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Precision dynamic equivalent circuit model of a Vanadium Redox Flow Battery and determination of circuit parameters for its optimal performance in renewable energy applications

Ankur Bhattacharjee*,[1], Anirban Roy[1], Nipak Banerjee, Snehangshu Patra, Hiranmay Saha

Centre of Excellence for Green Energy and Sensor Systems, Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India

HIGHLIGHTS

- Dynamic internal circuit parameters are estimated for VRFB system.
- The model parameters are extracted using the experimental data as input to the model.
- The dynamic internal parameter estimation model shows better performance accuracy.
- The impacts of scalability and cycle number on VRFB internal parameters are shown.
- Flow rate is optimized considering both stack internal lo**ss and pump power loss.**

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ABSTRACT

In this work it is established for the first time that the internal parameters of the electrical equivalent circuit of vanadium redox flow battery (VRFB) are variable not only with flow rate and stack current but also the state of charge (SOC) and operational cycle number. The dynamic internal circuit parameters are extracted by using the charge-discharge characteristics of a practical 1 kW 6 h VRFB system as input to the proposed model. The role of temperature on the VRFB internal parameters is also discussed. It is further demonstrated that the average error in estimation of VRFB stack voltage using dynamic parameters reduces by 28% (charging) and 14% (discharging) compared to that of using static internal parameters. The proposed model exhibits robustness and validity for large scale applications as evidenced by further extracting the internal parameters of a 125 kW 2 h VRFB system. Another significant contribution of this paper is the optimization of flow rate by considering both the stack internal power loss and pump power loss simultaneously to achieve optimal performance of the VRFB system. The proposed model involving dynamic parameter extraction and loss optimization is very useful for designing suitable battery management system (BMS) for interfacing VRFB with renewable energy sources.

1. Introduction

The present era of fossil fuel depletion and rapid implementation of renewable energy harvesters necessitates a paradigm shift in energy storage technologies. For large-scale renewable power system applications, Vanadium Redox Flow Battery (VRFB) possesses huge potential because of its several merits; such as, independent scalability of its power and energy capacity, deep discharge capacity, free from cross-contamination and above all its very long life cycle, closely matching that of a solar PV Power Plant. The VRFB technology was invented by Maria Skyllas-Kazacos [1,2] and her research group at University of New South Wales (UNSW) in the mid-1980s. Over the years, efforts to make the VRFB technology more efficient has led to several avenues of research –namely stack design [3–12], modifications to the electrode [13–25], membrane [26–32] and electrolyte [33–42]. The realization of practical VRFB operation and performance is incomplete without an electrical equivalent model. However, very few published papers have addressed the electrical equivalent model and internal circuit parameters estimation. A basic equivalent circuit model of a VRFB was first proposed by Barote et al. [43,44] and then followed by Chahwan et al. [45] where they introduced a voltage source, a controlled current source, a fixed resistor representing parasitic losses, two fixed internal resistors and a fixed capacitor as circuit elements. Nonetheless, their models were not realistic because they did not consider the dynamic

* Corresponding author. ().
E-mail address: ankur.bhattacharjee@iemcal.com (A. Bhattacharjee).
[1] Both the authors contributed equally to this work.

