Field Test Results for a 1 kW, 50 kWh Vanadium Redox Flow Battery

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Introduction and purpose of the field test

In September 2004 a 1 kW, 50 kWh vanadium redox flow battery (VRB) was installed at a roadside location in Austria. The test system is supplied by solar and wind input and used to power a traffic display board. It has a long discharge time (50 h at full power), to demonstrate the possibility of using moderately sized renewable power sources without electricity supply from the grid (an island system) in a seasonal climatic region. The system is shown in figs. 1 and 2.

Figure 1 - A 1 kW, 50 kWh vanadium redox battery (in container) with wind and solar power sources at a roadside location in Austria

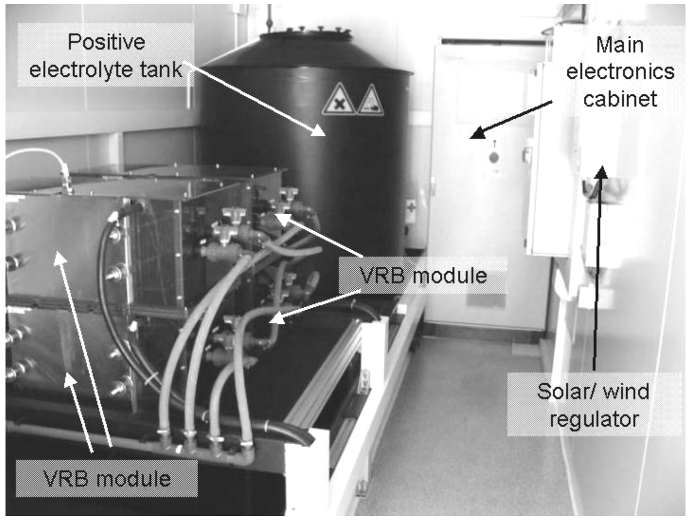

Figure 2 - A 1 kW, 50 kWh vanadium redox battery with electronics cabinets viewed from inside container

The chemistry of the vanadium redox battery has been developed progressively by several independent groups including Kangro [1], Thaller [2], Pellegri and Spaziente [3] and finally Skyllas-Kazacos [4, 5]. Skyllas-Kazacos developed the current all vanadium in sulphuric acid chemistry that is used in this field test system.

The system was equipped with many sensors to determine the voltage variation between cells, pressure and flow rate in the electrolyte lines, hydrogen concentration within the container, temperatures in the electrolyte and internal and external air. These sensors were used to monitor the “state-of-health” and “state-of-charge” of the battery and to show that laboratory results could be directly extrapolated to a field-test system.

Because the VRB was intended for remote, unmanned applications it was also equipped to transmit the measurements to a remote computer at daily intervals and emergency signals instantly by SMS in case of unsafe conditions (fire, blockage in the electrolyte lines, leakage, etc.) and to bring the battery into a “safe state” automatically.

The field test was also conducted to verify that the electrolyte temperature could be maintained between the specified operating limits of 5 - 40°C, despite a wide range of ambient, external air temperatures, and that the system provided the specified power and energy. The positive electrolyte is liable to precipitate V_2O_5 if the temperature exceeds 40°C in the positive electrolyte for an extended period of time [6, 7]. This could lead to eventual clogging of the filters and blocking of the cells. The precipitation is not redissolved when the electrolyte cools down and would require expensive maintenance work to remove.
Alternatively very low temperatures can cause the negative electrolyte to become very viscous and ultimately freeze out the salts.

Field test results and observations

The maximum temperature of the positive electrolyte and minimum of the negative are shown in fig. 3 for the first test year. As can be seen there was little difference between the two electrolyte temperatures on any given day. The electrolytes remained well within the desired temperature limits despite the wide variation in external air temperature.

