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Nonlinear control algorithm for a self-excited induction generator for wind power applications

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Abstract - *A non-linear state-feedback input-output linearizing control with tracking controllers for an isolated Induction Generator (IG) driven by a wind turbine and supplying an AC load is presented. For this purpose, an appropriate mathematical model of the IG based on the so-called stator-flux field oriented is detailed. Simulation results show that the input-output linearizing control provides an excellent control performances and a perfect tracking for both IG stator voltage magnitude and DC bus voltage. The proposed system can be directly explored for wind power generation purposes. Simulation results are curried out to demonstrate the feasibility of the proposed approach.*

Résumé - *Un état non-linéaire de commande d'entrée-sortie de linéarisation avec les contrôleurs de suivi pour un générateur à induction isolé (IG) entraîné par une turbine éolienne et fournissant une charge CA est présenté. A cette fin, un modèle mathématique approprié du générateur à induction sur la base du flux statorique du champ orienté est détaillé. Les résultats des simulations montrent que le contrôle d'entrée-sortie de linéarisation fournit un contrôle excellent des performances et un suivi parfait à la fois pour l'ampleur de la tension statorique du générateur et de la tension continue du bus. Le système proposé peut être directement exploré à des fins de production d'énergie éolienne. Les résultats de simulation sont réalisés pour démontrer la faisabilité de l'approche proposée.*

Mots clés: Cellule solaire tandem - Mode dichroïque - Division du spectre.

1. INTRODUCTION

The use of induction generators is becoming more and more popular for renewable energy sources, especially for wind electric systems, both in grid connected and stand alone mode. It is well known that the induction generator can operate in self-excited mode using only the input mechanical power from the rotating prime mover and a source of reactive power. The reactive power can be supplied by a variety of methods, from simple capacitors to complex power conversion systems.

Owing to its many advantages, the Self-Excited Induction Generator (SEIG) has emerged from among the well known generators as a suitable candidate to be driven by wind turbine. Some of its advantages are small size and weight, robust construction, absence of separate source for excitation and reduced maintenance cost.

When the induction generator is connected to an infinite power net, the analysis becomes simple, since the voltage and frequency are determined by the driving network. However, an autonomous induction machine is able to generate electric power only if self excitation occurs [1-6] and it can be sustained. The main drawback of such

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generators however is its inherently poor voltage regulation, and it becomes necessary to have an appropriate voltage regulating scheme.

To overcome poor voltage regulation of the Self-Excited Induction Generator (SEIG), a number of schemes have been proposed. The scheme based on switched capacitors finds limited application because it regulates the terminal voltage in discrete steps [7-9].

A saturable reactor scheme of voltage regulation involves potentially large size and weight due to the necessity of a large saturating inductor [10, 11].

In the short shunt and long shunt configuration, the series capacitor used causes the problem of resonance while supplying power to an inductive load [12, 13].

Schemes discussed above with their disadvantages can outline by the use of the pulse-width modulated voltage source inverter and it can eliminate all the problems caused by these schemes.

Researches concerning this topic know another way through the different algorithms of control where we can essentially count field oriented control. The use of field oriented control strategies for voltage regulation constrained researchers to neglect the voltage drop across the stator and rotor leakage impedance to simplify the model [14-16].

We chose to control our system the input-output linearization technique that will take into account all of the nonlinearities of this system.

In this paper, the used technique is going to improve the induction generator stator voltage and the DC bus voltage control performances. It shows the feasibility of designing a nonlinear controller with good performance even beyond some specific operating points, as this is the drawback of linear controllers.

2. GLOBAL SYSTEM MODELING

The schematic system contains essentially an induction generator (IG) excited by a three-phase capacitor bank and a pulse width modulation (PWM) bi-directional voltage-fed inverter. The IG is connected to the PWM inverter AC side through filter inductances (Fig. 1).

Moreover, a capacitor in the DC side of the PWM inverter is employed as the voltage source. The capacitor bank and converter can supply the required reactive power to regulate both the IG output and the dc-link voltages.