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Nomenclature

E^{0+}	VRFB Positive half-cell equilibrium potential (V)
α_a	Charge transfer coefficient in the anolyte side
α_c	Charge transfer coefficient in the catholyte side
I_0	Exchange current (A)
E^0	VRFB Negative half-cell equilibrium potential (V)
E^0	VRFB cell equilibrium potential (V)
SOC	State of Charge
I_{stack}	Stack current (A)
Q	Electrolyte flow rate (L min^{-1})
N	Electrolyte capacity (A. sec cm^{-3})
n_e	No. of electrons transferred per mole
F	Faraday's constant (96485C mol^{-1})
c_v	Vanadium concentration (mol L^{-1})
$P_{pump\,electrical}$	Pump electrical power consumption (W)
$P_{pump\,hydraulic}$	Pump hydraulic power consumption (W)
η_{pump}	Pump efficiency
R	Universal gas constant (8.3144 J K^{-1}mol^{-1})
T	Ambient temperature (K)
K	Proportionality constant
$E_{Stack(OCV)}$	VRFB stack open circuit voltage (V)
n_s	No. of stacks connected in series for the entire VRFB system
n	No. of series cells in VRFB stack
$E_{Cell\,eq(at\ 50\%\ SOC)}$	VRFB cell equilibrium potential (V)
I_d	Diffusion current (A)
C_i	Concentration of Vanadium Species (mol L^{-1})
D_m	Diffusion coefficient (m^2 s^{-1})
x	Thickness of the membrane (μm)
C_O^+	Concentration of oxidized vanadium species in the positive electrolyte side (mol L^{-1})
C_O^-	Concentration of oxidized vanadium species in the negative electrolyte side (mol L^{-1})
C_R^+	Concentration of reduced vanadium species in the positive electrolyte side (mol L^{-1})
C_R^-	Concentration of reduced vanadium species in the negative electrolyte side (mol L^{-1})
E^+	Positive electrode potential (V)
E^-	Negative electrode potential (V)
$E_{selfdischarge}$	Self-discharge potential drop (V)
$R_{selfdischarge}$	Self-discharge resistance (Ω)
$E^*_{Stack(OCV)}$	$E_{Stack(OCV)}$ considering self discharge potential drop (V)
E^*_t	Stack terminal voltage considering self-discharge potential drop (V)
τ	Time constant
R^c_{Ct}	Cathodic charge transfer resistance (Ω)
R^a_{Ct}	Anodic charge transfer resistance (Ω)
C^c_{dl}	Cathodic double layer capacitance (F)
C^a_{dl}	Anodic double layer capacitance (F)
R_0	Series resistance (Ω)
$\widetilde{R}_{half\ cell}$	Hydraulic resistance (Pa s m^{-3})
K	Dynamic viscosity of the electrolyte (Pa s)
μ	Permeability of porous electrode
Δp_{stack}	Pressure drop across the stack (Pa)
Δp_{pipe}	Pressure drop due to pipes (Pa)
P	density of the electrolyte (kg m^{-3})
V_s	Velocity of the electrolyte inside the pipe (m s^{-1})
Z	height of the pipe (m)
G	acceleration due to gravity (m s^{-2})
h_m	minor losses (m)
h_f	friction losses (m)
$P_{hydraulic}$	Pump hydraulic power consumption (Watt)
$P_{pump\,electrical}$	Pump electrical power consumption (Watt)
f	friction factor
L	Length of pipe (m)
D	Hydraulic diameter of the pipe (m)
Re	Reynolds' number
η_{pump}	Pump efficiency
Ψ	Aging factor

nature of the parameters of a flow battery and also lacked experimental validation. In addition, an electrical equivalent model of VRFB where the RC network parameters were estimated by extended Kalman filter approach was proposed by Mohamed et al. [46,47]. However, their model did not consider the impact of practical parameters like flow rate and pump power consumption on VRFB model performance. Another unique method of identifying battery internal parameters is to perform electrochemical impedance spectroscopy (EIS) [48–50], where the RC network parameters were estimated under a wide range of frequencies. However, this technique seems to be much more complex for system level and hence applicable for single cell studies only. Therefore, modelling and simulation based studies are more prevalent. Recently, Zhang, et al. [51] introduced a comprehensive electrical equivalent circuit model of VRFB consisting of an open-circuit voltage (OCV) source, two parasitic shunt circuits, a 1st order RC network and a hydraulic circuit model signifying the pump operation. The model circuit parameters in their work were estimated by curve fitting with the experimental results of Kim et al. [52]. Yet, the dynamic nature of VRFB internal parameters was not demonstrated as a function of the state of charge (SOC) in their work. Furthermore, the optimization of electrolyte flow rate considering both aspects of minimising the internal losses and pump power consumption was not investigated. Wei et al. [53] proposed an online estimation model of VRFB State of Charge (SOC) and equivalent circuit model parameters by multi time scale estimator. In their paper the robustness of the SOC estimation model was validated by experimental result on a single VRFB cell for different flow rates and ageing levels. A MATLAB based model of VRFB was introduced by Turkar et al. [54] and was compared with kW scale VRFB system performance. But they did not consider the flow rate optimization which plays a key role in improving the VRFB system efficiency. Tang et al. [9] proposed a flow rate optimization technique where the optimal flow rate helps in reducing pump power consumption resulting in improved VRFB system efficiency. However, in their paper, the variability of battery internal circuit parameters and associated losses were not taken into account under varying flow rates. A similar study by Averbukh et al. [55] considered only the pump loss in their flow rate optimization criteria to improve VRFB system efficiency. To realize the overall performance of a VRFB system, an electrochemical model was proposed by Blanc et al. [56] where the electrical equivalent network parameters were assumed constant for simplicity. However, for all practical applications, those parameters are observed to be variable with respect to of flow rate and SOC. The performance analysis of VRFB in micro grid and power system applications was discussed by Qiu et al. [57] and Nguyen et al. [58]. These practical applications of VRFB need proper modelling and dynamically estimated parameters in order to design efficient battery management systems (BMS). A recent work published by Bhattacharjee and Saha [59] proposed a generalised electrical equivalent model of VRFB system where the dynamic optimal flow rate was estimated to improve the VRFB overall system efficiency. The model performance was demonstrated by a hybrid micro-grid system. However in their work, the internal circuit parameters were assumed to be independent of state of charge (SOC). Also the flow rate optimization criteria did not consider the dynamicity of stack internal power loss with varying flow rate.