Vanadium battery technology – integration in future renewable energy systems

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Abstract

Energy systems with high penetrations of intermittent renewable energy sources face great challenges when it comes to demand-supply balancing and power reserves. The vanadium battery technology may offer solutions to this by providing both energy storage and power system services.

This paper presents the recent research activities on vanadium battery technology integration carried out at Risø National Laboratory. A vanadium battery has been installed in a research energy system SYSLAB. It has been characterized and its capabilities for the balancing of wind power have been demonstrated. A small simulation case study (based on the performance measurements of the real system) is presented and the results with respect to diesel fuel savings discussed.

Keywords: vanadium battery, energy storage, load management, wind power integration.

1 Introduction

In future energy systems with an increased share of fluctuating renewable energy sources, the challenge of balancing of electrical load and power production will grow. The need for increased balancing capabilities will be present on both longer (energy management) and shorter (regulation and reserve) timescales. Different electricity storage technologies, that can provide balancing capability and thereby facilitate a higher share of renewable energy, are available today (for an overview see [1]). This paper presents a study of one such technology, namely the vanadium redox flow battery. A 15kW/120kWh vanadium battery was installed at the renewable energy research facility SYSLAB and its performance

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characteristics as well as its integration in a renewable energy system have been studied during the last year [2]. This paper presents some of the test results obtained in this period. The results of the battery characterization have also been used as input to a modelling tool, which can provide insight to battery integration in energy systems.

The remaining parts of the paper are organised as follows: Section 2 gives a brief overview of the technology. Section 3 describes the battery installed at SYSLAB. Section 4 presents the results of test runs where the battery has been used to balance a wind turbine. Section 5 describes how the results from the battery characterization have been used to model the performance of a power system with a vanadium battery. Finally, Section 6 summarizes the work.

2 Vanadium redox flow battery technology

The vanadium battery technology is based on electron/H^+ transfer between different ionic forms of vanadium. The liquid electrolytes containing the vanadium ions flow from two separate containers through an electrochemical cell on each side of the membrane. The electrochemical potential across the cell is used to convert the chemical energy to electrical energy (in the discharge mode) or vice versa (in the charge mode). The chemical reactions are:

Positive electrolyte:

$$VO_2^+ + e^- + 2H^+ \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} VO^{2+} + H_2O$$

Negative electrolyte:

$$V^{3+} + e^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} V^{2+}$$

The voltage across one cell is around 1.4V and cells are therefore stacked in order to reach higher voltages. Figure 1 shows a schematic drawing of the battery technology. Note, that the electrolyte does not flow between the electrolyte tanks – the electrolyte is pumped through each of the half cells back to the same tank, ensuring that there is, at all times, sufficient electrolyte in the two half cells available to undergo the chemical reactions.

The concept is different from conventional batteries where the electrodes take part in the chemical reaction. The chemical reduction/oxidation and the flow of electrolyte (which facilitates the electron transfer and therefore the energy storage) give rise to the name: (vanadium) redox flow battery. More details on the technology can be found in ref. [1].

The technology has the advantage that the energy storage and power capacity can be sized independently (either by changing the amount of electrolyte in the system or the number of cell stacks). The fast response of the electrochemical reactions makes the technology suitable for primary reserves (real time balancing and frequency support). The lifetime of a vanadium battery system is expected to be long and there is in principle no self discharge since the electrolytes are physically separated. However, vanadium battery systems are still relatively expensive and the low energy density makes the footprint of the system considerable.

