

Stand-Alone Wind System with Vanadium Redox Battery Energy Storage

L. Barote*, R. Weissbach**, *Member, IEEE*, R. Teodorescu***, *Senior Member, IEEE*,

C. Marinescu*, *Member, IEEE*, M. Cirstea****, *Senior Member, IEEE*

* Transilvania University/Electrical Engineering and Computer Science, Brasov, Romania

** Penn State Erie/Electrical and Computer Engineering Technology, USA

*** Aalborg University/Institute of Energy Technology, Denmark

**** Anglia Ruskin University/ Department of Design and Technology, United Kingdom

Abstract – Energy storage devices are required for power balance and power quality in stand alone wind energy systems. A Vanadium Redox Flow Battery (VRB) system has many features which make its integration with a stand-alone wind energy system attractive. This paper proposes the integration of a VRB system 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 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 (to store a surplus of wind energy and to supply power during a wind power shortage). The main purpose is to supply domestic appliances through a single phase 230V, 50Hz inverter. Simulations are accomplished in order to validate the stability of the supply.

I. INTRODUCTION

Utilization of renewable energy sources such as wind and solar energy for electric power supply has received considerable attention in recent years due to global environmental concerns associated with conventional generation and potential worldwide energy shortages. Many remote communities throughout the world are supplied with electrical energy produced by diesel generators. In many of these communities, the cost of energy is largely determined by the landed cost of the diesel fuel. The urgent need to reduce the cost of energy has led to the investigation of the use of renewable energy sources, such as the wind, to replace some or all of the fuel consumed. The small wind turbines in conjunction with battery storage, can replace the electrical energy produced by diesel generators in stand-alone applications.

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 [1]. The lead acid battery (LAB) is the dominant energy storage technology for stand alone wind

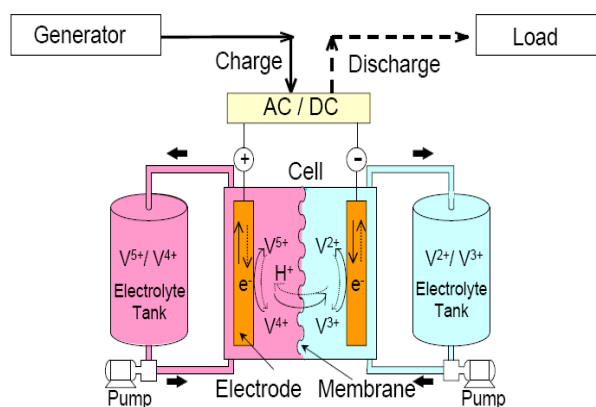


Figure 1. A vanadium redox flow battery

energy systems. However, in recent years, the Vanadium Redox flow Battery (VRB) has become a viable alternative to the LAB.

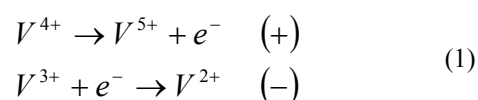
The VRB has a number of advantages relative to the LAB, which can be understood by comparing the various technologies. Thus, the VRB may be a better energy storage system for a stand alone wind energy system.

II. VANADIUM REDOX FLOW BATTERY (VRB)

The vanadium redox flow battery is an electrochemical cell divided into two compartments by an ionic membrane with acid vanadium sulfate electrolytes in each compartment. The electrolytes are pumped through the compartments from two separate electrolyte tanks. Fig. 1 shows the operating modes of the VRB.

The oxidation states of the vanadium are V^{2+} to V^{3+} in the negative electrolyte and V^{5+} to V^{4+} in the positive electrolyte.

The electrochemical processes for the VRB are:



When the electrodes of the cell are connected to an external load the differing oxidation states of the vanadium cause an electrical current to flow in the circuit.

The electrodes, which are made of carbon, do not participate in the chemical reactions.

