Control and Stability Analysis of Doubly Fed Induction during Voltage Sags

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Abstract- **Large wind turbines are often equipped with Doubly Fed Induction Generator -DFIG-.**

Today the penetration level of wind power on the network is high. The power system stability defined as the ability of the system, for given initial operation condition, to regain a normal state of equilibrium after being subjected to a disturbance is the major problem.

In numerous papers the stability problems are pointed out and there are also many papers describing control strategies for wind turbine equipped with DFIG.

In this paper we study dynamic behavior of the DFIG during voltage sag. Also we study the ability of the Control to remind the stability of the system.

I. INTRODUCTION

Wind energy is one of the most important and promising sources of renewable energy due to its clean character and free availability. Many variable speed winds turbines have been used with induction generator, permanent magnet and eventually switched reluctance generators. Nowadays the market is oriented on the design of high power wind generation systems based on multi-pole synchronous machine or doubly fed induction generators (DFIG).

Power system stability has been recognized as an important problem for secure system operation [1]. The pining of the market of electricity obligates us to make production of the generators near their physical limits, for economic reason. It is thus necessary to evaluate these limits, in particular the risk of instability of network voltage.

Different control strategies for such kind of generator have been proposed for active and reactive power control or voltage and frequency control. Direct field oriented control for active and reactive powers is presented in [2], [3].

In the proposed paper we present the control of the Active and reactive Powers by sliding mode. The system has the ability for simultaneous maximum wind power generation for large speed range of operation and achieves soft and fast synchronization to the grid. Power converters and associated control strategies are simulated using Simulink.

Some simulation results are presented to validate the theoretical analysis and to show the behaviour and performances of the proposed structure for power control.

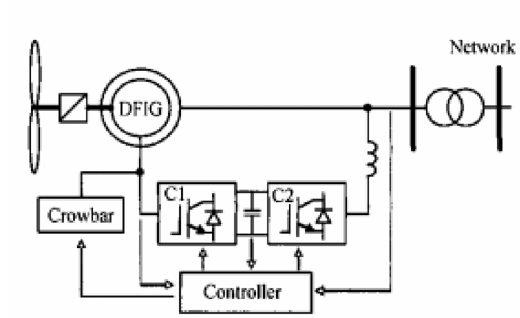


Figure.1. Representation of DFIG-based wind turbine

II. DESCRIPTION OF THE STUDIED SYSTEM

The basic configuration of the whole system is presented in Fig. 1. The rotor of DFIG is connected to the grid through two back to back bridge converters. The grid side converter (GSC) is used to control the DC-link voltage and to keep it constant regardless to the magnitude and direction of the rotor power.

The DFIG is controlled by the rotor side in order to generate the optimal active power depending on the wind speed and turbine characteristics.

III. GRID SIDE CONVERTER CONTROL

The role of the grid side converter is to keep the DC-link voltage constant regardless to the magnitude and direction of the rotor power. A vector control approach is used, allowing independent control of the active and reactive powers flowing between the supply and the GSC.

Fig.2 shows a simplified representation of the grid connected converter. AC-side series inductances accounts for transformer leakage reactance, and series resistances represents inverter and transformer conduction losses

The model of the system is given by the following equation:

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -\frac{R}{L}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L}\begin{bmatrix} V_a - V_{an} \\ V_b - V_{bn} \\ V_c - V_{cn} \end{bmatrix} \quad (1)$$

With the Park transformation, the equation system of the GSC is given by:

$$
\begin{cases}
v_{dr} = R\, i_d + L\dfrac{d\, i_d}{d\,t} - \omega_s\, L\, i_q + V_{dn} \\
v_{qr} = R\, i_q + L\dfrac{d\, i_q}{d\,t} - \omega_s\, L\, i_d + V_{qn}
\end{cases}
\tag{2}
$$

The direct axis current is used to regulate the reactive power and the quadratic axis current is used to regulate the DC-link voltage. The reference frame is considered oriented along the stator voltage vector

This method gives possibility to realise independent control of the active and reactive power between the GSC and the supply side.

