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Energy Procedia 36 (2013) 1147 – 1157
Energy Procedia

TerraGreen 13 International Conference 2013 - Advancements in Renewable Energy and Clean Environment

Wind Power Control System Associated to the Flywheel Energy Storage System Connected to the Grid

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Abstract

The aim of this work is the study of the integration of the flywheel energy storage systems in the wind generators at variable speed based to the doubly fed induction generator (DFIG) and to help these generators to contribute to the ancillary services. In this paper investigates also, the control method of the flywheel energy storage system (FESS) with a classical squirrel-cage induction machine associated to a variable speed wind generation using cascade rectifier filter inverter. Simulation results of the dynamic models of the wind generator are presented, for different operating points, to show the good performance of the proposed system.

Keywords: Wind turbine, Doubly fed induction generator, Variable speed, Matrix converter, Power control, Squirrel-cage induction machine, Flywheel energy storage system.

1. Introduction

In this paper, the energy storage system associated to a grid connected variable speed wind generation scheme using a DFIG is investigated. Therefore, the dynamic behaviour of a wind generator including models of the wind turbine DFIG matrix converter, converter control and power control is studied. This direct converter is proposed to substitute the conventional converter (cascade rectifier-inverter) in the purpose of improving the performances of the wind turbine. The matrix converter (MC) eliminates the dc-link filter elements and thus resolves size, weight and reliability issues and also provides an option for the design of the converter as a compact/ modular unit [1]. However the smooth running of wind turbines connected to the grid may be hindered by the quality of the power generated, which is a stochastic nature. This limits the participation of the wind in the service system. Hence the functioning of the generator alone is practically impossible [2]. The integration of the flywheel energy storage systems in the wind generators can be helping these generators to contribute to the ancillary services [3]. This work investigates also, the control method of the flywheel energy storage system with a classical squirrel-cage induction machine (IM) associated to a variable speed wind generation using cascade rectifier filter

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doi:10.1016/j.egypro.2013.07.130

inverter. Simulation results of the dynamic models of the wind generator are presented, for different operating points, to show the good performance of the proposed system. The synoptic diagram of the studied system is represented by figure 1

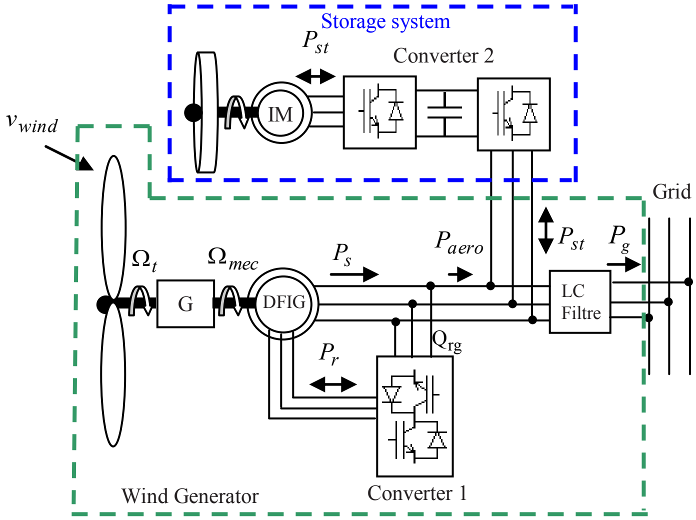


Fig.1 Scheme of the studied device

2. Modelling of the WIND GENERATOR

2.1 Modelling of the mechanical part

The total kinetic power of the wind through a wind disc of radius *R*, is given by (1)[4][5].

$$P_{wind} = \frac{1}{2}\rho\pi.R^2.v_{wind}^3 \quad (1)$$

The mechanical power, which is converted by a wind turbine, P_t is dependent on the power coefficient C_p . It is given by (2)

$$P_t = \frac{1}{2}C_p(\lambda).\rho.\pi.R^2.v_{wind}^3 \quad (2)$$

ρ Represent the air density and v_{wind} the wind velocity. A wind turbine can only convert just a certain percentage of the captured wind power. This percentage is represented by $C_p(\lambda)$ which is function of the wind speed, turbine speed and the pith angle of specific wind turbine blades [6][7]. Although this equation seems simple, C_p is dependent on the ratio λ between the turbine angular velocity Ω_t and the wind speed v_{wind} . This ratio is called the tip speed ratio.

