CONTROL DRIVES FOR FLYWHEEL ENERGY STORAGE SYSTEM USED IN WIND APPLICATIONS

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REZUMAT. Lucrarea prezintă o soluţie ce constă într-o centrală eoliană de mică putere dotată cu un Sistem de Stocare Inteligent şi Modular (SSIM). Acesta conţine următoarele trei module: un Modul de Stocare pe Termen Scurt (MSTS) ce are la bază un volant antrenat de un motor asincron şi un Modul de Stocare pe Termen Mediu/Lung (MSTML) ce are la bază o Baterie Redox Vanadium (BRV). Scopul lucrării este realizarea controlului motorul asincron al volantului prin următoarele două metode: reglarea neliniară şi adaptivă fără traductor de turaţie şi reglarea directă a cuplului.

Cuvinte cheie: volant, motor asincron, control neliniar, reglarea directă a cuplului, sistem de stocare, eoliene.

ABSTRACT. The paper presents a solution which consists of a wind small power plant with a Smart Storage Modular System (SSMS). The SSMS consists in the following three modules: a Short Time Storage Module (STSM) based on a flywheel with induction motor and a Medium/Long Time Storage Module (MLTSM) based on a Vanadium Redox flow Battery (VRB). The aim of this paper is to provide for the induction motor of the STSM two control methods: a nonlinear sensorless solution and a direct torque solution.

Keywords: flywheel, induction motor, nonlinear control, direct torque control, storage system, wind applications.

1. INTRODUCTION

The major problems of the wind energy conversion are:

- the direct dependence of the power generation capability for a given wind speed,
- the system controllability, taking into account that wind energy is with intermittent outputs.

A lot of remote communities are supplied with electrical energy produced by diesel generators which are not quite advantageous because of the price and fuel consumption. In order to reduce energy costs, renewable energy sources (RES) are considered as an interesting alternative. In this case the necessity of energy storage is becoming more important regarding specially the high energy costs during maximum load period and the constantly raising base load in the networks. Some main of services provided by the energy storage devices are the followings: frequency stability, balances of the maximal energy need, load balancing and ready-to-use stored energy during the blackouts.

In order to solve the conflict between the stochastic nature of the wind energy source and the need to schedule the power output, the author proposes a Smart Storage Modular System (SSMS) able to work for a small wind turbine in networking conditions and for insulated loads [1].

To store or retrieve electrical energy into a small generation system or stand alone loads, the flywheels can be used as short time energy buffers. Being robust and cheap, the induction motor (IM) is very suitable for small and medium power flywheel drives. The control of the flywheel IM requires very precise speed information. In this aim, the author recommends the following control methods: a nonlinear sensorless control and a direct torque control (DTC) one.

2. SYSTEM DESCRIPTION

For a small wind farm, the general block diagram of SSMS is presented in the Fig. 1.

As results from the Fig.1, the SSMS consists in the following main three modules:

- Stochastic Source Module (SSM) based on the wind energy source with stochastic output;
- Short Term Storage Module (STSM) based on a flywheel with Induction Motor (IM);
- Medium/Long Term Storage Module (MLTSM) based on a Vanadium Redox flow Battery (VRB).

An auxiliary module (Converter 4 + Filter + Transformer) represents the Grid Interface Module (GIM).

It provides connections with the main network and the insulated loads.