The voltage components in park frame are given at the output of the PI regulator. The voltage source components and the powers can be written as:

$$
v_d = 0\,,\ v_q = V
$$

$$
P = v_q\; i_q \ \text{ and }\ Q = v_q\; i_d \tag{3}
$$

By neglecting converter losses, we have:

$$
v_{dc}\; i_{dc} = v_q\; i_q \quad , \quad C\frac{dv_{dc}}{dt} = i_{dc} - i_m \tag{4}
$$

$$
v_{dc} C\frac{dv_{dc}}{dt} = P - P_m \tag{5}
$$

Based on the above relations, the GSC control diagram can be easily deduced as presented in Fig.2

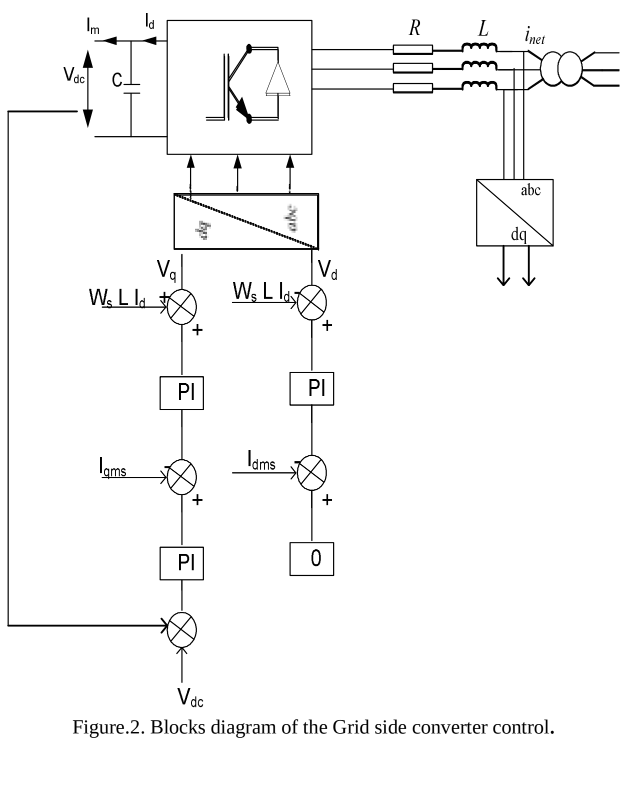


Figure.2. Blocks diagram of the Grid side converter control.

III. SLIDING MODE CONTROL

We will use the sliding Mode Control to control the rotor currents of the DFIG. The goal is to have a more stability in a disturbance cases then the PI regulators.we write the Park model of the DFIG [4] :

$$
\begin{cases}
\mathrm{V_{dqs}} = \mathrm{R_s I_{dqs}} + \dfrac{\mathrm{d\Phi_{dqs}}}{\mathrm{dt}} \mp \omega_s . \Phi_{\mathrm{qds}} \\
\mathrm{V_{dqr}} = \mathrm{R_s I_{dqr}} + \dfrac{\mathrm{d\Phi_{dqr}}}{\mathrm{dt}} \mp \omega_r . \Phi_{\mathrm{qdr}}
\end{cases}
\tag{6}
$$

$$
\begin{cases}
\Phi_{\mathrm{dqs}} = \mathrm{L_s I_{dqs}} + \mathrm{M.I_{dqr}} \\
\Phi_{\mathrm{dqr}} = \mathrm{L_s I_{dqr}} + \mathrm{M.I_{dqs}}
\end{cases}
\tag{7}
$$

By neglecting the stator resistance of the stator we can write:

$$
\begin{cases}
V_{ds} = 0 \\
V_{qs} \approx \omega_s \Phi_{ds}
\end{cases}
\tag{8}
$$

$$
\begin{cases}
\Phi_{\mathrm{dr}} = \mathrm{L_r}\sigma\ \mathrm{I_{dr}} + \dfrac{\mathrm{M}}{\mathrm{L_s}.\omega_s}\ \mathrm{V_{qs}} \\
\Phi_{\mathrm{qr}} = \mathrm{L_r}\sigma\ \mathrm{I_{qr}} + \dfrac{\mathrm{M}}{\mathrm{L_s}.\omega_s}\ \mathrm{V_{ds}}
\end{cases}
\tag{9}
$$

