2ème conférence Internationale des énergies renouvelables CIER-2014
Proceedings of Engineering and Technology - PET

Modeling and Control of IM-based Flywheel Energy-Storage System Associated to a Variable-Speed Wind Generator

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***Abstract*— The flywheel energy-storage systems (FESSs) are suitable for improving the quality of the electric power delivered by the wind generators. They are used for controlling the power flow from a variable-speed wind generator (VSWG) to the power grid or to an isolated load. The FESS is based on a squirrel-cage Induction Machine (IM) coupled to a flywheel. This paper investigates the performance evaluation of the rotor-flux oriented control (FOC) applied to IM and the space vector pulse width modulation (SVPWM) applied to rectifier. The proposed system with the control strategy adopted is validated through simulations using MATLAB- SIMULINK. The obtained results are presented and discussed.**

***Keywords*— FESS, squirrel-cage IM, rotor-FOC, SVPWM, MATLAB- SIMULINK.**

I. INTRODUCTION

In the last years, Flywheel Energy Storage Systems (FESSs) have been rediscovered by the industrials due to their advantages in comparison with other energy storage systems [1]. FESSs have thus found a specific application for the electric power quality, as far as the voltage and frequency maintenance between imposed limits is concerned. By virtue of their high dynamics, long lifetime and good efficiency, FESSs are well suited for short-term storage systems, which are generally sufficient to improve the electric power quality [1]. In the case of variable-speed wind generators (VSWGs), by using the power electronics, energy generation and storage systems can be coupled via a DC bus [2]. In such a configuration, the FESS ensures the DC-bus voltage control, thus contributing to the generation/consumption balance.

For accomplishing these objectives, a generating system, which must be able to feed isolated loads, is here considered. The wind generator must then work without auxiliary source to contribute to the generation/ consumption balance.

A low-speed FESS, whose electric machine is a classical squirrel-cage induction machine (IM), is considered in this paper. FESS is connected to the DC bus of the system in order to control the power flow from the VSWG to the isolated loads. The converter of the FESS is controlled on the one hand, by a rotor flux-oriented control strategy, on the other hand by the SVPWM technique. This paper describes the modeling and control of IM-based FESS. The proposed control system is then simulated using MATLAB- SIMULINK. The obtained results are presented and discussed.

The configuration of the studied generation system in this paper is represented in Fig 1.

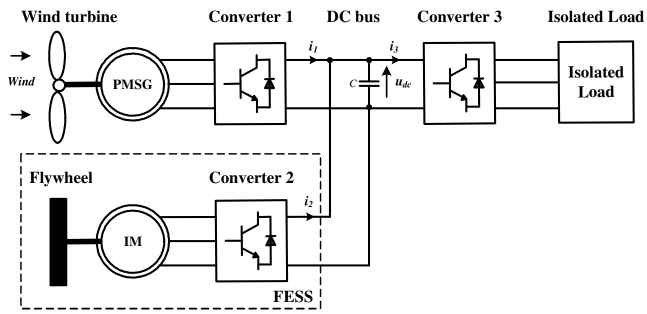

Fig. 1. Configuration of the studied generation system

II. MODELING OF THE FESS

The Flywheel Energy Storage System (FESS), as shown in Fig 3, comprises a flywheel, an induction machine (IM) and a converter 2 (rectifier/inverter), which controls the speed of the flywheel and therefore the exchanged power.

A. *Flywheel modeling*

The energy stored in the flywheel is dependent on the square of the rotational speed [3], for a given inertia, as represented as follow :

$$E_f = \frac{1}{2} J_f \, \Omega_f^2 \tag{1}$$

with J_f (kg.m^2) and Ω_f (rad/s) are the inertia moment and the speed of the flywheel, respectively.