$$\begin{cases} \lambda = \dfrac{\Omega_t.R}{v_{wind}} \\ \Omega_t = \dfrac{\Omega_{mec}}{G} \end{cases} \quad (3)$$

The aerodynamic torque is defined as the relationship between the aerodynamic power and the angular velocity of the turbine

$$T_{aero} = \frac{P_{aero}}{\Omega_t} \tag{4}$$

The machine torque shaft is T_g given by

$$T_g = \frac{T_{aero}}{G} \tag{5}$$

The mechanical speed evolution is determined from the total torque T_{mec} applied to the rotor

$$J\frac{d\Omega_{mec}}{dt} = T_{mec} \tag{6}$$

$$T_{mec} = T_g - T_{em} - T_{visq} \tag{7}$$

The torque resist due to frictions T_{visq} is modelled by a coefficient of viscous frictions f

$$T_{visq} = f.\Omega_{mec} \tag{8}$$

The expression of the optimal mechanical power $P_{mec-opt}$ is obtained as follows

$$P_{mec\_opt} = \frac{1}{2}\frac{C_{p_{\max}}.\rho.\pi.R^5}{G^3.\lambda^3_{C_{p\max}}}.\Omega^3_{mec} \tag{9}$$

2.2 The DFIG model

The DFIG dynamic model in Park's reference is expressed as follows [3][9].
Voltage equations are given by

$$\begin{cases} v_{ds} = R_s i_{ds} + \dfrac{d}{dt}\phi_{ds} - \omega_s\phi_{qs} \\ v_{qs} = R_s i_{qs} + \dfrac{d}{dt}\phi_{qs} + \omega_s\phi_{ds} \\ v_{dr} = R_r i_{dr} + \dfrac{d}{dt}\phi_{dr} - (\omega_s - \omega)\phi_{qr} \\ v_{qr} = R_r i_{qr} + \dfrac{d}{dt}\phi_{qr} + (\omega_s - \omega)\phi_{dr} \end{cases} \tag{10}$$

Flux linkage equations are obtained from

$$\begin{cases} \phi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \phi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \phi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \phi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \tag{11}$$

Electromagnetic torque equation

$$T_{em} = p(\phi_{ds}.i_{qs} - \phi_{qs}.i_{ds}) \tag{12}$$

Active and reactive powers (stator and rotor) of the DFIG can be written as

$$\begin{cases} P_s = v_{ds}.i_{ds} + v_{qs}.i_{qs} \\ Q_s = v_{qs}.i_{ds} - v_{ds}.i_{qs} \\ P_r = v_{dr}.i_{dr} + v_{qr}.i_{qr} \\ Q_r = v_{qr}.i_{dr} - v_{dr}.i_{qr} \end{cases} \quad (13)$$

And the wind generator powers (active and reactive) are expressed by

$$\begin{cases} P_{aero} = P_s + P_r \\ Q_{aero} = Q_s + Q_{rg} \end{cases} \quad (14)$$

2.3 The IM model

A commonly used model for the IM is the Park model [1] [5][9]. The classical voltage equations are given as follows

$$\begin{cases} v_{sd\_IM} = R_{s\_IM}.i_{sd\_IM} + \dfrac{d\phi_{sd\_IM}}{dt} - \omega_{s\_IM}.\phi_{sq\_IM} \\ v_{sq\_IM} = R_{s\_IM}.i_{sq\_IM} + \dfrac{d\phi_{sq\_IM}}{dt} + \omega_{s\_IM}.\phi_{sd\_IM} \\ 0 = R_{r\_IM}.i_{rd\_IM} + \dfrac{d\phi_{rd\_IM}}{dt} - \omega_{r\_IM}.\phi_{rq\_IM} \\ 0 = R_{r\_IM}.i_{rq\_IM} + \dfrac{d\phi_{rq\_IM}}{dt} + \omega_{r\_IM}.\phi_{rd\_IM} \end{cases} \quad (15)$$

Where v, i, ϕ, ω, R_{s_IM} *and* R_{r_IM} represent the voltage, the current, the flux linkage, the electrical frequency and the IM resistance stator and rotor, respectively.

