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Study on Sliding Mode Control of a Wind Energy Conversion System Associated to a Flywheel Energy Recovery System

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***Abstract*— This paper proposes an adaptable sliding mode control (A-SMC) scheme for a variable speed wind energy conversion system associated to a flywheel energy storage system. The controller should keep the DC voltage across the capacitor constant and equal to the reference value regardless of changes in wind speed. It is based on vector control algorithm; sliding mode approach is used to control the concerned variables. Adaptable gains and a tangent hyperbolic function work together and manage to attenuate the chattering phenomenon. Due to the important fluctuation of the wind speed, a flywheel energy storage system is associated in order to improve the quality of the electric power delivered by the wind generator when the wind speed does not meet the electricity needs.**

***Keywords*— Vector control; sliding mode; adaptable gains; storage; flywheel.**

I. Introduction

The demand for electrical energy is rapidly growing worldwide. On the other hand, fossil fuels resources will be depleted and the environmental pollution is inevitable which makes the mankind look for alternative energy resources. Besides, the renewable energy sources are promising solutions. Among these solutions, wind energy is the wide used one [1].

Squirrel type Induction generators are widely used in variable speed wind energy applications. They have found applications in renewable energy (wind and hydro) due to their ability to generate electric power at frequencies that are not exactly tied to their frequency of rotation [2]. Their capability to operate as a generator without external power supply allows their use in stand alone power generation systems without any reactive power from the grid. This interest is enhanced through its many advantages over other types of electric generators such as robustness, low price and maintenance free operation. They are usually excited by three AC capacitors (capacitor bank) connected across their stator terminals and are known as self-excited induction generators (SEIGs). Although this excitation method appears to be the cheapest and simplest technique, until recently, it was not possible to effectively utilize it due to the fact that this method has some important drawbacks. The magnitude and frequency of the stator voltage are very sensitive to the variations of the rotation speed and the load value. Thus, this needs an appropriate voltage regulating scheme to maintain a constant voltage level regardless of load and/or speed by controlling the reactive power transmitted to the generator. To achieve this purpose, many schemes have been suggested [3-7].

The widely used solution consists in connecting the stator windings of the induction generator directly to a rectifier/inverter system. In this case, the device must be controlled. To reach this goal vector control is widely used. However, most of the SEIG vector control systems reported in literature use classical PI controllers for voltage and/or flux control [3, 4]. Besides, PI-controller is very interesting due to its high mathematical accuracy but it is sensitive to the system parameter variations.

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 [8-11]. However, in the case of standalone applications, storage cost still represents the major economic restraint. Besides, an inertial storage system is well adapted to abrupt changes of the power from the wind generator.

A flywheel is a simple form of mechanical energy storage. Energy is stored by causing a disk or rotor to spin on its axis. Stored energy is proportional to the flywheel's mass and the square of its rotational speed. Although generally more expensive than batteries. Besides, the longer life, simpler maintenance, low risk of overcharge or over-discharge, wide range of operation temperature, and the absence of environmental footprint of the flywheel systems make them attractive battery alternatives [12]. They allow obtaining high power to weight ratio and a very high number of charge and discharge cycles. Thus, as emergent tools, flywheel energy storage systems have become an important field of research.

In this paper, SMC based on vector control concepts is used to control the whole system. The Lyapunov direct method is used to ensure the reaching and sustaining of the sliding mode.

A self-adjustable gains and a tangent hyperbolic function are used, so that, the transient of the hitting control will be smoothed and the chattering phenomenon is alleviated without loosing the system robustness. A flywheel anergy storage system is participating to improve the quality of the electric power transmitted to the autonomous load.

The whole system is simulated using MTALAB-SIMULINK® package. Results are presented and discussed.

II. Description of the Studied System

The studied system, shown in Fig 1, is constituted of a squirrel cage three-phase induction machine (IM), a flywheel energy storage system, a PWM rectifier/inverter, a DC side capacitor, and an autonomous load. The Power delivered by the wind generator is modelled by a random function block. The control scheme is shown in the same figure. The main role of the controller is to provide a constant power to the autonomous load regardless of wind speed fluctuations. This can be achieved mainly by the control of the DC bus voltage at constant value. The flywheel energy storage system contributes by feeding the load when the wind power is not sufficient to meet the electricity need. This can be achieved by controlling the speed of the flywheel energy storage system. To achieve this task, we must find the operating speed of the flywheel system that permits to transfer the required energy.