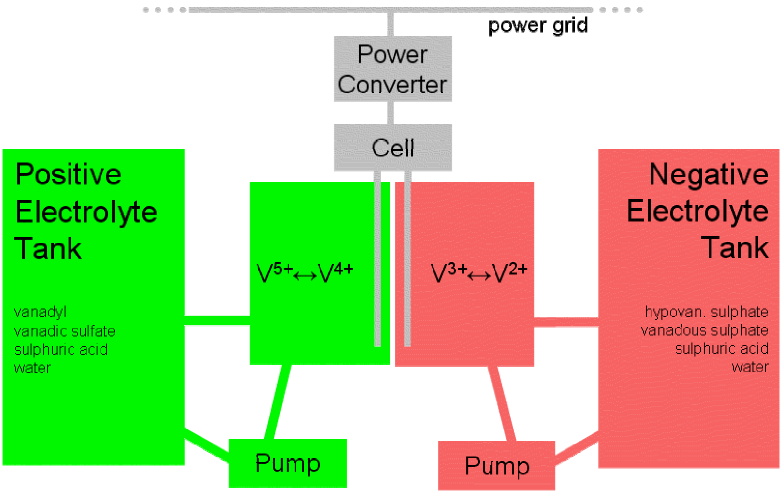

Figure 1: Schematic drawing of a vanadium battery. The aqueous electrolyte is pumped into the fuel cells (here only one cell is depicted) on each side of the cell membrane. The concentration of the different vanadium ions in the two electrolytes leads to an electrochemical potential over the cells.

Figure 2: Photo of the vanadium battery installation at SYSLAB. The three blue units in front are the cell stacks, each containing 40 cells. Behind the cell stacks and the pump/pipe system, the two 6500 liter electrolyte tanks are situated. The box to the right is the control unit.

3 Vanadium battery at SYSLAB

SYSlab is a research facility at Risø-DTU that has been built to study integration of energy technologies. It includes two wind turbines (11 and 55kW), solar panels (9kW), office building (max. load of 20kW), hybrid vehicle-to-grid car (9kWh), a diesel generator (48kW), a dump load (75kW) and a vanadium battery (15kW/120kWh). The research activities focus on renewable energy integration, intelligent (distributed) control and communication. For more information on SYSlab see ref. [2].

In 2007 the 15kW/120kWh vanadium redox battery was connected to the system as part of the research project "Characterization of vanadium battery" funded by the PSO framework (ForskEl project 6555). Figure 2 shows a photo of the battery system. In order to understand the battery performance and be able to develop a realistic model, the losses in the different parts of the battery system have been analyzed independently. There are losses in the power converter, losses in the cell stack and parasitic losses (due to the auxiliary system and self-discharge).

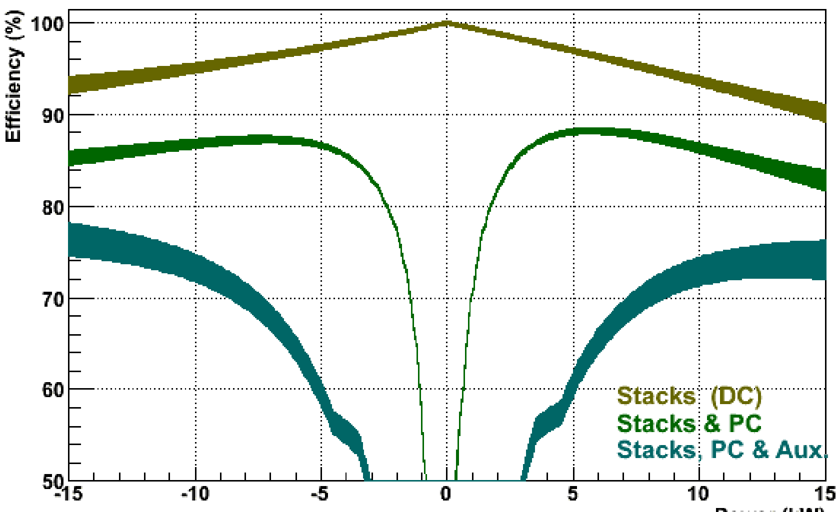

Figure 3: Battery efficiency as function of power for the stacks only (upper yellow curve), stacks and power converter (middle green curve) and total (lower curve). The widths indicate the spread depending on state of charge. When the power is negative, the battery is being charged.