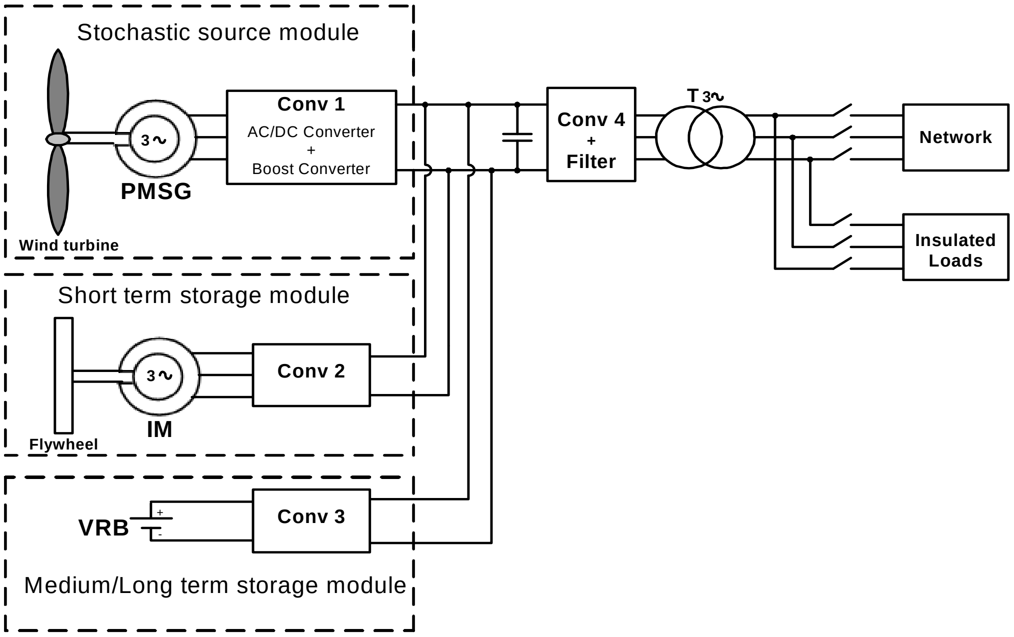

Fig. 1. Smart Storage Modular System (SSMS) block diagram.

All the modules are interconnected through a dc bus. The designed SSMS includes the following desirable features: based on renewable energy, active & reactive power deterministic generation, clean energy, good controllability and efficient maintenance costs.

2. STOCHASTIC SOURCE MODULE

This module has the following parts: a) the wind energy source with stochastic output; b) the Permanent Magnet Synchronous Generator (PMSG) and c) the power Converter 1. The wind energy source with stochastic output is considered as an aerodynamic wind mathematical model based on the main parameters as: aerodynamic wind power, aerodynamic torque and tip speed ratio. All of these are described in [3].

3. SHORT TERM STORAGE MODULE

The STSM consists in a flywheel that stores kinetic energy, based on the following equation:

$$E_k = \frac{J\Omega^2}{2} = P_{N(IM)} \cdot \Delta t, \tag{1}$$

where: J is the flywheel inertia; Ω – the mechanical angular speed; $P_{N(IM)}$ – the IM rated power and Δt is the storage period.

The flywheel is connected to the dc bus by the bidirectional AC/DC Converter 2 (rectifier/inverter), which controls the flywheel speed and power.

The IM converts the electromechanical energy in accordance with the waveforms depicted in Fig.2.

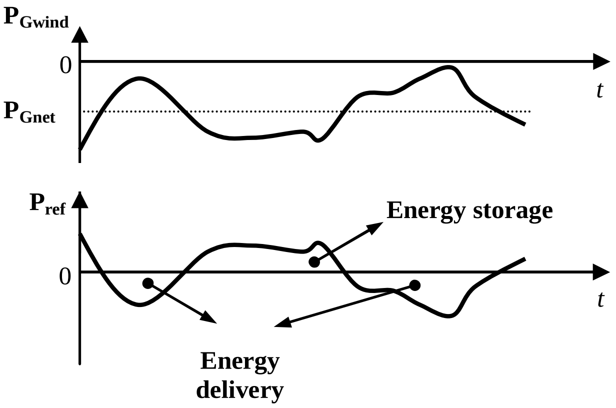

Fig. 2. Waveforms to control the flywheel.

In this figure, P_{Gwind} is the power provided by the wind generator (as known one), P_{Gnet} – the power provided by the flywheel into the network and P_{ref} is the reference power, calculated as follows:

$$P_{ref} = P_{Gnet} - P_{Gwind} \tag{2}$$

If $P_{ref} > 0$, in excess energy exists which will be stored. If $P_{ref} < 0$, a lack in energy exists and it will be replaced by the flywheel stored energy.

For this module are presented two drive systems dedicated to control the flywheel IM during the storage process, using the following methods:

- nonlinear sensorless and adaptive control,
- direct torque control (DTC).

A comparison between the both control methods will be presented as practical results point of view.

A. Nonlinear Sensorless and Adaptive Control

To nonlinear control the flywheel induction motor, we impose control references (Ω_{ref}, $\psi_{r(ref)}$) concerning the stator reference frame by considering the rotor field oriented control (in α-β stationary reference frame) with the d-axis.

The fixed stator reference frame is used in order to have a state system matrix (vector) depending on the mechanical flywheel speed and IM rotor flux.