The electrochemical cell stores or releases power by shifting the ratio of the two vanadium species present at each electrode. The system power is determined by the rate of reaction of the vanadium species at each electrode and the total surface area of the electrodes. The amount of energy stored in the system is determined by the concentration of the vanadium species and the volume of the reservoirs, [1, 2].

In the fully charged state (V^{2+} in the negative electrolyte and V^{5+} in the positive electrolyte) the potential across the cell is 1.6 V. In the discharged state (V^{3+} and V^{4+}) the potential is 1.1 V. By connecting stacks of cells electrically in series, larger voltages can be fixed [3, 4].

Currently installed vanadium batteries include [5]:

- A 1.5MW UPS system in a semiconductor fabrication plant in Japan.
- A 275 kW output balancer in use on a wind power project in the Tomari Wind Hills of Hokkaido, Japan.
- A 200 kW, 800 kWh output leveler in use at the Huxley Hill Wind Farm on King Island, Tasmania (this is a wind power station) – it is used to help maintain the electricity supply when demand exceeds turbine output (load balancing).
- A 250 kW, 2MWh load leveler in use at Castle Valley, Utah.
- A 12 MWh flow battery is also to be installed at the Sorne Hill wind farm, Ireland – this is one of the largest contracts for an energy storage system in the wind power industry, VRB Power Systems Inc. has contracted to supply a 2MW x 6 hour VRB system - this will enable surplus electricity to be generated when demand is low, and will improve consistency of supply to the electricity network.

These applications have demonstrated the viability of using a VRB energy storage system as a planning solution for utilities, and the results of these projects may offer support for future utility applications using the VRB.

In this paper, the authors will demonstrate the energy balance during transients of a stand alone wind energy system with VRB energy storage. Potential applications of the VRB will first be described. Then, the VRB and LAB will be compared. A model of a stand alone wind energy system with VRB will then be presented, along with variable wind and transient variable load simulation results. Finally, a set of conclusions and future work will be discussed.

III. POTENTIAL APPLICATIONS OF THE VANADIUM REDOX BATTERY

Energy storage systems absorb energy during times when excess capacity exists so that it can be released later when needed. The fundamental requirement in stand-alone applications is a balance between the power demanded by the loads and the power that is generated. Applications of the VRB energy storage system include:

A. Load Levelling Applications

The VRB can be designed for both high power and large energy storage, thus making it a viable option for load leveling at a customer facility. In this application,

electricity during peak hours (when the cost per kWh is high) is partially supplied by the VRB, while during non-peak hours the VRB is recharged. Securing a place for installing the tanks may be problem, especially in urban areas, because the VRB tanks have considerable size. However, the battery cell and the electrolyte tanks can be installed separately and electrolyte tanks can be installed in unused space in office buildings, such as underground cisterns.

B. Power Quality Control Applications

The VRB system response time is less than 1ms and the maximum short-time overload output can be several times that of rated capacity. This makes the VRB a viable option for both voltage and frequency control [6]. The VRB also can be used as a battery-backed uninterruptible power supply (UPS) system for protection against faults on the power utility transmission and distribution system.

The charged electrolyte is stored in separate positive and negative tanks when the battery has been charged. Therefore no self-discharge occurs during stand-by mode. The VRB can restart even after being idle for a long time simply by starting the pump to flow electrolyte to the cell stacks within 1 min. Furthermore, the VRB can be used for long duration back-up power by properly sizing the separate battery cells and electrolyte tanks.

C. Stable Output of Renewable Energy Sources Applications

As well as applications such as load leveling and reliable power, the VRB is well suited for storing electricity produced by intermittent renewable energy sources such as wind or solar power. An example is the use of renewable energy to provide power in locations where a utility grid connection is physically and/or economically unviable. The VRB is especially suitable for use with a wind generator, because it can absorb the fast fluctuations in wind power due to its quick response time and overload capacity. Thus, the VRB can be used to stabilize the output of a wind energy system.

IV. LEAD ACID – VANADIUM REDOX BATTERIES COMPARISON

A comparison between the two types is given in Table 1, [2, 7, 8, 9].

