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Vector Control of a Flywheel Energy Storage System Associated to Wind Energy Conversion System

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***Abstract*— This paper deals with the study of a variable speed wind induction generator associated to a flywheel energy storage system. Variable speed wind energy conversion allows capturing more energy from the wind compared to constant speed generating systems. The extra energy produced, compared to the autonomous load request, must be stored. In the case of standalone applications, the flywheel energy storage system is used to improve the quality of the electric power delivered by the wind generator to the load. The proposed system, controlled thanks to vector control strategy, is validated through simulations. The obtained results are presented and discussed**

***Keywords*— Vector control, flywheel storage, induction machine, variable speed, wind turbine.**

I. INTRODUCTION

Several electrical machines can be used to implement the electromechanical conversion, each of which presents different advantages and drawbacks [1-5]. For this special operation, the induction machine, and more precisely the three-phase squirrel induction machine, remains widely used. Indeed, the structure is robust, needs little maintenance, and is relatively inexpensive. Therefore, in remote and isolated areas, the study of self-excited induction generators (SEIGs) has been the subject of much research [5-7].

In autonomous operating of the induction generator, the magnitude of the stator voltage and frequency are very sensitive to both speed and load values. In order to maintain the DC voltage at a constant value whatever the speed and the load values as long as the wind power is sufficient to satisfy the electric needs, different solutions have been suggested [7-10]. When, we connect the stator windings a rectifier/inverter and to control the device, the most strategy of control used to achieve this task is the rotor flux oriented control [11-13]. In our paper, we propose the rotor flux oriented control. The choice of this control is justified by its robustness with respect to the electric parameters of the generator.

Variable speed wind energy conversion is attractive as it reduces the mechanical stresses that the turbine blades and the tower are subjected to. Moreover, it allows capturing more energy from the wind compared to constant speed generating systems. The extra energy produced, compared to the autonomous load request, must be stored. This can be achieved in different ways [14-16]. However, in the case of standalone applications, storage cost still represents the major economic restraint.

The aim of this paper is the transformation of a renewable energy generator into an active generator by using energy storage systems. In our application, we choose to use an inertial storage system because it is well adapted to abrupt changes of the power from the wind generator. Moreover it allows obtaining high power to weight ratio and a very high number of charge and discharge cycles.

In this paper, we propose to study the use of the vector control strategy to control the DC voltage of an autonomous induction generator connected to a rectifier when the input speed varies. Due to the important fluctuations of the wind, a flywheel energy storage system is associated to improve the quality of the electric power delivered by the wind generator. The proposed control system is then simulated using MATLAB®-SIMULINK® package [17]. The obtained results are presented and discussed.

II. STUDIED SYSTEM

The system studied is constituted of a wind turbine, an induction generator, a rectifier/inverter and a flywheel energy storage system as shown in Fig. 1. The goal of the device is to provide a constant power and voltage to the load connected to the rectifier/inverter even if the speed varies. This can be achieved mainly by the control of the DC bus voltage at a constant value and the flywheel energy storage system participate to maintain the power of the load constant as long as the wind power is sufficient. To control the speed of the flywheel energy storage system, we must find the reference speed to which the system must operate to ensure the energy transfer required at each time. The reference speed can be determined from the reference energy. The power assessment of the overall system is given by:

$$P_{ref} = P_{load} - P_{wind} - \Delta P \qquad (1)$$

where P_{ref} is the reference power, P_{load} the load power; P_{wind} the wind power and ΔP is the power required to control the DC voltage V_{dc} at a constant value.

III. Model of Induction Machine

The linear model of the induction machine is widely known and used. It yields results relatively accurate when the operating point studied is not so far from the conditions of the model parameter identification.

This is often the case when the machine operates (in motor or generator cases) at rated voltage. In our approach, we adopt the d-q model of the induction machine expressed in the synchronous frame noted by (dq). The electrical equations are then written as follows:

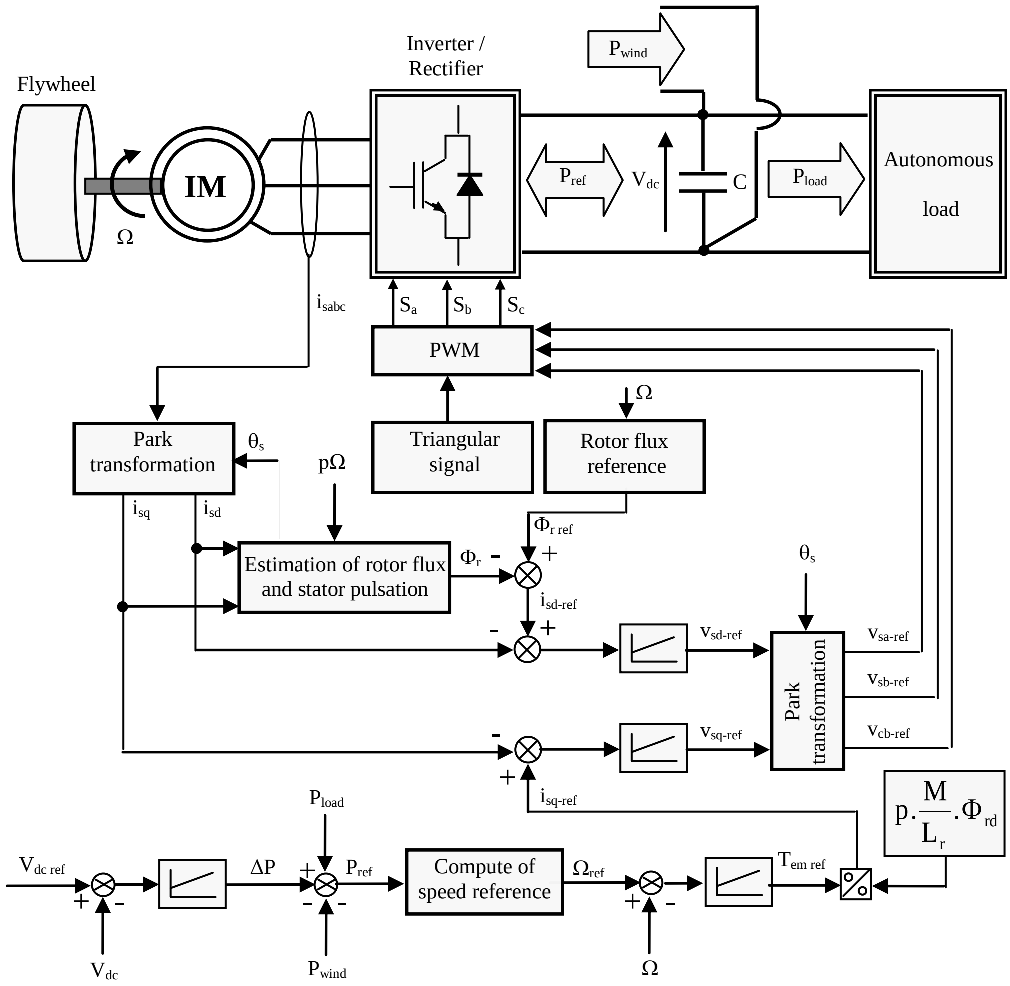

Fig. 1 The studied system

$$\begin{bmatrix} v_{sd} \\ v_{sq} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & -\omega_s.L_s & 0 & -\omega_s.M \\ \omega_s.L_s & R_s & \omega_s.M & 0 \\ 0 & -\omega_r.M & R_r & -\omega_r.L_r \\ \omega_r.M & 0 & \omega_r.L_r & R_r \end{bmatrix} . \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} . \begin{bmatrix} \frac{di_{sd}}{dt} \\ \frac{di_{sq}}{dt} \\ \frac{di_{rd}}{dt} \\ \frac{di_{rq}}{dt} \end{bmatrix} \quad (2)$$

Where R_s, R_r, L_s and L_r are the stator and rotor phase resistances and self inductances respectively, M is the mutual inductance and Ω the speed.

Besides, v_{sd}, i_{sd} , v_{sq} and i_{sq} are the d-q stator voltages and currents respectively along the d and q axes. i_{rd} and i_{rq} are the d-q rotor currents along the d and q axes.

IV. Control Strategy

The control strategy is based on the choice of the reference frame orientation. In our application, we choose this orientation such as: $\Phi_{rd} = \Phi_r$ and $\Phi_{rq} = 0$. This means that the flux Φ_r is aligned permanently along the d-axis. Φ_r can be maintained constant by acting on the currents.

