A study of non-linear control for energy storage systems

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Abstract: - This paper presents an overall solution consisting of a wind plant with a Smart Storage Modular System (SSMS). The SSMS consists in 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). The aim of this paper is to provide a nonlinear sensorless control solution for the induction motor (IM) within the inertial storage system based on flywheel. To this related one, computer simulations and laboratory tests are accomplished.

Key-Words: - Flywheel, induction motor, nonlinear sensorless 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) and the system controllability, taking into account that wind energy is with intermittent outputs.

The majority of the 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, investigation of renewable energy sources (RES) represents 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.

The energy storage devices are providing the main following services: frequency stability, balances of the maximal energy need, load balancing and ready-to-use stored energy during the blackouts. Based on the Kai Strunz concept of Stochastic Energy Source Access Management (SESAM) introduced in [1], and in order to solve the conflict between the stochastic nature of the wind energy source and the need to schedule the power output, the authors proposed a Smart Storage Modular System (SSMS) able to work for a small wind turbine in networking conditions and for insulated loads. In order to store or retrieve electrical energy into a small generation system or stand alone loads, the flywheels can be used as energy buffers. Because is robust and cheap, the IM is very suitable for medium and high power flywheel drives. The control of the flywheel IM requires very precise speed information, and in this aim, the authors recommend a nonlinear sensorless control of it.

2 System description

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

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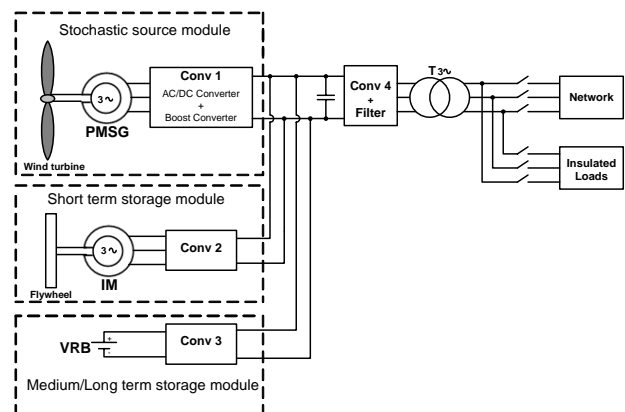
As results from the Fig.1, the SSMS consists in the following main three modules:

- 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) and provides connections with the main

network and the insulated loads. 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.

2.1 Stochastic Source Module

The SSM contains 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 following main parameters: aerodynamic wind power, aerodynamic torque and tip speed ratio. All of these are described in [3].

2.2 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 is the mechanical angular speed, $P_{N(IM)}$ is the IM rated power and Δt is the storage period.

The flywheel is connected to the dc bus by a bidirectional AC/DC converter (Converter 2-rectifier/inverter), which controls the flywheel speed and also the exchanged power, as shown in Fig.1. The IM converts the electromechanical energy in accordance with the waveforms depicted in Fig.2.
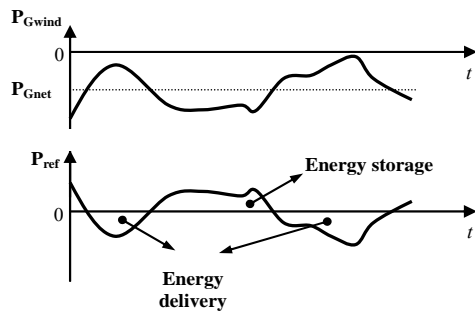

Fig.2. Waveforms to control the flywheel.

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

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

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

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:

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

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

$$A = \begin{bmatrix} \dfrac{p\psi_r L_m}{JL_r} \cdot i_{sq} - \dfrac{T_r}{J} - \dfrac{T_f}{J} \cdot \Omega \\[2mm] \dfrac{L_m}{\tau_r} \cdot i_{sd} - \dfrac{\psi_r}{\tau_r} \\[2mm] -\dfrac{R_s + \dfrac{L_m^2}{L_r^2} \cdot R_r}{\sigma L_s} \cdot i_{sd} + \dfrac{\psi_r L_m}{L_r L_s \sigma \tau_r} + \omega_s i_{sq} \\[4mm] -\dfrac{R_s + \dfrac{L_m^2}{L_r^2} \cdot R_r}{\sigma L_s} \cdot i_{sq} - \omega_s i_{sd} - \dfrac{\psi_r L_m}{L_r L_s \sigma} \cdot p\Omega \end{bmatrix} \tag{5}$$

- 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 $u = [u_{sd}\, u_{sq}]^T$ $\qquad$ (7)
- the outputs vector is $y = [\Omega \;\; \psi_r]^T$ $\qquad$ (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 $\psi_r = \Phi_r^2$ $\quad$ (12)
- the IM speed constant is $\tau = L_r/R_r$ $\qquad$ (13)
- L_s, L_r are the stator and rotor inductances,

- L_m is the mutual inductance,
- R_s, R_r are the stator and rotor resistances,
- T_r is the IM resistant torque,
- T_f is the total friction torque.

