

A comprehensive and practical framework for advanced battery management system of vanadium redox flow batteries

Hao Wang^{a,*}, S. Ali Pourmousavi^a, Wen L. Soong^a, Xinan Zhang^b, Aleksandar N. Nikoloski^c, Nesimi Ertugrul^a

^a*School of Electrical & Mechanical Engineering, The University of Adelaide, Australia*

^b*School of Engineering, The University of Western Australia, Australia*

^c*Harry Butler Institute (Centre for Water Energy and Waste), College of Science, Health, Engineering and Education, Murdoch University, Australia*

Abstract

The practical and effective design of the battery management system (BMS) is crucial to achieving high performance, long service life, and safe operation of all battery types, including vanadium redox flow batteries (VRFBs). However, without having a comprehensive and practical battery management scheme design as the foundation to develop an industrial or commercial-scale BMS for VRFBs, various underlying factors that promote the deployment of VRFBs in many projects that incorporate renewable energy sources (RESs) for decarbonisation resulting in economic benefits cannot be accomplished. In this paper, an advanced VRFB-BMS scheme is proposed that achieves high performance in state of charge (SOC) estimation, hydraulic control and thermal management without requiring excessive computational resources. Rigorous validations of this proposed VRFB-BMS scheme are carried out based on a state-of-the-art zero-dimensional (0-D) model to demonstrate the performance of the proposed BMS scheme design including case studies that showed: (1) a 8.1% increase in round-trip efficiency; (2) automatic capacity rebalancing and highly accurate half-system SOC estimation method with a mean absolute percentage error (MAPE) less than 1% when the system is severely imbalanced; and (3) the ability to conduct effective thermal management with the use of a heating, ventilation and air-conditioning system (HVAC). The studies also demonstrated the capability of integrating the BMS with the energy management system (EMS) to achieve specified objectives for the users. This can bring numerous economic and environmental benefits to satisfy the objectives of the decision-makers or the investors.

Keywords: Vanadium redox flow battery; Battery modelling; Battery management system; Energy management system; Thermal management

*Corresponding Author

Email address: hao.wang05@adelaide.edu.au

1 Nomenclature

2 Home energy management system

3	α_{ch}, β_{ch}	Charge power regulation coefficients
4	$\alpha_{dch}, \beta_{dch}$	Discharge power regulation coefficients
5	η_{inv}	Inverter efficiency [%]
6	η_{rt}	Round-trip efficiency of the VRFB system [%]
7	C^{im}, C^{ex}	Import/export cost from/to utility grid [A\$/kWh]
8	E_n	Nominal energy [kWh]
9	P^{aux}	Power consumption of battery's auxiliary system [kW]
10	P^{ch}, P^{dch}	Charge/discharge power to/from battery [kW]
11	$P_{max}^{ch}, P_{max}^{dch}$	Maximum charge/discharge power to/from battery [kW]
12	$P_{min}^{ch}, P_{min}^{dch}$	Minimum charge/discharge power to/from battery [kW]
13	P^{im}, P^{ex}	Import/export power from/to utility grid [kW]
14	P^{load}	Load power [kW]
15	P^{PV}	Solar PV generation power [kW]
16	u^{ch}, u^{dch}	Battery charge/discharge status

17 Multi-physics VRFB model

18	$\eta_{con}^+, \eta_{con}^-$	Positive/negative half-cell concentration overpotentials [V]
19	η_{rt}	Round-trip efficiency [%]
20	κ_{φ}	Membrane electro-kinetic permeability [m ²]
21	κ_e	Electrode hydraulic permeability [m ²]
22	κ_m	Membrane hydraulic permeability [m ²]
23	λ_{KC}	Kozeny-Carman constant
24	μ^+, μ^-	Positive/negative electrolyte viscosity [Pa · s]
25	μ_w	Mean viscosity of electrolyte [Pa · s]
26	ϕ_{diff}^m	Effective diffusion potential [V]
27	$\phi_{pos}^m, \phi_{neg}^m$	Ionic potential at positive/negative sides [V]
28	ρ	Electrolyte density [kg m ⁻³]