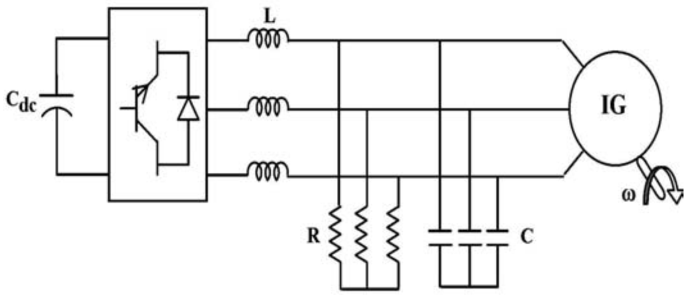

Fig. 1: Global system structure

3. INDUCTION MACHINE-PWM INVERTER d-q MODEL

In the synchronous reference frame, the induction generator model is given by:

$$\begin{cases} -v_{ds} = R_s \times i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_s \times \varphi_{qs} \\ -v_{qs} = R_s \times i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_s \times \varphi_{ds} \\ 0 = R_r \times i_{dr} + \frac{d}{dt}\varphi_{dr} - \omega_r \times \varphi_{qqr} \\ 0 = R_r \times i_{qr} + \frac{d}{dt}\varphi_{qr} + \omega_r \times \varphi_{dr} \end{cases} \tag{1}$$

$$\omega_r = \omega_s - \omega$$

$$\varphi_{ds} = l_s \times i_{ds} + \varphi_{dm} \qquad \varphi_{qs} = l_s \times i_{qs} + \varphi_{qm}$$

$$\varphi_{ds} = l_s \times i_{ds} + \varphi_{dm} \qquad \varphi_{qr} = l_r \times i_{qr} + \varphi_{qm}$$

$$\varphi_{dm} = M \times i_{dm} \qquad \varphi_{qm} = M \times i_{qm}$$

$$i_{dm} = i_{ds} + i_{dr} \qquad i_{qm} = i_{qs} + i_{qr}$$

where subscripts d and q are used to indicate direct and quadrature axis, respectively.

s, r and i denote stator, rotor and inverter quantities.

v, i and φ represent instantaneous voltages, currents and fluxes respectively.

subscript m is used to indicate magnetizing related variables.

l_s, l_r and M are leakage inductances and magnetizing inductance respectively.

ω and ω_s are rotor and d_q frame angular speed respectively.

R_s and R_r are the stator and rotor resistances respectively.

C and R are the shunt capacitor and resistor load respectively.

L is the inductance of the AC side filter of the PWM converter.

Equations of the shunt capacitor and the load resistor in the synchronously rotating reference frame can be presented also by:

$$\begin{cases} v_{ds} = v_{di} + L \times \frac{d i_{di}}{dt} - L \times \omega_s \times i_{qi} \\ v_{qs} = v_{qi} + L \times \frac{d i_{qi}}{dt} - L \times \omega_s \times i_{qi} \end{cases} \tag{2}$$

$$\begin{cases} i_{ds} = i_{di} + C \times \frac{d v_{ds}}{dt} - C \times \omega_s \times v_{qs} + \frac{v_{ds}}{R} \\ i_{qs} = i_{qi} + C \times \frac{d v_{qs}}{dt} + C \times \omega_s \times v_{ds} + \frac{v_{qs}}{R} \end{cases} \tag{3}$$

The boost rectifier dq model can be presented as:

$$\begin{cases} v_{di} = \frac{1}{2} S_d \times v_{dc} \\ v_{qi} = \frac{1}{2} S_q \times v_{dc} \end{cases} \tag{4}$$

Finally, the DC bus voltage equation is given by:

$$C_{dc}\frac{d\nu_{dc}}{dt} = \frac{1}{2}\left(S_d \times i_{di} + S_q \times i_{qi}\right) \tag{5}$$

C_{dc} is the DC link capacitor filter and ν_{dc} is the DC output voltage.

