VRB Modeling for Storage in Stand-Alone Wind Energy Systems

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Abstract--**This paper proposes into determining an appropriate electrical Vanadium Redox Flow Battery (VRB) model and its integration with a typical stand-alone wind energy system during wind speed variation as well as transient performance under variable load. The investigated system consists of a 3kW variable speed wind turbine with permanent magnet synchronous generator (PMSG), diode rectifier bridge, buck-boost converter, bidirectional charge controller, transformer, inverter, ac loads and VRB. Vanadium Redox batteries are well suited for this type of application because of their high efficiency, high scalability, fast response, long life and low maintenance requirements.**

Index Terms--**VRB, battery modeling, wind energy, SOC, energy storage, stand-alone system.**

I. Introduction

WIND power is an energy source whose industrial applications in the world has at the fastest rate in the last 10–15 years.

Powerful grid-connected megawatt-scale wind generators 0.5–5.0 MW per unit are mostly manufactured and installed as pollution-free sources of renewable energy in the world in last years. At the same time many smaller wind turbines are required for certain installations and local consumption as fuel-free independent power suppliers. A small-scale wind power turbine of the capacity 0.2–30 kW, with rotor diameters from 1 m up to 15 m may be used as a flexible and vital alternative for local power demand in isolated regions or locations [1].

Permanent-magnet (PM) synchronous generators are one of the best solutions for small-scale variable-speed wind power plants.

The advantages of variable-speed wind turbines are an increased energy capture, improved power quality and reduced mechanical stress on the wind turbine. The disadvantages are losses in power electronics, the use of more components and the increased cost of equipment because of the power electronics [2].

The motivation for developing and implementing electrical equivalent battery models for batteries comes from an interest in studying their application in wind energy systems. As wind energy penetration levels increase, there is a growing interest in using short and long-term storage devices to aid in managing the fluctuations in wind turbine output power.

For stand-alone systems, energy storage devices are essential to store electricity for use when the wind is absent. Wind energy systems have a fluctuating power output due to the variability of the wind speed with power output varying by the cube of the speed. Integrating an appropriate energy storage system in conjunction with a wind generator removes the fluctuations and can maximize the reliability of power to the loads. In addition, both system voltage and frequency can be regulated and controlled [3].

Advantages using storage devices in wind energy systems include:

- sort–term (seconds), medium–term (minutes) and possibly long–term (hours) management of wind power fluctuations;
- providing real true and reactive power for local voltage support during transmission system short–circuits and large transients;
- meeting peak–load demand without interruption and without increase in generation, maximizing wind plant capacity.

Energy storage systems can be used within stand-alone applications, also as grid connected wind parks. In remote hybrid systems, there is an interest in increasing wind penetration, reducing the diesel fuel consumption costs, as well as avoiding voltage and frequency variations. In interconnected power system wind systems, the focus is on improving power quality and stability for different power range [4].

In order to study various aspects of battery storage in wind energy systems, fast and accurate battery models are needed. Vanadium redox batteries have many advantages comparing with other storage technologies, including operation over a wide range of power outputs, high storage efficiency, rapid response, low maintenance cost and long lifecycle. Also the VRB system can be used for power smoothing and load leveling applications [3], [5], [6]. Operation under rapidly changing conditions is possible without impact on efficiency, because the integrated pump ensure the availability of electrolyte at all times near the electrodes. The power and voltage range of a VRB depends on the cell stack, while the energy capacity depends on the tank size. This independence between energy and power ratings provides high flexibility in

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terms of design. These characteristics make VRB suitable for energy applications.

Our objective is to determine a VRB model that is suited for the study of wind energy storage systems. This paper provides an overview of a VRB model that is implemented in SIMULINK.

The paper is organized as follows: in Section II the VRB description and modelling is presented, Section III presents the system configuration with the studied VRB model characteristics; Section IV describes the Simulink implementation of developed model and simulation results while conclusions are provided in Section V.

II. Vanadium Redox Flow Battery (VRB)

A. VRB description model

A Vanadium redox flow battery (VRB) is an electrochemical cell divided into two compartments, positive and negative tanks containing electrolyte, and a pump and piping for circulating the electrolyte from the tanks to the cell. The active material for both the positive and negative electrodes of the VRB is vanadium ions that are dissolved in sulfuric acid and serve as metal ions whose valence number changes. Fig. 1 shows the operating modes of the VRB, [5]-[7].