1	σ_m	Effective conductivity of the membrane [S m^{-1}]
2	ε	Electrode porosity
3	$\vec{v}_{electro-osmosis}$	Electrolyte velocity driven by electro-osmosis across membrane [m s^{-1}]
4	$\vec{v}_m$	Electrolyte velocity across membrane [m s^{-1}]
5	$\vec{v}_{osmosis}$	Electrolyte velocity driven by osmosis across membrane [m s^{-1}]
6	A_e	Cross-sectional area of porous electrode [m^2]
7	A_m	Membrane surface area [m^2]
8	A_t	Surface area of the tank [m^2]
9	c_i^s	Concentration of V^{i+} in the stack [mol m^{-3}]
10	c_i^t	Concentration of V^{i+} in the tank [mol m^{-3}]
11	c_f	Fixed acid concentration [mol m^{-3}]
12	c_{H^+}	Hydrogen ion concentration [mol m^{-3}]
13	C_p	Specific heat capacity of electrolyte [$\text{J kg}^{-1} \text{K}^{-1}$]
14	c_{total}	Total concentration of V^{i+} [mol m^{-3}]
15	D	Thickness of the membrane [m]
16	d_f	Fibre diameter [m]
17	$E^{0'}$	Equilibrium open-circuit potential of the cell [V]
18	E^{OCV}	Open-circuit voltage [V]
19	$E_p^{0'}, E_n^{0'}$	Equilibrium open-circuit potential of the positive/negative half-cell [V]
20	$E_{oc,p}, E_{oc,n}$	Open-circuit potential of the positive/negative half-cell [V]
21	E_s	Stack voltage [V]
22	F	Faraday's constant [C mol^{-1}]
23	H_e	Height of the electrode [m]
24	I	Current [A]
25	k_{H^+}	Diffusion coefficient of H^+ [$\text{m}^2 \text{s}^{-1}$]
26	k_i	Diffusion coefficient of V^{i+} [$\text{m}^2 \text{s}^{-1}$]
27	L_e	Length of the electrode [m]
28	N	Number of cells in the stack
29	n_i^{con}	Convection fluxes of V^{i+} [$\text{mol m}^{-2} \text{s}^{-1}$]

1	n_i^{cross}	Overall crossover fluxes of V^{i+} [$\text{mol m}^{-2} \text{s}^{-1}$]
2	n_i^{diff}	Diffusion fluxes of V^{i+} [$\text{mol m}^{-2} \text{s}^{-1}$]
3	n_i^{mig}	Electro-migration fluxes of V^{i+} [$\text{mol m}^{-2} \text{s}^{-1}$]
4	P_{self}	Self discharge losses [W]
5	Q_c	Electrolyte flow rate in cell [$\text{m}^3 \text{s}^{-1}$]
6	Q_{rb}	Rebalance electrolyte flow rate [$\text{m}^3 \text{s}^{-1}$]
7	Q_s	Electrolyte flow rate of the system [$\text{m}^3 \text{s}^{-1}$]
8	R	Gas constant [$\text{J mol}^{-1} \text{K}^{-1}$]
9	r'	Overall cell resistance [Ω]
10	r_s	Overall stack resistance [Ω]
11	SOC, SOC_p, SOC_n	State of charge of the system, positive and negative half-system [%]
12	SOE	State of energy [%]
13	T_p, T_n	Electrolyte temperature at positive/negative tank [K]
14	T_s	Electrolyte temperature in the stack [K]
15	T_{air}	Air temperature [K]
16	U_t	Heat transfer capability of tank [$\text{J K}^{-1} \text{s}^{-1} \text{m}^{-2}$]
17	V_p, V_n	Electrolyte volume in the positive/ negative tank [m^3]
18	V_s	Electrolyte volume in the stack [m^3]
19	W_e	Width of the electrode [m]
20	z	Number of electrons involved in the redox reactions
21	z_i	Valency of i-th vanadium ions
22	Room temperature model	
23	$\alpha_{pump}, \alpha_{inv}$	Heat loss percentage of pumps and inverters [%]
24	$\dot{Q}_{ac}$	Cooling energy by air-conditioner [J]
25	$\dot{Q}_{cool}, \dot{Q}_{heat}, \dot{Q}_{loss}$	Cooling, heat generation and heat exchange loss energy [J]
26	ω	Angular frequency and phase [rad s^{-1}]
27	φ	Angular phase [rad]
28	A_{wall}	Total surface of walls [m^2]