The general model of the machine is given by:

$$
\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix}
=
\begin{bmatrix}
R_s a\Phi_{ds} - R_s c\left(L_r\sigma I_{dr} + \dfrac{M}{L_s\omega_s}V_{qs}\right) - \omega_s\Phi_{qs} + \dfrac{d\Phi_{ds}}{dt} \\
R_s a\Phi_{qs} - R_s c\left(L_r\sigma I_{qr} + \dfrac{M}{L_s\omega_s}V_{ds}\right) + \omega_s\Phi_{ds} + \dfrac{d\Phi_{qs}}{dt} \\
R_r b\left(L_r\sigma I_{dr} + \dfrac{M}{L_s\omega_s}V_{qs}\right) - R_r c\Phi_{ds} - \omega_r\left(L_r\sigma I_{qr} + \dfrac{M}{L_s\omega_s}V_{ds}\right) + L_r\sigma\dfrac{dI_{dr}}{dt} \\
R_r b\left(L_r\sigma I_{qr} + \dfrac{M}{L_s\omega_s}V_{ds}\right) - R_r c\Phi_{qs} + \omega_r\left(L_r\sigma I_{dr} + \dfrac{M}{L_s\omega_s}V_{qs}\right) + L_r\sigma\dfrac{dI_{qr}}{dt}
\end{bmatrix}
\tag{10}
$$

With: $a = \dfrac{1}{\sigma Ls}$, $b = \dfrac{1}{\sigma Lr}$, $c = \dfrac{M}{\sigma Ls Lr}$

The state model is put in the following form:

$$
\dot{\mathrm{X}} = \mathrm{f(x,t)} + \mathrm{g(x,t)U_{dq}} \tag{11}
$$

With:

$$
U_{dq} = \left[V_{ds}\ V_{qs}\ V_{dr}\ V_{qr}\right]
$$

$$g(\mathrm{x,t})=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & \frac{1}{\sigma Lr} & 0\\ 0 & 0 & 0 & \frac{1}{\sigma Lr}\end{bmatrix}$$

$$f(\mathrm{x,t})=\begin{bmatrix}-R_s a\Phi_{ds}+R_s c\left(L_r\sigma I_{dr}+\frac{M}{L_s\omega_s}V_{qs}\right)+\omega_s\Phi_{qs}\\ -R_s a\Phi_{qs}+R_s c\left(L_r\sigma I_{qr}+\frac{M}{L_s\omega_s}V_{ds}\right)-\omega_s\Phi_{ds}\\ \frac{1}{\sigma L_r}\left(-R_r b\left(L_r\sigma I_{dr}+\frac{M}{L_s\omega_s}V_{qs}\right)+R_r c\Phi_{ds}+\omega_r\left(L_r\sigma I_{qr}+\frac{M}{L_s\omega_s}V_{ds}\right)\right)\\ \frac{1}{\sigma L_r}\left(-R_r b\left(L_r\sigma I_{qr}+\frac{M}{L_s\omega_s}V_{ds}\right)+R_r c\Phi_{ds}-\omega_r\left(L_r\sigma I_{dr}+\frac{M}{L_s\omega_s}V_{qs}\right)\right)\end{bmatrix}$$

The slip surfaces in the Park reference are defined to control the rotor currents.

They are given by the following equations [5]:

$$\begin{cases}\sigma_d=\lambda(I_{drref}-I_{dr})\\ \sigma_q=\lambda(I_{qrref}-I_{qr})\end{cases} \tag{12}$$

Where V_{dr} and V_{qr} are the two control vectors of, they force the trajectory of the system to converge towards surfaces $\sigma_{dq}=0$.

