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Smart Storage Solution for Wind Systems

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***Abstract*—Energy storage devices and solutions are required for power quality and balance within wind systems. In the context of rapidly expanding of distributed energy sources, the wind energy converters are in the center of interest. In this case, the direct dependence of the power generation capability for a given wind speed represents a major problem of wind energy conversion with regard to large-scale network integration. This paper proposes an overall solution which consists of a wind plant with a smart Storage Modular System (SSMS) where the wind source -as stochastic one- is coupled over a dc bus with two storage modules and a smart grid interface. The investigated system consists of three modules: a) the stochastic module (variable wind turbine with PMSG and ac/dc + bust converters), b) the short term storage module (flywheel with power electronic converter) and c) the medium/long term module (Vanadium Redox Flow Battery with power electronic converter). All of three modules are interfaced with the network and insulated loads by a grid interface module (power electronic converter, filter and transformer). To the related SSMS, are accomplished computer simulations. In order to validate them, laboratory tests are also presented.**

***Index Terms*—Computer simulation, digital control, direct torque control, distributed generation, energy storage, flow batteries, flywheels, induction motor, permanent magnet synchronous generator, power electronics, power system simulation, renewable energy, wind energy.**

I. INTRODUCTION

DURING the recent years, renewable energy sources for electric power supply have received a considerable attention due to the global concerns associated with the conventional generation and potential worldwide energy shortages. In the context of a market rapid expansion, for distributed energy, a major interest is represented by the wind energy systems. A major problem of the wind energy conversion regarding the large-scale network integration is the direct dependence of the power generation capability on the given wind speed. Also, an important problem is the system controllability, taking into account that wind energy is with intermittent output. Generally, the majority of the remote communities in the world are supplied with electrical energy produced by diesel generators which are not quite advantageous because of the fuel consumption and price. In order to reduce energy costs, investigation of renewable energy sources 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. Ones connected to the network, 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. All these features bring advantages for both to the energy producers and users providing possibilities to reduce the energy transmission costs by energy losses. 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 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.

II. SYSTEM DESCRIPTION

The general block diagram of the SSMS for a small wind farm is presented in Fig. 1. As results from the figure, the SSMS consists in the following main three modules:

- Stochastic Source Module (SSM) which comprises the renewable energy source (wind) 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) is represented by the Grid Interface Module (GIM) and provides connections with the main network and the insulated loads. It allows in addition both the active power transfer and the reactive power generation. The whole SSMS is managed by a Global System Control (GSC) which automatically controls all the modules through local control units (LCU) and is based on fuzzy logic algorithms. All the modules are interconnected through a dc bus.

The active power and reactive power outputs to the grid are adjusted by the GIM. The GSC is hierarchically structured being associated with the LCU controllers. The GSC and LCU maintain by control the desired value of the dc bus voltage across the capacitor in order to obtain the desired output power value.

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.

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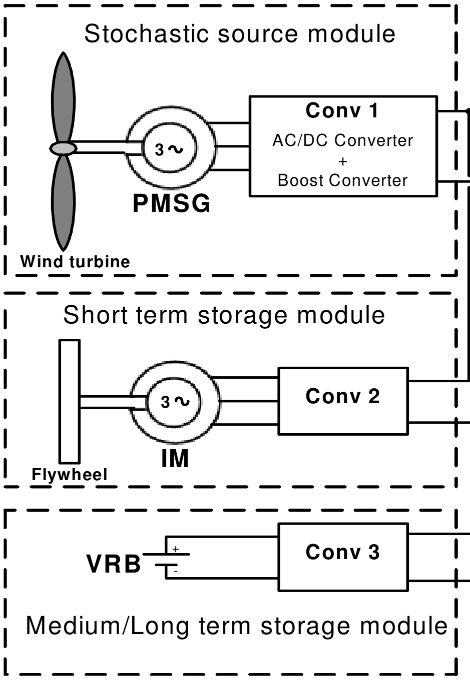


Fig. 1. Block diagram of the SSMS for wind systems.

The cost and maintenance efficiency of SSMS is promoted by the design into modules with well defined interfaces and control units.