Subscript *s* and *r* refer to stator and rotor quantities, respectively. The subscript *d* and *q* the direct and quadratic axis components of the reference frame, respectively

Flux linkage equations are obtained from

$$\begin{cases} \phi_{sd\_IM} = L_{s\_IM}.i_{sd\_IM} + M_{IM}.i_{rd\_IM} \\ \phi_{sq\_IM} = L_{s\_IM}.i_{sq\_IM} + M_{IM}.i_{rq\_IM} \\ \phi_{rd\_IM} = L_{r\_IM}.i_{rd\_IM} + M_{IM}.i_{sd\_IM} \\ \phi_{rq\_IM} = L_{r\_IM}.i_{rq\_IM} + M_{IM}.i_{sq\_IM} \end{cases} \quad (16)$$

Electromagnetic torque is calculated as

$$T_{em\_IM} = p_{IM}\left(\phi_{sd\_IM}.i_{sq\_IM} - \phi_{sq\_IM}.i_{sd\_IM}\right) \quad (17)$$

The active and reactive stator and rotor powers are given by

$$\begin{cases} P_{s\_IM} = v_{sd\_IM}.i_{sd\_IM} + v_{sq\_IM}.i_{sq\_IM} \\ Q_{s\_IM} = v_{sq\_IM}.i_{sd\_IM} - v_{sd\_IM}.i_{sq\_IM} \end{cases} \quad (18)$$

3. MODELING OF THE AC/AC CONVERTER

Direct frequency converter called Matrix converter consists of nine bidirectional switches which are considered ideal for the ease of this presentation [8]. Each output phase is associated with three switches set connected to three input phases. This configuration of bidirectional switches enables the connection of any input phase a, b or c to any output phase A, B or C at any instant (Fig. 2).

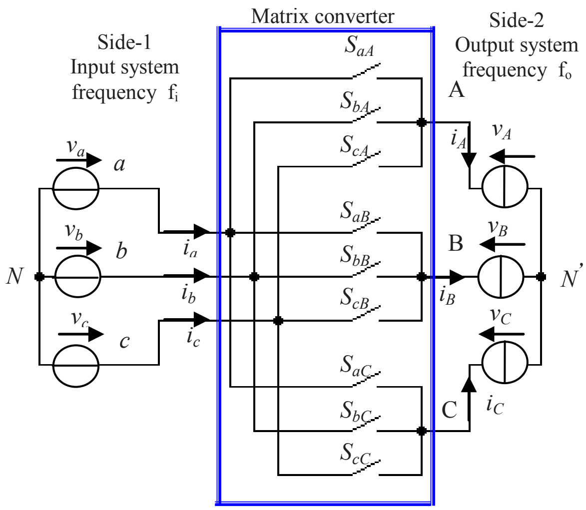


Fig 2 A matrix converter circuit

✓ . *The switching angles formulation*

The switching angles, of the nine bidirectional switches S_{ij} which will be calculated, must comply with the following rules:

1. At any time 't', only one switch S_{ij}(j=1,2,3) will be in 'ON' state. This assures that no short circuit will occur at the input terminals.
2. At any time 't', at least two of the switches S_{ij} (i=1,2,3) will be in 'ON' state. This condition guarantees a closed-loop path for the load current (usually this is an inductive current).

During the k[th] switching cycle T_s ($T_s=1/f_s$). Fig.2, the first phase output voltage is given by:

$$v_a = \begin{cases} v_A & 0 \le t-(k-1)T_s < m_{aA}^k T_s \\ v_B & m_{aA}^k T_s \le t-(k-1)T_s < \left(m_{aA}^k + m_{aB}^k\right)T_s \\ v_C & \left(m_{aA}^k + m_{aB}^k\right)T_s \le t-(k-1)T_s < T_s \end{cases} \tag{19}$$

Where m_{ij}^k are defined by:

$$m_{ij}^k = \frac{t_{ij}^k}{T_s} \tag{20}$$

Where t_{ij}^k : time interval when S_{ij} is in 'ON' state, during the k[th] cycle, and k is being the switching cycle sequence number. The m_{ij}^k has the physical meaning of duty cycle.

Also,

$$m_{iA}^k + m_{iB}^k + m_{iC}^k = 1 \quad \text{and} \quad 0 < m_{ij}^k < 1$$

Which means that during every cycle T_s all switches will turn on and off once.