In this aim we consider the system state equation of the flywheel, as follows:

$$x = A\cdot x + B\cdot u \;\rightarrow\; \dot{x} = A + b_1\cdot u_{sd} + b_2\cdot u_{sq},\qquad y = C\cdot x \tag{3}$$

where:

- the state vector is: $x = [\Omega\ \ \psi_r\ \ i_{sd}\ \ i_{sq}]^T$ (4)
- the system vector is

$$A = \begin{bmatrix} \dfrac{p\psi_r L_m}{JL_r}\cdot i_{sq} - \dfrac{T_r}{J} - \dfrac{T_f}{J}\cdot\Omega \\ \dfrac{L_m}{\tau_r}\cdot i_{sd} - \dfrac{\psi_r}{\tau_r} \\ -\dfrac{R_s + \dfrac{L_m^2}{L_r^2}\cdot R_r}{\sigma L_s}\cdot i_{sd} + \dfrac{\psi_r L_m}{L_r L_s \sigma \tau_r} + \omega_s i_{sq} \\ -\dfrac{R_s + \dfrac{L_m^2}{L_r^2}\cdot R_r}{\sigma L_s}\cdot i_{sq} - \omega_s i_{sd} - \dfrac{\psi_r L_m}{L_r L_s \sigma}\cdot p\Omega \end{bmatrix} \tag{5}$$

- the input vector components are

$$b_1 = \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{\sigma L_s} \\ 0 \end{bmatrix} \qquad b_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{1}{\sigma L_s} \end{bmatrix} \tag{6}$$

- the stator voltage vector is

$$u = [u_{sd}\ u_{sq}]^T \tag{7}$$

- the outputs vector is

$$y = [\Omega\ \ \psi_r]^T \tag{8}$$

- the output matrix is

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{9}$$

- the stator pulsation is

$$\omega_s = p\Omega + \frac{L_m}{\psi_r \tau_r}\cdot i_{sq} \tag{10}$$

- the leakage coefficient is:

$$\sigma = 1 - \left(L_m^2 / L_s L_r\right) \tag{11}$$

- the square of the IM rotor flux is:

$$\psi_r = \Phi_r^2 \tag{12}$$

- the IM speed constant is:

$$\tau = L_r/Rr \tag{13}$$

and: L_s, L_r are the stator and rotor inductances, L_m – the mutual inductance; R_s – the stator resistance; R_r – the rotor resistance; T_r – the IM resistant torque; T_f – the total friction torque.

Based of all previously considerations, the flywheel control system state equation is given by:

$$\begin{bmatrix} u_{c1} \\ u_{c2} \end{bmatrix} = \Delta_0(x) + \begin{bmatrix} 0 & \dfrac{pL_m}{\sigma J L_s L_r}\cdot\psi_r \\ \dfrac{2L_m}{\tau_r \sigma L_s}\cdot\psi_r & 0 \end{bmatrix}\cdot\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = \Delta_0(x) + \Delta(x)\cdot\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix}, \tag{14}$$

where: u_{c1} is the control signal direct proportional with Ω; u_{c2} – the control signal direct proportional with ψ_r; $\Delta_0(x)$ – a matrix including the derivation of the outputs vector [2]; $\Delta(x)$ – a matrix defined in equation(14).

From this equation, can be deduced the state of the nonlinear feedback, as follows (see also [2]):

$$\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = -\Delta(x)^{-1}\Delta_0(x) + \Delta(x)^{-1}\cdot\begin{bmatrix} u_{c1} \\ u_{c2} \end{bmatrix} = \alpha(x) + \beta(x)\cdot\begin{bmatrix} u_{c1} \\ u_{c2} \end{bmatrix} \tag{15}$$

During the flywheel operation, its speed Ω is defined between the minimum (Ω_{min}) and maximum (Ω_{max}) values, as follows:

$$\Omega_{\max}^2 - \Omega_{\min}^2 = \frac{2\cdot P_{N(IM)}\cdot\Delta t}{J}, \tag{16}$$

where are used the symbols from equation (1). The speed reference (Ω_{ref}) also will be defined within the minimum and maximum values and will be applied to the control of the flywheel IM.

Concerning the reference flux ($\psi_{r(ref)}$), it is imposed by:

$$\psi_{r(ref)} = \begin{cases} \sqrt{3}\cdot\dfrac{L_r u_{sN}}{L_m \omega_{sN}} & for\quad \Omega \le \Omega_N \\ \dfrac{L_r P_{N(IM)}}{pL_m\Omega}\cdot i_{sq\max} & for\quad \Omega > \Omega_N \end{cases}, \tag{17}$$

where: u_{sN} is the rated stator voltage, ω_{sN} – the rated stator pulsation, Ω_N – the rated speed and i_{sqmax} – the maximum stator q-axis current.

