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Flywheel Energy Storage Drive System for Wind Applications

This paper presents a wind small power plant with a Smart Storage Modular Structure (SSMS), as follows: a Short Time Storage Module (STSM) based on a flywheel with Induction Motor (IM) and a Medium/Long Time Storage Module (MLTSM) based on a Vanadium Redox flow Battery (VRB). To control the speed and torque of the IM are used a nonlinear sensorless solution and a direct torque solution which have been compared. Now, the author proposes to replace the IM by a dc motor with permanent magnet energy injection. In this aim, are accomplished some laboratory tests.

Keywords: flywheel, induction motor, magnetic device, wind energy.

1. Introduction

A lot of holiday homes and remote communities are supplied with electrical energy by diesel generators which have some disadvantages related to the price and fuel consumption. To reduce the energy costs, renewable energy sources (RES), as wind energy small plants, are considered as an interesting alternative. In this case, the following major problems of the wind energy conversion are considerd:

- 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.

Within wind applications, 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 provide some of the following main services, as: frequency stability, balances of the maximal energy need, load balancing and ready-to-use stored energy during the blackouts. To solve the conflict between the stochastic nature of the wind energy source and the need to schedule the power output, the author proposed a

Smart Storage Modular System (SSMS) able to work for a small wind turbine in networking conditions and for insulated loads [1].

In this case, the 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 drive systems. The control of the flywheel IM requires very precise speed information. In this aim, the author developed as control methods a nonlinear sensorless and a direct torque control (DTC) ones [1], [2].

Now, the author tries to replace the IM by a DC motor with Permanent Magnet Energy Injection [3], [4]. In this aim, are accomplished only some laboratory tests, because a mathematical and computer simulation are not until now developed for the dc motor with permanent magnet energy injection.

2. Smart storage modular system description

The block diagram of the Smart Storage Modular System (SSMS) is depicted in figure 1.

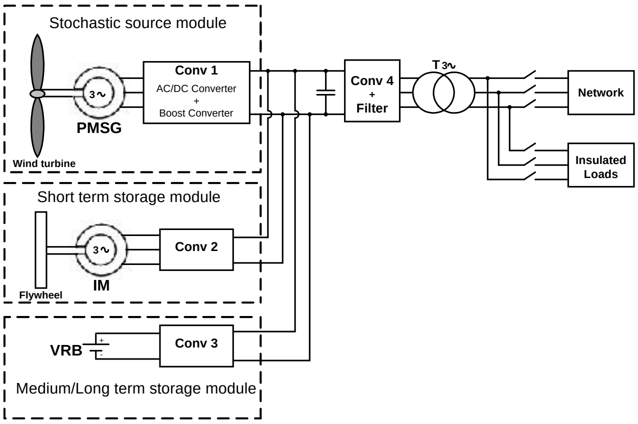


Figure 1. Block diagram of the Smart Storage Modular System.

As results from the figure 1, the SSMS consists in the following main modules:

- Stochastic Source Module (SSM) based on: a) the wind energy source with stochastic output; b) the PMSG and c) the Power Converter 1, [1];
- Short Term Storage Module (STSM) based on the IM flywheel;
- Medium/Long Term Storage Module (MLTSM) based on the Vanadium Redox flow Battery (VRB), [1];
- Auxiliary module (Converter 4 + Filter + Transformer) which is 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 STSM, based on the IM flywheel, stores kinetic energy and is connected to the dc bus by the bidirectional AC/DC converter (Converter 2-rectifier/inverter), which controls the flywheel speed and also the exchanged power [1].To control the IM flywheel during the storage process, are used a nonlinear sensorless based on adaptive control and a direct torque control (DTC) methods [1, 2].

Within the nonlinear sensorless based on adaptive control method, we impose control references (Ω_{ref}, $\psi_{r(ref)}$) by considering the rotor field oriented control (in α-β stationary reference frame) with the d-axis of the IM [1]. 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 [1]. The stored kinetic energy by the IM flywheel is 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.

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

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

The speed reference (Ω_{ref}) also will be defined between the minimum and maximum values and will be applied to the control of the IM flywheel. Concerning the reference flux ($\psi_{r(ref)}$), it is imposed by:

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

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

The block diagram of the control drive system is based on the mathematical model presented in [1] and is depicted in the figure 2, where $\hat{\psi}_r, \hat{\Omega}$ are the estimated values of the IM rotor flux and angular speed.

To control the IM flywheel, a DTC control system has been implemented in the laboratory, as depicted in the figure 3, [1, 2].

The author estimates a meaning of 50% decrease in calculus time of DSPs within the DTC, comparable with the vector control method. The interface to the dc bus is accomplished by the power Converter 2 which is a PWM-VSI one. The dc bus current is supplied by the Converter 2 and is necessary to have a correct estimation of it because provides the voltage V_{dc} value which must kept constant.

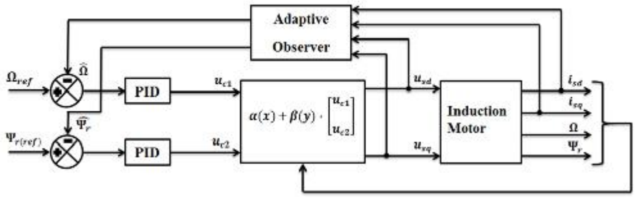


Figure 2. Block diagram of the nonlinear control system.

