$

$$u_{rq}^* = u_q^* + \frac{M}{L_s} u_{sq} \quad (37)$$

5. Simplified input-output feedback linearization

The aim of the proposed method is to achieve a simultaneous control of the considered outputs that are the active power to be injected in the dc-bus P_g , and the reactive power of this later U_{dc} [4]. So, if P_{load} denote the active power consumed by the load, which is given by :

$$P_{load} = u_{rd} i_{rd} + u_{rq} i_{rq} \quad (38)$$

So, the relationship between the two kinds of power is expressed as:

$$\dot{Q}_c = P_g - P_{load} \quad (39)$$

Taking into account the relations (38) and (39):

$$\dot{Q}_c = C U_{dc} \dot{U}_{dc} = P_g - P_{load} \quad (40)$$

The regulation error of on the reactive power is:

$$e_Q = Q_c^* - Q_c \quad (41)$$

The derivation of the equation (41) gives:

$$\dot{e}_Q = \dot{Q}_c^* - \dot{Q}_c \quad (42)$$

Taking into account the equations (38), (39) and (42):

$$\dot{e}_Q = \dot{Q}_c^* - \left(P_g^* - P_{load}\right) \quad (43)$$

If the reactive power controller is a proportional gain, the following control law governs this error:

$$\dot{e}_Q = -k_Q e_Q \quad (44)$$

In the case of the PI controller, the equation (44) must be modified as:

$$\dot{e}_Q = -k_{Q1} e_Q - k_{Q2} \int e_Q dt \quad (45)$$

The coefficients k_Q are calculated by a pole placement.
The equations (43) and (44) serve to determine the active power reference to be injected into the dc-bus:

$$P_g^* = \dot{Q}_c^* + k_Q e_Q + P_{load} \qquad (46)$$

From the equation (46), it's clear that P_{load} acts as a disturbance.
The stator currents component $i_{s\alpha}^*$ and $i_{s\beta}^*$ are given by:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \begin{bmatrix} u_\alpha^{inv} & u_\beta^{inv} \\ -u_\beta^{inv} & u_\alpha^{inv} \end{bmatrix}^{-1} \begin{bmatrix} P_g^* \\ Q_g^* \end{bmatrix} \qquad (47)$$

The voltages u_α^{inv} and u_β^{inv} are the inverter output voltage components in the stationary reference frame.
The active power reference can be calculated from an other method which consists to regulate directely the dc-bus voltage U_{dc} (Fig.3).

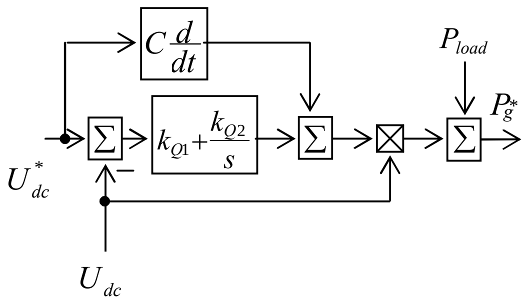

Fig.3 The input/output linearization method applied to the dc-bus voltage regulation.

6. Simulation results

The proposed DFIM control has been simulated for the machine parameters (1.5kW, 4 poles, U_s=220V(RMS), R_s=4.85Ω, R_r=3.805Ω, L_s=0.274H, L_r=0.274H, M=0.258H).

A. Rotor side control
Results shown in Fig.4 and 5 were obtained when the DFIG is operated in super synchronous mode; the active power is increased from –1200W to 800W while the reactive power is set to 800Var.
The rotor current waveform when the generator shaft speed is gradually increased through synchronous speed is shown in Fig.6. and 7 it is seen that smooth transition of the rotor currents from sub to super synchronous modes is achieved. The fluctuations of the synchronous rotor currents i_{rd} and i_{rq}, and of the magnetizing current i_{ms} and also of the stator voltages u_{sd} and u_{sq} are essentially due to the stator resistance effect which introduce a nonlinear aspect between the active and reactive powers. The different results presented indicate that stable operation of the DFIG can be realized by means of nonlinear input-output feedback linearization algorithm.