1	C_{air}	Heat capacity of air in [$\text{J kg}^{-1} \text{K}^{-1}$]
2	EER	Energy efficiency ratio
3	h	Heat transfer coefficient of concrete [$\text{W m}^{-2} \text{K}^{-1}$]
4	M_{air}	Air mass inside the room [kg]
5	m_{fan}	Air mass flow through fan [kg s^{-1}]
6	P_{pump}, P_{ac}	Power consumption of the pump and air-conditioner [W]
7	P_{VRFB}	VRFB power [W]
8	T_{max}, T_{min}	Maximum/minimum outside temperature [$^{\circ}\text{C}$]
9	T_{room}, T_{out}	Internal room/ outside temperature [$^{\circ}\text{C}$]

10 **1. Introduction**

11 It is well known that to achieve global greenhouse gas emission reduction targets, we need
12 to deploy renewable energy sources (RESs) at an unprecedented rate throughout the world to
13 replace existing fossil fuel power plants. However, due to the variable and intermittent nature
14 of RES, there is a need for short-, medium-, and long-term energy storage systems to ensure the
15 safe operation of electricity grids and provide consistent quality power to end users. Among the
16 different energy storage technologies, the vanadium redox flow battery (VRFB) is recognised
17 as a practical solution due to its stable performance, low levelized cost of energy (LCOE) and
18 long lifespan with almost no degradation over 20 years [1]. However, without a well-designed
19 battery management system (BMS), the anticipated high performance of VRFBs might not be
20 achievable. Thus, innovative designs for VRFB-BMSs are becoming increasingly important to
21 manufacturers who want to improve the reliability and performance of their products [2].

22 A significant amount of research and development has been conducted on BMS for non-
23 aqueous batteries, mainly Li-ion batteries, within both the academic and industrial sectors. How-
24 ever, because of different operational principles and designs of aqueous batteries, certain as-
25 pects of these BMSs must be redesigned for VRFBs. Unfortunately, the development of VRFB-
26 BMS has so far received limited attention compared to other mainstream battery energy stor-
27 age systems (BESS) technologies, which has significantly impeded its development. Trovo and
28 Guarnieri et al. [3, 4] provided a detailed BMS design for a 9 kW/27 kWh industrial-scale
29 VRFB (IS-VRFB), covering both hardware and software aspects. Later, Vishnu et al. [5] pro-
30 posed a BMS design for standalone VRFB applications. To the best of our knowledge, these
31 are the few publications available on the detailed design and implementation of a VRFB-BMS.
32 While these two papers provide detailed and comprehensive descriptions of the VRFB-BMS
33 hardware and software design, they did not thoroughly introduce or explain the working princi-
34 ples and framework of the BMS. For example, they do not provide a mechanism to control the
35 VRFB operational modes or to estimate the critical states of the system for monitoring within the
36 BMS. A review of other studies linked to VRFB-BMS reveals a clear roadblock to development
37 progress, namely the lack of effective tools to manage and operate the battery. For instance, cur-
38 rent VRFB-BMS designs overlook issues related to state of charge (SOC) imbalance in half-cells

1 and lack comprehensive thermal management mechanisms, often only considering standby thermal
2 management [6]. Moreover, most of the work on estimating half-system SOC and optimising
3 flow rates has proposed complex algorithms that exceed real-world computational capabilities of
4 BMSs. As such, we believe developing a practical VRFB-BMS design for commercial- and
5 industrial-scale VRFBs requires significantly more attention.

6 Another profound concern arises from the absence of robust VRFB-BMS, where most re-
7 search studies do not consider the true operational dynamics of VRFBs in their design. For
8 instance, while the operation of a VRFB can be divided into charging, discharging, standby, and
9 shutdown modes, most of the reported studies only evaluated proposed BMS design and oper-
10 ational optimisation methods under continuous charge-discharge operation, neglecting standby
11 and shutdown modes. In addition, the existing BMS and operational strategies were not vali-
12 dated under a comprehensive battery management framework, and therefore their feasibility in
13 actual operation remains questionable. For example, all existing model-based flow rate methods
14 assumed that the system states (SOC, vanadium species concentration, electrolyte temperature,
15 etc.) are accurately measured, and so the information from the model was used directly. How-
16 ever, obtaining accurate system states is difficult in an industrial- or commercial-scale VRFB
17 system. As a result, it is of great urgency to develop a well-designed and comprehensive VRFB-
18 BMS scheme that incorporates detailed battery information and a completed design framework
19 for researchers and operators to validate their proposed battery management methods in the con-
20 text of actual field implementation.