A. *Stochastic Source Module*

The SSM comprises the following parts: a) the wind energy source with stochastic output; b) the Permanent Magnet Synchronous Generator (PMSG) and c) the power Converter 1.

To describe the wind energy source with stochastic output is considered an aerodynamic wind mathematical analysis based on the following main parameters:

- aerodynamic wind power:

$$P_W = \frac{1}{2}\rho\pi R^2 v_{weq}^3 C_p(\lambda,\beta), \qquad (1)$$

- aerodynamic torque:

$$T_W = \frac{1}{2}\rho\pi R^3 v_{weq}^2 C_p(\lambda,\beta)/\lambda, \qquad (2)$$

- tip speed ratio:

$$\lambda = \frac{\omega_{WTR}\cdot R}{v_{weq}}. \qquad (3)$$

where ρ is the air density, R the rotor blades lenght, v_{weq} is the equivalent wind speed, λ is the tip speed ratio, $C_p(\lambda,\beta)$ is the performance coefficient, β is tilting angle of wind turbine rotor and ω_{WTR} is the angular velocity of the rotor blades. The wind generator rotates with a variable speed and generates a variable power which strictly depends on the wind speed. In Fig. 2 is depicted the speed/time characteristic of the wind generator, for a short time and in the absence of storage system. Taking into account this characteristic, and the wind mathematical model Kaimal [2], [3] it was depicted the aerodynamic model in Matlab/Simulink, as shown in [3].

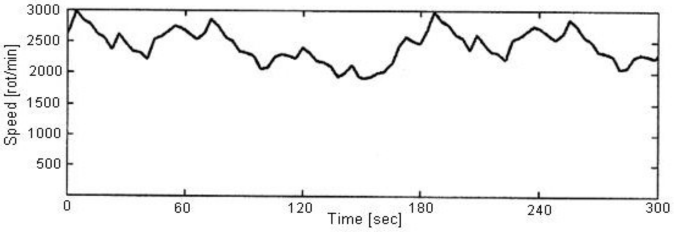


Fig. 2. Wind generator speed.

It was used the Kaimal mathematical model because it is in accordance with the Danish Standards. Another important parameter for the wind turbine is the power curve as relationship of C_p and λ wich is represented in the Fig. 3. For a given wind speed, the power captured by the wind turbine highly depends on C_p. Usually the power curve characteristics are included in the warranty assessment procedures as part of the wind plant commissioning.

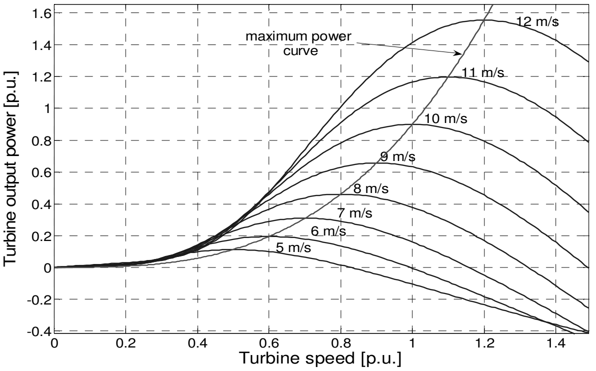
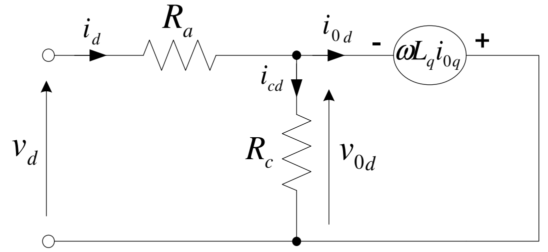
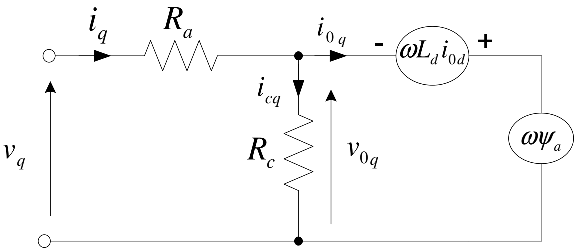


Fig. 3. Wind turbine power characteristic.