TABLE I.
COMPARISON BETWEEN LEAD ACID BATTERY AND REDOX FLOW BATTERY

| | LAB | VRB |
|-----------------------------|--------------|-------------|
| Energy Density [Wh/litre] | | |
| Theoretical | 40 | 30-47 |
| Practical | 12-18 | 15-25 |
| Power Density [W/kg] | 370 | 166 |
| Temperature Range | -5 to 40°C | 0 to 40°C |
| Efficiency | 45% | 65-75% |
| Charge/Discharge Ratio | 5 to 1 | 1.8 to 1 |
| Depth of Discharge (DOD) | 25 to 30% | 75% |
| Life Cycle | 1500 | > 10000 |
| Maintenance Cost [\$ / kWh] | \$0.02 | \$0.008 |
| Cost [\$ / kWh]* | \$500-\$1550 | \$300-\$650 |

*The metric \$/kWh is used to compare durations of longer than an hour. This factors in Life and allows for energy storage and UPS application. The ranges are determined by size of storage required.

Based on the discussion of the two technologies, and the comparison provided in Table 1, the VRB has a number of advantages when compared to the LAB:

1. The VRB is a more flexible system because the energy storage and power can be separately designed, whereas in the LAB the power and energy storage are functions of each other (i.e., based on the number of battery cells).
2. The VRB has a higher efficiency.
3. The VRB can accept a larger depth of discharge.
4. The VRB has a slightly higher energy density.
5. The maintenance cost of the VRB is lower.
6. The VRB can withstand a significantly larger number of charge/discharge cycles, and thus has a longer life span. This is because the active materials are kept in solution and are not lost nor degraded by battery cycling.
7. The VRB is more environmentally friendly, not only because of the longer life span, but also because the VRB does not use either lead or cadmium. The VRB electrolyte has an indefinite life span and is reusable.
8. In addition, a life-cycle assessment approach of the environmental impact of both the VRB and LAB for use in stationary applications indicates that the VRB contributes between 7-25 % of emissions of key environmental impact components (CO_2 , SO_2 , CO , CH_4 , NO_x) during its life cycle, when compared with lead-acid batteries [1].

The VRB has a lower cost per kWh of energy storage. The cost of the system will increase with the power output of the system based on the cost of the electrochemical cell, and the cost will increase with the energy storage capacity of the system based on the (typically lower) cost of the reservoirs and the vanadium solution.

A VRB system has a high speed response and is not aged by frequent charging and discharging. The battery efficiency actually increases when the charge/discharge period becomes shorter, unlike the LAB battery [4]. The VRB also has a short duration overload capacity and a long service life. Thus, this relatively new electrochemical technology seems well suited for enhancing the utilization of renewable energy.

One disadvantage of the VRB relative to the LAB is in its power density. Because the solubility of the redox species in the working fluid is limited, the volumetric and specific energy densities are low. This makes the VRB an ineffective solution for systems where a high power per unit volume is desired, such as transportation systems. Therefore, the development of these systems focuses on stationary applications.

V. WIND ENERGY SYSTEM CONFIGURATION

The proposed wind stand-alone system for a residential location is a 3kW 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. It supplies single-phase consumers, at 230V and 50Hz.

A model of the stand-alone wind energy system with VRB energy storage is provided in Fig. 2.

The wind turbine generates a variable ac voltage, which is converted to a variable dc voltage by the bridge rectifier.

The buck-boost converter controls the electromagnetic torque by means of wind speed, in order to extract optimum power from the available wind resource, as discussed below. 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.