S_d and S_q are the Park's transformation of the switching functions S_a, S_b and S_c for the PWM technique and their state is defined by the following function:

$$S_k = \begin{cases} +1, & \overline{S}_k = -1 \\ -1, & \overline{S}_k = +1 \end{cases} \quad \text{for} \quad k = a, b, c$$

When the induction generator is operated under the vector control conditions, the rotor flux estimator can be expressed as:

$$\frac{di_{dm}}{dt} = \frac{R_r}{L_r} \times (i_{ds} - i_{dm}) \tag{6}$$

and the synchronous frame velocity is given by:

$$\omega_s = \omega + \frac{R_r}{L_r} \times \frac{i_{qs}}{i_{dm}} \tag{7}$$

The variables to be controlled are the stator voltages magnitude and the DC voltage in the DC side.

The DC bus voltage must be more than the peak of stator voltage for satisfactory PWM control.

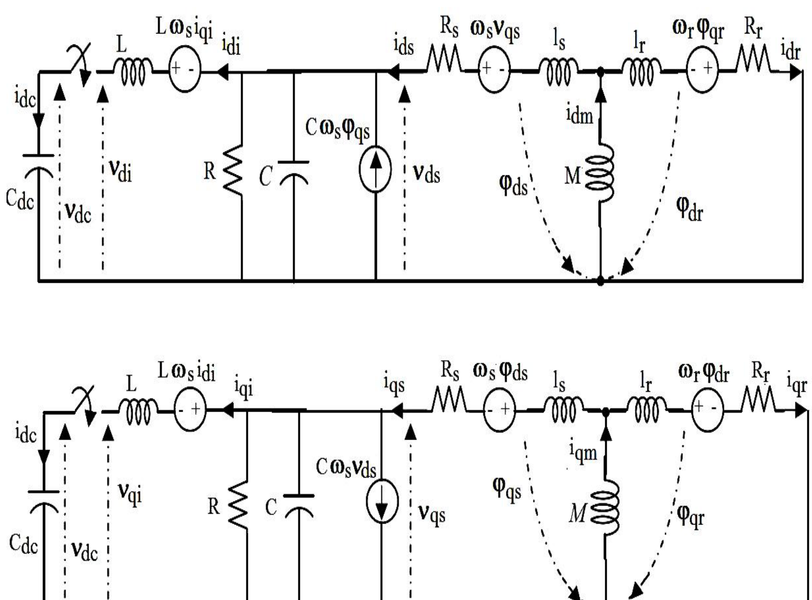

Fig. 2: d-q model of induction generator with capacitor bank and load resistor

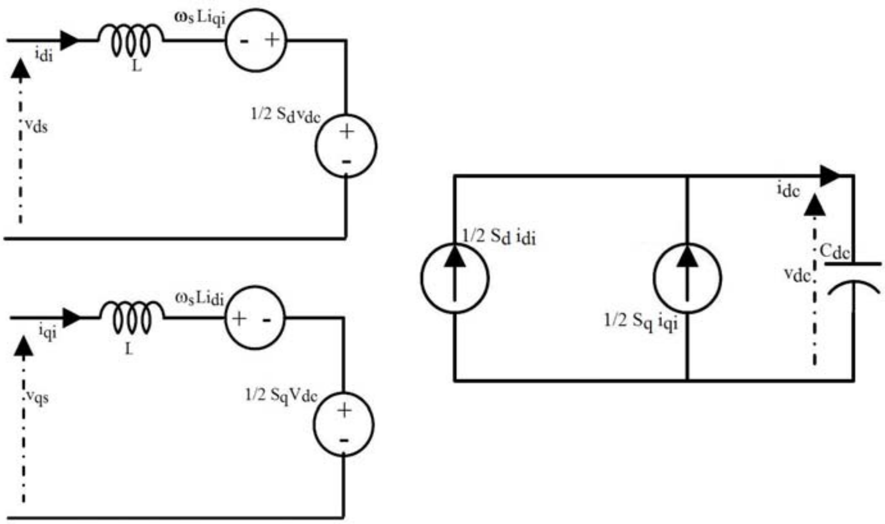

Fig. 3: d-q model of the boost rectifier

4. INDUCTION GENERATOR CONTROL

A nonlinear control system of the induction generator and its loads is obtained by applying a feedback linearization technique where its compact form is written as [17-21]:

$$\begin{cases} \dot{x} = f(x) + g(x) \times u \\ y = h(x) \end{cases} \tag{8}$$

where, x state vector; u controls 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.