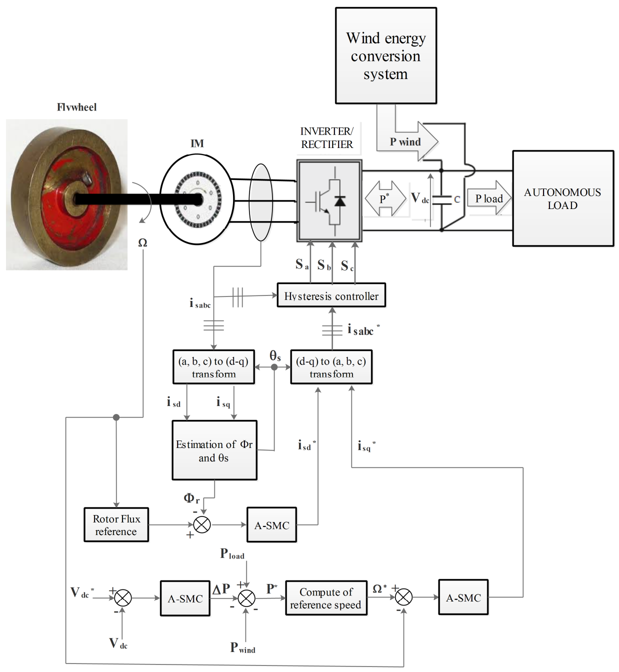

Fig. 1 Studied system and control scheme

This reference speed can be calculated as follows [10]:

$$\Omega^* = \sqrt{\frac{2E_{Fly}^{\ *}}{J_t}} \tag{1}$$

With: $J_t = J_{IM} + J_{Flywheel}$ is the total inertia.

$E_{Fly}^{\ *}$ is the reference energy of the flywheel energy storage system and it is given as follows:

$$E_{Fly}^{\ *} = E_c + \int P^* dt \tag{2}$$

Where E_c is the flywheel initial energy and P^* is the reference power and it is given as follows:

$$P^* = P_{load} - P_{wind} - \Delta P \tag{3}$$

Where P^* is the reference power, P_{load} is the load power, P_{wind} is the transmitted wind power and ΔP is the required power to control the DC bus voltage.

III. Induction Machine Model

The mathematical equations of the IM expressed in synchronous reference frame are given as follows:

$$V_{sd} = R_s i_{sd} - \omega_s \Phi_{sq} + \frac{d\Phi_{sd}}{dt} \tag{4}$$

$$V_{sq} = R_s i_{sq} + \omega_s \Phi_{sd} + \frac{d\Phi_{sq}}{dt} \tag{5}$$

$$0 = R_r i_{rd} - (\omega_s - \omega)\Phi_{rq} + \frac{d\Phi_{rd}}{dt} \tag{6}$$

$$0 = R_r i_{rq} + (\omega_s - \omega)\Phi_{rd} + \frac{d\Phi_{rq}}{dt} \tag{7}$$

$$\Phi_{sd} = L_s i_{sd} + L_m i_{rd} \tag{8}$$

$$\Phi_{sq} = L_s i_{sq} + L_m i_{rq} \tag{9}$$

$$\Phi_{rd} = L_r i_{rd} + L_m i_{sd} \tag{10}$$

$$\Phi_{rq} = L_r i_{rq} + L_m i_{sq} \tag{11}$$

Where R_s, L_s, R_r and L_r are the stator and rotor phase resistances and inductances respectively and L_m is the magnetising inductance. ω_s and ω are the stator and mechanical pulsations respectively. Besides, V_{sd}, i_{sd} , V_{sq} and i_{sq} are the d-q stator voltages and currents respectively and i_{rd} and i_{rq} represent the d-q rotor currents. Φ_{sd}, Φ_{sq} and Φ_{rd}, Φ_{rq} are the d and q-axis stator and rotor flux components respectively.

In the case of the present work, the orientation of the d-q frame is chosen such as $\Phi_{rd} = \Phi_r$ and $\Phi_{rq} = 0$. Therefore:

The rotor flux can be written as a function of the current i_{sd} and the rotor time constant $T_r = L_r/R_r$ such as [3]:

$$\Phi_r = \frac{L_m \ . \ i_{sd}}{1 + T_r \ . \ s} \tag{12}$$

Where: s is the derivative operator.

In another hand, θ_s can be estimated by the following equation:

$$\theta_s = \int \left(\frac{L_m \ .i_{sq}}{T_r \ . \ \Phi_r} + p \ . \ \Omega \right) .dt \tag{13}$$

Where: Ω is the mechanical speed of the machine which is measured continuously and p is the pole pair number.

