Journal of Power Sources 281 (2015) 272–284

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Model based examination on influence of stack series connection and pipe diameters on efficiency of vanadium redox flow batteries under consideration of shunt currents

S. König*, M.R. Suriyah, T. Leibfried

Karlsruhe Institute of Technology, Institute of Electric Power Systems and High Voltage Technology, Engesserstrasse 11, 76131 Karlsruhe, Germany

HIGHLIGHTS

- Multi-physical modeling approach is presented in detail.
- Massive increase in shunt currents complicates the design of high voltage systems.
- Optimal hydraulic design is affected by electric design.

ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form
16 January 2015
Accepted 20 January 2015
Available online 31 January 2015

Keywords:
Vanadium redox flow battery
Design
Shunt currents
Modeling
Simulation
VRFB

ABSTRACT

Model based design and optimization of large scale vanadium redox flow batteries can help to decrease system costs and to increase system efficiency. System complexity, e.g. the combination of hydraulic and electric circuits requires a multi-physic modeling approach to cover all dependencies between subsystems. A Matlab/Simulink model is introduced, which covers a variable number of stacks and their hydraulic circuit, as well as the impact of shunt currents. Using analytic approaches that are afterward crosschecked with the developed model, a six-stack, 54 kW/216 kWh system is designed. With the simulation results it is demonstrated how combining stacks to strings and varying pipe diameters affects system efficiency. As cell voltage is comparatively low, connecting stacks in series to strings seems reasonable to facilitate grid connection. It is shown that this significantly lowers system efficiency. Hydraulic circuit design is varied to lower efficiency drop. In total, four different electric designs are equipped with 21 hydraulic design variations to quantify dependencies between electric and hydraulic subsystems. Furthermore, it is examined whether additional shunt current losses through stack series connection can be compensated by more efficient energy conversion systems.

1. Introduction

1.1. Vanadium redox flow battery

In the 1980s, M. Skyllas-Kazacos and co-workers proved the feasibility of the all-vanadium redox flow battery (RFB) [1]. It is recently regaining interest, as electric energy storage is required for the transformation of energy systems from fossil to renewable energy sources [2].

A redox flow battery consists of a number of flow cells that form a battery stack, as well as of at least two tanks, see Fig. 1. The tanks contain the electrolyte, which is subdivided into anolyte and catholyte. In all-vanadium RFBs, the electrolyte consists of vanadium ions in diluted sulfuric acid. Both fluids are pumped in two closed loops through the battery stacks. While passing through the stack, the oxidation state of the vanadium species in anolyte and catholyte is altered, corresponding to the positive or negative electric current that is applied to the battery stack. Cell and stack number, as well as cell area define how fast the electrolyte can be charged or discharged, which directly corresponds to battery power. Battery operation time is determined by the amount of electrolyte that is stored in tanks, which directly corresponds to battery storage capacity. Therefore, power and energy ratings are decoupled [3]. This makes flow batteries attractive for large scale storage applications [4]. Additional benefits of the all-vanadium RFB are unlimited cycles, low toxicology and no risk of explosion or fire [5].

* Corresponding author.
E-mail address: sebastian.koenig@kit.edu (S. König).

http://dx.doi.org/10.1016/j.jpowsour.2015.01.119

Nomenclature

A	Cross-sectional area, m^2
C	Storage capacity, Ws
c	Concentration, mol/m^3
CE	Coulomb efficiency, %
d	Diameter, m
E	Voltage, V
E^0	Standard oxidation potential, V
E'^0	Cell formal potential, V
F	Faraday constant, A·s/mol
f	Friction factor, –
G	Universal gas constant, J/mol·K
H	Hydraulic resistance, $Pa\cdot s/m^3$
I	Electric current, A
K	Kozeny–Carman constant, –
K_L	Pressure loss coefficient, –
l	Length, m
N	Number, –
P	Electric power, W
p	Pressure, Pa
Q	Volumetric flow rate, m^3/s
R	Electric resistance, Ω
SE	System efficiency, %
Re	Reynolds number, –
T	Temperature, K
t	Time, s
V	Volume, m^3
W	Electric energy, Ws
X	Electric charge, As

Abbreviations

RFB	Redox flow battery
ECS	Energy conversion system
AC	Alternating current
DC	Direct current
OCV	Open circuit voltage
SOC	State of charge

Greek variables

ε	Porosity, –
ζ	Equivalent roughness, m
η	Efficiency, %
μ	Dynamic viscosity, Pa·s
ρ	Density, kg/m^2
σ	Electric conductivity, S/m

Subscripts

2	V^{2+}-ions
3	V^{3+}-ions
4	VO^{2+}-ions
5	VO_2^+-ions
H^+	Hydrogen-ions
An	Anolyte
B	Bend
Bat	Battery
C	Cell
Ca	Catholyte
Ch	Channel
E	Electrolyte
El	Electrode
F	Felt
Fi	Felt fiber
l	Laminar
M	Manifold
O	Object (channel, manifold or pipe)
P	Pipe
S	Stack
T	Tank
t	Turbulent
TJ	T-junction
V	Vanadium

1.2. Motivation

Concerning RFB design, literature only reports single stack test systems [3,6–8]. Design parameters, e.g. pipe diameters or tank size is given, but the method of determination is not, as it is not the key point of the examination. Therefore, we present an overview over system design criteria in Section 3.

Key point of this study is the influence of stack series connection on efficiency of the battery system. In an all-vanadium RFB, the comparatively low cell voltage requires the series connection of many cells and stacks to achieve a reasonable system voltage. Unfortunately, flow cells electrically connected in series suffer from shunt currents [9]. As the electrolytes have a very limited insulation capacity, electrolyte connections offer additional current paths between all battery cells which are supplied via a common hydraulic circuit. During charging, shunt currents lower the effective charging current that flows through each cell and waste a part of the energy which has been injected into the battery by the ECS. During discharging, the current that effectively discharges the battery is increased by shunt currents without increasing the current that is available at the battery string clamps. Therefore, some of the energy that has been stored in the battery is wasted by shunt currents. If several stacks are connected, the effect becomes more severe, as reported in Ref. [4].

Shunt currents in single stacks and systems with up to three stacks have been studied in Refs. [4,6,9]. In Ref. [4] electrolyte inlet and outlet positions have been varied to reduce shunt currents. To the authors knowledge, there are no known works that deal with optimizing the hydraulic circuit of a large multi-

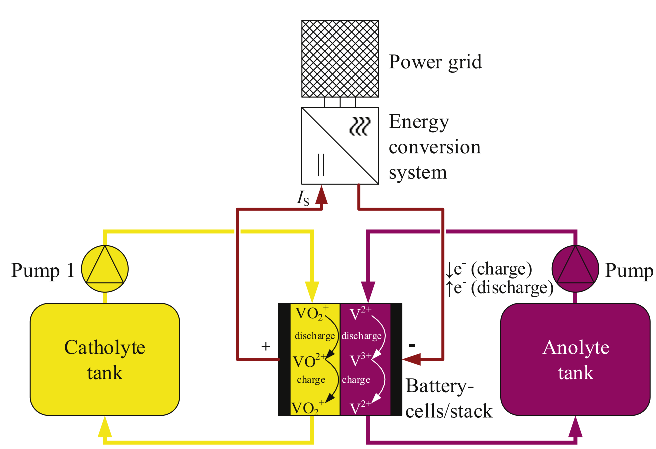

Fig. 1. All-vanadium RFB working principle.