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Study and Power Flow Analysis of Grid-Connected Double Fed Induction Generator as Wind Energy Conversion System

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***Abstract* – this paper deals with study and analysis of powers flow of grid-connected double fed induction generator (DFIG) driven by a wind turbine, in which the impact of the proposed rotor shaft speed has been pointed out, taking into account the three expected operation modes (Sub-synchronous, Synchronous and Super-synchronous) where the system is controlled by means of vector control strategy using a discrete PI controllers on the aim to control the stator active and reactive powers flow of the generator, with possibility to keeping stator power factor at a unity. However, regarding to the operation limits of the WECS, the powers exchange between the different parts of the system has been well analyzed.**

***Keywords*— doubly fed induction generator, WECS, active/reactive power, power factor, Sub/Super-synchronous, vector control, discret PI.**

I. INTRODUCTION

Large-scale integration of Wind Generators (WGs) with distribution systems is underway right across the globe in a drive to harness green energy. The Doubly Fed Induction Generator (DFIG) is an important type of WG due to its robustness and versatility [1]. So exploiting these advantages in WECS needs to achieve a strategy of control taking into account the complexity of the global structure, and the quality of the energy to be generated into the grid, because usually the lack or scarcity of control of the produced active and reactive powers causes problems on the electrical systems which they are connected to. Hence several designs and arrangements have been implemented so as to cope with these difficulties [2][3]. However, an alternative approach consists to use wound-rotor induction generator fed by variable frequency rotor voltage. So this topology allows extracting fixed-frequency electric power from the stator generator. One of the main advantages of these generators is that, if the rotor currents are controlled applying a vector control strategy on the commercial machine side rotor PWM converter a decoupling control of stator active and reactive powers is realized [2][4].

Since the Double Fed Induction Generator Powers flow is the focus of this paper (Fig1.A-B-C), detailed analysis of the different parts of the topology is presented, starting by the Mechanical part, which is represented by the mechanical energy delivered by the wind turbine till the power exchange between the Stator/Rotor DFIG and the electrical Grid in three possible rotor speed operation modes (Sub-synchronous, Synchronous and Super-synchronous). The analysis of the powers flow will give a deep view on the control performances in which it can be seen by the good track of the power responses of their set-points and also the efficiency of the Discrit PI controllers during the disturbance regions, as well as to have a knowledge on the WECS operating limits and in which degree the DFIG can operate without any risks, especially in the rotor circuit, by monitoring the transmitted power via the rotor and hence the rotor voltage and current [5].

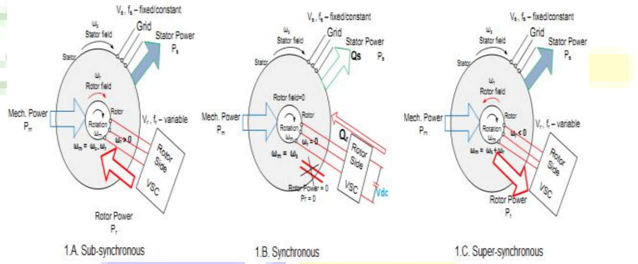

Figure1: Operating modes of DFIG [1]

II. SYSTEM MODELING

A. DFIG MODEL

The complex DFIM model in the synchronous reference frame write as follow [6]:

$$\bar{V}_s = R_s\bar{i}_s + \frac{d\bar{\Phi}_s}{dt} + j\omega_s\bar{\Phi}_s,$$
$$\bar{V}_r = R_r\bar{i}_r + \frac{d\bar{\Phi}_r}{dt} + j(\omega_s - \omega)\bar{\Phi}_r. \tag{1}$$

The current-flux equations are

$$\bar{\Phi}_s = L_s\bar{i}_s + M\bar{i}_r,$$
$$\bar{\Phi}_r = L_r\bar{i}_r + M\bar{i}_s. \tag{2}$$

The electromagnetic torque expression is

$$C_{em} = \frac{3}{2} M \mathrm{Im}\left(\bar{i}_s \otimes \bar{i}_s^*\right). \quad (3)$$

The stator power expressions are

$$P_s = \mathrm{Re}\left(\bar{V}_s \otimes \bar{i}_s^*\right),$$
$$Q_s = \mathrm{Im}\left(\bar{V}_s \otimes \bar{i}_s^*\right). \quad (4)$$