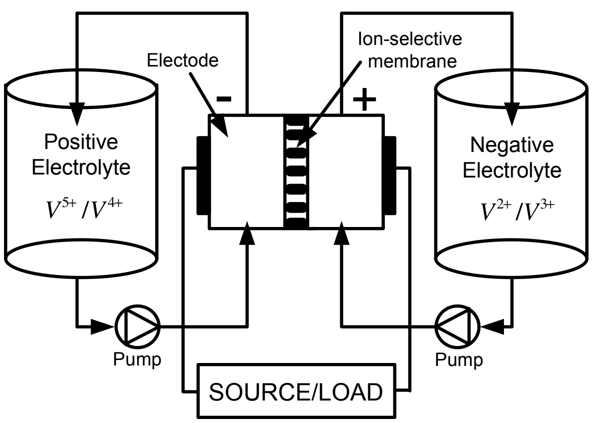

Fig. 1. VRB operating principle

Vanadium – redox flow batteries use a controlled pump to induce flow, which improves battery performance and efficiency. In a VRB battery, the total energy storage of the system depends on the State of Charge (SOC) and amount of active chemicals in the system. The total power available is related to the electrode area within the cell stacks.

B. VRB Moddeling

The proposed VRB model will be based on a 5 kW – 20 kWh, and 56 Vdc, with an initial voltage of 48 V assumed during these proposed model. The simple flow battery model, as shows in Fig. 2, takes into account internal resistance and parasitic resistance. The internal resistance accounts for losses due to reaction kinetics, mass transport resistance, membrane resistance, solution resistance, electrode resistance and bipolar plate resistance. Parasitic resistance accounts for power consumption by recirculation pumps, the system controller, and power loss from cell stack by-pass currents. The step-by-step procedure for deriving the parameters should be easily repeatable for different sized VRB systems, [8] - [10].

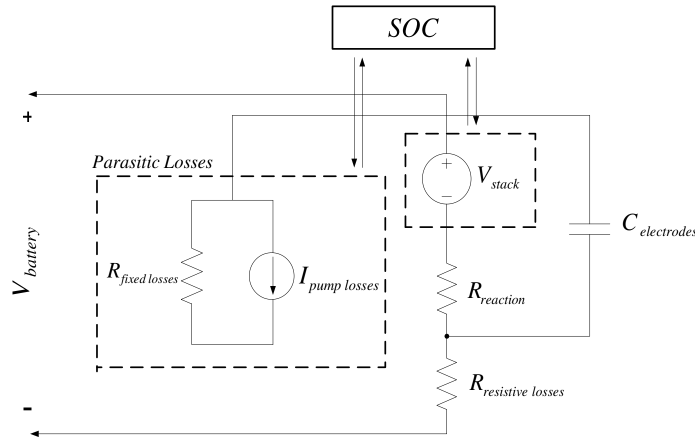

Fig. 2. Studied VRB model.

The calculations VRB parameters are based on estimating losses of 21% (15 % internal losses + 6% parasitic losses) in the worse case operating point, for a minimum voltage of 42V, and a current of 112A. For the battery to be able to ensure 5kW with 21% losses, the cell stack internal power should be, [8], [9]:

$$P_{stack} = \frac{5000}{1-0.21} = 6329{,}11W \tag{1}$$

The battery internal stack voltage is directly related to the SOC of the battery based on the following equations:

$$V_{cell} = V_{equilibrium} + 2\frac{RT}{F}\ln\left(\frac{SOC}{1-SOC}\right) \tag{2}$$

where:

- T – the temperature impact on battery operation;
- R – the VRB internal resistance (in VRB cases the internal resistance is constant). $R_{internal}$ is set to 0.075Ω, which is obtained by estimating 21% losses at a maximum current of 112 A;
- F – the Faraday's number.

For n cell stacks, $V_{equilibrium}$ would be equal to $n \cdot V_{cell}$. In this case, 39 cell stacks are needed. This is modeled as a controlled voltage which depends on both the number of cell stacks and the SOC.