Besides, the expression of the electromagnetic torque is given as:

$$T_{em} = p \ .\frac{L_m}{L_r} .\Phi_r \ . \ i_{sq} \tag{14}$$

TABLE I
PARAMETERS OF THE INDUCTION MACHINE

P_n	5,5kW/230/400V
R_s	1.07131Ω
R_r	1.29511Ω
J	0.230kg.m^2
N_{rat}	690rpm
p	4

IV. CONTROL STRATEGY

The controller is based on vector control algorithm; it consists of two loops that operate in parallel, as can be seen in Fig. 1, and allows controlling two output variables. The components i_{sd}^* permits the control of the reactive power and the components i_{sq}^* permits to control the active power and permits in an indirect way to keep a constant DC voltage regardless of wind speed fluctuations by controlling the speed of the flywheel energy storage system.

To achieve this task, three adaptable sliding mode controllers (A-SMC) are used.

SMC is a robust nonlinear algorithm which uses discontinuous control to force the system trajectories to join some specified sliding surface; it has been widely used for its robustness to model parameter uncertainties and external disturbances.

According to the SMC theory, the first designing step concerns the definition of the sliding surface for each concerned variable. In our case, the following sliding surfaces are defined:

$$S(V_{dc}) = V_{dc}^* - V_{dc} \tag{15}$$

$$S(\Phi_r) = \Phi_r^* - \Phi_r \tag{16}$$

$$S(\Omega) = \Omega^* - \Omega \tag{17}$$

A. DC voltage sliding mode control design:

The state equation of the DC bus voltage can be modelled as follows:

$$\frac{dV_{dc}}{dt} = \frac{1}{C}\left(i_{wind} - i_{load} - i_{dc}\right) \tag{18}$$

Where C is the DC bus capacitor, i_{wind} represents the current injected by the wind energy conversion system, i_{load} is the current absorbed by the autonomous load and i_{dc} is the rectified current.

By differentiating (15) with respect to time and substituting the corresponding relation from (18), yields:

$$\frac{dS(V_{dc})}{dt} = \frac{dV_{dc}^*}{dt} - \frac{1}{C}\left(i_{wind} - i_{load} - i_{dc}\right) \tag{19}$$

The sufficiency conditions for the existence and sustaining of the sliding mode is given as follows [13]:

$$\frac{dS(x)}{dt} sign(S(x)) \leq -\eta \tag{20}$$

With η is a positive constant. If we keep a different signs for the sliding surface and its derivative, the controlled variable will be attracted toward its sliding surface, which means the existence of a sliding motion on the sliding surface *S(x)*. In other words, the verification of the condition (20) implies stability of the system.

By substituting (19) in (20), yields:

$$\frac{dV_{dc}^*}{dt} - \frac{1}{C}\left(i_{wind} - i_{load} - i_{dc}\right).sign\left(S(V_{dc})\right) \leq -\eta \tag{21}$$

The control law must be designed in attempt to satisfy the hitting condition given by (20). Therefore, the control law of DC bus voltage can be designed as follows:

$$i_{dc}^* = -k_{vdc} sign\left(S(V_{dc})\right) + \left(i_{wind} - i_{load}\right) \tag{22}$$

The derivative term of the reference voltage is zero because we impose a constant reference value.

In order to find the required power to control the DC voltage (ΔP), we multiply the equation (22) by V_{dc}, and we obtain the following control law:

$$\Delta P = V_{dc} i_{dc}^* = V_{dc}\left(-k_{vdc} sign\left(S(V_{dc})\right) + \left(i_{wind} - i_{load}\right)\right) \tag{23}$$

However, the control law given in (23) leads to limited performance due to the high control activity resulting in chattering. To reduce the latter, we will introduce a hyperbolic tangent function instead of sign function, then, the control law (23) becomes:

$$\Delta P = V_{dc}\left(-k_{vdc}\tanh\left(\frac{S(V_{dc})}{\varepsilon_{vdc}}\right)+\left(i_{wind}-i_{load}\right)\right) \quad (24)$$

B. Rotor flux sliding mode control design:

The sliding mode control law for the rotor flux can be deduced with the same manner as in section *A*. then, it is given as follow:

$$i_{sd}^{\ *} = k_{\Phi r}\tanh\left(\frac{S(\Phi_r)}{\varepsilon_{\Phi r}}\right)+\left(\frac{d\Phi_r^{\ *}}{dt}+\frac{\Phi_r}{T_r}\right) \quad (25)$$