The losses in the cell stacks are primarily ohmic losses. The area specific resistance has been estimated to be around $0.16\Omega cm^2$. The efficiency of the cell stack can be determined from the ratio of the actual voltage (at a certain current level) and the open circuit voltage (which depends slightly on the state of charge of the battery). The cell stack efficiency lies in the range from 88% to 100% in the DC power range from -15kW to 15kW. The cell stack efficiency is lowest when the battery is close to being discharged and delivering full DC power (+15kW) and highest when the DC power is close to zero. The efficiency of the power converter is about 55% at 1kW, 80% at 2kW and 93% at full power (15kW). The power consumption of the auxiliaries (pumps and control) varies with the power as follows. The pumps have two operational speeds resulting in a power consumption of about 1.2kW at battery powers lower than 4kW and about 1.5kW above 4kW. This auxiliary power consumption could probably be optimized by installing pumps with higher efficiency and an energy saving control unit. The electrolyte level in the tanks may change slightly due to water diffusion through the membranes of the electrochemical cells (caused by the osmotic pressure). The levels are equalized every 24 hours by opening a valve for half an hour, allowing the electrolyte to flow between the two tanks. The losses during this *equalization process* depend on the state of charge, but on average it corresponds to a constant power loss of about 110W. Figure 3 shows the efficiency of the different parts of the system. It is expected that the energy consumption of the auxiliary system (pumps and control) and the losses in the equalization process can be reduced significantly in larger battery systems.

4 Test run VRB-WT balancing

The vanadium battery at the SYSLAB facility at Risø-DTU has been operated in parallel with the 11kW Gaia wind turbine, balancing the combined output to a constant 4kW. The flexible configuration of SYSLAB has allowed for the connection of the two components to the same busbar, which was then connected to the national grid. Measurements of the power flow from the turbine, the battery and the total output to the grid is shown in Figure 4 (5 minute averages). The power from the wind turbine is balanced and the desired output of 4kW is sustained (when the battery state of charge is not zero or 100%). Due to the speed of the communication and control program, complete balance on the shorter timescale has not been achieved. Measurements taken every second show a mean variation of 0.8kW around the 4kW set point. Further studies will include operating the battery in *droop* mode in an island system together a wind turbine and a variable load. In such a system, the battery can be the grid-forming unit and at the same time provide energy management on the longer timescale.

5 Modelling of vanadium battery in power system

A vanadium battery model has been developed and implemented in the IPSYS modelling environment [3]. IPSYS offers the possibility of modelling energy systems with a special emphasis integration of renewable energy technologies. Detailed modelling of power systems is provided with a quasi-static description of the power flows, voltages, frequencies, as well as losses.