Hence, when using the flux expressions, the electrical equations of the induction machine can be written, in a synchronous frame, as follows [13]:

$$v_{sd} = R_s.i_{sd} - \omega_s.\Phi_{sq} + \frac{d\Phi_{sd}}{dt} \quad (3)$$

$$v_{sq} = R_s.i_{sq} + \omega_s.\Phi_{sd} + \frac{d\Phi_{sq}}{dt} \quad (4)$$

$$0 = R_r.i_{rd} - \omega_r.\Phi_{rq} + \frac{d\Phi_{rd}}{dt} \quad (5)$$

$$0 = R_r.i_{rq} + \omega_r.\Phi_{rd} + \frac{d\Phi_{rq}}{dt} \quad (6)$$

The different fluxes are expressed with respects to the currents, for a given constant saturation level, under the following forms:

$$\Phi_{sd} = L_s.i_{sd} + M.i_{rd} \quad (7)$$

$$\Phi_{sq} = L_s.i_{sq} + M.i_{rq} \quad (8)$$

$$\Phi_{rd} = M.i_{sd} + L_r.i_{rd} \quad (9)$$

$$\Phi_{rq} = M.i_{sq} + L_r.i_{rq} \quad (10)$$

As $\Phi_{rd} = \Phi_r$ and $\Phi_{rq} = 0$, this implies, using the relations (5) and (6), that the expressions of the flux Φ_r and its derivative take the forms:

$$\frac{d\Phi_r}{dt} = -R_r.i_{rd} \quad (11)$$

$$\Phi_r = -\frac{R_r.i_{rq}}{\omega_r} \quad (12)$$

Moreover, the rotor currents can be expressed, from the relations (9) and (10), in the following way:

$$i_{rd} = \frac{\Phi_r - M.i_{sd}}{L_r} \quad (13)$$

$$i_{rq} = -\frac{M.i_{sq}}{L_r} \quad (14)$$

Hence, by introducing the leakage flux coefficient $\sigma = 1 - \frac{M^2}{L_r.L_s}$, the stator voltage equations can be re-written as:

$$v_{sd} = R_s.i_{sd} + \sigma.L_s.\frac{di_{sd}}{dt} - \omega_s.\sigma.L_s.i_{sq} + \frac{M}{L_r}.\frac{d\Phi_r}{dt} \quad (15)$$

$$v_{sq} = R_s.i_{sq} + \sigma.L_s.\frac{di_{sq}}{dt} + \omega_s.\sigma.L_s.i_{sd} + \omega_s.\frac{M}{L_r}.\Phi_r \quad (16)$$

Finally, as the chosen frame implies $\Phi_{rq} = 0$, the expression of the electromagnetic torque becomes:

$$T_{em} = p.\frac{M}{L_r}.\Phi_r.i_{sq} \quad (17)$$

Using equations (5) and (13), we can write the rotor flux as a function of the current i_{sd} and the rotor time constant $T_r = L_r/R_r$

$$\Phi_r = \frac{M \cdot i_{sd}}{1 + T_r \cdot s} \tag{18}$$

Where: s represents the derivative operator.

The knowledge of ω_s makes it possible to ensure the validity of the equations because the reference d-q frame must follow the rotating field constantly. To do that, we use the internal angular relation $\omega_s = \omega_r + p.\Omega$. As the mechanical speed of the machine Ω is measured continuously, the speed of the rotor field must be estimated. This can be obtained by replacing in (12) the expression of i_{rq} given in the equation (14):

$$\omega_r = \frac{M . i_{sq}}{T_r \cdot \Phi_r} \tag{19}$$

Then, ω_s can be written in the following way:

$$\omega_s = \frac{M . i_{sq}}{T_r \cdot \Phi_r} + p \cdot \Omega \tag{20}$$

V. Modeling of the Flywheel Energy Storage System

The reference energy for the flywheel energy storage system can be expressed as follows [16]:

$$E_{c\,ref} = E_c^{t_1} + \int_{t_1}^{t_2} P_{ref}.dt \tag{21}$$

Where: $E_c^{t_1}$ is the flywheel initial energy.

We determine the reference speed as follows:

$$\Omega_{ref} = \sqrt{\frac{2.E_{c\,ref}}{J_t}} \tag{22}$$

With:

$$J_t = J_{IG} + J_{Flywheel} \tag{23}$$

The reference speed is limited in order to maintain the induction generator in the area of operation at constant power and without exceeding the maximal speed of the flywheel [16].