The parasitic losses are separated into fixed losses (are represented as a fixed resistance) and variable losses (are represented as a controlled current source). The losses are as follows:

$$P_{parasitic} = P_{fixed} + k\left(\frac{I_{stack}}{SOC}\right) = 127 + 42.5\left(\frac{I_{stack}}{SOC}\right) \tag{3}$$

The parasitic and pump losses are derived as follows:

$$R_{fixed} = \frac{V_{stacks}^2}{P_{fixed}} = \frac{42^2}{127} = 13.889\,\Omega \tag{4}$$

$$I_{pump} = \left(\frac{42.5\left(\frac{I_{stack}}{SOC}\right)}{42} \right) = 1.011\left(\frac{I_{stack}}{SOC}\right) \tag{5}$$

The pump losses are modeled as a controlled current source that is dependent on the SOC and stack current in parallel with the fixed parasitic resistance (see Fig. 2).

One way to estimating the VRB state of charge is to update the SOC variable from one time step to the next, based on the power that goes through the cell stack. The SOC is computed each cycle based on the previous SOC, using a fixed step simulation.

An important issue in battery modeling is transient behavior. The ability of the system to respond quickly to fast changes is especially important for power smoothing applications. In a VRB battery, the transient effects are related to electrode capacitance.

The model will focus on transient behavior related to electrode capacitance, as shown in Fig. 2. $R_{internal}$ is divided into $R_{reaction}$ (0.045) and $R_{resistive\ losses}$ (0.03). $C_{electrodes}$ is estimated to be 0.15 F for a 39 cell stack, where each cell has a 6 F series capacitance.

III. System Configuration

The proposed wind stand-alone system for a residential location is a 3 kW wind turbine system with a permanent magnet synchronous generator (PMSG), rectifier bridge, buck-boost converter, bidirectional charge controller, VRB storage device, inverter, transformer and loads.

In a studied stand-alone wind turbine system, the AC energy source voltage is rectified to DC and coupled at the VRB battery, and an inverter is used to provide AC electricity for the consumers (see Fig. 3). Our purpose is to supply domestic appliances through a single-phase 230V - 50Hz inverter.

This solution allows variable speed operation of the wind turbine, solution which extracts larger amounts of energy from the variable wind, without requiring blades control, costly in small power turbines.

Although the inverter slightly lowers the overall efficiency of the system, the motivation of the chosen this wind energy system is that most households are alternating current and consequently this type of configuration is used in stand-alone applications [11], [12].

A model of the studied stand-alone wind energy system with VRB energy storage is provided in Fig. 3.

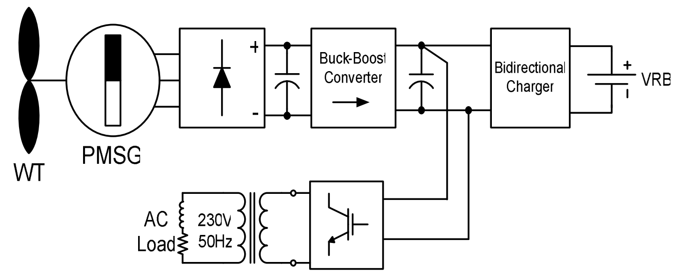

Fig. 3. System configuration.

The buck-boost converter controls the electromagnetic torque by means of wind speed, in order to extract optimum power from the available wind resource. While the input voltage to the buck-boost converter (from the bridge rectifier) varies with the wind speed, the output voltage is kept constant to the VRB. This is important because a variable DC voltage is unsuitable for battery charging as the power provided may be too high and volatile, causing damage to the battery. The VRB is able to supplement the power provided to the load by the wind turbine when the wind speed is below a threshold value. Current flow into and out of the VRB is controlled by the bidirectional charge controller [7].

The bidirectional charge controller provides suitable charging conditions and regulates the current flow to avoid overcharge for battery protection. It also enables the VRB to provide the necessary power to maintain a constant load voltage.

IV. Simulink Implementation and Simulation Results

A different type of redox flow battery models are presented in a literature [13], [14], but the developed VRB model was studied by authors of [8], [9], [10] and the motivation of the chosen this VRB model is presented below:

- the SOC of the VRB, which represents the amount of active chemicals in the system is modeled as a variable that is dynamically updated. The control method is described in [15];
- the stack voltage is modeled as a controlled voltage source, the power flow through this source impacts the changes in the SOC;
- the variable pump loses are modeled as a controlled current source.