The PMSG is equipped with permanent magnets and has not damper windings. Fig. 4 shows the equivalent circuits in the *d-q* coordinates that synchronously rotate with angular speed ω.



(a) *d* – axis equivalent circuit



(b) *q* – axis equivalent circuit

Fig. 4. Equivalent circuit of the PMSG.

The PMSG torque is expressed as [4]:

$$T_G = P_n[\psi_a i_{0q} + (L_d - L_q)\cdot i_{0d} i_{0q}], \tag{4}$$

where ψ_a is the magnet flux-linkage, P_n is the number of pole pairs L_d , L_q are the d- and q-axis inductances and the currents are indicated in the figure. For this application is used a salient pole PMSG with the model in rotor oriented axis and the currents as state variables. The electromagnetic torque control rule for the PMSG is the following one:

$$T_e = k\cdot\Omega_W = K\cdot f^2, \tag{5}$$

where *k, K* are constants, Ω_W is the wind turbine rotations number and f is the PMSG stator frequency.

The power Converter 1 consists in a diode rectifier and a boost converter. To maximize the wind turbine output power and adjust the PMSG speed, a Maximum Power Point Tracking (MPPT) control is used [5]. Depending on the wind speed, the MPPT control adjust the power transferred to bring the turbine operating points onto the maximum power curve, as shown in the Fig. 4. This leads in changing the angular velocities ω_{WTR} in order to generate ac voltages at different frequencies. The PMSG ac waveforms are rectified in the diode converter. The boost converter (buck chopper) helps to obtain the dc bus desired voltage. Here, the capacitor is an energy buffer for the generator.

B. Short Term Storage Module

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

$$E_k = \frac{J\omega^2}{2}, \tag{6}$$

where *J* is the flywheel inertia which rotates with the angular speed ω.

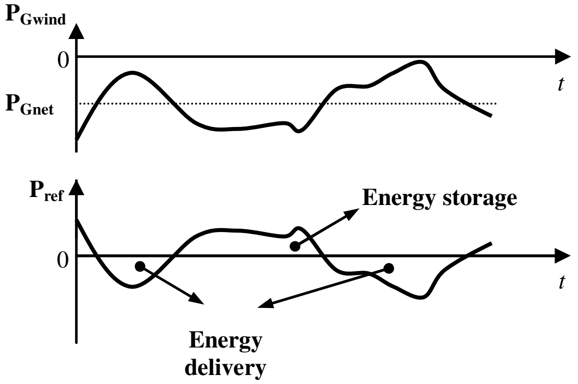


Fig. 5. Waveforms to control the system flywheel-wind generator.

As indicated in Fig. 1, the Induction Motor (IM) is suitable to convert the electromechanical energy in accordance with the following waveforms (Fig. 5), where PG wind is the power provided by the wind generator (as known one), PG net is the power which is provided by the flywheel into the network and the P_{ref} is the reference power, calculated as follows:

$$P_{ref} = P_{Gnet} - P_{Gwind} \tag{7}$$

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

To control the IM, a DTC control scheme has been considered and implemented in the laboratory, as shown in Fig. 6, as follows [6], [7], [8]:

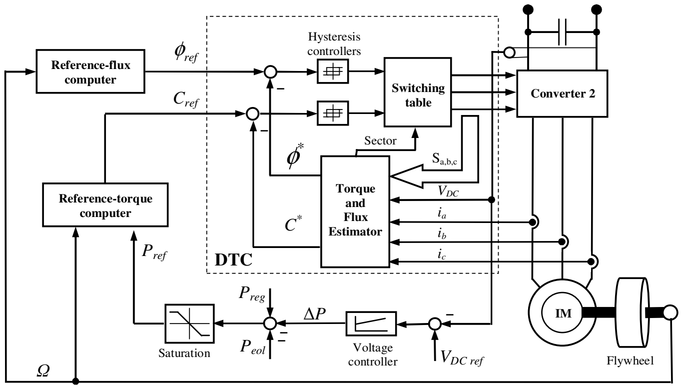


Fig. 6. Control diagram for the IM using DTC.