Figure 2 represents the torque and power as a function of the speed. We notice that:

- For $0 \le \Omega \le \Omega_{rated}$, the torque may be maximal giving up a power proportional to the speed $P_{IG} = k \cdot \Omega$.
- For $\Omega \rangle \Omega_{rated}$, the power is maximum and corresponds to the rated power of the machine; the electromagnetic torque is inversely proportional to the speed $T_{em} = \frac{k}{\Omega}$.

So, if we want the machine to operate at its rated power, it is necessary to use it beyond its rated speed. Thus, we can consider that this rated speed constitutes the lower limit of the storage system and twice this speed ad the upper limit.

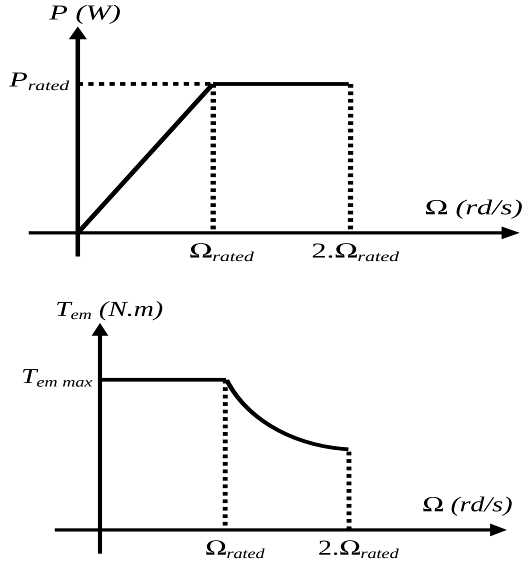

Fig. 2 Power and torque as a function of speed

Thus, a field weakening operation will be necessary to obtain a constant power in the speed range of 1500 to 3000 rpm.

The reference flux is then determined by:

$$\Phi_{r\text{-}ref} = \begin{cases} \Phi_{r\text{-}rated} & \Rightarrow \text{ if } |\Omega| \le \Omega_{rated} \\ \Phi_{r\text{-}rated} \dfrac{\Omega_{rated}}{|\Omega|} & \Rightarrow \text{ if } |\Omega| \rangle \Omega_{rated} \end{cases} \tag{24}$$

With

Ω : Flywheel speed, Ω_{rated} : rated speed, $\Phi_{r-rated}$: rated rotor flux and Φ_{r-ref} : Reference flux.

The parameters of the machine are listed in the table 1.

TABLE I
Parameters of the Induction Machine

Parameter	Value	Parameter	Value
U_N	220/380 V	$L_s = L_r$	0.08132H
N_{rated}	1500 rpm	M	0.07767H
p	2	J	0.2271 kg.m^2
$R_s = R_r$	0.76 Ω	f	0.0022 Nm/rd.s^{-1}

Simulations are made with a wind power profile which provides power continuously required by the load through the flywheel energy storage system. Figure 3 shows the waveform of wind power which varies between 1125W and 2625W. We can notice that the power supplied to the load is kept constant through the flywheel energy storage system.

Figure 4 corresponds to the power of the flywheel energy storage system. This power can be positive or negative. It depends on the wind power and the power required by the load. We notice that it is positive when the wind power produced is greater than the power required by the load and it is negative when there is less power produced compared to that of the load. To regulate the bus voltage, we need the required power represented in Fig. 5.

The flywheel and the reference speeds are represented in Fig. 6. The rotational speed increases when the energy is transferred to the flywheel, and decreases when the flywheel is unloaded. The electromagnetic torque follows the evolution of the speed (Fig.7). The waveform of the rotor flux is represented in Fig. 8. The rotor flux Φ_r follows the variations of the speed when $|\Omega| \rangle \Omega_{rated}$ and is kept constant at the nominal flux ($\Phi_{r\text{-}rated}$) when $|\Omega| \leq \Omega_{rated}$.