B. VECTOR CONTROL STRATEGY

To simplify calculations, let us consider the stator voltage constraint given as follows in dq-axis [4].
In dq-axis, there is

$$V_{ds} = 0,$$
$$V_{qs} = V_s. \quad (5)$$

If the stator flux vector is aligned on the d axis, it is found that:

$$\Phi_{ds} = L_s i_{ds} + M i_{dr} = M i_{ms},$$
$$0 = L_s i_{qs} + M i_{qr}. \quad (6)$$

Substitute Eq. (6) in Eq. (2), it is found that

$$\Phi_{dr} = \sigma L_r i_{dr} + \frac{M}{L_s} i_{ms},$$
$$\Phi_{qr} = \sigma L_r i_{qr}. \quad (7)$$

Where σ is the dispersion factor

$$\sigma = 1 - \frac{M^2}{L_s L_r} \quad (8)$$

The electromagnetic torque becomes

$$C_{em} = -P \frac{M}{L_r} i_{ms} i_{qr}. \quad (9)$$

Similarly, suppose that the stator resistance is neglected ($V_{sn} \approx \mathrm{d}\Phi_{sn}/\mathrm{d}t$), it is found that

$$V_s = \omega_s \Phi_s = \omega_s M i_{ms}. \quad (10)$$

Then the stator active and reactive power expressions become:

$$P_s = -k_t \omega_s \frac{M^2}{L_r} i_{ms} i_{qr},$$
$$Q_s = k_t \omega_s \frac{M^2}{L_r} i_{ms}\left(i_{ms} - i_{dr}\right). \quad (11)$$

The stator powers are decoupled and dependents to the rotor current components [3].

Substitute Eq. (7) in Eq. (1), the following equations can be obtained:

$$V_{dr} = R_r i_{dr} + \sigma L_r \frac{\mathrm{d}i_{dr}}{\mathrm{d}t} + \frac{M^2}{L_s}\frac{\mathrm{d}i_{ms}}{\mathrm{d}t} - \omega_r \sigma L_r i_{qr},$$
$$V_{qr} = R_r i_{qr} + \sigma L_r \frac{\mathrm{d}i_{qr}}{\mathrm{d}t} + \omega_r \frac{M^2}{L_s} i_{ms} + \omega_r \sigma L_r i_{dr}. \quad (12)$$

The above equations are coupled between themselves, so the coupling terms are considered as disturbances which will be removed by the controller [3][4].
In this work, Discrete PI controller is proposed and designed by the poles placement method. This choice is due to experimental implantation simplicity. The transfer function with a zero order holds (ZOH) is giving as follows [3]:

$$H(s) = \frac{\frac{K}{\tau}(1-e^{-hs})}{(1+\frac{1}{\tau})s}$$

Where: $K = \frac{1}{R_r}$, $\tau = \frac{\sigma L_r}{R_r}$ and h is the sample time.

After discrete, we obtain:

$$H(s) = \frac{K(1-e^{-\frac{h}{\tau}})}{(z-e^{-\frac{h}{\tau}})}$$

The discrete-PI has the following form:

$$PI(z) = K_p(K_i h+1)\frac{z - \frac{1}{(K_i h+1)}}{z-1}$$

The slow dynamic can be eliminated, so:

$$K_i = \frac{e^{\frac{h}{\tau}} - 1}{h}$$

The closed loop transfer function is:

$$H_{cl} = \frac{K(1-e^{-\frac{h}{\tau}})K_p(K_i.h+1)}{z-1+K(1-e^{-\frac{h}{\tau}})K_p(K_i h+1)}$$

It can be to take the response as a first order with $t_{dés}$ (Around of 1 ms), so Kp must be verified the following relation:

$$e^{-\frac{h}{\tau_{des}}} = 1 - K(1-e^{-\frac{h}{\tau}})K_p(K_i h+1) \; ; \quad K_p = \frac{(1-e^{-\frac{h}{\tau_{des}}})}{K(1-e^{-\frac{h}{\tau}})(K_i h+1)}$$