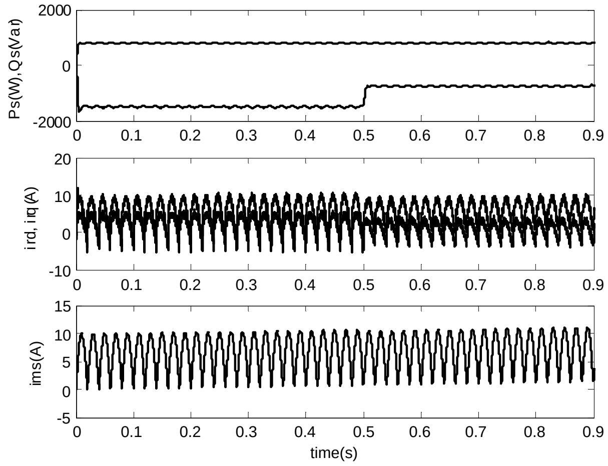

Fig.4 Step responses to active and reactive powers in super synchronous mode

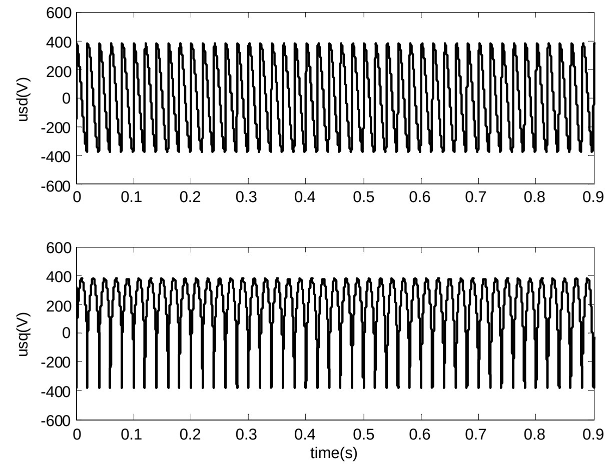

Fig.5 Synchronous stator voltag

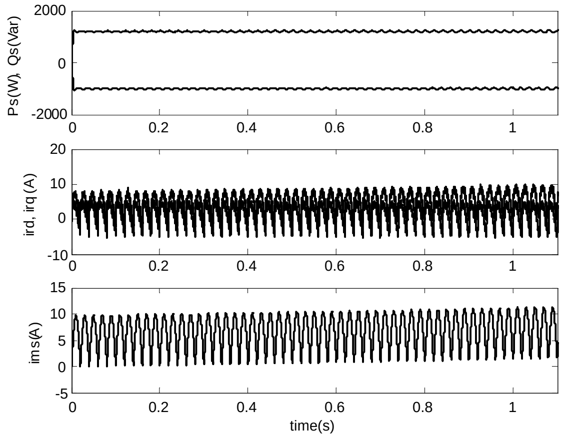

Figure 6 tep responses to active and reactive powers during shaft acceleration through synchronous speed

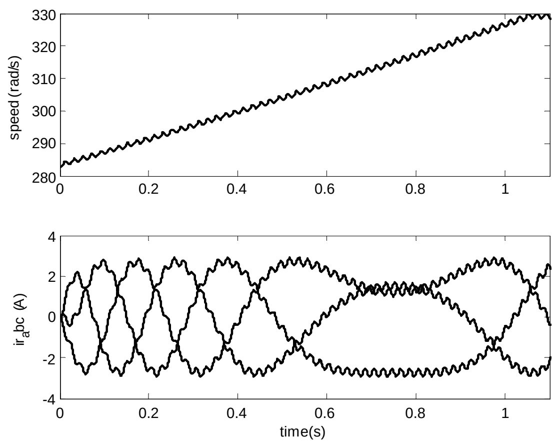

Fig. 7 Rotor currents during shaft acceleration through synchronous speed

B. DC-Bus voltage control

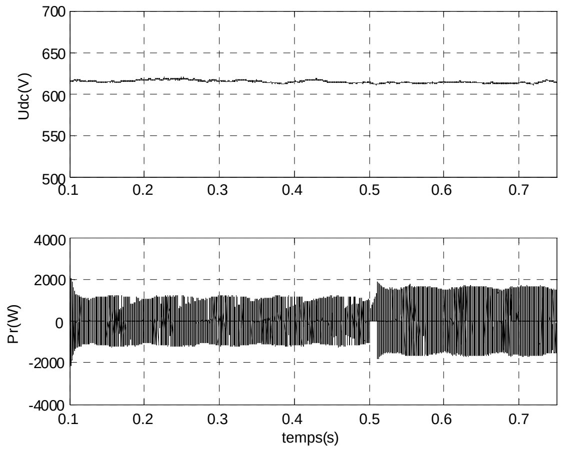

Fig.8 DC-bus voltage regulation under $P_{load} = P_r$ variations

The Fig.8 shows the DC-Bus voltage control performance by the simplified input-output feedback linearization technique presented when the grid converter is operated at unity power factor. In spite of the rotor power demand P_r variation which acts as a disturbance, the DC-Bus voltage regulation is not affected.

7. Conclusion

A variable speed wind power generator using a DFIG with an AC-DC-AC converter is proposed. Stable and independent control of the DFIG active and reactive powers by applying the nonlinear input-output feedback linearization method is demonstrated. For a comparable complexity of control structures, the input-output linearizing control provides better dynamic performances of DFIG powers control than the vector control does.

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