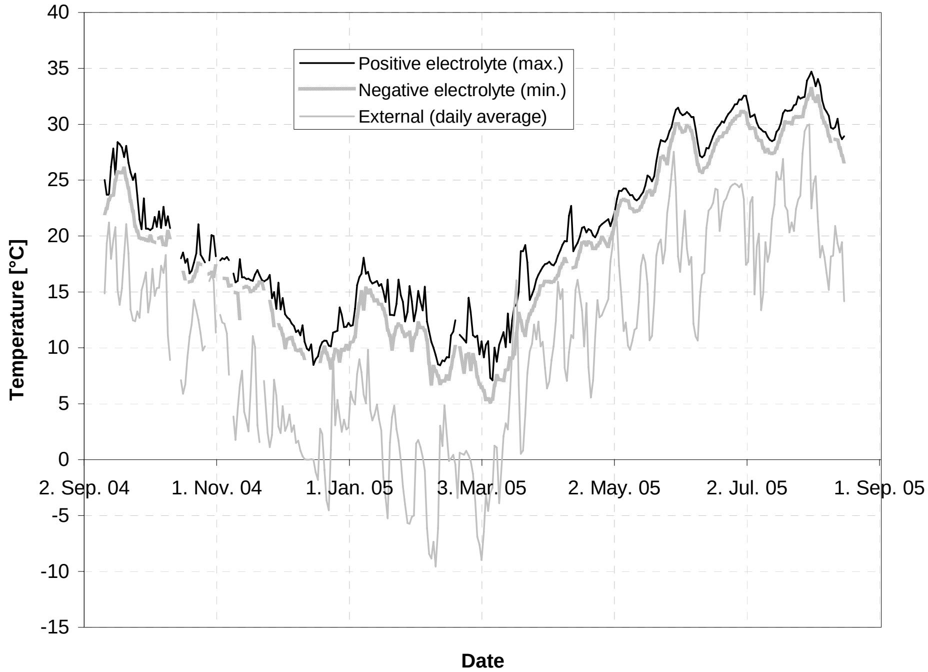

Figure 3 - Daily maximum and minimum electrolyte temperatures together with the external air temperature over the first test year of the vanadium redox battery system

In fig. 3 the few gaps in the curves represent missing data (due to servicing, communications problems, software updates, sensor failures and so on). It should also be noted that although the average daily external air temperature varied from -9 to +30°C, the minimum spot temperature in winter was ca. –14°C and maximum in summer +36°C.
The temperature of the electrolytes in the fluid lines was also measured. The positive electrolyte as it entered and exited the battery stack was typically within 2°C of that in the tanks, and did not exceed 40°C.

Hydrogen formation occurs in all aqueous batteries. Hydrogen forms typically as a parasitic reaction on the negative electrode during charging. In lead-acid batteries, for example, hydrogen can be formed in large quantities during “equalization” charging. Because hydrogen is a potentially explosive gas at above 4.0% in air the headspace above each tanks was connected externally via pipe work with an inline dust filter to hinder hydrogen from collecting in the container. Also the hydrogen concentration in container was continuously monitored, with an automatic alarm triggered if levels rose above critical set points. However, it was found that under normal operation within the first year the level never exceeded 0.02% (the accuracy of the sensor). If the tanks were opened the local concentration rose momentarily, indicating that some hydrogen was present in the headspace, but was very rapidly dispersed and returned to the background level with 300 s.

It is common practice to quote a round-trip efficiency (overall or energy efficiency) for a battery system as one indication of its suitability for a particular application. For the VRB the calculation of round-trip efficiency (W_{eff}) should take into account the amount of energy going into (W_{in}) and coming from (W_{out}) the battery, but also the amount of energy stored in the electrolyte (W_{stored}). A moving average of 60-days was used to calculate the W_{eff} in order to reduce noise arising from uncertainties in W_{stored}. Therefore:

$$W_{eff} = \frac{\sum_{day=1}^{60} W_{out}}{W_{stored,day=1} - W_{stored,day=60} + \sum_{day=1}^{60} W_{in}} \qquad \text{Equation 1}$$