Our objective is to determine a VRB model that is suited for the study of wind energy storage systems. This paper provides an overview of a VRB model that is implemented in SIMULINK with a typical 3 kW stand-alone wind energy system during wind speed variation as well as transient performance under variable load for validate the stability of the supply.

Fig. 4 shows the VRB Simulink block diagram. The main library used for system modeling was SimPowerSystem.

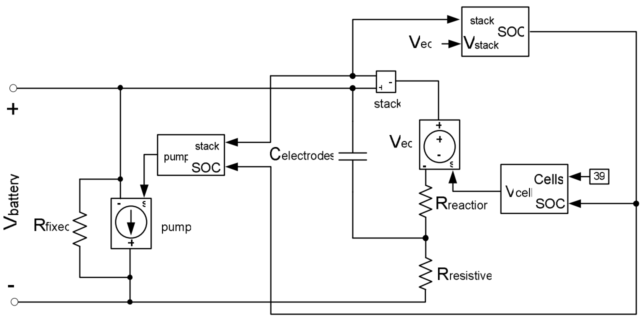

Fig. 4. VRB model in Simulink.

The proposed system has been modeled and simulated using the Matlab/Simulink environment. Fig. 5 shows the block diagram. The configuration includes the PMSG, a three-phase rectifier bridge, a buck-boost converter, a bidirectional charge controller, 5kW VRB battery, inverter, transformer, resistive loads and a block that models the wind turbine. Measurement blocks are also included.

The 3kW PMSG has a sinusoidal flux distribution and 4 pairs of poles. It is a 2300-RPM and 14.2 Nm machine. Its parameters are listed below:

Per-phase stator resistance:

$$R = 0.4578\ \Omega$$

The d-axis and q-axis stator inductances:

$$L_d = L_q = 0.00334\,H$$

Flux induced by magnets in the stator windings:

$$\Psi = 0.171\,Wb$$

In order to validate proper system operation with the developed VRB model, the following simulations were carried out:

- variation in wind speed with a fixed load;
- transient change in load with a fixed speed.

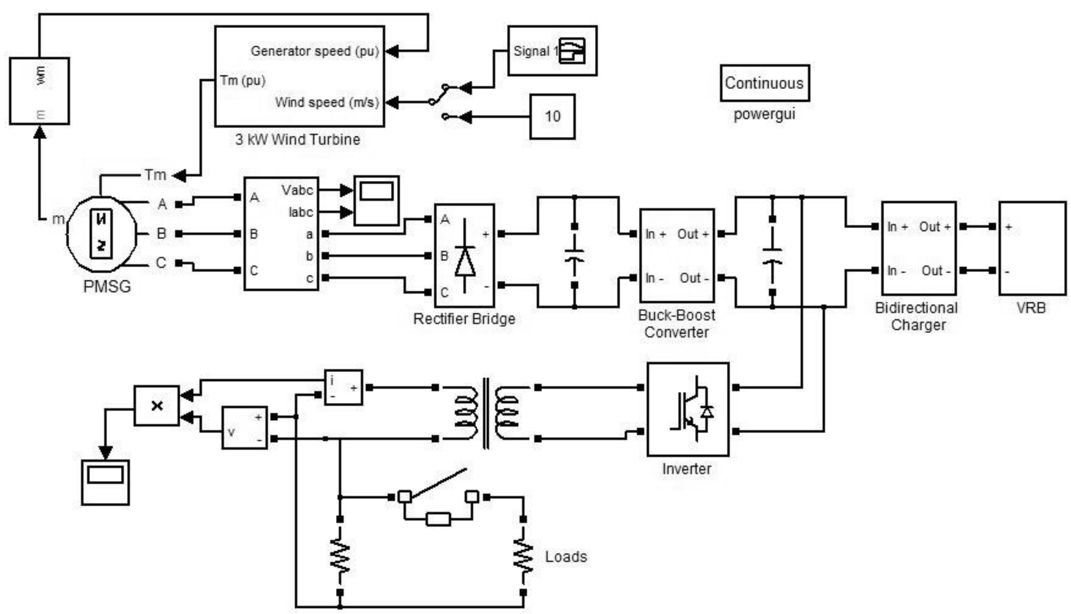

Fig. 5. Simulink block diagram.