The vector U_{eqdq} is obtained by imposing $\sigma_{dq}=0$

$$f(x,t)+g(x,t)\,V_{dq}=0 \tag{13}$$

$$U_{eqdq}=\begin{bmatrix}-\left(-R_r b\left(L_r\sigma I_{dr}+\frac{M}{L_s\omega_s}V_{qs}\right)+R_r c\Phi_{ds}+\omega_r\left(L_r\sigma I_{qr}+\frac{M}{L_s\omega_s}V_{ds}\right)\right)\\ -\left(R_r b\left(L_r\sigma I_{qr}+\frac{M}{L_s\omega_s}V_{ds}\right)+R_r c\Phi_{qs}-\omega_r\left(L_r\sigma I_{dr}+\frac{M}{L_s\omega_s}V_{qs}\right)\right)\end{bmatrix} \tag{14}$$

The Fig. 3 presents the global diagram for the DFIG with sliding mode control.

V. SIMULATION RESULTS

In this section we present the simulation results of the system (Fig.1). The rotor voltage the stator voltage, the speed and the powers are keeping at their nominal values.

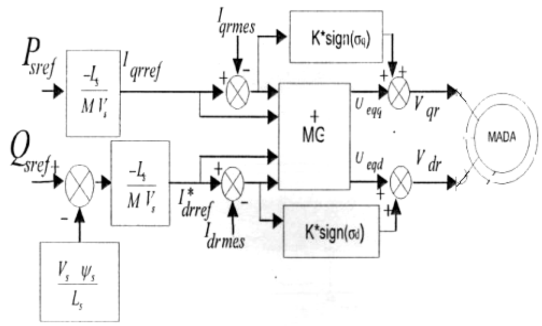


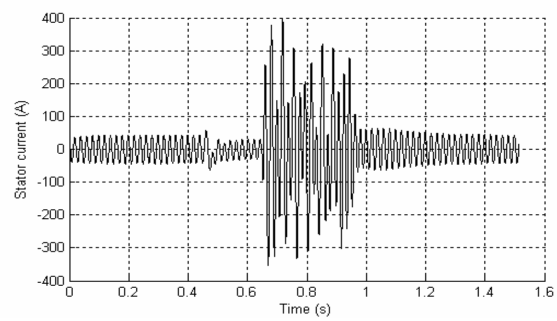
Figure.3. Sliding mode control of the DFIG

powers are keeping at their nominal values.

The DFIG used has a nominal power of 20kw.

We make a voltage sag of 50% during 200 ms (Between t=0,45s and t=0,65s).

The results in the Fig.4 (figures of the currents, powers and the torque) prove the validity of proposed model, and the good stability of the system.



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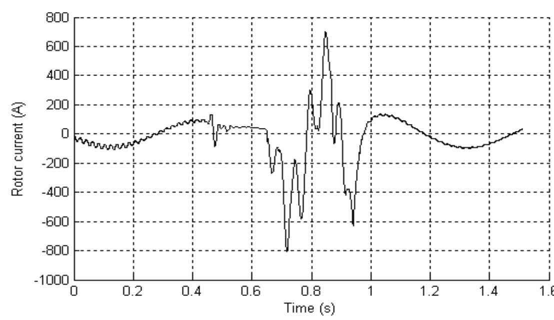

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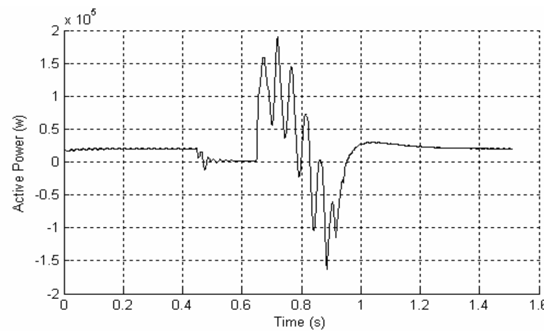