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

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

$$= \Delta_0(x) + \Delta(x)\cdot\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix}, \tag{14}$$

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

From the equation (14), 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, it 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:

$$\psi_{r(ref)} = \begin{cases} \sqrt{3}\cdot\dfrac{L_r u_{sN}}{L_m \omega_{sN}} & for \quad \Omega \le \Omega_N \\[2em] \dfrac{L_r P_{N(IM)}}{pL_m \Omega}\cdot i_{sq\,max} & for \quad \Omega > \Omega_N \end{cases}, \tag{17}$$

where u_{sN} is the rated stator voltage, ω_{sN} is the rated stator pulsation, Ω_N is the rated speed and $i_{sq\,max}$ is the maximum stator q-axis current.
The block diagram of the control system is depicted in the Fig. 3, where $\bar\psi_r, \hat\Omega$ are the estimated values of the IM rotor flux and angular speed.
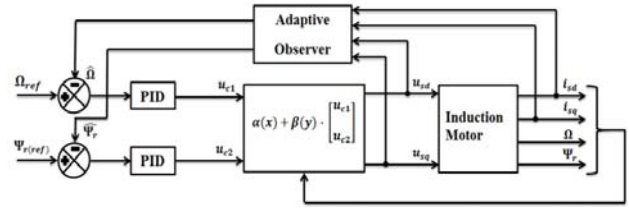

Fig.3. Block diagram of the control system.

3 Practical Solution

To give a practical solution for the SSMS a test laboratory bench was built in the *Power Electronics* laboratory of the Transylvania University of Brasov. 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, $R_S = 0{,}11\ \Omega$, $L_d = L_q = 0{,}97$ mH, $\Psi_0 = 0{,}1119$ 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 nonlinear and sensorless 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 without the storage system;
- system operation with the flywheel connected only with the network for a short time;
- system operation with VRB connected only with the insulated loads.

3.1 Operation without the Storage System

When the wind generator rotates with variable speed it delivers variable power which depends on the wind speed (see Fig. 1). In this case, taking into account the whole storage system absence, the delivered power in the network is depicted in the Fig. 4, as follows:
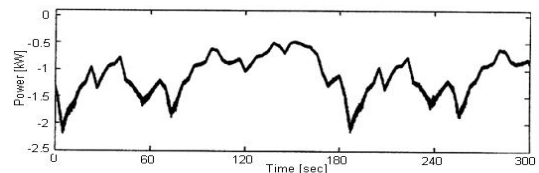

Fig.4. Delivered power in the network.

3.2 Operation with the Flywheel Connected

Are tested the following laboratory situations:

1. During the flywheel IM idle starting, at zero angular speed, the motor magnetic flux reaches the rated value, as seen in Fig. 5.
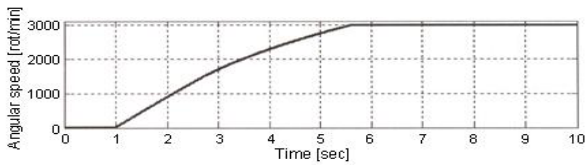

Fig.5. Angular speed at IM idle starting.

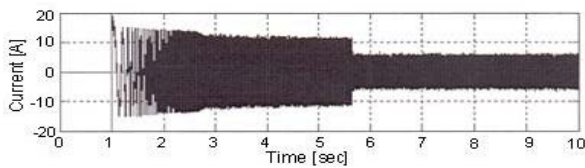2. Induction motor starts at rated flux and the field weakening begins after the speed of 160 rad/sec, (Fig. 6).

Fig.6. 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.

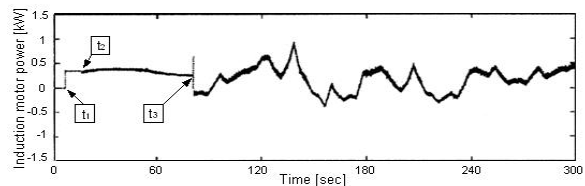3. At the moment t_1 is starting the IM and in the moment t_2 is starting the flywheel (Fig.7).

Fig.7. Flywheel induction motor power.

4. After the time t_3 the dc bus voltage is kept 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 400 V 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.8.
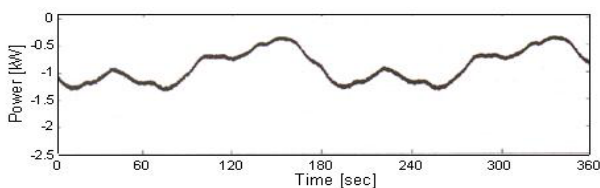

Fig.8. Active power delivered in the network.

3.3 Operation with VRB 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].

4 Conclusion

A smart storage system designed and used for wind farms, which has a modular and flexible structure has been presented. In order to eliminate the speed sensor with all its disadvantages (costs increase, requirement of a connection line between the motor and control system and interference from the signal line), the authors 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 by the authors 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.

References:
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