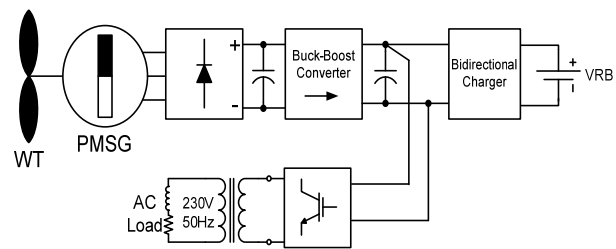


Figure 2. System configuration

Charge controllers are electronic devices that keep the VRB operating within its safety limits. Typically, charge controllers protect the battery by disconnecting the energy source when the battery has reached 100% of their charge capacity and by disconnecting the load when the state of charge has reached a lower limit.

The bidirectional charge controller provides suitable charging conditions and regulates the current flow to avoid overcharge for battery protection [11]. It also enables the VRB to provide the necessary power to maintain a constant load voltage.

The simplified layout of the charge control is presented in Fig. 3. This control algorithm uses a constant dc voltage to charge/discharge a VRB.

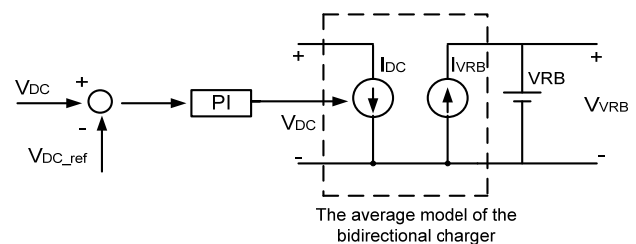


Figure 3. The control mode of the bidirectional charge controller

The dc voltage (V_{DC}) is compared with a reference voltage (V_{DC_ref}) and an error signal is obtained. With a PI (proportional-integrator) controller, the dc value of the charge/discharge current (I_{DC}) is obtained. When $I_{DC} > 0$ the VRB is charging, and when $I_{DC} < 0$ the VRB is discharging.

Because the charge controller can be modeled as a lossless device, the current of the VRB (I_{VRB}) can be calculated as:

$$I_{VRB} = \frac{V_{DC} \cdot I_{DC}}{V_{VRB}} \quad (2)$$

where:

V_{DC} - The dc voltage at the output of the buck-boost converter;

I_{DC} - The dc current at the PI output;

V_{VRB} - The VRB voltage.

A Maximum Power Point Tracking (MPPT) control is used to maximize the turbine output power and adjust the generator speed [8, 10]. Depending on the wind speed, the MPPT control adjusts the power transferred to bring the turbine operating points onto the "maximum power curve" like in Fig. 4.

To obtain maximum power from a controlled wind energy converter system, the buck-boost converter has to operate in the variable speed mode. Thus, an adequate controlling method based on MPPT must be used, in order to maximize the electric output power [10].

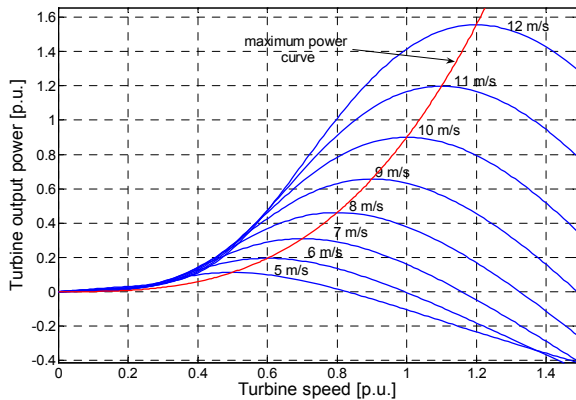


Figure 4. Wind turbine power characteristics

The PMSG ac currents are transformed into dc currents through the three-phase rectifier bridge (see Fig. 2 above). Here, the capacitor, C, is an energy buffer for the generator. The PMSG voltage varies directly with its rotor speed, and the DC voltage at the rectifier bridge output behaves similarly.

Fig. 5 shows the MPPT control block diagram. The measured wind speed (V_w), is supplied to a lookup table that determines the maximum power point from the turbine characteristics.