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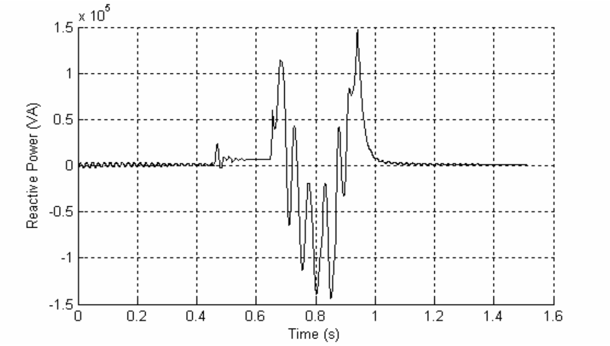

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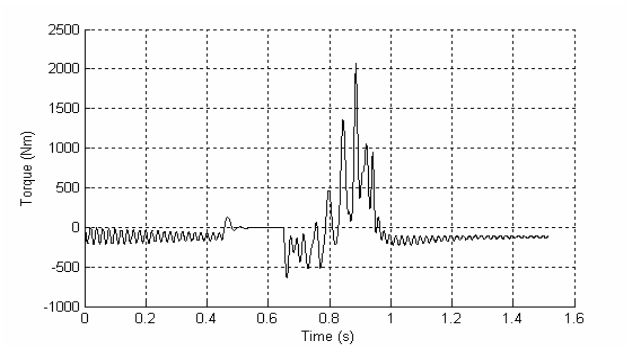

-e-

Figure.4. Dynamic behaviour of the DFIG during Voltage sag of 50 %
a- Stator Current, b- Rotor current
c- Active Power. d- Reactive Power. e- Torque

VI. CONCLUSION

In this paper a doubly fed induction generator connected to the grid was presented.

The aim of the paper was to develop the decoupled d-q vector control technique of DFIG supply by a back-to-back PWM converter in the rotor side. The control strategy contains two control levels: DFIG control level (control of active and reactive power using sliding mode approach) and the control of the grid side converter.

The mathematical model of the system (DFIG-Converters-Grid) has been implemented in MATLAB & Simulink.
The main goal of the grid side converter control is to keep the dc-link voltage constant by balancing the real power on the machine side and on the grid side converter, and to compensate reactive power of the DFIG to get the unity power factor.

The control system is applied to the rotating reference frame fixed on the gap flux of the generator. It has been proved that this control system can control the active and reactive power independently and stably.

The simulation results show that we can make decoupling between active and reactive power and in the same time have a good stability in a case of voltage sag.

Also, the DC-link voltage was kept constant to the reference value. The torque has the same dynamic like the active power.

NOMENCLATURE

J, C_{fr} : Inertia and viscous friction

Ω : Mechanical speed

$\Omega_{turbine}$: the turbine angular frequency

V_d, V_q, I_d, I_q stator and rotor Voltages, currents

$\Phi_{ds}, \Phi_{qs}, \Phi_{dr}, \Phi_{qr}$: Two-phase stator and rotor flux

$i_{ds}, i_{qs}, i_{dr}, i_{qr}$ Two-phase stator and rotor currents

I_{dms}, I_{qms} Two-phase measured rotor currents

C_r, C_e Prime mover and electromagnetic torque

R_s, R_r : Per phase stator and rotor resistance

M : Magnetising inductance

L_s, L_r : Total cyclic stator and rotor inductances

ω_s, ω_r : Pulsation

g : Generator slip

i_d, i_q Two-phase grid side converter currents

v_d, v_q Two-phase network voltages

v_{dc}, i_{dc} : Dc-bus voltage and current delivered by the grid side converter

P, Q : Active power delivered by the grid side converter and

i_m, P_m : Current and Active power delivered to the rotor side converter

C : Capacitance of the DC–ink

R, L Resistance and Inductance of the grid

P_s, P_r : Stator active power and rotor active power

$Q_s\ Q_r$: Stator reactive power and rotor reactive power

$v_{ds}, v_{qs}, v_{dr}, v_{qr}$:Two-phase stator and rot

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