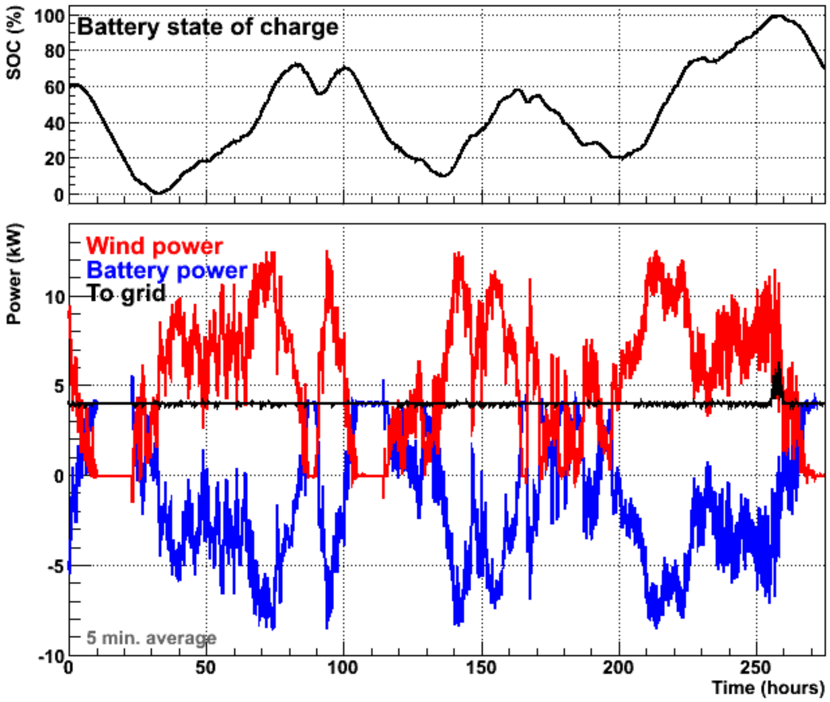

Figure 4: Lower panel: Power as function of time for the wind turbine (positive, red line), the battery (blue line) and the sum (around 4kW, black). After a period with no wind (around hour 20 and hour 110), the turbine consumes power in a short period to start up – this can be seen as a small dip below zero in the wind turbine power output. Upper panel: Battery state of charge (SOC). When the battery is fully charged (around hour 260), the 4kW output cannot be sustained.

Based on the power set point (and the state of charge), the battery model recalculates the state of charge after each time step, taking into account the different losses in the system:

- Stack losses: The efficiency of the electrochemical cells is simply the cell voltage relative to the electromotoric force (open cell voltage). The model includes the open cell voltage dependence on the state of charge and a linear change in the voltage depending on the current over the stack.
- Power converter losses: The power converter efficiency (both AC to DC and DC to AC) and its dependence on power has been used to model the losses in this part of the system.
- Parasitic losses: The auxiliary power consumption is modelled a linear function of the AC power of the battery (400W losses at zero power and 7% losses at full power).

This parameterization of losses in the battery system is based on the measurements of losses in the vanadium battery installed at Risø-DTU (see section 3), which makes the model both detailed and realistic.

5.1 A small island system simulation case study

The IPSYS model including the newly added battery component has been used to simulate a small imaginary island power system including a wind turbine, two diesel generators, a variable load (emulating a number of households), a dump load and a vanadium battery. The layout of the systems is shown in Figure 5.

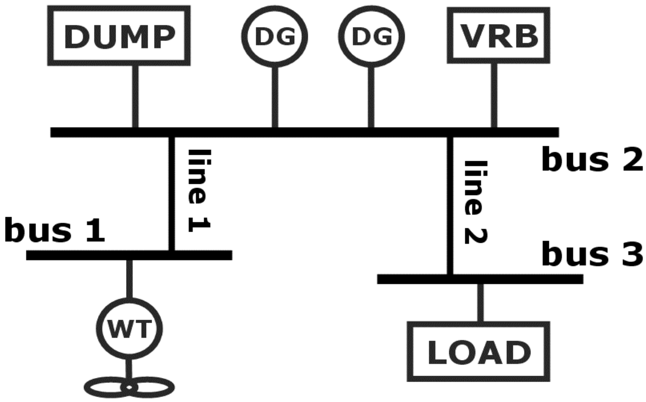

Figure 5: Layout of the small island system. The diesel generators, the vanadium battery (VRB) and the dump load are connected the same busbar (bus 2). The wind turbine and the load are connected to the two other busbars (bus 1 and bus 3).

The load has a weekday and a weekend load profile with an additional stochastic behaviour and it ranges from approximately 30 to 70 kW. The wind speed input is based on measurements from the Risø-DTU meteorological mast over a full year. The wind power is determined from the measured wind speed and a simple power curve. The turbine capacity is 75kW. The two diesels can supply 60kW each and they have a lower power limit of 6kW. The battery has a power capacity of 40kW.

