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Dynamic electro-thermal modeling of all-vanadium redox flow battery with forced cooling strategies

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HIGHLIGHTS

- A dynamic electro-thermal model is proposed for VRB with forced cooling.
- The Foster network is adopted to model the battery cooling process.
- Both the electrolyte temperature and terminal voltage can be accurately predicted.
- The flow rate of electrolyte and coolant significantly impact battery performance.

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ABSTRACT

The present study focuses on the dynamic electro-thermal modeling for the all-vanadium redox flow battery (VRB) with forced cooling strategies. The Foster network is adopted to dynamically model the heat dissipation of VRB with heat exchangers. The parameters of Foster network are extracted by fitting the step response of it to the results of linearized CFD model. Then a complete electro-thermal model is proposed by coupling the heat generation model, Foster network and electrical model. Results show that the established model has nearly the same accuracy with the nonlinear CFD model in electrolyte temperature prediction but drastically improves the computational efficiency. The modeled terminal voltage is also benchmarked with the experimental data under different current densities. The electrolyte temperature is found to be significantly influenced by the flow rate of coolant. As compared, although the electrolyte flow rate has unremarkable impact on electrolyte temperature, its effect on system pressure drop and battery efficiency is significant. Increasing the electrolyte flow rate improves the coulombic efficiency, voltage efficiency and energy efficiency simultaneously but at the expense of higher pump power demanded. An optimal flow rate exists for each operating condition to maximize the system efficiency.

1. Introduction

The redox flow batteries (RFBs) are promising in the large-scale storage market and have made it possible for the intermittent renewables to be coupled into power systems [1,2]. Among multiple large-capacity batteries, the all-vanadium redox flow battery (VRB) initialized by Skyllas-Kazacos and co-workers [3,4] has been widely investigated and commercialized due to the outstanding virtues such as capacity and output power design separation, cross contamination elimination, long life cycle, high deep discharge tolerance and high energy efficiency [5].

The researches on VRB have been concentrating on membrane investigation, electrode enhancement, electrolyte measurement, and stack structure optimization during the past decades [6–10]. However, the works on thermal modeling and temperature management are rather limited although they are crucial for the safe and efficient operation of battery system [11]. It is known that the electrolyte temperature of VRB should be carefully controlled within a specific range to confirm its stability. For example, the electrolyte temperature should be strictly controlled between 5°C and 40°C for typical electrolytes with 1.8–2 M vanadium sulfate in 2.5–3 M sulfuric acid. Otherwise, the precipitation of vanadium ions can happen, potentially leading to the performance deterioration and even channel blocking [12]. The accurate and real time prediction of electrolyte temperature is the main challenge to establish such a temperature management system. During the past few years, some attempts on dynamic thermal modeling of VRB have been reported. Tang et al. [13] proposed a dynamic thermal model based on the conservation of mass and energy. The dynamic temperature response was obtained from the given surrounding temperature and current density. The effect of self-discharge

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Nomenclature

CF	coulombic efficiency (%)
C_p	specific heat of electrolyte (J kg^{-1} K^{-1})
c	concentration of species (mol L^{-1})
D	diffusion coefficient (m^2 s^{-1})
E	open circuit voltage (V)
$E^{\ominus}$	standard electrode potential (V)
EF	energy efficiency (%)
F	Faraday's constant (C mol^{-1})
$\Delta G^{\ominus}$	standard molar Gibbs free reaction enthalpy (J mol^{-1})
$\Delta H_r^{\ominus}$	standard molar reaction enthalpy (J mol^{-1})
I	current, positive for charge and negative for discharge (A)
i	current density (A m^{-2})
J	diffusion flux (mol m^{-2} s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
k_m	local mass transfer coefficient at electrode surface (m s^{-1})
N	number of cells
P	power/heat generation rate (W)
R	gas constant (J K^{-1} mol^{-1})
R_{eq}	equivalent internal resistance (Ω)
SF	system efficiency (%)
$\Delta S_r^{\ominus}$	standard molar reaction entropy (J K^{-1} mol^{-1})
T	temperature (K)
t	time (h)
U	terminal voltage (V)
V	volume (m^3)
VF	voltage efficiency (%)
v	velocity of electrolyte (m s^{-1})
z	number of moles of electrons exchanged in a reaction

Greek symbol

ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)
η	overpotential (V)
γ	activity coefficient

Subscript

b	bulk solution
c	charge
d	discharge
$entro$	entropic
p	pump
s	electrolyte in stack
t	tank

Abbreviations

CFD	computational fluid dynamics
EMF	Electromotive Force
LTI	linear and time-invariant
OCV	open circuit voltage
RNG	renormalization group
SOC	state of charge
UDF	User-Defined Function

reactions was then incorporated into the thermal model to better predict the electrolyte temperature during both charging/discharging cycles and standby periods [14]. After that, Tang et al. [15] further took the effect of shunt current on battery efficiency and stack temperature into account. More recently, in the work of Xiong et al. [16], the effect of pump power was considered into the thermal–hydraulic model. Wei et al. investigated the inhomogeneity of flow rate distribution in different cells and further established a more refined dynamic thermal hydraulic model for both real-time temperature monitor and stack flow pattern design optimization [17].

The existing works on dynamic thermal modeling of VRB have been focusing on the stand-alone VRB system without any additional equipment. In practical application, however, the VRB systems are mostly integrated with the forced cooling equipment such as the heat exchanger to better control the temperature [18,19]. Unfortunately, the dynamic thermal model being able to simulate the scenario with heat exchangers has not been investigated. Confronted with a practical system with heat exchangers, the existing dynamic models are likely to loss accuracy because the heat exchanger aided battery cooling process is complicated and difficult to be estimated with the empirical correlations [20]. Computational fluid dynamics (CFD) approach is a powerful tool to solve the complicated thermal problems and has been widely used in research and industrial application [21–26]. Recently, CFD method has also been employed for the 3-dimensional simulation of batteries [27,28]. The high computational complexity and long running time, however, have limited its applicability for the real time prediction and transient analysis.

Foster network, commonly used for the cooling study of power electronic elements [29], is potentially an effective approach to overcome the shortcomings of the existing dynamic thermal models and CFD method. The aim of Foster network is using a simplified circuit model to dynamically represent the cooling process of thermal system, under either natural cooling or forced cooling condition. Constructed with couples of resister/capacitor (RC) pairs, Foster network can be viewed as a linear and time invariant (LTI) system with the heat generation rate in stack as input and the transient temperature response as output. By fitting the step response of Foster network with the CFD results under linearization assumption, the parameters can be extracted to make the fast Foster network model approximately equivalent to the time-consuming CFD model. To the best of our knowledge, the usage of Foster network in thermal modeling of battery is considerably rare. The only report is from the works by Hu et al. [30,31], in which the temperature response of lithium-ion battery package is studied under given power generation profiles. These works give valuable inspirations on the dynamic thermal modeling of battery system with forced cooling strategies, but only concentrate on the cooling process under given power generation rate rather than the complete thermal model. To our knowledge, there are hitherto no any works on the complete electro-thermal modeling for VRB system with forced cooling strategies.

In this study, the Foster network is parameterized and applied to model the heat exchanger aided cooling process. By coupling the Foster network, heat generation model and electrical model, a complete dynamic electro-thermal model is proposed. After that, the effect of flow rate of both the coolant and electrolyte on the VRB performance is investigated. The proposed dynamic electro-thermal model is meaningful for both the design and the real time control of VRB system.

2. Investigation on battery cooling

2.1. CFD modeling for cooling process

Forced cooling strategies are commonly applied in the VRB systems. In this paper, the shell and tube heat exchanger is assumed