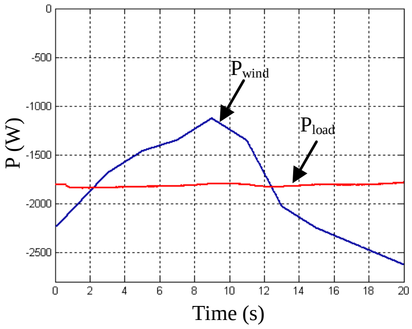

Fig.3 Wind and load power

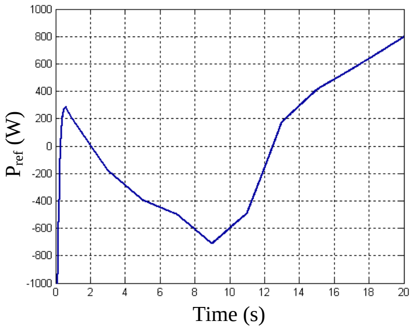

Fig. 4 Power of the flywheel energy storage system

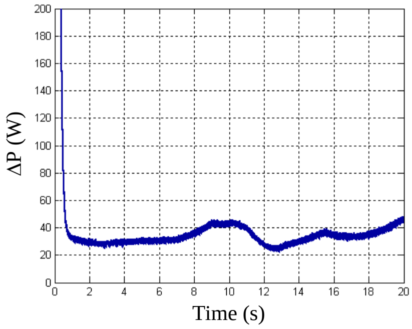

Fig. 5 Power of the DC bus

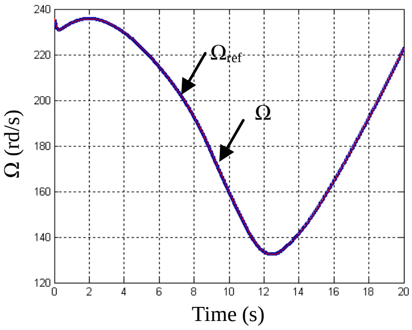

Fig. 6 Flywheel speed and its reference

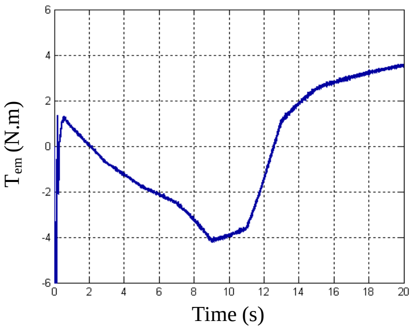

Fig.7 Electromagnetic torque

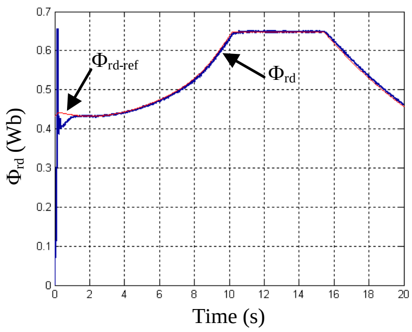

Fig. 8 Stator flux

Fig. 9 presents the stator current along the d-axis (i_{sd}) which is maintained constant independently of the q-axis current (i_{sq}).

It may be noted that the waveform of the current i_{sd} is similar to that of the rotor flux. On the other hand, the waveform of the current i_{sq} shows the influence of the variation of the speed which introduces a variation of the electromagnetic torque of the induction generator.

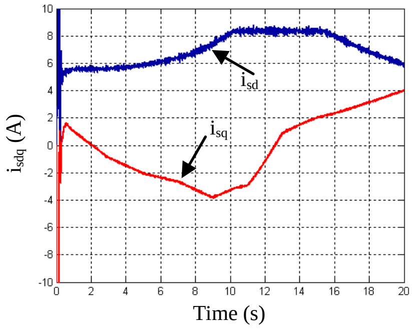

Fig. 9 Stator currents d-q axis components

The voltage of the DC bus is kept constant around 465 V (Fig. 10).

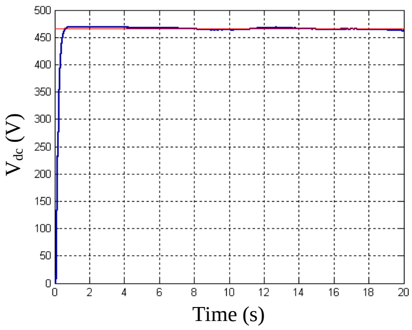

Fig. 10 DC voltage V_{dc}

VI. Conclusion

In this paper, a variable speed wind system with a flywheel energy storage system has been presented and studied. A vector control is applied to the induction machine of the flywheel energy storage system generator. From the diphase model of the machine, we defined a vector control for the machine operating. The developed control reaches the assigned objectives. The simulation results clearly show the good operation of the flywheel energy storage system. Simulation calculations show the well control of the DC bus voltage.

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