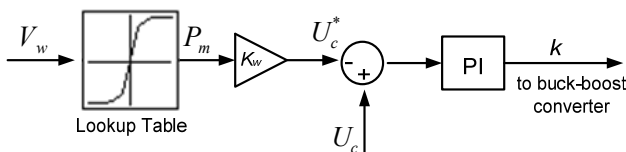


Figure 5. MPPT control block diagram

The output of this processing block is therefore a power (P_m). A coefficient K_w is then used to linearly

convert this maximum power point to a reference voltage (U_c^*). A properly tuned PI regulator is then used to control the duty cycle (k) of the buck-boost converter, thus controlling the power flow from the generator.

In order to validate proper system operation, the following simulations were carried out:

- variation in wind speed with a fixed load,
- transient change in load with a fixed wind speed, and
- simultaneous wind speed and load variations.

VI. SIMULATION RESULTS

The proposed system has been modeled and simulated using the Matlab/Simulink environment. To fully validate the model, the VRB energy storage capacity (20kWh) has been reduced, thus yielding results that can be more easily analyzed and displayed. Fig. 6 shows the block diagram. Measurement blocks are also included. The main library used for system modeling was SimPowerSystem.

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:

$$\Psi = 0.171 Wb.$$

A. Variation in wind speed with a fixed load

In the following example a wind speed drop from 12 m/s (at $t=5s$) to 7 m/s (at $t=10s$) has been considered. After 5 additional seconds (in this period the wind speed is constant at 7m/s) wind speed increases to its initial value. Steady state conditions have been considered. 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. 7. The 3 kW wind turbine can't supply the total energy for the load (4kW), therefore the difference of energy is ensure by the VRB. Fig. 8 shows that the power balance of the system is maintained with the VRB operating in its discharge mode.