When the global system dynamic model of the equation (1) till equation (3) is expressed in the form of (8), we obtain:

$$x = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 \end{bmatrix}^T = \begin{bmatrix} i_{ds} & i_{qs} & v_{ds} & v_{qs} & i_{di} & i_{qi} & v_{dc} \end{bmatrix}^T$$

$$u = \begin{bmatrix} u_1 & u_2 \end{bmatrix}^T = \begin{bmatrix} v_{di} & v_{qi} \end{bmatrix}^T$$

$$\frac{di_{ds}}{dt} = \frac{1}{\sigma L_s}\left[v_{ds} - \left(R_s + \frac{M^2}{L_r^2} \times R_r \right) \times i_{ds} + \frac{M^2}{L_r^2} \times R_r \times i_{dm} \right] + \omega_s \times i_{qs} = f_1(x)$$

$$\frac{di_{qs}}{dt} = \frac{1}{\sigma L_s}\left[v_{qs} - \left(R_s + \frac{M^2}{L_r^2} \times R_r \right) \times i_{qs} - \omega \times \frac{M^2}{L_r^2} \times i_{dm} \right] - \omega_s \times i_{ds} = f_2(x)$$

$$\frac{dv_{ds}}{dt} = \frac{1}{C}\left[i_{ds} - \frac{v_{ds}}{R} - i_{di} \right] + \omega_s \times v_{qs} = f_3(x)$$

$$\frac{d\nu_{qs}}{dt} = \frac{1}{C}\left[i_{qs} - \frac{\nu_{qs}}{R} - i_{qi} \right] - \omega_s \times \nu_{ds} = f_4(x)$$

$$\frac{di_{di}}{dt} = \frac{1}{L}\left[\nu_{ds} - \nu_{di}\right] + \omega_s \times i_{qi} = f_5(x) - \frac{1}{L}\times u_1$$

$$\frac{di_{qi}}{dt} = \frac{1}{L}\left[\nu_{qs} - \nu_{qi}\right] - \omega_s \times i_{di} = f_6(x) - \frac{1}{L}\times u_2$$

$$\frac{d\nu_{dc}}{dt} = \frac{2}{2\times C_{dc}\times \nu_{dc}}\times\left(i_{di}\times u_1 + i_{qi}\times u_2\right)$$

$$g = \left[g_1 \quad g_2\right]$$

$$g_1 = \left[0 \quad 0 \quad 0 \quad 0 \quad -\frac{1}{L} \quad 0 \quad \frac{3i_{di}}{2C_{dc}\times\nu_{dc}}\right]^T \text{ and } g_2 = \left[0 \quad 0 \quad 0 \quad 0 \quad 0 \quad -\frac{1}{L} \quad \frac{3i_{qi}}{2C_{dc}\times\nu_{dc}}\right]^T$$

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

The two considered outputs are the DC bus voltage ν_{dc} and the square stator voltage magnitude ν_s^2.

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \nu_{dc} \\ \nu_s^2 \end{bmatrix} \tag{9}$$

The square stator voltage magnitude is expressed as:

$$\nu_s^2 = \nu_{ds}^2 + \nu_{qs}^2 \tag{10}$$

Differentiating y_1 and y_2 until a control input appears, we get:

$$\dot{y}_1 = \frac{d\nu_{dc}}{dt} = \frac{3}{2C_{dc}\times x_7}\times\left(x_5 u_1 + x_6 u_2\right)$$

$$\ddot{y}_2 = \frac{d^2\nu_s^2}{dt^2} = \frac{2}{C}\times\begin{bmatrix} f_3\left(x_1 - \frac{x_3}{R} - x_5\right) + x_3\left(f_1 - \frac{f_3}{R} - f_5\right) \\ +f_4\left(x_2 - \frac{x_4}{R} - x_6\right) + x_4\left(f_2 - \frac{f_4}{R} - f_6\right)\end{bmatrix} + \frac{2}{LC}\times(x_3 u_1 + x_4 u_2)$$