A. Variation in wind speed with a fixed load

In the following example a wind speed drop from 10 m/s (at t=10s) to 7 m/s (at t=15s) has been considered in steady state conditions. The rated capacity of the VRB is 5kW, 20kWh, and 56 Vdc, with an initial voltage of 48V assumed during these simulations.

The output voltage and current for the VRB are shown in Fig. 6. The 3 kW wind turbine cannot supply the entire energy for the load (4kW), therefore the difference will be ensured by the VRB (1 kW). Fig. 7 shows that the power balance of the system is maintained with the VRB operating in its discharge mode. Therefore when $I_{VRB} > 0$ the VRB is charging, and when $I_{VRB} < 0$ the VRB is discharging.

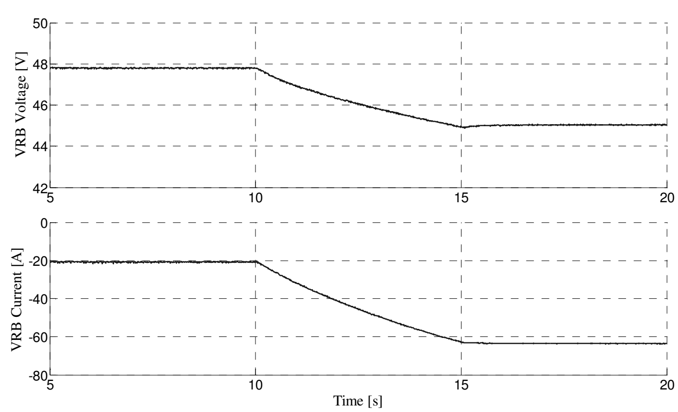

Fig. 6. The VRB current and voltage.

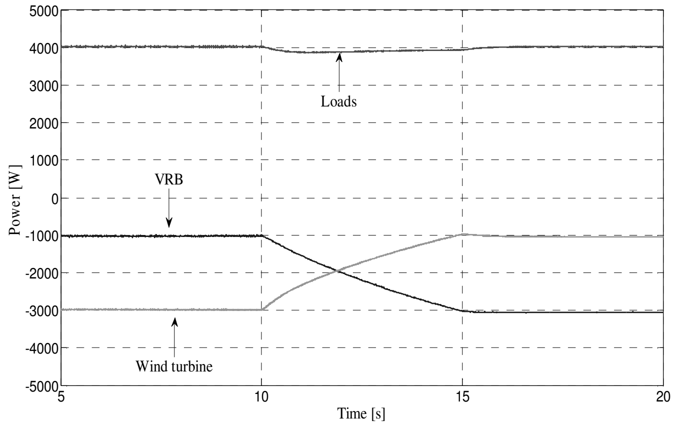

Fig. 7. The power balance of the system.

The initial VRB SOC is considered 0.8 (p.u.). When the VRB battery is discharging ($I_{VRB} < 0$), the battery SOC decreases in order to ensure the stable supply for the loads. The results can be seen in Fig. 8. Because the VRB is used in charging and discharging cycles of 4 hours, the 20 s simulation is irrelevant in analyzing the VRB SOC variation.

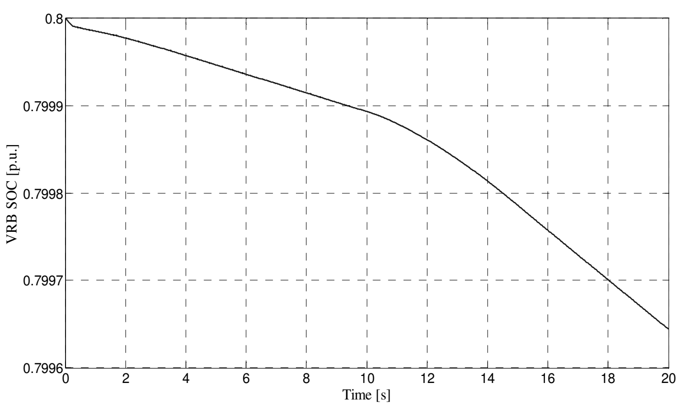

Fig. 8. The VRB state of charge (SOC) variation.

B. *Transient change in load with a fixed wind speed*

For the following simulation, the wind velocity is assumed constant at 10 m/s. The VRB voltage and current, along with the system power balance, are provided in Figures 9 and 10, respectively. A 1kW load is initially connected to the system. At t=10s, an additional 3kW load is connected until t=15s. In Fig. 9, it can be seen that the VRB operating mode changes from charge to discharge during the transient event, as power flow becomes negative (is discharging).