21 Additionally, like other battery technologies, a VRFB is typically integrated into a larger
22 hybrid power system controlled by an energy management system (EMS). The main goal of an
23 EMS is to maximise the economic benefits of the entire system, including installed BESSs, as
24 a high-level optimisation and control system. If the EMS is not designed based on predefined
25 rules, it continuously solves an optimisation problem at specific intervals for a specified future
26 period to determine the operating points of all assets in the energy system. To this end, a suitable
27 VRFB model should be integrated with the EMS, ensuring that it can be solved both reliably and
28 quickly within an optimisation problem. This is an area where VRFB research is largely lacking,
29 indicating the need for more studies and development [1]. Sumitomo Electric [7] demonstrated a
30 microgrid project with Taiwan Power Research Institute that installed a 125 kW/750 kWh VRFB,
31 a 150 kW PV system, a 50 kW generator system, a 10 kW wind turbine, and a 150 kW load. The
32 entire energy system is managed by a central EMS which demonstrates its practical application
33 in grid-level applications to accomplish different objectives.

34 In addition, VRFB thermal management is a critical part of the BMS design but has received
35 little attention from the research community. Tang et al. [8] studied standby thermal behaviour to
36 highlight the significance of the choice of cooling flow rate to reduce cumulative heat generation
37 inside the stack. Trovo et al. [6] expanded on this to develop a standby thermal management
38 system for a kW-level VRFB system. However, their cooling flow rate mechanism was only
39 practical in reducing the electrolyte temperature difference between the tank and the stack during
40 the standby period, which is not ideal for cooling the entire VRFB system. VRFB manufacturers
41 appear to prefer standard heating, ventilation, and air conditioning (HVAC) systems as an effec-
42 tive tool for passive cooling of VRFB systems [9]. Furthermore, recent studies by Wang et al.
43 [10] and Shu et al. [11] provided two different case studies using HVAC for thermal manage-
44 ment and validated its effectiveness. However, at this stage, there is no comprehensive thermal
45 management design for VRFB systems that considers the cooling flow rate and passive cooling
46 by HVAC under real-world load, temperature and operational conditions, which should be con-
47 sidered in future development. In summary, our literature review reveals a lack of effective and

efficient VRFB-BMS design, especially with respect to SOC estimation, thermal management, and integration of a BMS into an EMS.

To address these research gaps, this study introduces an advanced VRFB-BMS to overcome the limitations of existing VRFB-BMS designs. This study is conducted using a new zero-dimensional model (0-D) that incorporates all crossover and electrolyte transfer mechanisms and thermal dynamics of VRFBs. The key contributions and features of the proposed BMS presented in this paper are outlined below:

- A comprehensive and practical VRFB-BMS design is proposed, which is computationally-efficient for industrial and commercial-scale hardware design. The detailed design and working principles are given and evaluated in this paper.
- Four operational modes (charge/discharge/stop/standby) are considered in the BMS design to simulate the on-site operation of the VRFB systems. This provides useful information for researchers in the field to rigorously evaluate their proposed methods considering the operational dynamics of VRFB systems.
- High-performance and computationally-efficient half-system SOC estimation model, and flow rate control and automatic electrolyte rebalancing methods are proposed and rigorously validated in this work.
- A hybrid HVAC and flow rate cooling strategy is proposed to conduct energy-efficient and effective thermal management for VRFB systems.

The rest of this paper is organised as follows. In Section 2, a 0-D multi-physics VRFB model with thermal modelling is presented, which is developed based on the works by Wang et al. [12, 10], that incorporates all ion crossover and electrolyte transfer mechanisms with battery configurations. Rigorous validations for the 5 kW VRFB system are carried out in Section 3. The functionalities and critical battery management functions are explained in Section 4 and the integration of these functions into a comprehensive and advanced VRFB-BMS design. Lastly, real data are used to test the effectiveness of the proposed VRFB-BMS design in thermal management, accurate SOC estimation, energy savings, and capacity recovery are presented in Section 5.