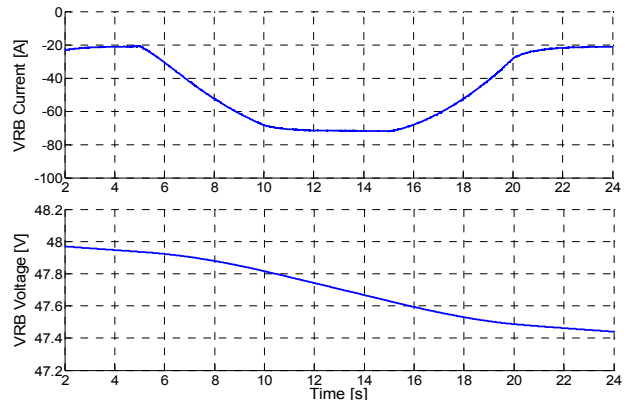


Figure 7. The VRB current and voltage

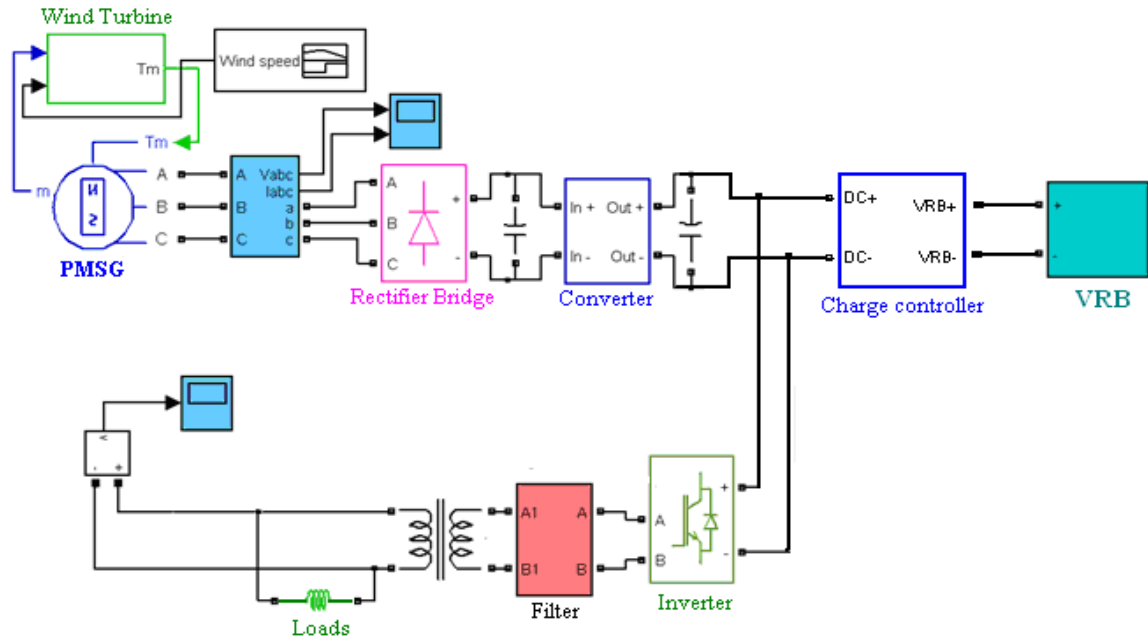


Figure 6. Simulink block diagram

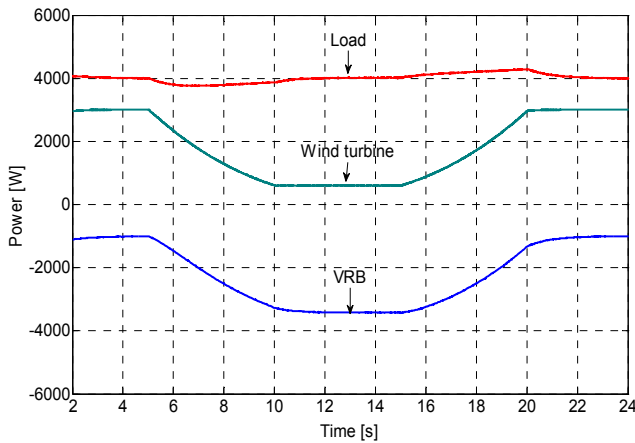


Figure 8. The power balance of the system

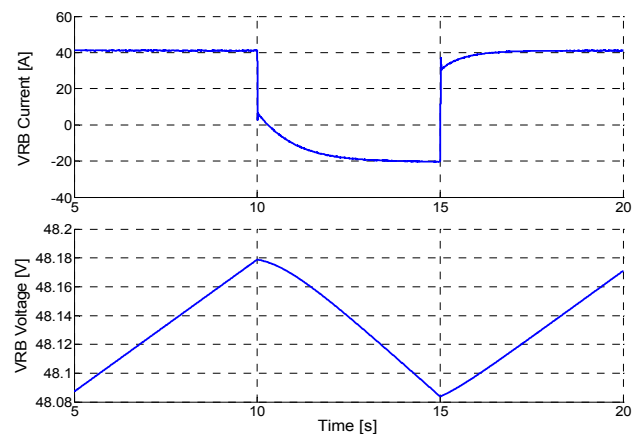


Figure 9. The VRB current and voltage

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 load of 1kW is initially connected to the system. At $t=10s$, an additional 3kW load is connected until $t=15s$. In Fig. 9, it is seen that the VRB transfers from charge to discharge mode during the transient event, as power flow becomes negative.

Because the initial load is 1kW, the difference in power supplied by the wind turbine is stored in the battery. 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.