To calculate the wheel inertia, we consider a power required during Δt time. In fact, to store the power P_f during Δt, the energy ΔE is then necessary such as :

$$\Delta E_f = P_f \, \Delta t \tag{2}$$

Combining equations (1) and (2), we define the necessary value of the wheel inertia as :

$$J_f = \frac{2P_f\,\Delta t}{\Delta\Omega_f^2} = \frac{2P_f\,\Delta t}{\Omega_{f\,\max}^2 - \Omega_{f\,\min}^2} \quad (3)$$

Ω_{fmax} and Ω_{fmin} represent the maximal speed limit and the minimal speed limit of the flywheel, respectively. Δt is then the storage period. This limit must be respected otherwise we risk to deteriorate the flywheel energy storage operation [4].

B. Mechanical shaft modeling

The evolution of the mechanical speed of the induction machine-based FESS can be easily determined using the dynamic equation. The simplified model of this equation is given by :

$$J_f \frac{d\Omega_f}{dt} = T_{em} - f\,\Omega_f \quad (4)$$

where T_{em} (N.m) is the electromagnetic torque and f (N.m.s.rad^{-1}) is a viscous friction coefficient.

C. IM modelling

The model generally used in the cage induction machine is the model of Park. The flux and the currents are given by the following equations :

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\dfrac{R_{sr}}{\sigma L_s} i_{sd} + \omega_s i_{sq} + \dfrac{M}{\sigma L_s L_r T_r}\phi_{rd} + \dfrac{Mp}{\sigma L_s L_r}\Omega_f \phi_{rq} + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{di_{sq}}{dt} = -\omega_s i_{sd} - \dfrac{R_{sr}}{\sigma L_s} i_{sq} - \dfrac{Mp}{\sigma L_s L_r}\Omega_f \phi_{rd} + \dfrac{M}{\sigma L_s L_r T_r}\phi_{rq} + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{d\phi_{rd}}{dt} = \dfrac{M}{T_r} i_{sd} - \dfrac{1}{T_r}\phi_{rd} + (\omega_s - p\Omega_f)\phi_{rq} \\ \dfrac{d\phi_{rq}}{dt} = \dfrac{M}{T_r} i_{sq} - (\omega_s - p\Omega_f)\phi_{rd} - \dfrac{1}{T_r}\phi_{rq} \end{cases} \quad (5)$$

where :
L_s, L_r : are the cyclique-propre inductances of the stator and of the rotor (H),
M : is the mutual inductance between the stator and the rotor (H),
$\sigma = 1 - \dfrac{M^2}{L_s L_r}$: is the dispersion coefficient of the machine,
R_s, R_r : are the resistances of the stator and rotor (Ω),
$R_{sr} = R_s + \dfrac{M^2}{L_r T_r}$ (Ω),
$T_r = \dfrac{L_r}{R_r}$: is the rotor speed constant,
ϕ_{rd}, ϕ_{rq} : are the d-q components of the rotor flux respectively (Wb),
i_{sd}, i_{sq} : are the d-q components of the stator currents respectively (A),
v_{sd}, v_{sq} : are the d-q components of the stator voltages respectively (V),
p : is the number of pairs of poles,
ω_s : is the stator pulsation (rad/s),

The electromagnetic torque is given by :

$$T_{em} = p\frac{M}{L_r}(i_{sq}\phi_{rd} - i_{sd}\phi_{rq}) \quad (6)$$

III. Control of the FESS associated to a VSWG

A. Control Strategy for the FESS

Fig 2 gives a graphic explanation of the control principle of the FESS. The FESS has two functions : to regulate the DC bus voltage and to regulate the power flow toward the load [5].

From Fig 1, the evolution of the DC bus voltage can be deduced :

$$\frac{du_{dc}}{dt} = \frac{1}{C}(i_1 + i_2 - i_3) \quad (9)$$

To regulate the DC bus voltage, a PI voltage controller is used and gives the value of the power ΔP required for maintaining this voltage at the reference value $u_{dc\text{-}ref}$.