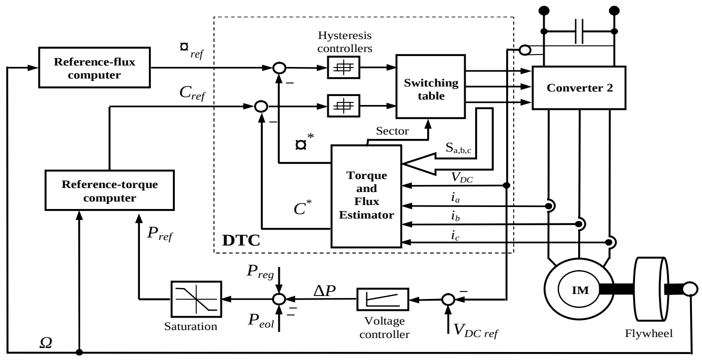


Figure 3. Block diagram of IM flywheel direct torque control.

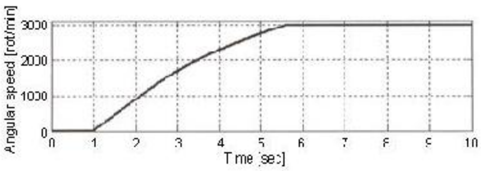
A comparison between the both control methods will be presented as practical results point of view.

3. Practical results.

Practical results are obtained on a test laboratory bench which has been built in the Power Electronics laboratory of the Transylvania University of Brasov having the main following parts:

- Wind turbine simulator with an IM motor of 3 kW, 1500–3000 rot/min supplied by a Danfoss VLT-FC302 (3 kW) converter and controlled by a dSPACE system DS1103. It rotates a 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.
- Flywheel with an IM of 3 kW at 1500 rot/min controlled for a maximum dc bus of 400-420V by a dSPACE system DS 1104 and having inertia of 0,15-0,65 kgm^2.
- VRB system which has been replaced in the laboratory by a lead acid battery bank of 56kV/112A, 6kW.

At idle starting, the flywheel IM angular speed reaches the rated value, as seen in figure 4. This curve is an imposed one and must be respected during the both control methods. At 3000 rot/min, the rated flux is reached.



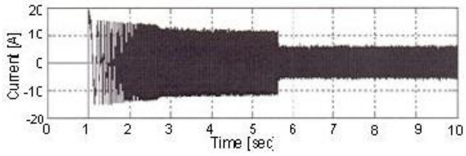
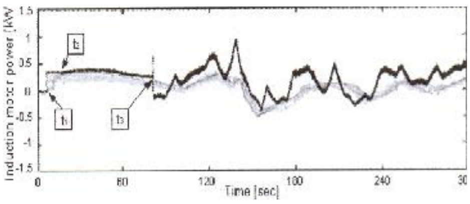


Figure 4. Idle starting of flywheel IM. Figure 5. IM flywheel current at starting.

After the IM starting at rated flux, the field weakening begins after the speed of 160 rad/sec, as seen in figure 5. The IM power is limited at rated value for a speed of n=3000 rot/min and a flywheel inertia of J=0,25 kgm^2. At starting, the wind generator supplies the dc bus capacitor with generated power providing to it 420V. All these considerations are quite similar for the both control methods.

In the figure 6 are presented the two following moments: t_1, for the IM starting and t_2 for the flywheel starting.



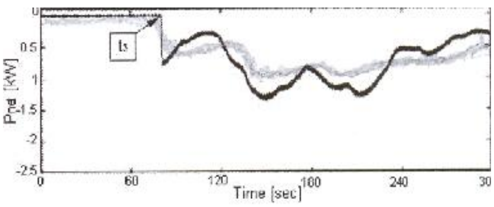


Figure 6. Flywheel IM power. Figure 7. Power delivered in the network.

At low power, the IM starts to not discharge the dc bus capacitor, accelerating the flywheel until 1900-2000 rot/min. After the time t_3 the dc bus voltage is kept constant at 400 V. Since 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 is depicted in the figure 7. In both figures, are depicted the power curves obtained within two control methods: black curve for DTC control and gray one for the nonlinear and adaptive control. It results the advantages of adaptive control: smoothing (attenuated ripples) and more flexible.

The author intends to replace the flywheel IM with a dc motor which has an original design based on adjustable permanent magnet (PM) energy injection. This dc motor is certified by a patent of invention registered in Romania [4].

A general configuration of it is depicted in the figure 8 and consists in two main sub-assemblies mechanic and galvanic coupled between them [3, 4]. This motor can be simultaneously powered from two different sources with two adjustable energies electric and magnetic ones.

The PM device is outside of the dc motor situated in order to provide more magnetic energy, taking into account the limited space inside the motor. It permits the transfer of magnetic energy only their fields inside, through magnetic injection (positions 0, 1, 2, 3, 4 as depicted in figure 8).

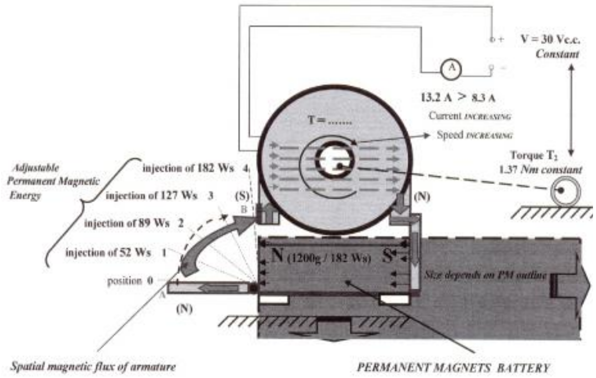


Figure 8. Configuration of the dc motor with permanent magnet energy injection.

Because is just a prototype, the mathematical model for this motor is in the course of development. Also it must increase the power of the motor up to 3kW.

4. Conclusion

To improve the SSMS performances, 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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