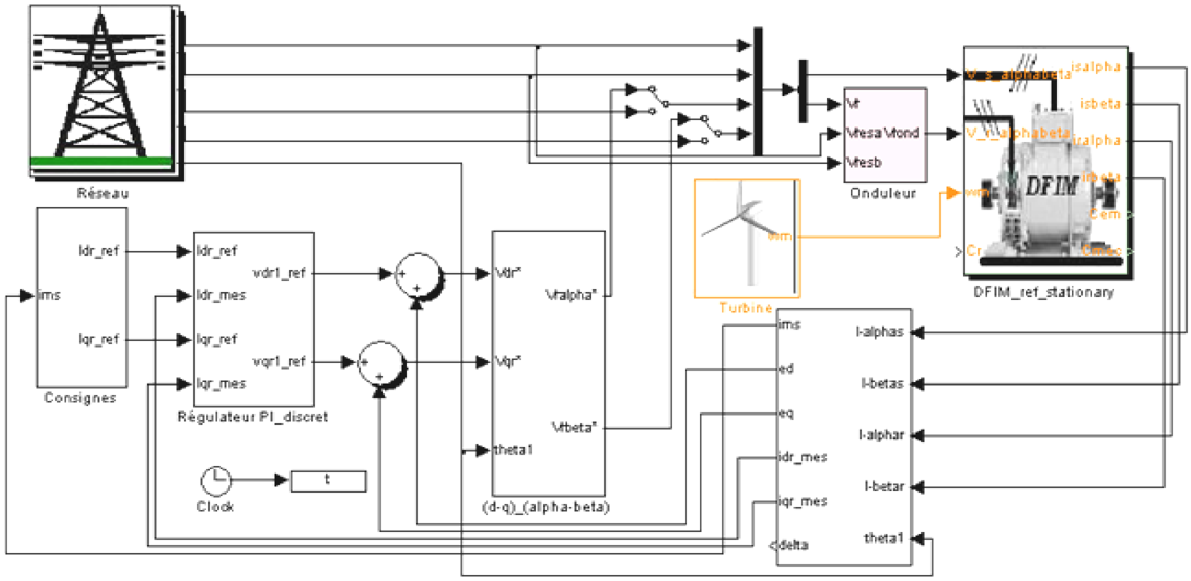

Fig.2 Simulation Scheme within Matlab/SIMULINK Environment.

III. Simulation Results

Simulations tests were carried out using the proposed scheme (Fig.2). In which the simulation is doing following to the rotor speed profile as shown in the figure (3). So all the expected operation modes were taking into account, so after the start up, the rotor speed is fixed at the minimum value which is synchronous speed minus 30% from 1 sec to 3 sec and then the rotor speed is increased to reach the synchronous speed from 4 sec to 8 sec and finally the rotor speed is increased again to reach the maximum value which is synchronous speed plus 30%.

For the stator active and reactive powers, a 5000 Watts and 0 Watt are chosen respectively as set-points.