To control the speed of the flywheel energy storage system we must find reference speed which with the system must turn to ensure the energy transfer required at each time. The reference speed can be determinate by the reference energy. The power assessment of the overall system is given by [5] :

$$P_{f-ref} = P_{load} - P_{wg} + \Delta P \quad (10)$$

where $P_{f\text{-}ref}$ is the reference value of the active power exchanged between the FESS and the load, P_{load} is the load demand power and P_{wg} is the optimal active power generated by the VSWG.

If $P_{f\text{-}ref}$ is positive, means that exists energy in excess which can be stored. If $P_{f\text{-}ref}$ is negative, a lack in energy exists and it will be replaced by the stored energy.

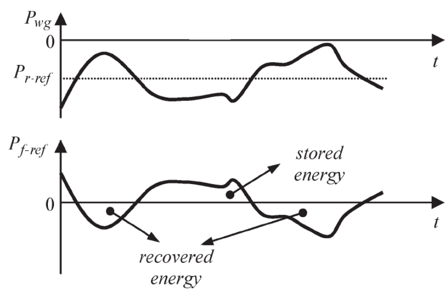

Fig. 2. Graphic representation of the FESS control strategy [6]

B. Control of the FESS IM

The IM is controlled by a rotor flux-oriented control (FOC) strategy cascaded with an external power loop for the setting of the reference speed [7]. Current references are built by means of a rotor flux oriented control algorithm. Estimation of rotor flux space vector position is achieved from measured generator stator currents and rotor speed, in rotor flux oriented reference frame. As operation with speeds both below and above base speed (i.e. in the field weakening region) is anticipated, induction machine is represented with a suitable full dynamic saturated machine model. The control of the converter 2 (rectifier) is assured by the space vector pulse width modulation (SVPWM) technique [8].

Application of the rotor flux oriented control constraints on the rotor voltage equilibrium equations of the model (5) give, by setting null the quadratic component of the rotor flux ($\phi_{rq}=0, \frac{d\phi_{rq}}{dt}=0$), the following equations :

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{R_{sr}}{\sigma L_s^{'}} i_{sd} + \omega_s i_{sq} + \frac{M}{\sigma L_s L_r T_r}\phi_{rd} + \frac{1}{\sigma L_s^{'}} v_{sd} \\ \frac{di_{sq}}{dt} = -\omega_s i_{sd} - \frac{R_{sr}}{\sigma L_s^{'}} i_{sq} - \frac{Mp}{\sigma L_s L_r}\Omega_f \phi_{rd} + \frac{1}{\sigma L_s} v_{sq} \\ \frac{d\phi_{rd}}{dt} = \frac{M}{T_r} i_{sd} - \frac{1}{T_r}\phi_{rd} \end{cases} \tag{11}$$

Then the torque is simplified into :

$$T_{em} = p\,\frac{M}{L_r} i_{sq}\phi_{rd} \tag{12}$$

The estimated rotor flux is as given below :

$$\phi_{r-estimated}(s) = \frac{M}{1+T_r s} i_{sd}(s) \tag{13}$$

The stator pulsation is defined by :

$$\omega_s = p\ \Omega_f + \frac{M}{T_r}\frac{i_{sq}}{\phi_{rd}} \tag{14}$$

The power reference value $P_{f\text{-}ref}$ allows us to determine the flywheel speed reference value controlled via converter 2 (Fig.3) with the help of a vector control strategy. The flywheel reference rotational speed can be deduced from (1) :

$$\Omega_{f-ref} = \sqrt{\frac{2E_{f-ref}}{J_f}} \tag{15}$$

The energy reference value $E_{f\text{-ref}}$ is determined from the power reference value :

$$E_{f-ref} = E_{f0} + \int P_{f-ref}\,dt \tag{16}$$

E_{f0} : is the initially flywheel stored energy.