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 $\overline{\Phi}_S$ for the IM

$$\frac{d\overline{\Phi}_S}{dt} = \overline{V}_S - R_S\cdot\overline{I}_S, \tag{8}$$

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

$$\Phi_{S\alpha} = \int\left(-R_S^*\cdot i_{S\alpha meas} + v_{S\alpha}\right)dt, \tag{9}$$

$$\Phi_{S\beta} = \int\left(-R_S^*\cdot i_{S\beta meas} + v_{S\beta}\right)dt, \tag{10}$$

- electromagnetic torque

$$T_{em} = P_n \cdot \left(\Phi_{S\alpha} \cdot i_{S\beta meas} - \Phi_{S\beta} \cdot i_{S\alpha meas} \right). \tag{11}$$

where R_S is the stator resistance, $\bar{I}_S$ is the phasor of stator currents, $\overline{V}_S$ is the phasor of stator voltages, i_S , v_S are the stator currents and voltages. The values marked with * are estimated ones and the other marked with *meas* are measured ones. The DTC is used to control the IM, because the authors estimated a meaning of 50% decrease in calculus time of DSPs comparable with the vector control method. To maintain the flywheel in a secured operating mode a General Monitoring System has been designed by the authors. It is a smart one because it works based on fuzzy logic control. The interface to the dc bus is achieved by the power Converter 2 which is a PWM voltage source inverter (VSI). 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.

C. *Medium/Long Term Storage Module*

The MLTSM is based on the Vanadium Redox Batteries (VRB) as storage source and the Converter 3 which provides a constant dc voltage to charge/discharge the battery. The authors consider that VRB is a viable option for both voltage and frequency control [3], [5], because of the main following advantages: more flexibility, higher efficiency, acceptably for larger depth of discharge, lower maintenance costs, longer life span, more environmentally friendly and lower cost per kWh of energy storage. The block diagram of VRB system configuration, the control mode of the bidirectional charge controller and Simulink modeling are presented in [9].The bidirectional charge controller provides suitable charging conditions controlling the current flow to avoid overcharge for the battery protection [5].

Because the charge controller, included within the Converter 3, has been modeled as a lossless device, the VRB current is calculated as follows:

$$I_{VRB} = \frac{V_{DC} \cdot I_{DC}}{V_{VRB}}, \tag{12}$$

where V_{DC} is the dc voltage at the output of the buck-bust converter (included in Converter 1), I_{DC} is the dc bus current and V_{VRB} is the VRB voltage. In this paper, the VRB is used as storage device only for the insulated loads.

III. SIMULATION AND EXPERIMENTAL RESULTS

The proposed system has been mathematical modeled and computer simulated using the Matlab/Simulink software package. To validate modeling and computer simulations, by practical results, a test laboratory bench was built in the laboratory. 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 controlled by a PWM inverter and using DTC for a maximum dc bus of 400-420V. The flywheel inertia is of 0,15-0,65 kgm^2. The flywheel is controlled by a dSPACE system DS 1104.
- VRB system has been replaced in the laboratory of Transilvania University of Brasov by a lead acid battery bank of 56kV/112A, 6kW.

The simulations and laboratory experiments consist in:

- system operation in the case of storage system absence;
- system operation with the flywheel connected only with the network for a short time;
- system operation with VRB connected only with the insulated loads.

A. *Operation in the case of storage system absence*

The wind generator rotates with variable speed generating 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. 7, as follows:

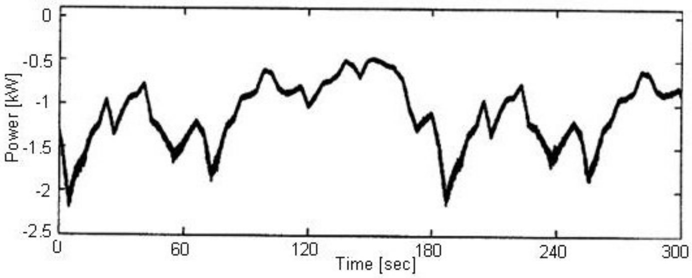


Fig. 7. Delivered power in the network (case of the storage system absence).