The block diagram of the control system is depicted in the Fig.3, where $\hat{\psi}_r, \hat{\Omega}$ are the estimated values of the IM rotor flux and angular speed.

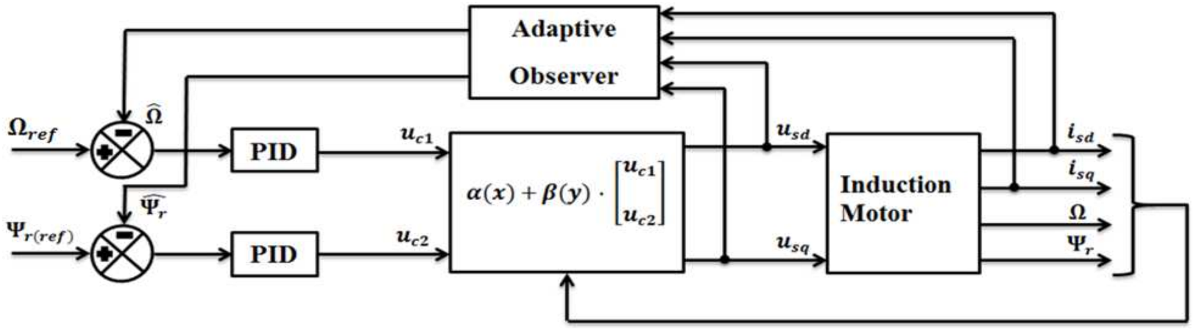

Fig. 3. Block diagram of the control system.

B. Direct Control Torque

To control the flywheel IM, a DTC control system is considered. It has been implemented in the laboratory, as depicted in Fig. 4, as follows [6], [7], [8]:

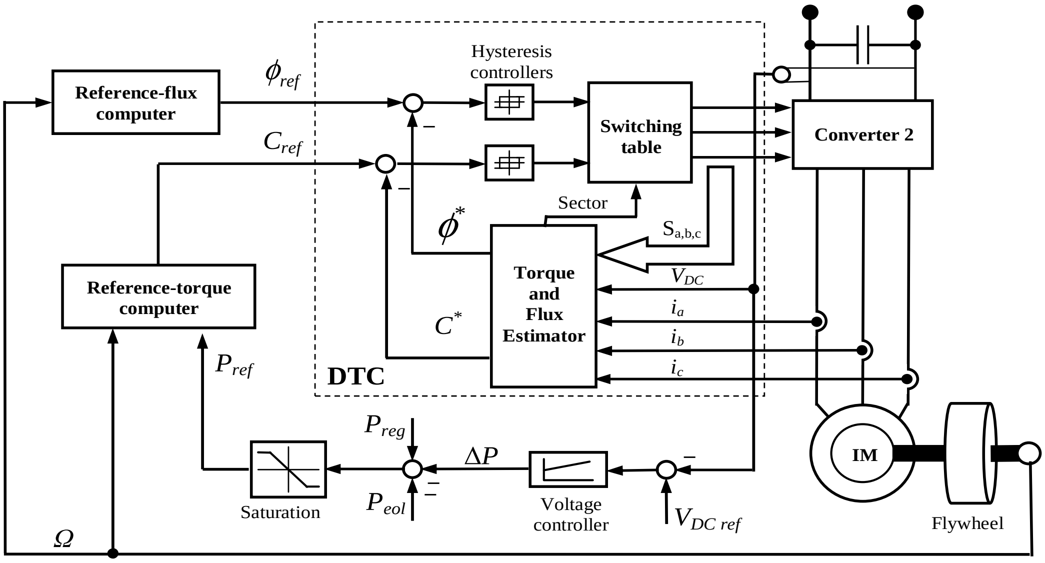

Fig. 4. Control diagram for the IM using DTC.