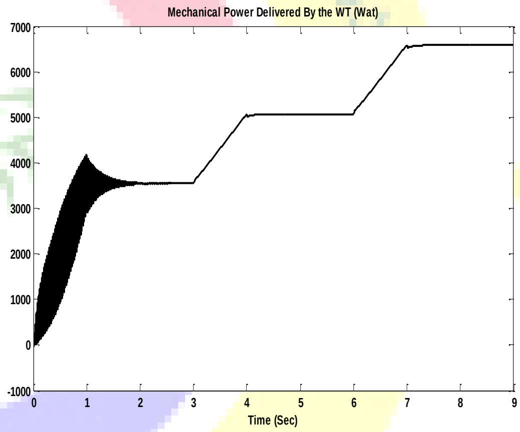

Fig.4. Mechanical Power of the Wind Turbine

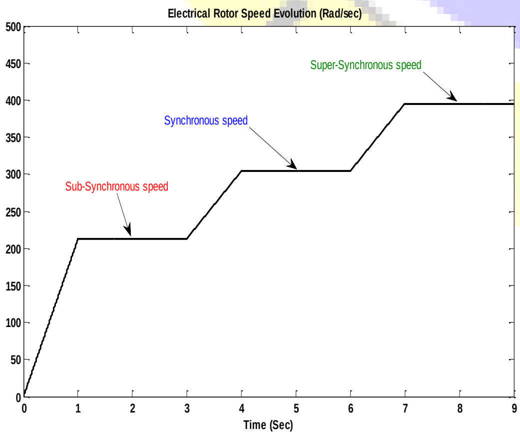

Fig.3. Electrical Rotor Speed Evolution

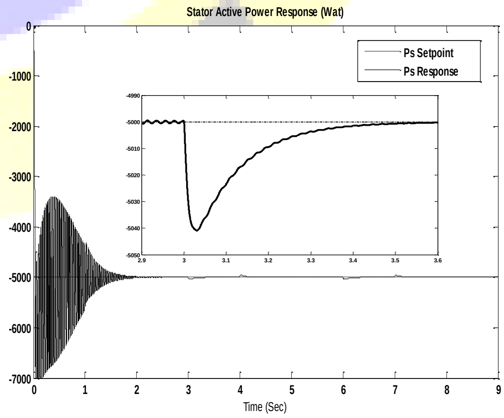

Fig.5. Stator Active Power Response

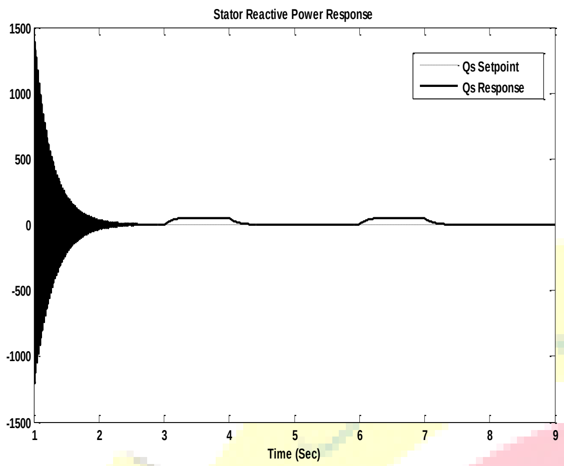

Fig.6. Stator Reactive Power Response

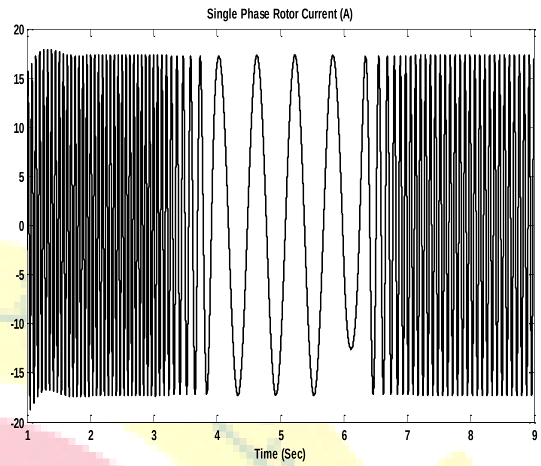

Fig.9. Single Phase Rotor Current

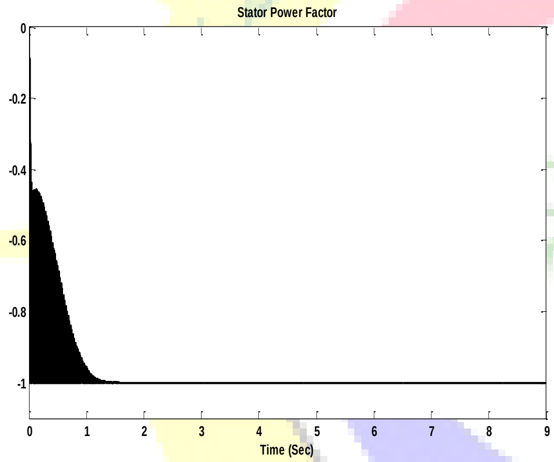

Fig.7. Stator Power Factor

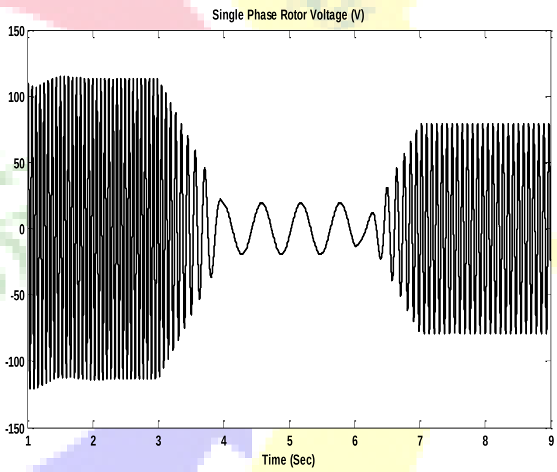

Fig.10. Single Phase Rotor Voltage

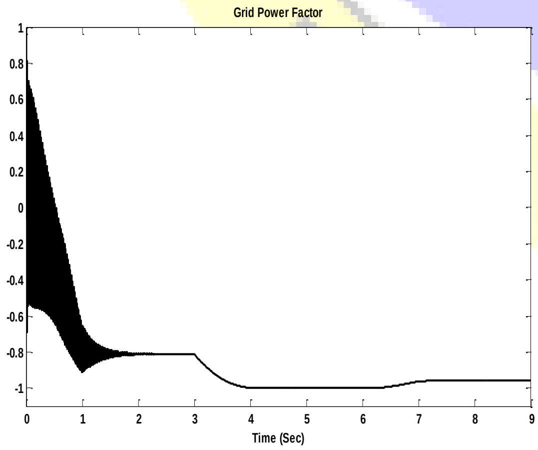

Fig.8. Grid Power Factor

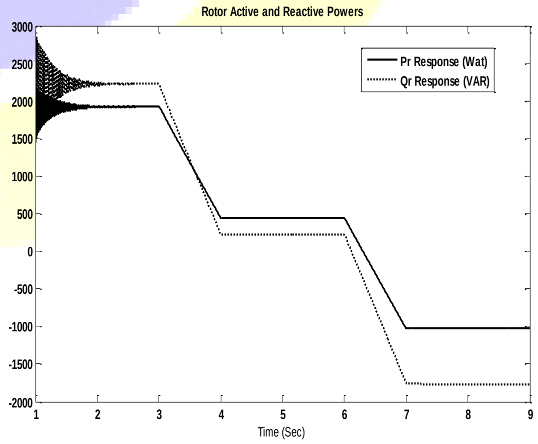

Fig.11. Rotor Active/Reactive Powers

IV. RESULTS INTERPRETATION

The simulation scenario is based on the assumption that the mechanical power of the wind turbine (see fig.2) will impose three rotor speed modes on the DFIG, as it is shown in the fig (1). So the fig (2) and fig (3) show respectively the stator active and reactive responses, so from there it can be seen clearly the good tracking of the set-points, even though there were a disturbances during the simulation test, so that's reflect the good behavior of the control structure and hence the discrit-PI controllers. Fig (4) and (5) show respectively the Stator and the Grid Power Factors, when it can be seen that the Stator Power Factor is set at unity during all the simulation test, that's mean, there is no pollution sent from the stator to the grid, However seeing the figure of the grid power factor, which is the representative of the total powers exchange quality of both Stator/Rotor and the grid, so from this figure, it is clear to see the influence of the DFIG rotor speed on the powers exchange quality. Hence in both Sub-synchronous and Super-synchronous modes the grid is largely disturbed by the rotor reactive power (See figure 11), but in the Synchronous mode there is no disturbance. Almost, the same explanation will be given for the Rotor Voltage/Current according to the rotor speed evolution and hence the admission of wind turbine mechanical power, in the Sub-synchronous mode, the mechanical power isn't enough to provide the required set-point stator power which