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Development of an efficient thermal management system for Vanadium Redox Flow Battery under different charge-discharge conditions

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HIGHLIGHTS

- An efficient thermal management system is developed for VRFB.
- The stack temperature forecasting and control model is designed in MATLAB/Simulink.
- The stack temperature is controlled online by dynamically optimizing the flow rate.
- The dynamic optimal flow rate also helps achieving improved VRFB system efficiency.
- The proposed controller model performance is experimentally validated.

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ABSTRACT

The temperature rise inside VRFB stack may exceed its safe limit at higher charging and discharging currents leading to thermal precipitation. A thermal management and control model of VRFB is developed in this paper for the first time in MATLAB/Simulink environment and experimentally validated in the lab. Online monitoring of VRFB stack temperature and flow rate control is executed by dsPIC microcontroller platform. The usual practice of applying higher flow rate by increasing pump speed during charging and discharging operations for keeping the stack temperature within safe limit leads to reduction of overall VRFB system efficiency due to higher pump power loss. In this work a model for determining the dynamic optimal flow rate is developed to ensure efficient thermal management and improvement of overall system efficiency of VRFB. The proposed thermal management scheme is validated by a practical 1 kW 6 h VRFB system operation. It is observed that at a lower flow rate of 180 ml/sec the stack temperature during fast charging and discharging at the rate of 60A rises up to 47 °C which is well above the specified safe limit of operating temperature of VRFB and leads to incomplete charging due to premature thermal shut down of the system. Increasing the flow rate to 300 ml/sec keeps the stack temperature within safe limit but the overall VRFB efficiency becomes around 83%. However, by applying dynamic optimal flow rate (160–300 ml/sec) over the range of SOC (10–90%), this is managed within the safe level of 35.8 °C and at the same time improving the overall VRFB system efficiency up to 88.55%. The model performance shows very good agreement with the experimental results having maximum error of 0.85%. The thermal management and control scheme demonstrated in this paper is a generalised one and hence very useful for large scale VRFB applications as well.

1. Introduction

The intermittent nature of renewable energy sources (solar, wind etc.) restricts uninterrupted power supply to the distribution network and utility grid. A high capacity energy storage system could be a solution to overcome this problem. Compared to the conventional secondary batteries, the redox flow batteries have greater flexibility of scaling up of their capacity for large scale renewable energy systems. Vanadium Redox Flow Battery (VRFB) is a promising redox flow battery technology for peak power shaving especially in the case of large scale grid connected solar/wind energy systems. VRFB exhibits some commendable merits such as independent scalability of power and energy capacity, free from cross contamination and degradation and hence very long life cycle, deep discharge capacity and reliability for long term operation with renewable energy sources and power grid. VRFB technology was first developed by Maria Skyllas-Kazacos [1,2] and her

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research group at University of New South Wales (UNSW) in the mid-1980s and a 1 kW VRFB performance characterization [3] was reported. Since then significant research and developments have been reported on VRFB [4,5]. The necessity of modelling of VRFB to understand the key aspects of VRFB research from commercial to material level was discussed by Zheng et al. [6]. Al-Yasiri et al. [7] introduced a novel cell design of vanadium redox flow batteries for enhancing energy and power performance. For designing efficient electrical interface and battery management system (BMS) of VRFB with renewable energy sources, besides dynamic electrical equivalent model and performance analysis of VRFB [8–16], the thermal modelling is also very much essential. Tang et al. [17] first introduced a thermal model of VRFB using thermodynamic equations and mass transfer theory. The electrolyte solutions of the VRFB consist of sulfuric acid containing vanadium redox couples with four different states of oxidation V^{2+}/V^{3+} and V^{4+}/V^{5+} at the negative and positive sides respectively. At temperatures below 5 °C, precipitation of V2+/V3+ in the negative electrolyte occurs. Likewise, thermal precipitation of V5+ occurs at temperatures above 40 °C. This may block the electrolyte channels inside stack and lead to degradation of membrane, thus deterioration in battery performance. Battery temperature is therefore a very important parameter that needs to be considered in the VRFB design and controlled for its efficient and safe operation. Al-Fetlawi et al. [18] developed a non-isothermal model to investigate the temperature in the stack of the VRFB under different conditions. A three dimensional model of VRFB for thermal analysis was reported by Zheng et al. [19]. Their work left a good prospect of thermal management of VRFB. Tang et al. [20] and Yan et al. [21] discussed the effect of self-discharge on the thermal behaviour of VRFB considering the battery in idle or no operating condition. The rise in battery temperature due to self-discharge drop was found significant. It is well known that during charge-discharge operation of VRFB the electrolyte flow rate acts as carrier of heat generated inside the battery stack. Therefore, proper control of flow rate is recommended for controlling the battery temperature within safe limit. In the paper of Xiong et al. [22] an optimal flow rate was determined to control the electrolyte temperature and maximize the system efficiency of VRFB. Wei et al. [23] described the effect of different patterns of stack flow channels on the temperature variation of electrolyte and their simulation result showed that a serpentine-parallel pattern of stack flow channel could be suitable for uniform distribution of flow rate and thus controlling the electrolyte temperature. Tang et al. [24] investigated the effect of shunt current on the VRFB efficiency and thermal behaviour considering the VRFB system in idle operating condition. Cao et al. [25] described the membrane permeability rates of vanadium ions with temperature variation. Yan et al. [26] discussed the effects of battery design, environmental temperature and electrolyte flow rate on thermal behaviour of vanadium redox flow battery in different applications. Zhang et al. [27] described the effect of operating temperature on VRFB performance. Their work showed that the coulombic efficiency and capacity of VRFB decreases with increasing operating temperature. The results reported in their work suggested that a thermal management model is necessary to ensure optimal thermal operating condition to achieve reliable and efficient operation.