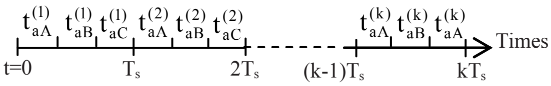


Fig. 3. Segmentation of the axis time for the consecutive orders of intervals closing of the switches

4. ACTIVE AND REACTIVE POWER CONTROL

By choosing a diphasic reference frame *d-q* related to the stator spinning field pattern, and to make the stator flux in quadrature with the *q* axis, the Park frame oriented such that [10].

$$\begin{cases} \phi_{ds} = \Phi_s \\ \phi_{qs} = 0 \end{cases} \tag{21}$$

Once ϕ_{ds} assigned to Φ_s, the electromagnetic torque will only depend on i_{qr}

$$T_{em} = -P\frac{L_m}{L_s} i_{qr} \Phi_s \tag{22}$$

By neglecting R_s per phase stator resistance, we can then write:

$$\begin{cases} v_{ds} = 0 \\ v_{qs} = V_s \end{cases} \tag{23}$$

In order to calculate angles for the Park transformation for stator and rotor variables, the stator pulsation and the mechanical speed must be sensed.

By choosing this reference frame, stator voltages and fluxes can be rewritten as follows:

$$\begin{cases} v_{ds} = 0 \quad ; \quad v_{qs} = V_s = \omega_s \Phi_s \\ \phi_{ds} = \Phi_s = L_s i_{qs} + L_m i_{qr} \quad ; \quad \phi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \phi_{qs} = 0 = L_s i_{ds} + L_m i_{dr} \quad ; \quad \phi_{qr} = L_s i_{qr} + L_m i_{qs} \end{cases} \tag{24}$$

The stator active and reactive power can then be expressed only versus these rotor currents as

$$\begin{cases} p_s = -V_s \dfrac{L_m}{L_s} i_{qr} \\ Q_s = \dfrac{V_s \Phi_s}{L_s} - \dfrac{V_s L_m}{L_s} i_{dr} \end{cases} \tag{25}$$

The expressions of the rotor voltages become

$$\begin{cases} v_{dr} = R_r i_{dr} + \left(L_r - \frac{L_m^2}{L_s} \right) \frac{di_{dr}}{dt} - s.\omega_s \left(L_r - \frac{L_m^2}{L_s} \right) i_{qr} \\ v_{qr} = R_r i_{qr} + \left(L_r - \frac{L_m^2}{L_s} \right) \frac{di_{qr}}{dt} + s.\omega_s \left(L_r - \frac{L_m^2}{L_s} \right) i_{dr} \\ +s \frac{L_m.V_s}{L_s} \end{cases} \quad (26)$$

With : s generator slip.

The active reference power is determined by the following expression

$$P_{aero\_ref} = -\eta.P_{mec\_opt} \quad (27)$$

With η is the efficiency of the DFIG

5. CONTROL OF A STORAGE SYSTEM ASSOCIATED TO A WIND GENERATOR [2][11].

By choosing a diphasic reference frame *d-q* related to the rotor spinning field pattern, and by aligning the rotor vector flux Φ_r with the axis *d*, we can write

$$\begin{cases} \phi_{dr} = \Phi_r \\ \phi_{qr} = 0 \end{cases} \quad (28)$$

Electromagnetic torque can be written as

$$T_{em\_IM} = p_{IM} \cdot \frac{M_{IM}}{L_{r\_IM}} .\Phi_{r\_IM} .i_{sq\_IM} \quad (29)$$

The electromagnetic torque will only depend on the quadratic axis stator current.