C. Flywheel speed sliding mode control design:

The mechanical equation is given as follow:

$$J_t\frac{d\Omega}{dt} = T_{em} - T_{Flywheel} \quad (26)$$

The mechanical friction is neglected. The SMC speed control law is given as follows:

$$T_{em}^{\ *} = k_{\Omega}\tanh\left(\frac{S(\Omega)}{\varepsilon_{\Omega}}\right)+\left(J_t\frac{d\Omega^*}{dt}+T_{Flywheel}\right) \quad (27)$$

From (14) the reference of the quadratic stator current component show in Fig. 1 is obtained as follows:

$$i_{sq}^{\ *} = \frac{L_r}{pL_m\Phi_r}\left(k_{\Omega}\tanh\left(\frac{S(\Omega)}{\varepsilon_{\Omega}}\right)+\left(J_t\frac{d\Omega^*}{dt}+T_{Flywheel}\right)\right) \quad (28)$$

ε_i (i=vdc, Φr, Ω) represents the thickness of the boundary layer.

The gains k_j (j=vdc, Φr, Ω) are self-adjustable for performance improvement and are given as following:

$$k_j = \lambda_j\left|S(j)\right|^{\alpha} \quad (29)$$

Where: $0 \le \alpha \le 1$, λ_j is a positive integer. The parameters λ_j, α and ε_i are chosen by trial and error procedure and are tunned optimally, focussing on criteria of fast response, robustness, low chattering and small steady state error.

Note that, the fact of using a sign function in the control laws will lead to a harmful chattering. However, in the case of the present work, the problem of chattering is largely alleviated, thanks to the adaptable gains and to the hyperbolic tangent function which smoothes the transient of the hitting control without loosing the system robustness.

D. Rotor flux and speed references choice:

The reference speed is limited in order to maintain the IM in the area of operation at constant power and without exceeding the maximal speed of the flywheel [10].

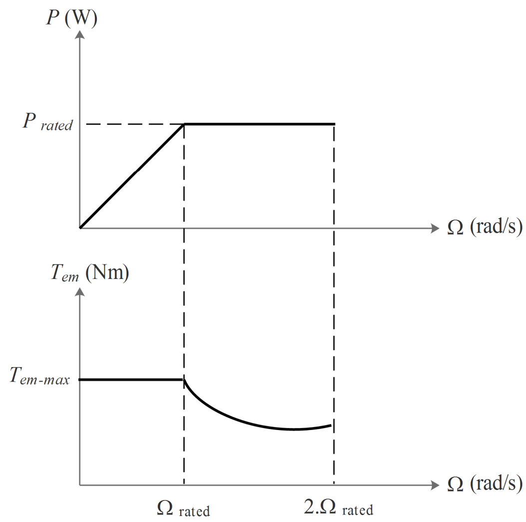

Fig. 2 Power and torque as a function of speed.

From Fig. 2 we notice that:

- For $0 \le \Omega \le \Omega_{rated}$ the torque is maximal, thus the power is proportional to the speed P=$K\Omega$.
- For $\Omega > \Omega_{rated}$ the power is maximal and correspond to the rated power of the IM, thus the torque should be reduced in order to keep a constant power.

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 as the upper limit. Thus, a flux weakening mode operation is necessary to keep a constant power in the speed range of 750-1500 rpm.

Then the rotor flux reference is given as follows:

$$\Phi_r^{\ *} = \begin{cases} \Phi_{r-rated} & \text{if} \quad \Omega \le \Omega_{rated} \\ \Phi_{r-rated}\dfrac{\Omega_{rated}}{\Omega} & if \quad \Omega > \Omega_{rated} \end{cases} \quad (30)$$

With: Ω_{rated} is the rated speed, $\Phi_{r\text{-}rated}$=0.7 Wb is the rated flux.

V. Simulation Results ans Discussion

The parameters of the IM are listed in Table 1. The wind energy conversion system is modelled by a block function which generates a power variable, corresponding to a given random wind profile. A resistive load of about 60Ω is used as an autonomous load.

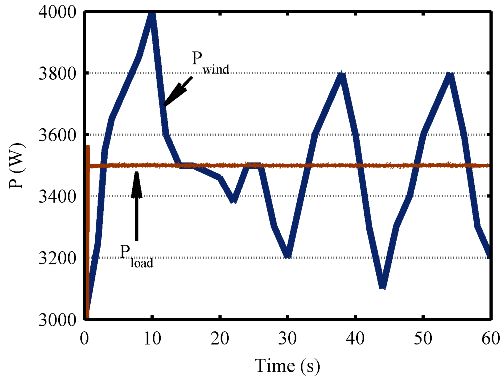

Fig. 3 Wind power transmitted to the DC bus and load power.