Based on the well known theory of the DTC control method [6], [7], [8] in this paper are only presented the main following equations:

- estimated statoric magnetic flux phasor $\overline{\Phi}_S$ of IM

$$\frac{d\overline{\Phi}_S}{dt} = \overline{V}_S - R_S \cdot \overline{I}_S \qquad (18)$$

- statoric magnetic flux components $\Phi_{S\alpha}$,$\Phi_{S\beta}$ in the α,β reference system

$$\Phi_{S\alpha} = \int \left(-R_S^* \cdot i_{S\alpha meas} + v_{S\alpha}\right)\cdot dt\,, \qquad (19)$$

$$\Phi_{S\beta} = \int \left(-R_S^* \cdot i_{S\beta meas} + v_{S\beta}\right)\cdot dt\,, \qquad (20)$$

- electromagnetic torque

$$T_{em} = P_n \cdot \left(\Phi_{S\alpha}\cdot i_{S\beta meas} - \Phi_{S\beta}\cdot i_{S\alpha meas}\right). \qquad (21)$$

where: R_S is the stator resistance; $\underline{I}_s$ – the phasor of stator currents; $\underline{V}_s$ – the phasor of stator voltages, i_S – the stator currents and v_S – the stator voltages.

The values marked with ***** are the estimated ones and the other values called *meas* are the measured ones.

The DTC is used to control the IM, because the author estimates a meaning of 50% decrease in calculus of DSPs time, comparable with the vector control method. To maintain the flywheel in a secured operating mode a General Monitoring System (GMS) has been designed. It is a smart one because it works based on fuzzy logic control.

The interface to the dc bus is accomplished by the power Converter 2 which is a PWM-VSI inverter.

The dc bus current is supplied by the Converter 2 and is necessary to have a correct estimation of it because determines the voltage V_{dc} value which must kept constant.

4. PRACTICAL SOLUTIONS

To give a practical solution for the SSMS a test laboratory bench was built in the *Power Electronics* laboratory of the university. It consists in:

- wind turbine simulator: IM motor of 3 kW, 1500 - 3000 rot/min controlled by a dSPACE system DS1103;
- PMSG of 3 kW, 3000 rot/min, 8 poles, R_S = 0,11 Ω, $L_d = L_q$ = 0,97 mH, Ψ_0 = 0,1119 Wb, T = 27,3 Nm. It is lead by a dc motor and controlled by a dSPACE system DS1103;
- flywheel which consists in an IM of 3 kW at 1500 rot/min controlled for a maximum dc bus of 400-420V. The flywheel inertia is of 0,15-0,65 kgm^2.
- VRB system has been replaced in the laboratory by a lead acid battery bank of 56kV/112A, 6kW.

The laboratory experiments consist in:

- system operation with no storage system;
- system operation with flywheel connected with the network for a short time;
- system operation with batteries connected for insulated loads.

4.1. OPERATION WITH NO STORAGE SYSTEM

When the wind generator rotates with variable speed, it delivers variable power which depends on the wind speed. The delivered power in the network is depicted in Fig. 5, as follows:

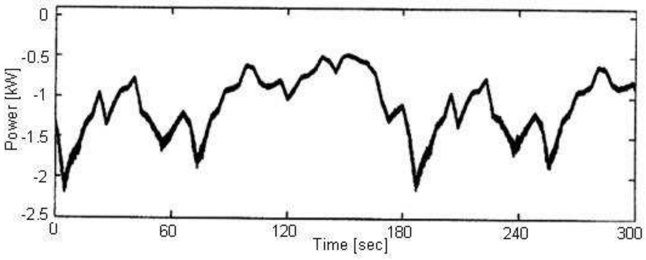

Fig. 5. Delivered power in the network.

4.2. OPERATION WITH FLYWHEEL CONNECTED

Are tested the following laboratory situations:

1. During the flywheel IM idle starting, at zero angular speed, the motor angular speed reaches the rated value, as seen in Fig. 6.

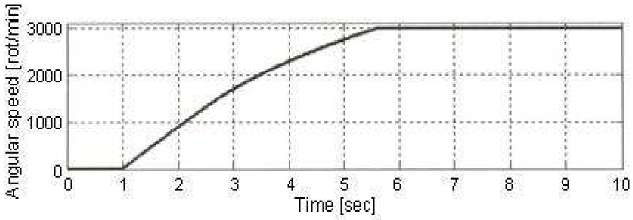

Fig. 6. Angular speed at IM idle starting.

This curve must be respected during the both control methods, as imposed one. The rated flux is reached at 3000 rot/min.