The equations may be rewritten in matrix form as:

$$\begin{bmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{bmatrix} = A(x) + E(x)\times\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{11}$$

Now if u is selected as:

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = E(x)^{-1}\times\left[\begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} - A(x)\right] \tag{12}$$

where:

$$\begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{bmatrix} \qquad A(x) = \begin{bmatrix} 0 \\ Q \end{bmatrix}$$

$$Q=\frac{2}{C}\times\left[f_3\left(x_1-\frac{x_3}{R}-x_5\right)+x_3\left(f_1-\frac{f_3}{R}-f_5\right)+f_4\left(x_2-\frac{x_4}{R}-x_6\right)+x_4\left(f_2-\frac{f_4}{R}-f_6\right)\right]$$

$$E(x)=\begin{bmatrix}\frac{3x_5}{2C_{dc}\times x_7} & \frac{3x_6}{2C_{dc}\times x_7}\\ \frac{2x_3}{L\times C} & \frac{2x_4}{L\times C}\end{bmatrix}$$

If the error function is defined by:

$$e = y_{ref} - y \tag{13}$$

The tracking control law assumes the following form:

$$\begin{bmatrix}\nu_1\\ \nu_2\end{bmatrix}=\begin{bmatrix}\dot{y}_{1ref}-k_{11}e_1\\ \ddot{y}_{2ref}-k_{21}\dot{e}_2-k_{22}e_2\end{bmatrix} \tag{14}$$

and the tracking error dynamics will be governed by equations:

$$\begin{cases}\dot{e}_1+k_{11}e_1=0\\ \ddot{e}_2+k_{21}\dot{e}_2+k_{22}e_2=0\end{cases} \tag{15}$$

An integral control action can be added to improve the control performances:

$$\begin{bmatrix}\nu_1\\ \nu_2\end{bmatrix}=\begin{bmatrix}\dot{y}_{1ref}-k_{11}e_1-k_{12}\int e_1\,dt\\ \ddot{y}_{2ref}-k_{21}\dot{e}_2-k_{22}e_2-k_{23}\int e_2\,dt\end{bmatrix} \tag{16}$$

The closed loop error equations including the additional integral actions are given by:

$$\begin{cases}\ddot{e}_1+k_{11}\dot{e}_1+k_{12}e_1=0\\ \dddot{e}_2+k_{21}\ddot{e}_2+k_{22}\dot{e}_2+k_{23}e_2=0\end{cases} \tag{17}$$

For the choice of the different controllers' parameters, we have used the well known poles placement method.

Fig. 4 shows the control structure used. In absence of capacitor bank, the system starts its excitation process from an external battery but when using three phase AC capacitors the self-excited induction generator can start its voltage build-up from a remnant magnetic flux in the core.

The voltage build-up process starts when the induction generator is driven at a given speed and an appropriate capacitance is connected at its terminals [5].

5. SIMULATION RESULTS

Simulation work has been implemented using MATLAB/SIMULINK programming toolboxes.

The proposed control has been simulated for an induction machine with the following parameters (the rated power $P = 1.5\,kW$, $\cos\varphi = 0.8$, 4 poles and the rated voltage $V = 220\,V$ (rms)), whose per-phase equivalent circuit constants are:

$l_s = l_r = 16\,mH$, $M = 0.258\,H$, $R_s = 4.85\,\Omega$ and $R_r = 3.805\,\Omega$.