A quite simple battery load management control strategy has been applied. The battery power is set to balance the wind power plus the load, i.e. charging the battery when there is excess of wind power and discharge the battery when the load exceeds the wind power. When the battery is fully charged, absorbing the excess wind is not possible and the battery power is then set to the standby power. Likewise, when the battery is fully discharged and the load exceeds the wind power. In effect, the battery will save excess wind power and supply power to the system when the wind does not meet the load. One diesel is required to be on constantly in order to maintain frequency and voltage on the grid (being the grid forming unit). The other diesel is turned off when there is sufficient power in the system.

The studied time period is one year and simulation has been carried out with 6 different battery capacity sizes: 0, 3, 5, 10, 15 and 20 hours (at full power, i.e. 0, 120, 200, 400, 600 and 800kWh).

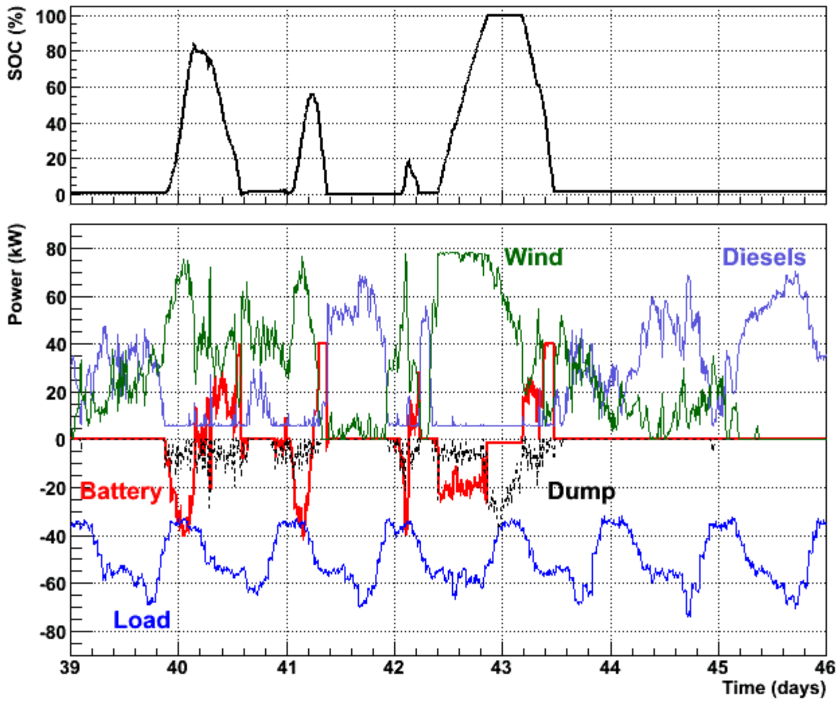

Figure 6: Upper panel: Battery state of charge (SOC) as function of time for an example week. Lower panel: power of the different components. This example is for battery storage capacity of 5 hours.

The lower panel of Figure 6 shows the power of the different system components during one week. The upper panel shows the battery state of charge as function of time. The lower panel shows the power of the different components. The battery power cycles are clearly seen in the figure: first a period of charging followed by a period of discharging that continues until the battery is fully discharged. The dump load is often used simultaneously with the battery – this undesirable behaviour comes from the fact that only the dump load and the diesels can actively react on the system frequency. When the wind exceeds the load, (downward) regulation of the frequency can only be provided by the dump load (the spinning diesel supplies the minimum power of 6kW and cannot regulate downward). Using more intelligent control, where the battery provides a part of the frequency regulation at times with excess wind power, would result in even less power being dumped.