Fig. 3 shows the waveform of the transmitted power by the wind energy conversion system, it varies between 3000 W and 4000 W. The power consumed by the autonomous load is also shown on the same figure; we notice that, it is kept constant at 3500 W whatever the wind speed fluctuations.

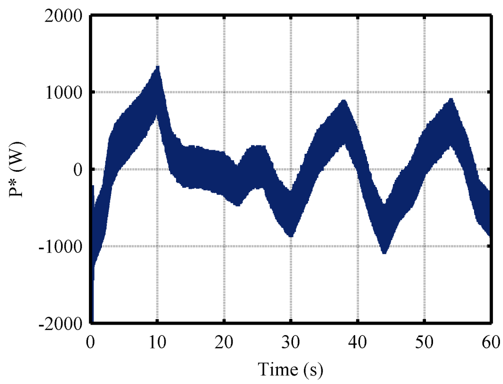

Fig. 4 Power of the flywheel energy storage system.

Fig. 4 shows the power waveform of the flywheel energy storage system. We notice that this power takes a positive value as well as a negative one; this mainly depends on the wind power transmitted by the wind energy conversion system. Thus, two operation modes can be distinguished, loading mode and the unloading mode. When the transmitted wind power is greater than the required load power, the power of the flywheel storage system is positive which means that, the extra power is transmitted to the flywheel, this is the loading mode. Otherwise, when the transmitted wind power is lower than the required load power, the flywheel power is negative, this is the unloading mode, and the stored energy is transmitted to the load.

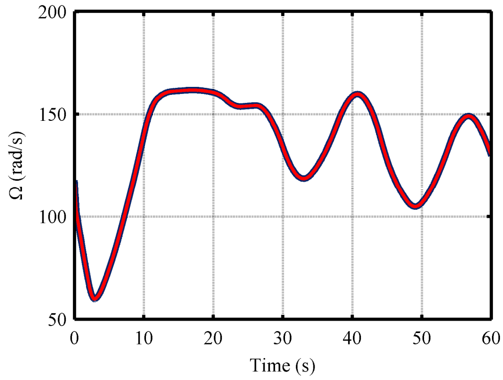

Fig. 5 Rotation speed of the flywheel energy storage system.

Fig. 5 shows the speed waveform of the flywheel energy storage system. The rotational speed increases when the energy is stored (loading mode), and it decreases when the flywheel energy storage system is unloading.

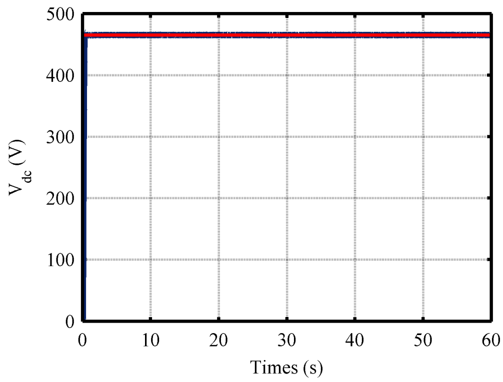

Fig. 6 DC bus voltage.

Fig. 6 shows the waveform of the regulated DC bus voltage, it is kept constant at 465V, no overshoot, and shows a very good robustness against the fluctuation of transmitted wind energy conversion system power.

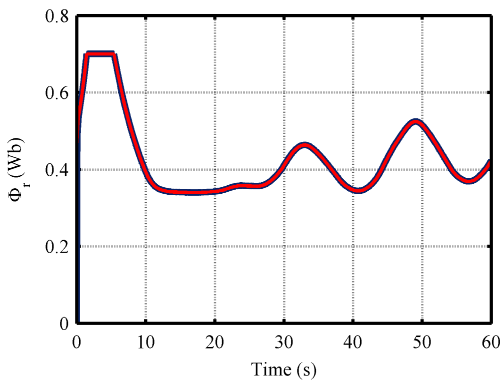

Fig. 7 Rotor flux.

Fig. 7 shows the waveform of the controlled Rotor flux. It tracks very well its reference value. Its behaviour is inversely proportional the speed as specified in relation (30).

VI. CONCLUSION

In this paper, a variable wind speed energy conversion system associated to flywheel energy storage system is studied. The whole system is controlled using the sliding mode approach based on vector control algorithm. The chattering problem encountered in SMC is largely alleviated, thanks to the self-adjustable gains and to the hyperbolic tangent function. The control leads us to feed the load with voltage of effective value whatever the speed fluctuations through a flywheel energy storage system which contribute greatly in this task.

As emerging tools, flywheel energy storage systems appear poised to replace batteries as a backup power supply in wind energy conversion system.

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