2. Induction motor starts at rated flux and the field weakening begins after the speed of 160 rad/sec, (Fig. 7).

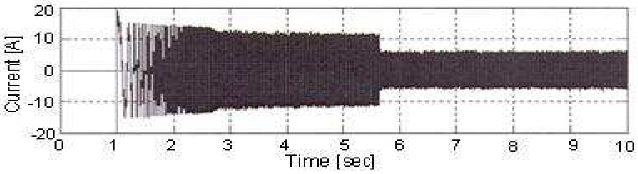

Fig. 7. Current of flywheel IM during the starting.

Since of the field weakening, the IM power is limited to its rated value for a speed of *n=3000 rot/min*. In this case the flywheel inertia is considered of *J=0,25kgm*^{2}. During the starting, the wind generator supplies the dc bus capacitor with generated power and provide to it 420V. All these considerations are quite similar for the both control methods.

3. At the moment t_1, the IM is starting and in the moment t_2 is starting the flywheel (Fig.8).

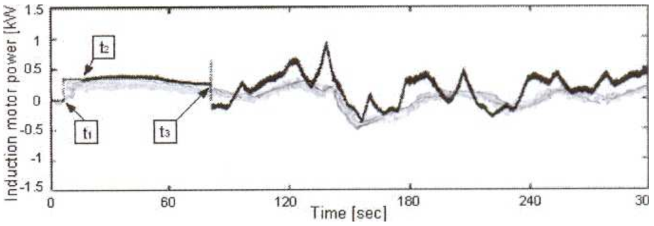

Fig. 8. Flywheel induction motor power.

In this case, the black curve represents the DTC control method and the gray one is for the nonlinear and adaptive control. It results the advantages of adaptive control: smoothing (attenuated ripples) and more flexible.

4. After the time t_3 the dc bus voltage is kept quite constant to 400V.

The IM starts at reduced power to not discharge the dc bus capacitor and accelerates the flywheel until 1900-2000 rot/min. From the time t_3 the flywheel is controlled to maintain 400V in the dc bus and to deliver power into the network.

After this moment, the active power delivered in the network by the flywheel, is depicted in the Fig.9.

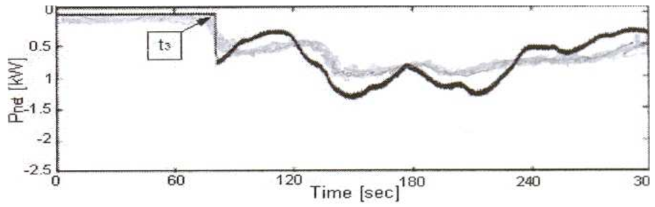

Fig. 9. Active power delivered in the network.

Also the black curve is depicted for DTC control method and the gray one for the nonlinear and adaptive one. Results the smoothing (no ripples) and flexible aspects for the adaptive control. The power provided by the flywheel IM controlled by the DTC (black curve) and adaptive (gray curve) control methods is represented in the Fig. 10.

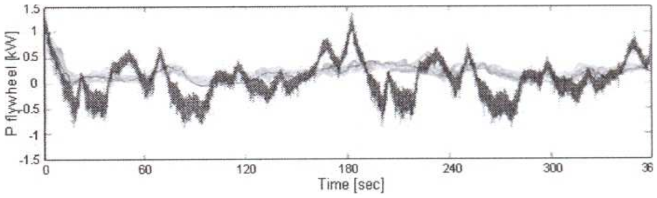

Fig. 10. Power of the flywheel induction motor.

It remarks the attenuated ripples in the case of insulated loads.

4.3. OPERATION WITH BATTERIES CONNECTED

In this case, the SSM works in parallel connected with the MLTSM and both of them coupled with the insulated loads through the GIM. Based on the VRB mathematical and Matlab/Simulink implemented models, other details are presented in [3]. In the laboratory work, series-parallel lead acid batteries are used.

5. CONCLUSIONS

A smart storage system designed and used for small wind farms, with a modular and flexible structure has been presented.

Are examined the advantages/disadvantages of two control drives for the flywheel storage system. In order to eliminate the speed sensor (used in DTC control) with all its disadvantages (costs increase, requirement of a connection line between the motor and control system and interference from the signal line), the author proposed a nonlinear sensorless control of the flywheel storage module, based on an adaptive observer. It is able to deliver power in standard networks. For insulated loads the system uses a storage module based on VRB. The power transfer between the individual modules is performed over a dc bus. Some laboratory tests are presented in order to have practical confirmations.

Other research works are made in order that all modular set up is controlled by a smart general system based on fuzzy logic algorithms. This one will provide efficient coordination and reduces the costs.

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