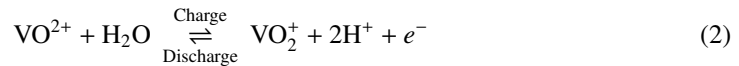
2. Multi-physics vanadium redox flow battery model

VRFB systems are normally used as medium- or large-scale BESSs for residential or grid-level applications. In Fig. 1, a general schematic of a large-scale VRFB system composed of two electrolyte storage tanks, a compact battery stack, two electrolyte circulation pumps, and piping systems. The main chemical reactions take place inside the cells in the stack. These chemical reactions in the positive/negative half cells and the overall cell reaction are:

Negative half-cell reaction:



Positive half-cell reaction:



Overall cell reaction:

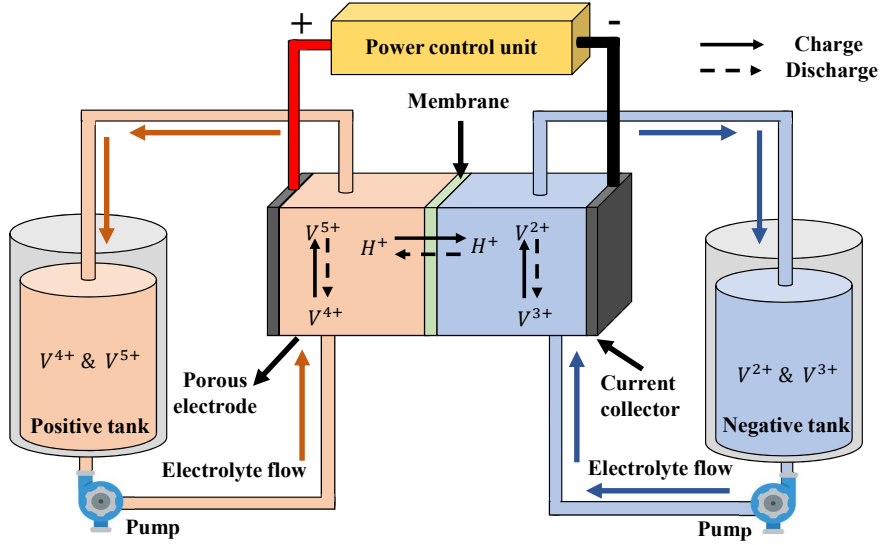
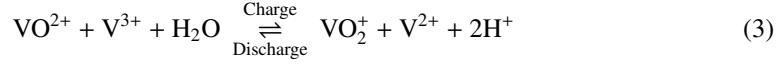


Figure 1: A schematic of a typical VRFB system showing its components and structure [12]

To comprehensively validate and analyse the performance of the proposed VRFB-BMS for an actual 5 kW VRFB system, a new and rigorously validated multi-physics model was utilised in this study for validation and in-depth analysis. This model incorporates all types of crossover and electrolyte transfer mechanisms. The basic assumptions for this model are:

- The gas evolution (hydrogen and oxygen) and membrane degradation are not considered in this study as these can be minimised by good battery design [13].
- It is assumed that the vanadium ions are perfectly mixed and uniformly distributed in the two tanks and stack [13, 14, 15].
- The stack overall resistance remains constant during the operation [14].
- The flow channel and hydraulic system of the stack are well designed and thus the effect of the shunt current is minor and can be ignored [13, 14, 15].
- The electrolyte volume difference between the half cells is caused by electrolyte transfer [12].

2.1. Mass balance model

A mass balance model is developed to simulate the vanadium ion crossover effect driven by the concentration gradient, electric field, and osmotic pressure across the membrane [12]. The

1 diffusion flux, osmotic pressure flux, and electro-migration flux are derived using the following
2 equations:

$$n_i^{diff} = k_i \frac{c_i}{D} \quad (4)$$

$$n_i^{con} = \vec{v}_m c_i \quad (5)$$

$$n_i^{mig} = \frac{z_i F}{RT} k_i c_i \nabla (\phi_{neg}^m - \phi_{pos}^m) \quad (6)$$

5 Note that n_i^{diff} , n_i^{con} and n_i^{mig} represent the diffusion fluxes, convection fluxes, and electro-
6 migration fluxes correspondingly. The overall crossover flux is given as:

$$n_i^{cross} = n_i^{diff} + n_i^{con} + n_i^{mig} \quad (7)$$

7 For the vanadium ions in the cell:

$$\frac{dc_2^s}{dt} = \frac{Q_c (c_2^t - c_2^s) \pm \frac{I}{zF} - n_2^{cross} A_m - 2n_5^{cross} A_m - n_4^{cross} A_m}{L_e W_e H_e} \quad (8)$$

$$\frac{dc_3^s}{dt} = \frac{Q_c (c_3^t - c_3^s) \mp \frac{I}{zF} - n_3^{cross} A_m + 3n_5^{cross} A_m + 2n_4^{cross} A_m}{L_e W_e H_e} \quad (9)$$

$$\frac{dc_4^s}{dt} = \frac{Q_c (c_4^t - c_4^s) \mp \frac{I}{zF} - n_4^{cross} A_m + 3n_2^{cross} A_m + 2n_3^{cross} A_m}{L_e W_e H_e} \quad (10)$$

$$\frac{dc_5^s}{dt} = \frac{Q_c (c_5^t - c_5^s) \pm \frac{I}{zF} - n_5^{cross} A_m - 2n_2^{cross} A_m - n_3^{cross} A_m}{L_e W_e H_e} \quad (11)$$