Flux linkage are expressed as follows

$$\begin{cases} \Phi_{r\_IM} = L_{r\_IM} .i_{rd\_IM} + M_{IM} .i_{sd\_IM} \\ \phi_{rq\_IM} = L_{r\_IM} i_{rq\_IM} + M_{IM} .i_{sq\_IM} = 0 \end{cases} \quad (30)$$

Voltage rotor equations are given by

$$\begin{cases} 0 = R_{r\_IM} .i_{rd\_IM} + \frac{d\Phi_{r\_IM}}{dt} \\ 0 = R_{r\_IM} .i_{rq\_IM} + (\omega_{s\_IM} - \omega_{IM}).\Phi_{r\_IM} \end{cases} \quad (31)$$

$$\Phi^*_{r\_IM} = \frac{M_{IM}}{1+\tau_r .P} .I_{sd\_IM} \quad (32)$$

Maximum power tracking controller P_{aero} and that fixed at the grid P_g as follows

$$P_{st\_ref} = P_g - P_{aero} \quad (33)$$

In our case, the power P_{st_ref} varies between –0,5 MW to +0,5 MW that are appropriate to store and with restore 30% of the power generated by the wind generator.
If P_{st_ref} is positive, it is that there is an excess energy which must be stored differently one has a deficit of energy which must be compensated.
The speed of reference for the flywheel of inertia is determined by

$$\Omega_{ref} = \sqrt{\frac{2.E_{cref}}{J}} \tag{34}$$

This speed of reference is limited in order to maintain the IM in the zone of operation at constant power and not to exceed the maximum speed of the flywheel of inertia.
The flow of reference is calculated according to speed by

$$\phi_{ref\_IM} = \begin{cases} \phi_{r\_nom}, \rightarrow if \ |\Omega_w|. \leq \Omega_{w\_nom} \\ \phi_{r\_nom}.\dfrac{\Omega_{w\_nom}}{|\Omega_w|}, \rightarrow if \ |\Omega_w| > \Omega_{w\_nom} \end{cases} \tag{35}$$

The energy of reference for the flywheel of inertia is calculated by

$$E_{cref} = E_{Co} + \int_{t1}^{t2} P_{st\_ref}.dt \tag{36}$$

E_{Co} Represent the initial energy of the flywheel.

6. Results and interpretation

In this section, the dynamic behaviour of the wind generator system (the wind generator included the storage system) is presented in figures below. The control of the transit is realized through the orientation of the flow on the axis. The results of numerical simulation are obtained powers between the system FSS, the wind generator and the network is realized by the command with a power of reference for the SISE and varies between -0.5MW with 0.5MW this reference is obtained by making the difference between the power generated by wind turbine P_{aero_mes} and that fixed at the grid which -1.5MW(the minus sign means this is a generated power) and η represents the DFIG efficiency and varies around 95% and in our study we neglected the iron losses. The losses of active and reactive power in the static inverter are neglected; therefore we can be writing