From (12), the reference electromagnetic torque is given by :

$$T_{em-ref} = p\,\frac{M}{L_r} i_{sq-ref}\,\phi_{rd-ref} \tag{17}$$

Thus, the reference current will be defined by :

$$i_{sq-ref} = \frac{L_r}{pM\,\phi_{rd-ref}} T_{em-ref} \tag{18}$$

C. Flux-Weakening Operation of the FESS IM

Since the maximum speed of the flywheel is 3000 rpm, whereas the base speed of the IM is 1500 rpm, the FESS IM must operate in its flux-weakening region in order to reach the maximum speed of the flywheel. In this region, the rated power of the IM is still available from 1500 to 3000 rpm.

Considering equation (1), flux-weakening operation is then appropriate for this control application. Flux-weakening control of the IM is usually accomplished by regulating the rotor flux according to the following control law [9]-[10] :

$$\phi_{rd-ref}(\Omega_f) = \begin{cases} \phi_{rd-n} & \text{if } \Omega_f \le \Omega_{fn} \\ \frac{L_r}{pM\,.i_{sq-\max}}\frac{P_{n-IM}}{\Omega_f} & \text{if } \Omega_f > \Omega_{fn} \end{cases} \tag{19}$$

where ϕ_{rd-n} is the rated value of the d-axis rotor-flux component, $i_{sq\text{-}max}$ is the maximum stator q current, $P_{n\text{-}IM}$ is the nominal power of the IM and Ω_{fn} is the nominal speed of the flywheel IM.

The control scheme of the FESS IM is presented in Fig 3.

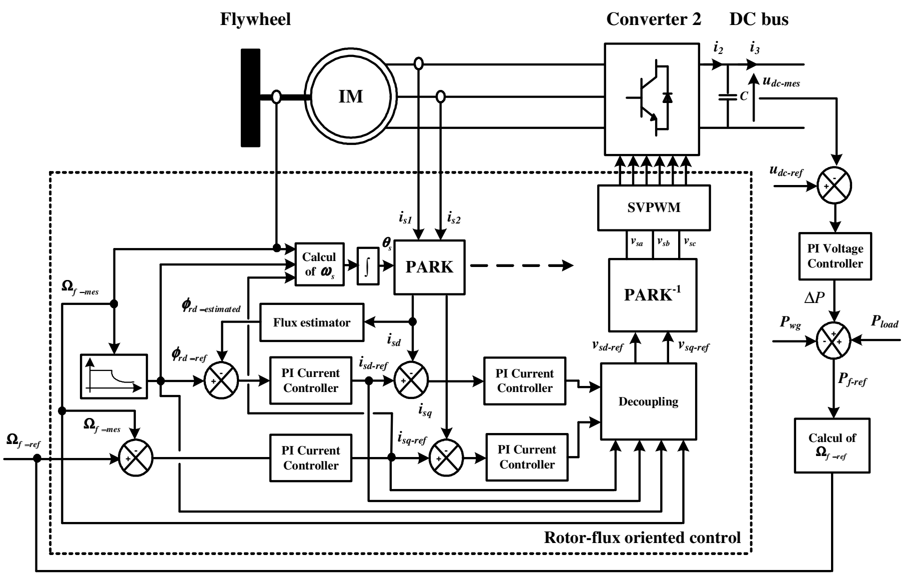

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Fig. 3. FESS IM control scheme

IV. SIMULATION RESULTS AND INTERPRETATIONS

We present the simulations results, using numerical simulations carried under the Matlab–SIMULINK, of the FESS IM.

The objective of the simulations presented in this section is to examine the rotor-FOC strategy of the FESS IM.

The parameters of the studied IM are illustrated in the appendix.

The IM is supplied by the converter 2 controlled by the SVPWM technique. The frequency and voltage of this SVPWM are respectively 8 KHz and 462 V.

The reference flux rotor is equal to the nominal flux rotor $\phi_m = 0.92\ Wb$. The reference speed is equal to 100 rad/s.