B. *Operation with the flywheel connected*

The first simulated situation for the IM of the flywheel it was the following: at idle starting, the magnetic flux has rated value and the angular speed is zero, as seen in Fig. 8.

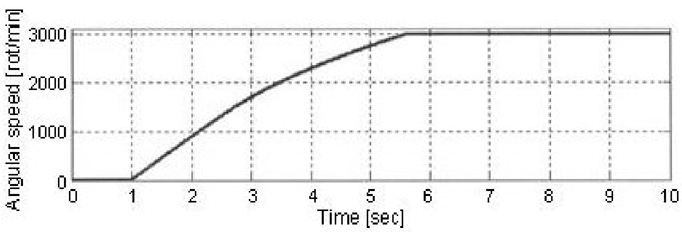


Fig. 8. Angular speed during the idle starting of the flywheel IM.

After one second, a sudden torque is applied to the flywheel, as reference torque for the IM (see Fig. 9).

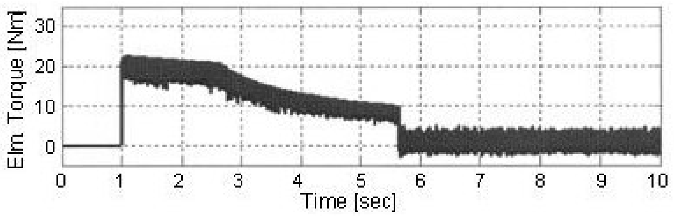


Fig. 9. Electromagnetic torque of flywheel induction motor, at starting.

The IM starts at rated flux, but after the speed of 160 rad/sec, the motor field weakening begins (see Fig. 10).

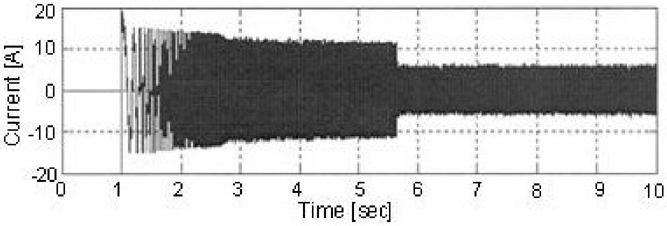


Fig. 10. Flywheel IM current, at starting.

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 $J=0,25\ kgm^2$.

Based on the Matlab/Simulink implemented model [10], are presented the characteristics during the operating mode of the system wind generator-flywheel (Figs. 11-13).

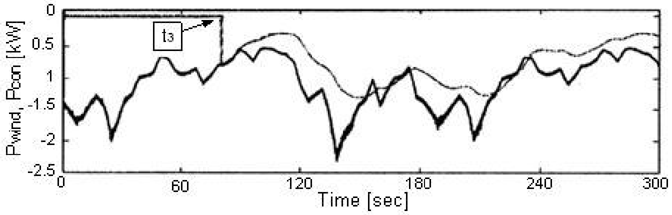


Fig. 11. Generated power (continue curve) and controlled power (point curve).

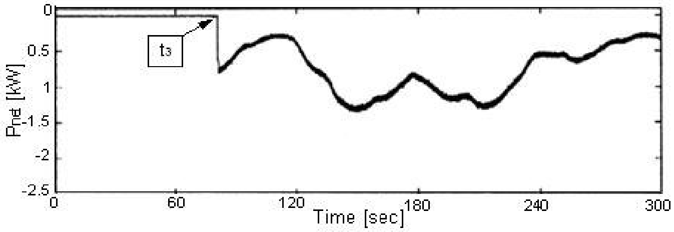


Fig. 12. Active power delivered in the network.

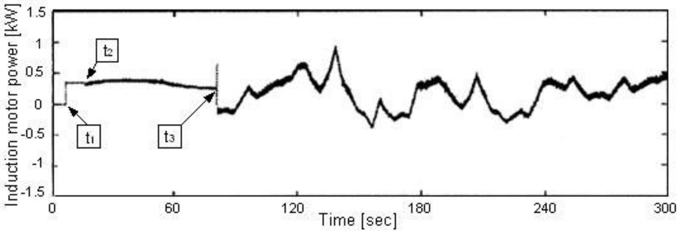


Fig. 13. Flywheel induction motor power.