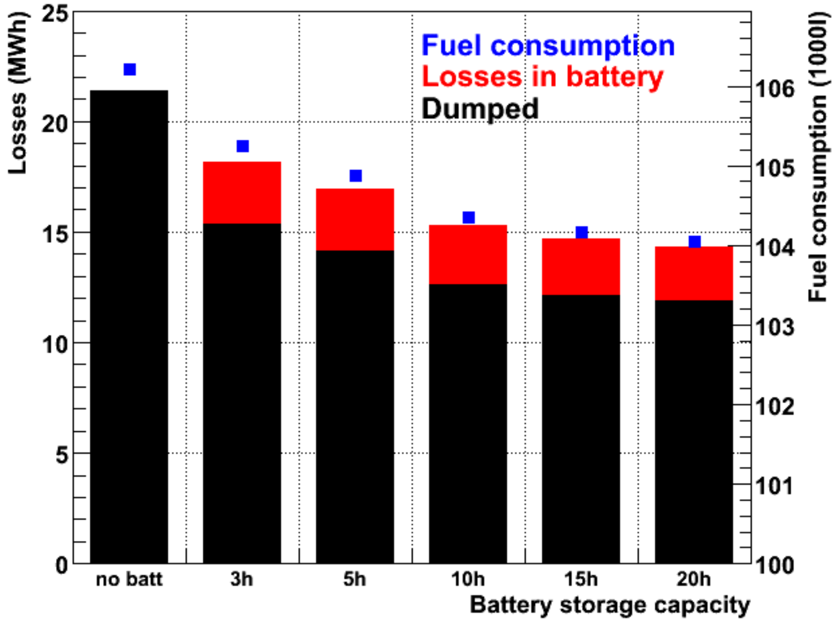

Figure 7: Amount of energy dumped and lost in the battery as function of battery size. The corresponding diesel fuel consumption is shown as square markers (axis on right side of the plot).

Figure 7 shows the amount of dumped energy, the losses in the battery and the diesel fuel consumption as function of battery storage capacity. The figure illustrates that the energy dumped can be reduced by about 45% if a 20-hour battery storage capacity is used. When the losses in the battery are also taken into account, the reduction in lost energy is about 35%. In terms of diesel fuel savings the battery only saves about 2000 litres per year (with the present control strategy). This is only about 2% of the total fuel consumption and clearly not sufficient to cover the cost of installing and operating a vanadium battery. It is expected that larger saving on the diesel fuel consumption can be achieved by applying more intelligent control strategies. First, the diesels can be turned off during hours where the battery (and wind) can supply the load consumption, i.e. the battery can be the grid-forming unit during some periods. This would prevent the diesels from running close to minimum power, which results in high fuel consumption (per kWh). Secondly, the battery can be controlled so that the diesels primarily are operated at full power. This will also save diesel fuel, since diesels are more efficient at full power. Finally, wind power forecasts can be used to charge and discharge the battery depending on the expected wind power in the coming hours. The potential fuel saving is to the first approximation limited by the total amount dumped energy times the heating value of diesel (about 10kWh/liter) divided by the electrical efficiency of the diesels. If the latter is 30%, the maximum diesel fuel savings is about 7100 litres. Future studies on island systems with wind, diesel and vanadium batteries will be focussed on more intelligent control strategies and the possibilities for diesel fuel saving.

6 Summary and outlook

This paper has outlined the research activities on the vanadium battery technology integration carried out at the Risø National Laboratory. A 15kW/120kWh battery has been characterized and its capabilities to balance wind power has been demonstrated at the SYSLAB facility.

The results from the battery characterization have been used to implement a realistic battery model in the IPSYS modelling environment. A simulation case study has been presented showing how a battery can be integrated and controlled in a small island system. The case study illustrates a simple strategy for control of the battery depending on the wind power and the load. With this strategy (in this island system) the savings of diesel fuel are very limited, even with a battery storage capacity of 20 hours. More intelligent control strategies are needed in order to decrease diesel fuel consumption further. Whether or not the saving on diesel fuel consumption can become sufficient to ensure economic viability of vanadium battery integration in island systems depends on many factors, like system design, system control, price of diesel fuel and the cost of a battery system. These issues will be treated in further studies.

Acknowledgement

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