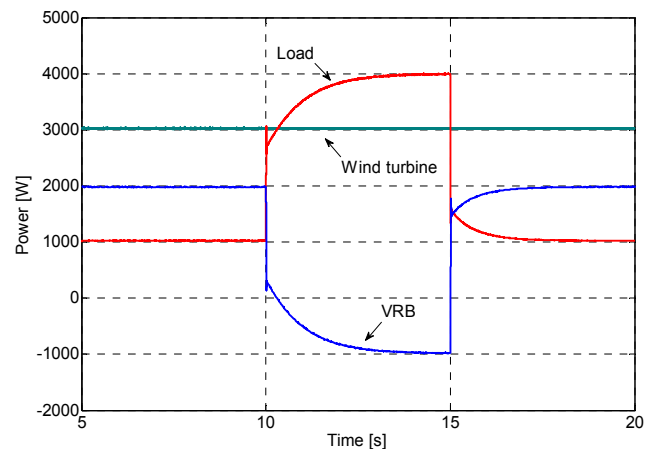


Figure 10. The power balance of the system

C. Simultaneous wind speed and load variations

In this case wind speed decreases from 12 m/s (at $t=10s$) to 7 m/s (at $t=15s$). A 1kW load is initially connected. At $t=10s$, an additional load is connected for a 5s duration. In Fig. 11, the voltage and current of the VRB are presented. During the transient event the VRB voltage decreases, and the negative current implies that the VRB has gone from charge to discharge mode. At 15s the 3kW load is disconnected and the wind speed returns to its initial value (12m/s). The increasing VRB voltage and positive current indicate that the VRB has returned to its charge mode.

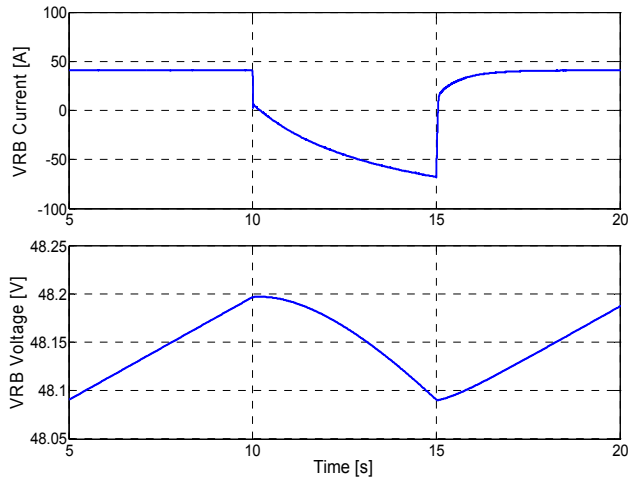


Figure 11. The VRB current and voltage

In Fig. 12, the power balance of the system is satisfied during the transient load and variable wind speed conditions.

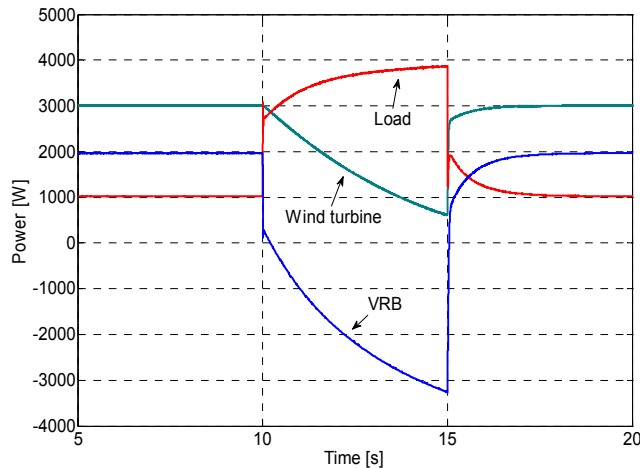


Figure 12. The power balance of the system

VII. CONCLUSION

In this paper, a stand-alone wind energy conversion system using a VRB as an energy storage device to stabilize the output voltage is analyzed. A bidirectional charge/discharge controller is presented that successfully uses the VRB to maintain the load voltage while also regulating the current flow to the VRB to avoid overcharge. Simulation case studies show that the power balance of the system is satisfied during transient load and variable wind speed conditions.

The VRB is intended to replace the lead acid battery. The LAB is considered the dominant energy storage device for stationary applications, but a comparison of the technical data shows that the VRB may be better suited for renewable energy applications.

Future work involves the setup of a VRB system in the Aalborg University laboratory to verify the simulations with experimental results.

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