During the starting, the wind generator supplies the dc bus capacitor with generated power (Fig. 11) and provide to it 420V voltage. After the time t3 this voltage is constant kept to the value of 400V. During this time, the controlled power and the power delivered in the network are zero ones (Figs. 11, 12). At the moment t1 is starting the IM and in the moment t2 is starting the flywheel (see Fig. 13). The motor starts with a reduced power to not discharge the dc bus capacitor and accelerates the flywheel until 1900-2000 rot/min. From the time t3 the flywheel is so controlled to maintain 400 V in the dc bus and to deliver power into the network.

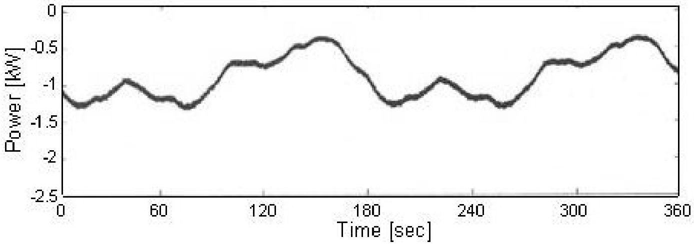


Fig. 14. Active power delivered in the network.

After this moment, the active power delivered in the network by the flywheel, is depicted in the Fig. 14.

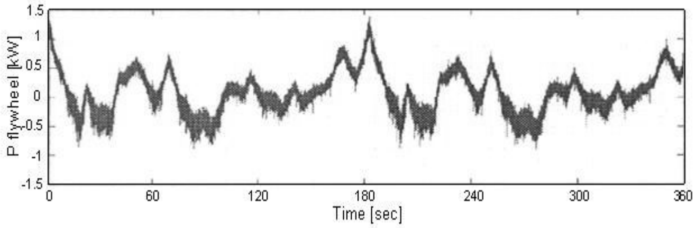


Fig. 15. Power of the flywheel induction motor.

The power of the flywheel IM controlled by the DTC method is represented in Fig. 15.

All the simulation/laboratory tests presented are made in the absence of the reactive power.

C. *Operation with the 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 [9], are presented computer simulation results, as depicted in Figs. 16-18. As example, at constant wind speed of 10 m/s, the turbine power of 3 kW can't supply the total power of 4 kW requested by loads. Figure 16 shows that the difference of power is supplied by the charging/discharging operating modes of VRB, which is able to maintain the power balance of the system.

The VRB parameters for the maximum State of Charge (SOC) are 56 V/ 112 A/ 6 kW. In the Figs. 17 and 18 are depicted the VRB voltage and current waveforms for a battery SOC of 80%.

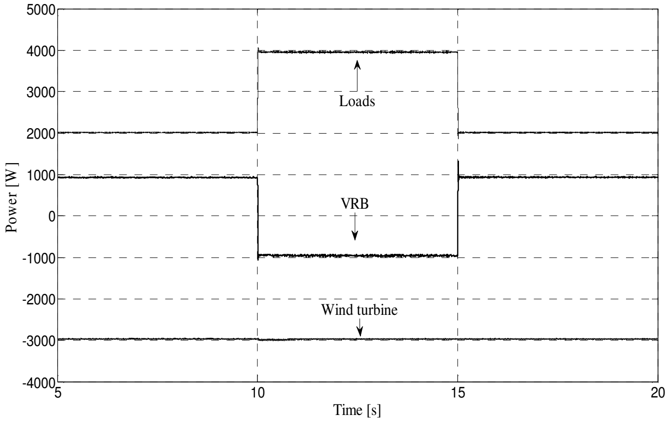


Fig. 16. Power balance of the system provided by the VRB.

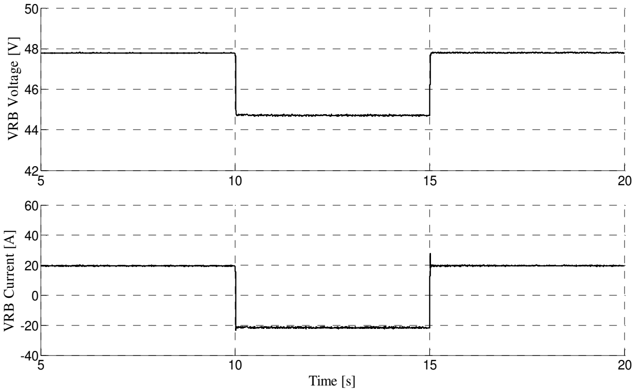


Fig. 17. VRB voltage and current waveforms.