$$Q_{IM} = Q_{aero} = Q_{g\_ref} = 0$$

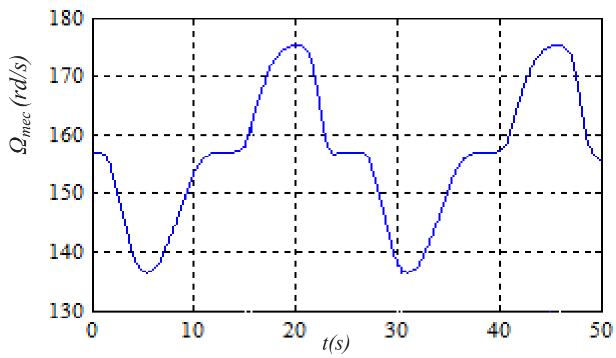


Fig 4. Random of the DFIG rotor speed

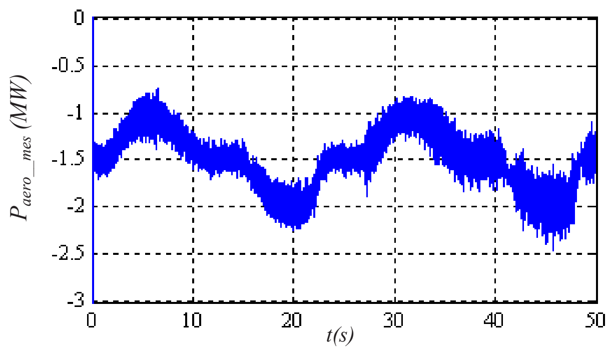


Fig 5. Wind generator power

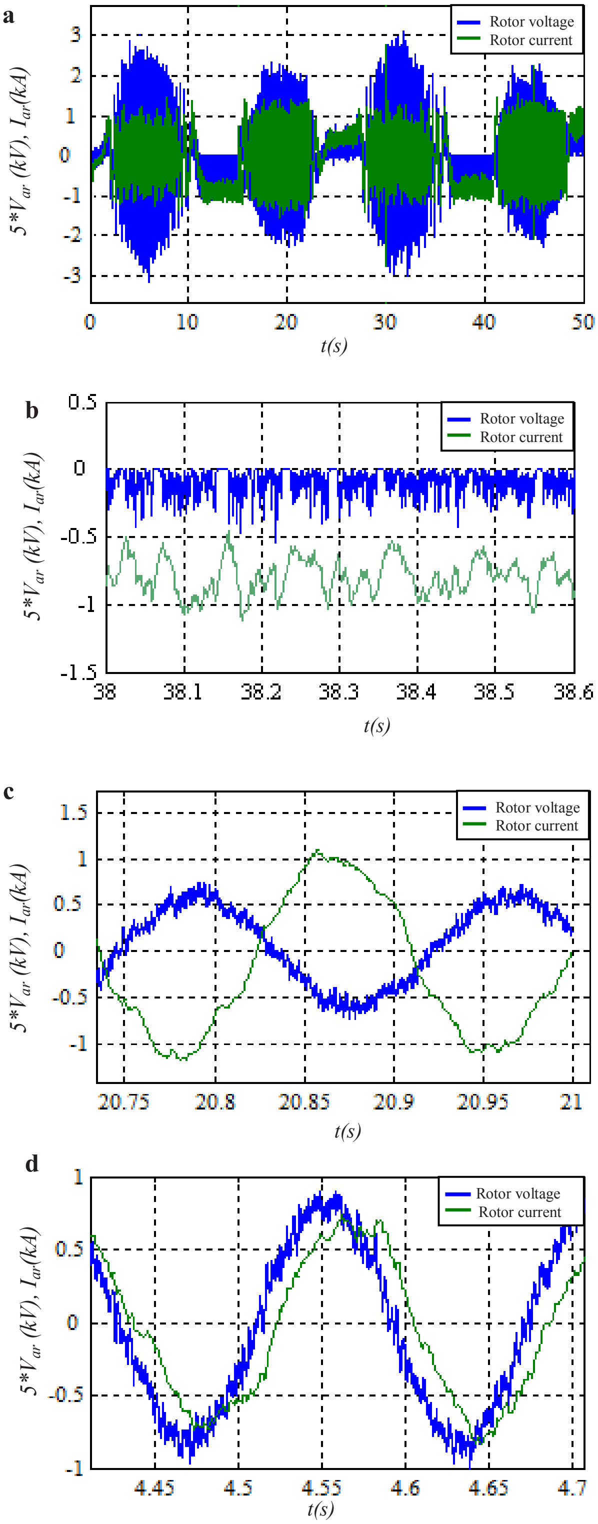


Fig 6.(a) Rotor current and voltage. (b) Zoom of rotor current and voltage(s=0). (c) Zoom of rotor current and voltage (s<0). (d) Zoom of rotor current and voltage (s>0)

