

An innovative approach for the model-based flow rate optimization of vanadium redox flow batteries

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Motivation

A sophisticated flow rate control is essential for the efficient operation of a flow battery. So far, it has been shown that flow rates close to the theoretical minimum (stoichiometric flow rate) minimize pump energy consumption but do not lead to a maximum system efficiency [1,3]. Amongst others this is due to concentration polarization within the flow cells. Beside experimental approaches, multi-physics models are often applied to perform the task of flow rate optimization. Blanc and Rufer [1] demonstrated how the optimal flow rate can be derived depending on state-of-charge (SoC) and battery power. However the deployed model did not include the effect of shunt currents and diffusion of vanadium ions across the membrane. In addition, the concentration over-potential caused by the diffusion layer around the fibers of the porous graphite electrode was not considered. Tang, Bao and Skyllas-Kazacos [3] included these effects but only derived the optimal flow rate for round-trips, not for operation points. So in fact, the SOC dependence of the optimal flow rate was not considered.

Methodology

Our previously published model [2] has been extended to include all relevant loss mechanisms. The model was validated with the results presented in [3]. With the internal signals from the model, which are hardly accessible in real systems, it is possible to derive an SoC and load current dependent system efficiency. Key point of this approach is the computation of the electro-chemical power, which is actually fed to or drawn from the tank.

$$P_{\text{Tank}} = \min(\dot{n}_{\text{V}^{2+}, \text{Tank}}, \dot{n}_{\text{V}^{5+}, \text{Tank}}) \cdot F \cdot \text{OCV}(\text{SoC}_{\text{Tank}})$$

Therein, \dot{n} is the particle flux of the respective vanadium ion from or to the tank. Because of ion diffusion across the membrane which varies for the different vanadium ions, particle flux of V^{2+} - and V^{5+} -ions is not equal. During charging of the battery, only the smaller value can be taken as it limits the SoC increase of the system. During discharging of the battery, the more negative value has to be taken as it governs the SoC decrease of the system. By multiplying particle flux rate with the open circuit voltage (OCV) of a bypass-cell and Faraday's constant F , electro-chemical tank power P_{Tank} is obtained.

System power P_{System} is derived using the electrical power of the stack $U_{\text{Stack}} \cdot I_{\text{Stack}}$ multiplied or divided by the efficiency of the battery inverter respectively, depending on power flow direction, as well as pump power P_{Pumps} . If the battery is charged, system efficiency is tank power over system power and vice versa.

$$P_{\text{System}} = \begin{cases} U_{\text{Stack}} \cdot I_{\text{Stack}} / \eta_{\text{Inverter}} + P_{\text{Pumps}}, & \text{for charging} \\ U_{\text{Stack}} \cdot I_{\text{Stack}} \cdot \eta_{\text{Inverter}} + P_{\text{Pumps}}, & \text{for discharging} \end{cases}$$

Operation points defined by tank SoC and battery current are simulated. During the simulation, tank SoC is fixed at a defined value. After the system reaches its steady state, system efficiency for the simulated stack current and tank SoC is derived. For every operation point, an independent flow rate optimization is performed using the Matlab Optimization Toolbox.

Results

Figure 1 shows the optimization process for discharging of the battery with -5 kW at SoC 0.2. The optimization algorithm identifies the optimal flow rate very fast. The optimization results for all operation points are shown in Figure 2. In a real system, the content of this figure could be implemented into the flow battery management system and would then indicate the optimal flow rate depending on actual tank SoC and stack current.

In Figure 3, optimized flow rate curves for a cycle between SoC 0.1 and 0.9 with 150 A charging/discharging current are depicted. It can be seen that they differ strongly from the established approach of stoichiometric flow rate, scaled by a flow factor. Exemplarily, a flow factor of 2 is depicted. The new strategy delivers a higher efficiency with a reduced pump rating, which also lowers investment costs. It has been found, that the optimal flow rate for an operation point is not only influenced by concentration polarization but by diffusion as well. E.g. at the beginning of the charging process it is useful to apply a higher flow rate to keep the concentration of V^{2+} - and V^{5+} -ions in the stack low, which lowers their diffusion rate into the opposite half-cell. Figure 4 finally shows that the presented approach delivers higher system round-trip efficiencies than the conventional flow rate control strategy in cycles with various charging/discharging currents.

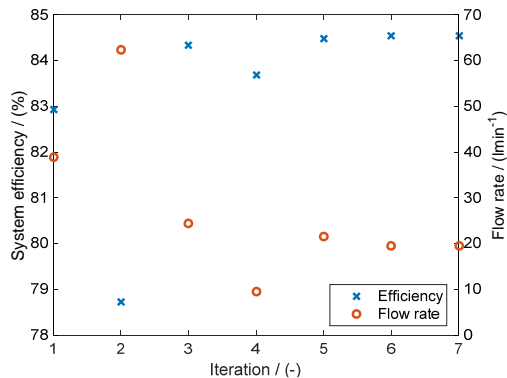


Figure 1: Optimization of one operation point (Discharging with -5 kW at SoC 0.2)

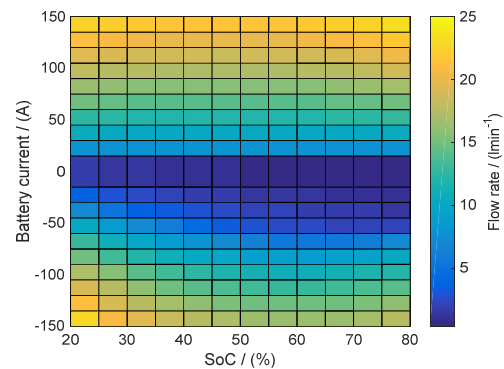


Figure 2: Optimal flow rate for a 5-kW-System

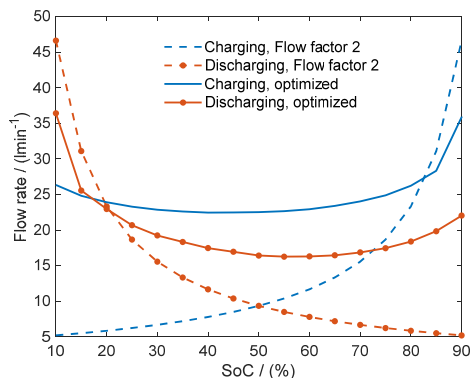


Figure 3: Flow rates for charging/discharging with 150 A, different pump strategies

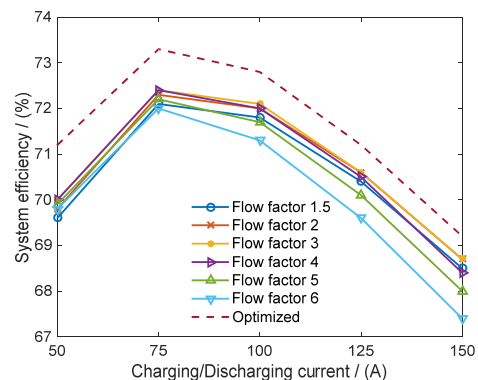


Figure 4: Round-trip efficiency with different pump strategies

References

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- [3] A. Tang, J. Bao, and M. Skyllas-Kazacos. Studies on pressure losses and flow rate optimization in vanadium redox flow battery. *Journal of Power Sources*, 248:154–162, Feb 2014.