Considering the factors discussed above, an efficient thermal management system for VRFB needs to be developed for its optimized interfacing with renewable energy sources to ensure smooth and long life operation. But till date, no such paper has reported the development and performance analysis of suitable thermal management system for VRFB under different charge-discharge conditions.

In this paper, a MATLAB/Simulink based model of VRFB system is introduced for developing a dynamic temperature controller as well as to achieve improved VRFB overall system efficiency by determining dynamic optimal range of flow rate during charging-discharging of VRFB. The proposed controller performance has been validated by a practical 1 kW 6 h VRFB system. The simulation results of the controller model shows very good agreement with the experimental results having maximum error of 0.85%. The thermal management model presented in this paper is a generalised one and can be applied for large scale VRFB systems also.

Rest of the paper is organised as follows, Section 2 gives a detail description of thermal characteristics model, flow pump hydraulic model and the thermal management model of VRFB in MATLAB/Simulink environment. Section 3 describes the experimental set up for the proposed thermal management scheme of VRFB. Section 4 discusses the simulation and experimental results of the proposed controller. Section 5 includes the conclusion of this paper.

2. Model formulation

2.1. VRFB thermal characteristics model

The MATLAB/Simulink model for the thermal characteristics of VRFB is developed using the dynamic equations based on conservation of mass and energy. The dynamic model is developed with some assumptions mentioned below;

I. Electrolyte in both the tanks is fully filled and the tanks are sealed.
II. The volume of the electrolyte in both the tanks and the cells remain constant.
III. The electrolytes are perfectly mixed in both the cells and the tanks.
IV. Gassing effect inside VRFB is controlled by restricting the SOC within its overcharge threshold.
V. Temperature and ion concentrations in each cell are uniform [17].
VI. Heat generation due to mixing of electrolytes is very small therefore neglected.
VII. Temperature rise due to self discharge reaction during charging-discharging is negligibly small [20].
VIII. VRFB stack internal resistance variation is within a very small range with flow rate and current hence taken as constant.
IX. Effect of shunt current during VRFB operation and associated heat generation is also neglected.
X. Effect of self discharge during idle condition of VRFB on its thermal behaviour is not considered taking the view point of continuous operation for renewable power systems.

Thermodynamic Eqs. (1)–(4) of VRFB during charging and discharging are presented as [16],

$$C_P \rho V_S \frac{dT_S}{dt} = Q_+ C_P \rho (T_+ - T_s) + Q_- C_P \rho (T_- - T_s) + I_C^2 R_C + I_C T_s \frac{dE}{dT} \tag{1}$$

$$C_P \rho V_S \frac{dT_S}{dt} = Q_+ C_P \rho (T_+ - T_s) + Q_- C_P \rho (T_- - T_s) + I_D^2 R_D + I_D T_s \frac{dE}{dT} \tag{2}$$

$$C_P \rho V_+ \frac{dT_S}{dt} = Q_+ C_P \rho (T_S - T_+) + U_+ A_+ (T_a - T_+) \tag{3}$$

$$C_P \rho V_- \frac{dT_S}{dt} = Q_- C_P \rho (T_S - T_-) + U_- A_- (T_a - T_-) \tag{4}$$

where

T_S = Stack electrolyte temperature (°C)
T_+ = Temperature of the positive electrolyte in the tank (°C)
T_- = Temperature of the negative electrolyte in the tank (°C)
T_a = Ambient temperature (°C)
C_P = Specific heat of the electrolyte ($Jg^{-1}\ K^{-1}$)
ρ = Density of electrolyte (gm^{-3})
V_S = Volume of the battery stack (L)
V_+ = Volume of positive electrolyte tank (L)
V_- = Volume of positive electrolyte tank (L)
Q_+ = Outlet flow rate of the positive electrolyte in the tank ($ml\ sec^{-1}$)

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