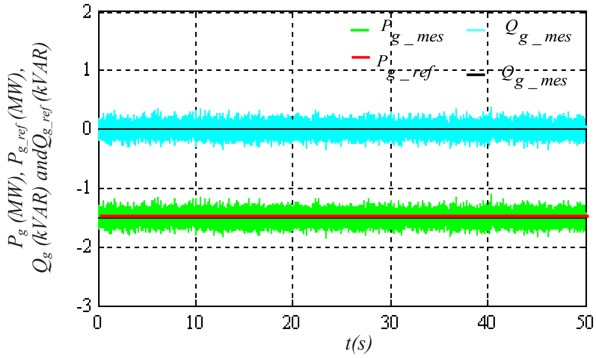


Fig 7. Grid active and reactive powers

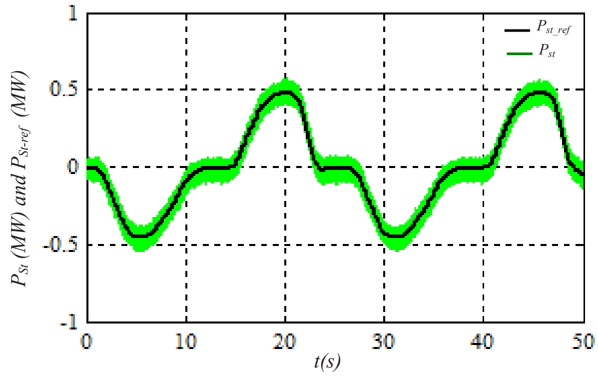


Fig 8. Reference power and delivered IM power

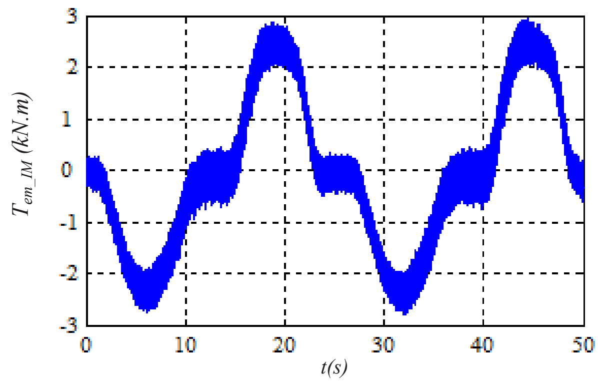
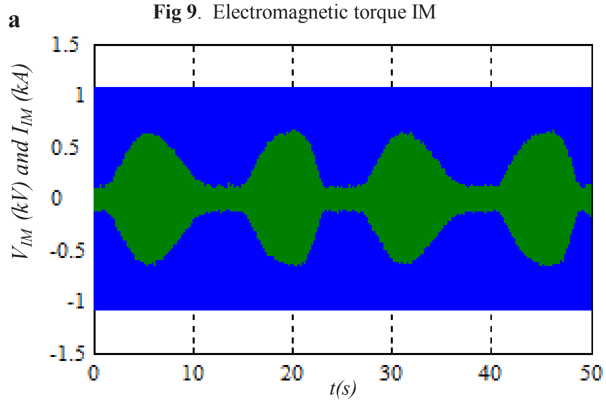
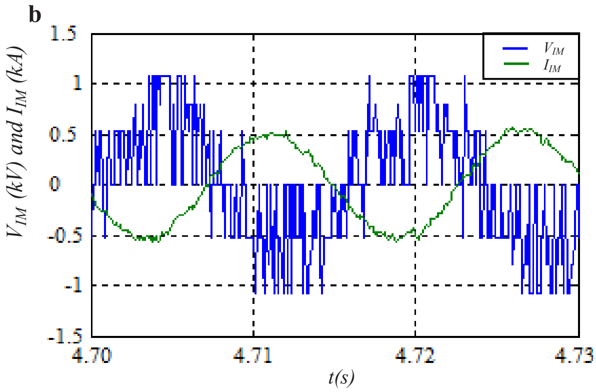


Fig 9. Electromagnetic torque IM





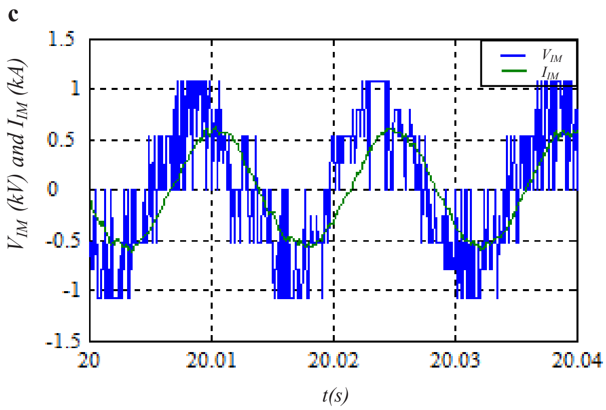


Fig 10. (a) Stator voltage and current of IM. (b) Zoom of stator voltage and current IM (generator). (c) stator of voltage and current of IM (storage).

Fig 4 represents the mechanical speed of DFIG. Fig.5 shows the variation of the electrical power output through wind generator. Fig.6.a shows the rotor voltage and current waveforms, and the frequency of those latter voltage and current vary according to the slip (Fig 6.b to Fig 6.d). For s=0 the rotor voltage and the current are continuous; and for s < 0 the current is behindhand to the voltage from an angle of $\pi < \varphi < \frac{\pi}{2}$. And for s >0 the dephasing angle between voltage and current is $0 < \varphi < \frac{\pi}{2}$ .The grid active and reactive powers are illustrated and they follow their references perfectly (Fig.7). Fig.8 shows the storage system power $P_{s.t}$ and those reference powers $P_{s.t\_ref}$. The IM electromagnetic torque is very fluctuant, like the wind generated power, and entails the freewheeling speed (Fig.9). (Fig 10.a to 10.c) shows the stator voltage and current waveforms and these zoom of the IM.