W_{stored} was calculated from the state-of-charge (SOC) of the electrolyte, by equation 2:

$$W_{stored} = W_{maximum}.SOC \qquad \text{Equation 2}$$

$W_{maximum}$ is the maximum theoretically energy density of the electrolyte. SOC was calculated based on the open-circuit voltage (OCV) of the electrolyte, which was measured in a cell that was connected in parallel with the fluid lines to the battery stacks. The OCV cell was however electrically isolated from the battery stacks.
The SOC is calculated from the OCV using a temperature-corrected working curve (e.g. [8, 9])
The efficiency was strongly dependent on the load. To keep the battery in a constant state of readiness electrolyte must be pumped at regular intervals and a trickle charge used to offset the self-discharge current. Therefore, the overall efficiency is lower with a smaller than optimum load, as shown experimentally in fig. 3.
It may also be noted that 4 kWh is slightly lower than the optimum for this system and so overall round-trip efficiencies of >72% can be attained. Recent improvements in cell design will raise this value still higher.
The Coulombic (charge) efficiency (Q_{eff}) and voltage efficiency (V_{eff}) were also calculated according to the following:

$$V_{eff} = \frac{\bar{V}_{discharging}}{\bar{V}_{charging}} \qquad \text{Equation 3}$$

$$Q_{eff} = \frac{W_{eff}}{V_{eff}} \qquad \text{Equation 4}$$

Where $V_{discharging}$ is the average voltage on discharge and V_{charge} the average voltage on charge.
The efficiencies are shown below:

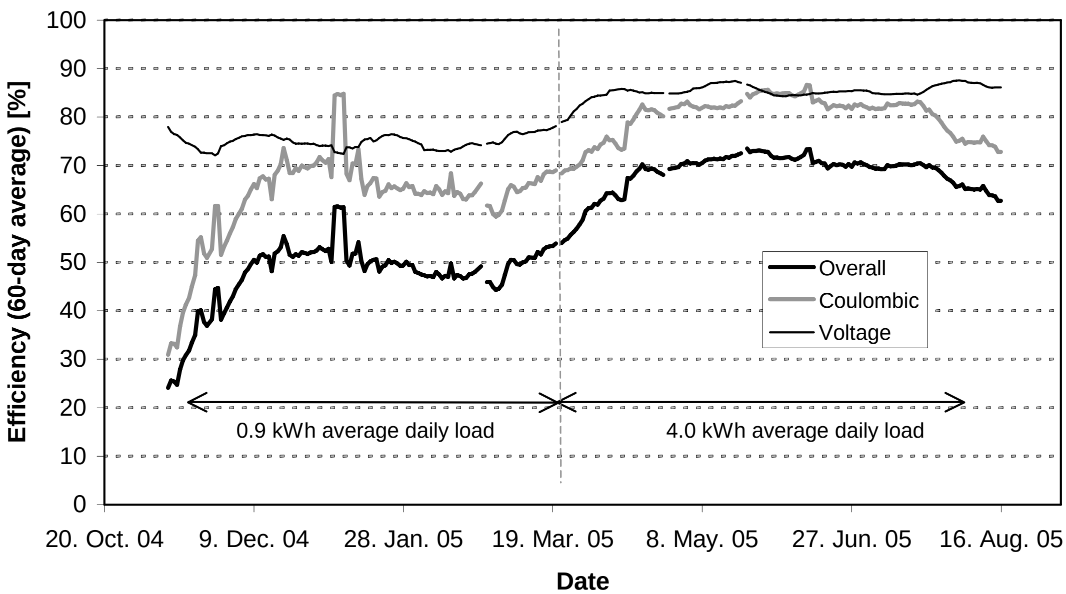

Figure 4 - 60-day running average efficiencies for the vanadium redox battery in the field test with two different average daily loads

As can be seen from fig. 4 the efficiencies were very dependent on the average daily load. With a daily load of 0.9 kWh, equivalent to 38 W continuously, W_{eff} was ~ 50%. With a load of 4.0 kWh, equivalent to 170 W continuously, W_{eff} was ~ 70%. The battery was rated at 1000 W. It is clear that the power of the VRB must be carefully matched with that of the load to ensure optimum efficiency.

Conclusion

A field test VRB installation has been running at a roadside location in Austria for 12 months, powered from wind and solar energy. The battery electrolyte has remained within the set temperature limits during the test phase and there has been no accumulation of hydrogen.
The VRB has shown a round-trip efficiency of 70% with an average daily load of 4.0 kWh.

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