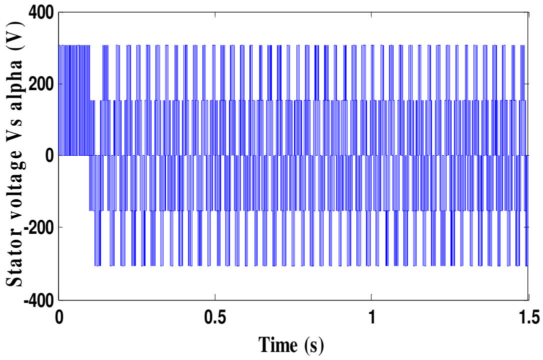

Fig. 3. Stator voltage $v_{s\alpha}$

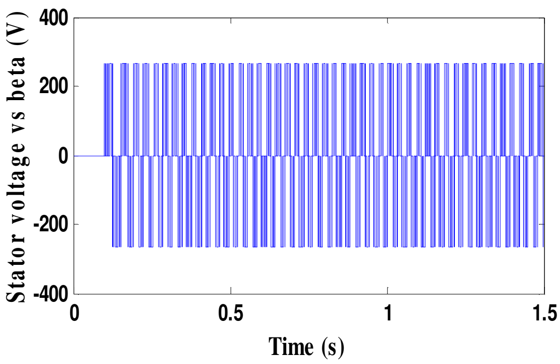

Fig. 4. Stator voltage $v_{s\beta}$

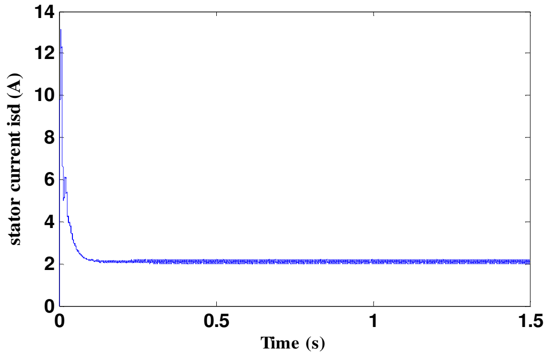

Fig. 5. Direct magnitude of stator current i_{sd} (A)

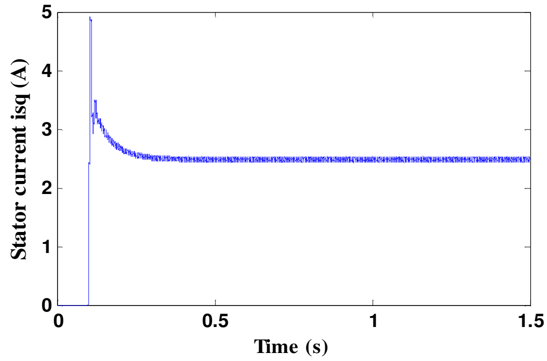

Fig. 6. Quadratic magnitude of stator current i_{sq} (A)

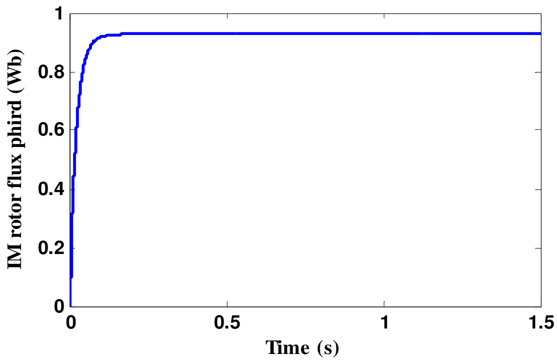

Fig. 7. Direct magnitude of IM rotor flux ϕ_{rd} (Wb)