6. Conclusion

The work presented in this research is devoted to the analysis, modelling and simulation of a wind generator with variable speed based on a double fed asynchronous machine controlled by the rotor using a matrix converter associated to the flywheel storage system. The model looks, has enabled us to store almost 30% of the power delivered by the wind generator and during the corresponding period the modus operandi of the DFIG in super-synchronous which provided up to -2 MW. Over a period or mode of operation is sub-synchronous DFIG, the latter shows a deficit of power by 30% compared to the fixed grid, is offset by the FESS. The simulation results presented show the suitable operation of the storage system; in effect the power measured faithfully follows the power of reference. With this flywheel we stored and restored the power. The integration of this storage system in wind speed variable connected to the network has enabled us to smooth the power injected into the network despite the stochastic nature of the wind.

Nomenclature

$P_{s.t}$, $P_{s.t\_ref}$	Active storage power;
P_g , Q_g	Active and reactive grid power;
P_{aero}, Q_{aero}	Active and reactive generator power;
L_m, M_{IM}	Magnetizing inductance of DFIG and of induction machine respectively;
J, f	Inertia and viscous friction respectively of DFIG and turbine;
Q_{rg}	Reactive power grid side;
Ω_w	Flywheel speed;
P, P_{IM}	Number of pole pairs of DFIG and IM machine respectively;
L_s, L_r, L_{s_IM}, L_{r_IM}	Total cyclic stator and rotor inductances.

References

[1] Han Ju Cha, «Analysis and design of matrix converter for adjustable speed drives and distributed power sources», PHD Thesis, Texas A&M University, August 2004.

[2] G.O.Cimuca, «Système inertiels de stockage d'énergie associe à des générateurs éoliens» Ecole Nationale Supérieure d'Arts et Métiers, Centre de Lille, Thèse Doctorat, 2005.

[3] K. Ghedamsi, D. Aouzellag, E.M. Berkouk, « Control of wind generator associated to a flywheel energy storage system», Renewable Energy Journal 33 (2008) 2145

[4] L. Chang, «Systèmes de conversion de l'énergie éolienne», *IEEE* Canadian Review, Summer *2002*, pp: 1-5.

[5] D.Aouzellag, K.Ghedamsi, E.M.Berkouk, « Network Flow Control of the Wind Generator», Renew able Energy Journal 34 (2009) 615-622.

[6] Alesina A. Venturini M. «Intrinsic amplitude limits and optimum design of switches direct PWM ac converter». Proceeding of PSEC conference. Rec. April 1988. p, 1284 90.

[7] El Aimani S. «Modelling and simulation of doubly fed induction generator for variable speed wind turbines integrated in a distribution network». In: 10th European conference on power electronics and application. Toulouse, France 2003.

[8] S.Taraft, D.Rekioua and D.Aouzellag «Performances Study of the DFIG Associated to the Variable Speed Wind Turbine Connected to the Grid» International Journal of Electrical and Power Engineering 2(5): 353-364, 2008. ISSN: 1990-7958. Medwell Journals, 2008.

[9] F.Poitier, «Etude et commande de génératrices asynchrone pour l'utilisation éolienne», Thèse de Doctorat, Université de Nantes 2003.

[10] D.Aouzellag, K.Ghedamsi, E.M.Berkouk «Modelling of Doubly Fed Induction Generator with Variable Speed Wind Turbine for Network Power Flow Control » WSEAS TRANSACTIONS on POWER SYSTEMS, ISSN 1790 – 5060, pp: 1995 – 2000, Issue 12, Volume 1, Dec 2006.

[11] S.Taraft, D.Rekioua et D.Aouzellag «Système de stockage inertiel dédie aux éoliennes connectées aux réseau» Fifth International Conference on Electrical Engineering CEE'08 27-29 October 2008 University of Batna, pp 1-6.