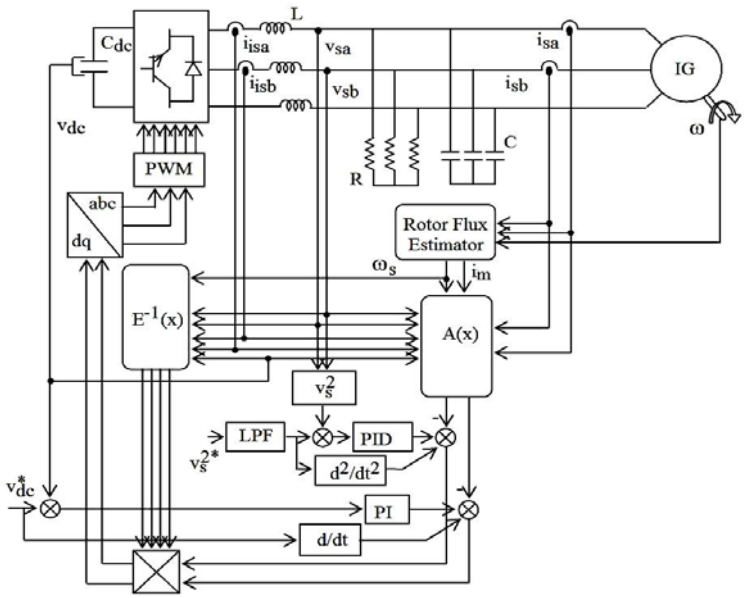

Fig. 4: Scheme control with an AC/DC converter with PWM controllers

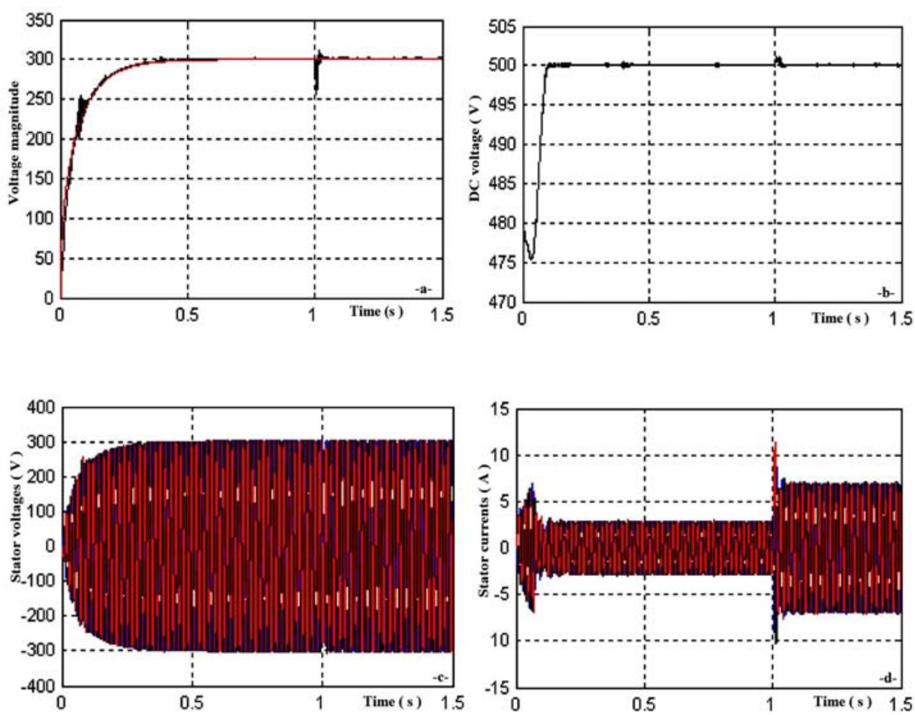

Fig. 5: Dynamics of the SEIG during startup and load variation at 1 s,
-a- Voltage magnitude, -b- DC link voltage, -c- Stator voltages, -d- Stator currents