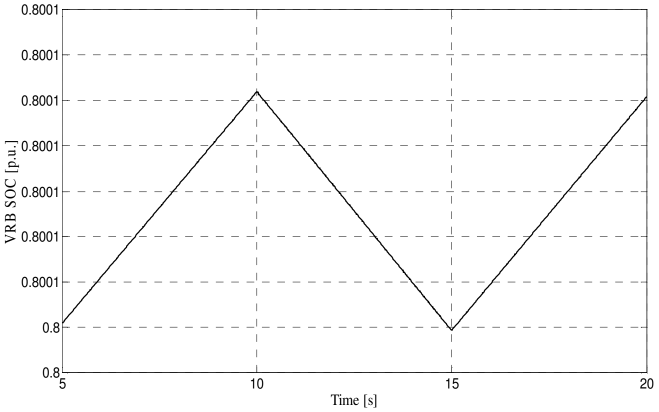


Fig. 18. VRB state of charge.

All these computer simulations are made for the steady state of PMSG and for a dc bus voltage of 50 V.

IV. CONCLUSION

This paper presents a smart storage system designed and used for a wind farm, which has a modular and flexible structure. It is able to deliver power in standard networks by using as storage module a flywheel. For insulated loads the system uses as storage module a VRB one. The power transfer between the individual modules is performed over a dc bus. Through this multi-level system deterministic wind power output to the grid is made possible in different time frames. All the modular setup is controlled by a smart general system based on fuzzy logic algorithms. This one provides efficient coordination and reduces the costs.

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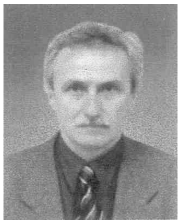
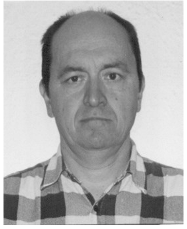
VI. BIOGRAPHIES

Luminita Barote was born in Onesti in Romania, on November 17, 1982. She received the Dipl. Ing. degree in Electrical Engineering and Computers Science from "Transilvania" University, Brasov in 2005, and Dipl. Master degree in Electrical Engineering from the same university, in 2007.

Currently, she is a Ph.D student at the Department of Electrotechnics, Faculty of Electrical Engineering and Computers Science, Transilvania University of Brasov. Her current research interests are in the area of renewable energy systems: the control of variable speed permanent magnet synchronous generator for small power wind turbine, working in stand-alone system with storage devices (lead acid battery, vanadium redox flow battery).



Marius Georgescu was born in Brasov, Romania, on October 20, 1952. He graduated from the University of Brasov, on 1976, the Faculty of mechanics, as Dipl. engineer in electro-mechanics. He has been an Assistant Professor with the University of Brasov, since 1980. He received the Ph.D. degree in electrical traction engineering from the University *Politehnica* of Bucharest, Romania, in 1997. Now he is Full Professor with *Transilvania* University of Brasov, Department of Electrical Engineering. His research interests include applied power electronics and control in electrical traction, renewable energies and electrical energy storage. He is member of the IEEE Power Electronics Society since 2006.



Corneliu Marinescu was born in Brasov in Romania, on May 26, 1948. He received the Dipl. Ing. degree in Electromechanics from Politehnic Institute, Brasov, in 1971, and the Ph. D. from the Politehnica University Bucharest in 1991.

Currently, he is full professor at the Department of Electrotechnics, Faculty of Electrical Engineering and Computers Science, Transilvania University of Brasov. Also, he is head of POWERELMA (Power Electronics and Electrical Machines) research laboratory in the same faculty mentioned above. His areas of interests include power electronics applied to renewable energy sources. He is author or co-author of more than 100 journal/conference papers in his research fields.