is imposed by the control, so the compensation of this lack should be given by the grid through the rotor circuit (positive sign of the active rotor power), this results an undesirable increase in the rotor voltage amplitude (see figure 10), which may damage the rotor circuit if it is not protected. In the Synchronous mode the power exchange between the rotor and the grid is very weak (the sleep = 0) and just the power which is compensate the losses has been transmitted (see Figure 11), finally in the Super-synchronous mode, almost the same are happen but in the opposite way, where here the mechanical power is up to the required set-point, so the exceeded power will be injected to the grid through the rotor circuit (negative sign of the active rotor power), finally in the Super-synchronous mode, almost the same are happen but in the opposite way, where here the mechanical power is bigger than the required stator power set-point, so the exceeded power will be injected to the grid through the rotor circuit (negative sign of the active rotor power), and the same story is repeated regarding to the rotor voltage overshoot.

V. CONCLUSION

The DFIG (Doubly-Fed Induction Generator) is largely used in wind generators because of its important advantage which is the double accessibility. This induces the good control of the powers flow between machine and the grid. In this paper, a study and power flow analysis of the DFIG works in WECS have been investigated, when we focused on the impact of the rotor speed on the system, taking into account the three expected operation modes (Sub-synchronous, Synchronous and Super-synchronous). The obtained results demonstrate that the proposed DFIG system control which operates at the variable speed may be considered as an interesting solution in renewable energy area.

VI. REFERENCES

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I. APPENDIX

The machine parameters in the following table:

Output power	Pn=7.5 KW
Stator resistance	Rs=0.455 Ω
Rotor resistance	Rr=0.62 Ω
Stator inductance	Ls=0.084 H
Rotor inductance	Lr=0.081 H
Mutual inductance	Msr= 0.078 H
Number of poles	4
Inertia moment	j=0.3125 Nms2
Rubbing factor	f=6.73e-3

TABLE.1: DFIM parameters