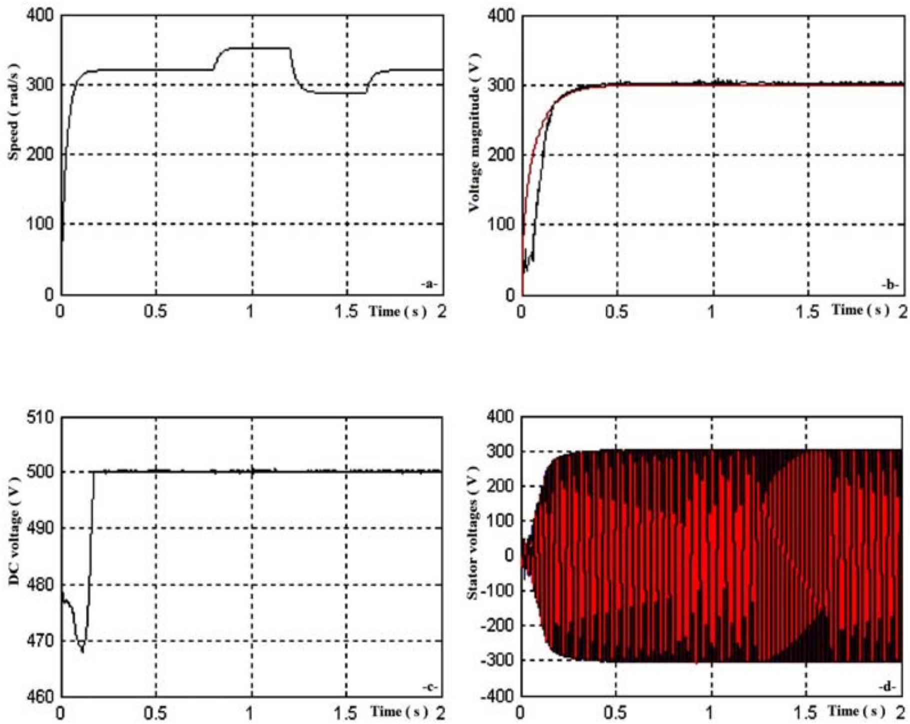

Fig. 6: Dynamics of the SEIG during startup and speed variation with constant load(50Ω)
-a- Electrical speed, -b- Voltage magnitude, -c- DC link voltage, -d- Stator voltages

The SEIG stator voltage regulation is obtained using the proposed algorithm controller in spite of the presence of disturbances such as step changing of the resistive load. Figure 5 shows a no-load operation flowed up by a step changing of the resistive load (50 Ω) introduced at $t = 1$ s when the DC-bus voltage is set to $V_{dc}^{*} = 500$ V. A rapid response is obtained and the introduced perturbation is immediately rejected by the control system.

The dynamic responses of the loaded induction generator (50 Ω) in the case of the speed variation (when the SEIG is driven by a wind turbine for example) are shown in figure 6. It is shown from the results that the input references of the stator voltages magnitude and the DC-bus voltage are perfectly tracked.

6. ROBUSTNESS AGAINST VARIATION IN GENERATOR PARAMETERS

To verify the robustness of the proposed nonlinear control algorithm, some parameters changing is considered (case of stator rotor resistances changing).

Figure 7 shows the control system performances when the resistances are augmented by 50 % with respect to the rated values.

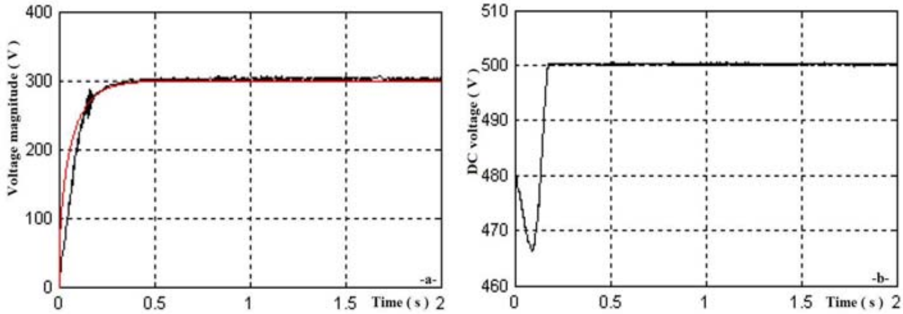

Fig. 7: Dynamics of the SEIG during start up and speed variation with constant load (50Ω) and variation in generator parameters, -a- Voltage magnitude, -b- DC link voltage

7. CONCLUSION

A variable speed system conversion using a SEIG with a PWM inverter is proposed. Stable and independent control of the SEIG stator voltages and the DC-bus voltage by applying the nonlinear input-output feedback linearization method is demonstrated.

In spite of taking in the account all the system parameters effects, the input-output linearizing control provides good dynamic performances of the global system behavior.

The proposed control structure can be integrated in a wind power conversion system.

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