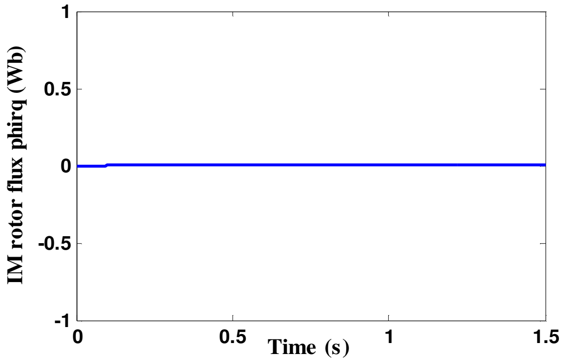

Fig. 8. Quadratic magnitude of IM rotor flux ϕ_{rq} (Wb)

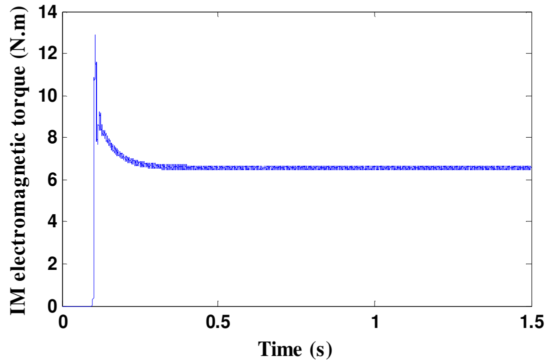

Fig. 9. IM electromagnetic torque *Tem*

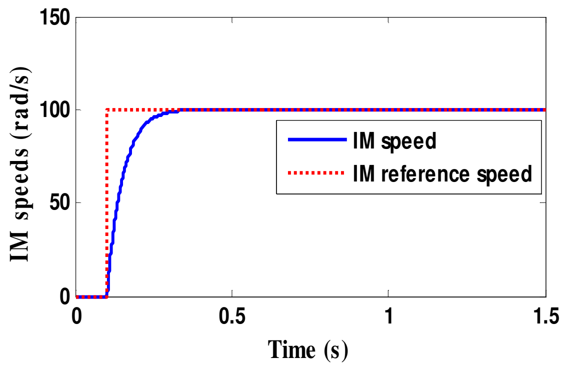

Fig. 10. IM speeds Ω_f et Ω_{f-ref}

The waveforms of SVPWM voltages according to axes α and β, are plotted in Figs 3 and 4.

It can be shown in Fig 6, that the direct magnitude of stator current is constant and equal to 2.2 A.

The quadratic magnitude of stator current represented in Fig 6, is nil at start, then it stabilizes at 2.5 A.

The decoupling effect between the direct and the quadratic rotor flux of the IM is shown in Fig 7 and 8. The direct magnitude of IM rotor flux ϕ_{rd} follows well its reference ϕ_m .

Fig 9 shows the IM electromagnetic torque which is constant and equal to 6.5 N.m.

Fig. 10 shows that the IM rotational speed follows well its reference. Consequently, the simulations prove that the rotor flux-oriented control strategy performs a good regulation of the rotational speed.

V. CONCLUSIONS

A FESS associated to a VSWG has been presented and studied. A low-speed FESS, whose electric machine is a classical squirrel-cage IM, is considered. A rotor FOC strategy is applied to the IM. The control of the rectifier is assured by the SVPWM technique. The FESS IM model and the proposed rotor-FOC strategy are simulated with the help a software like Matlab-Simulink. The simulation results showed the effectiveness of the control strategy adopted. As prospects for this work, we will simulate the global model of FESS associated to a VSWG.

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APPENDIX

Induction machine

Nominal power : $P_{n\text{-}IM} = 1.5$ kW
Nominal voltage : $V_n = 220/380$ V
Nominal rotational speed : $\Omega_{n\text{-}IM} = 157$ rad/s
Pole pairs : $p = 2$
Stator resistance : $R_s = 5.72\ \Omega$
Rotor resistance : $R_r = 4.2\ \Omega$
Stator inductance : $L_s = 0.462$ H
Rotor inductance : $L_r = 0.462$ H
Mutual inductance : $M = 0.44$ H
IM inertia : J = 0.0049 kg.m^2
Viscous friction coefficient : f = 0.0656 Nm.rad.s^{-1}