Because the initial load is 1kW, the difference in power supplied by the wind turbine is stored in the battery (2 kW). The VRB stored energy is used when the 3kW load is connected, in this way the supply of the load is ensured. Consequently, Fig. 10 shows that the power balance of the system is maintained.

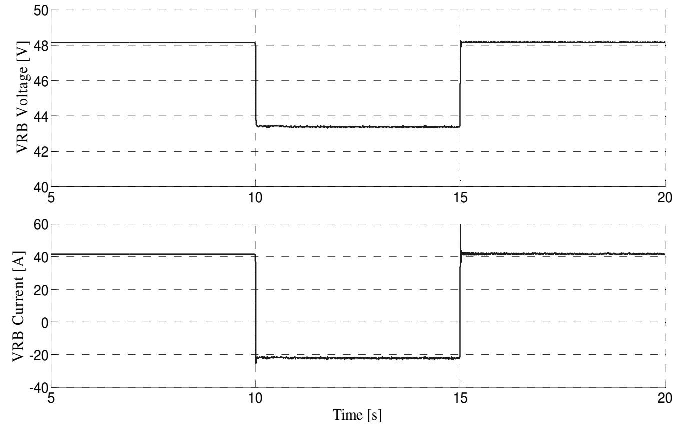

Fig. 9. The VRB current and voltage.

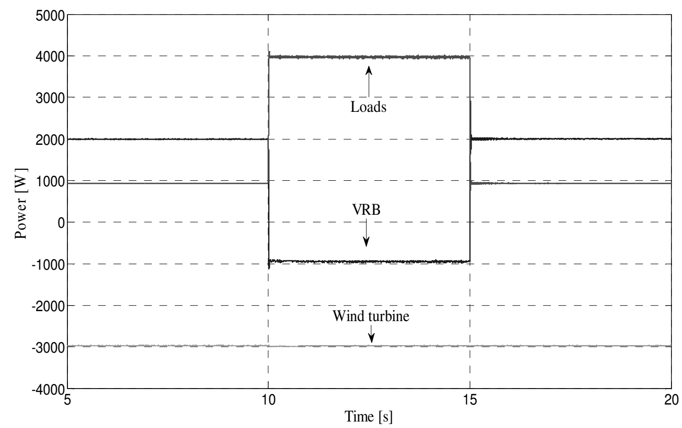

Fig. 10. The power balance of the system.

In order to ensure a permanent supply for the loads, the battery will pass from charging to discharging mode, as shown in Fig.11.

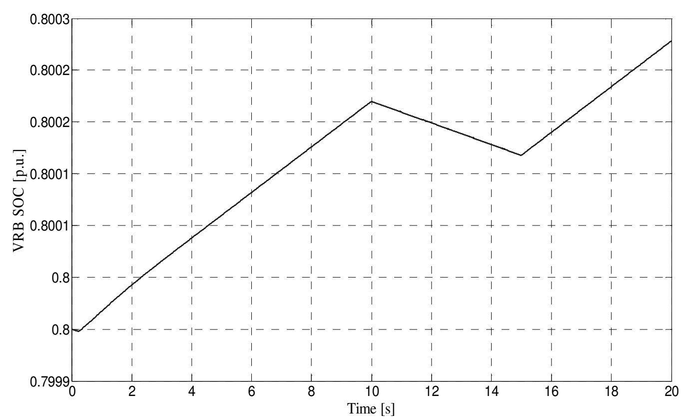

Fig. 11. The VRB state of charge (SOC) variation.

V. Conclusions

In this paper, a VRB model and its integration with typical stand-alone wind energy conversion system is analyzed.

The step-by-step procedure for deriving the parameters should be easily repeatable for different sized VRB systems.

Simulation case studies show that the power balance of the system proves to be satisfying during transient loads and variable wind speed conditions. VRB battery always ensure the safe supply of the loads (households) regardless of the problems caused by wind speed and loads variations.

In conclusion, the system's stability can be easily ensured by using the proposed configuration.

VI. References

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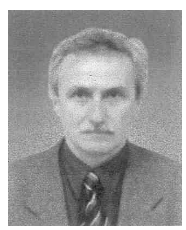
VII. Biographies

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).

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.



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.