8 For the vanadium ions in the tanks:

$$(V_n + N \Delta V_n) \frac{dc_2^t}{dt} = Q_s (c_2^s - c_2^t) \quad (12)$$

$$(V_n + N \Delta V_n) \frac{dc_3^t}{dt} = Q_s (c_3^s - c_3^t) \quad (13)$$

$$(V_p + N \Delta V_p) \frac{dc_4^t}{dt} = Q_s (c_4^s - c_4^t) \quad (14)$$

$$(V_p + N \Delta V_p) \frac{dc_5^t}{dt} = Q_s (c_5^s - c_5^t) \quad (15)$$

9 Note that in Eqs. (16)-(19), the electrolyte transfer mechanism is taken into account in the
10 dynamic model, where ΔV_p and ΔV_n are the electrolyte transfer rates. Assuming an a hydraulic
11 shunt is used for electrolyte rebalancing, the vanadium ions and electrolyte volume variations in
12 the tanks during the rebalancing process are:

$$(V_n + N \Delta V_n + Q_{rb} \Delta t) \frac{dc_2^t}{dt} = Q_s (c_2^s - c_2^t) + Q_{rb} (-c_4^t - 2c_5^t) \quad (16)$$

$$(V_n + N \Delta V_n + Q_{rb} \Delta t) \frac{dc_3^t}{dt} = Q_s (c_3^s - c_3^t) + Q_{rb} (2c_4^t + 3c_5^t) \quad (17)$$

$$(V_p + N \Delta V_p - Q_{rb} \Delta t) \frac{dc_4^t}{dt} = Q_s (c_4^s - c_4^t) - Q_{rb} c_4^t \quad (18)$$

$$(V_p + N \Delta V_p - Q_{rb} \Delta t) \frac{dc_5^t}{dt} = Q_s (c_5^s - c_5^t) - Q_{rb} c_5^t \quad (19)$$

2.1.1. Electrolyte volume modelling

The continuous electrolyte transfer from the negative side to the positive side is mainly driven by osmotic pressure and ionic potential. The electrolyte velocity across the membrane driven by osmotic pressure is given by the following equation [16].

$$\vec{v}_{osmosis} = \frac{\kappa_m}{D} \cdot \frac{L_e}{2\kappa_e A_e} \cdot \left(Q_c - \frac{\mu^+}{\mu^-} Q_c \right) \quad (20)$$

Note that κ_e is the permeability of the porous electrode which is given by:

$$\kappa_e = \frac{d_f^2}{16\lambda_{KC}} \frac{\varepsilon^3}{(1 - \varepsilon)^2} \quad (21)$$

The electrolyte velocity driven by the electro-osmotic is given by [17]:

$$\vec{v}_{electro-osmosis} = -\frac{\kappa_\varphi}{\mu_w} c_f F \left(\frac{I}{\sigma_m A_m} + \phi_{diff}^m \right) \quad (22)$$

where σ_m is the conductivity of the membrane, which is given by [18]:

$$\sigma_m = \frac{F^2}{RT} \sum_i z_i^2 c_i k_i \approx \frac{F^2}{RT} c_{H^+} k_{H^+} \quad (23)$$

The effective diffusion potential ϕ_{diff}^m is given as follows [19]:

$$\phi_{diff}^m = \frac{F \sum_i z_i k_i^m \nabla c_i^m}{\sigma_m} \quad (24)$$

$$\vec{v}_m = \vec{v}_{electro-osmosis} + \vec{v}_{osmosis} \quad (25)$$

As a result, the derivation of the electrolyte volume transfer rate is given below:

$$\Delta V_n = (\vec{v}_{electro-osmosis} + \vec{v}_{osmosis}) A_m \quad (26)$$

$$\Delta V_p = -(\vec{v}_{electro-osmosis} + \vec{v}_{osmosis}) A_m \quad (27)$$

2.2. Thermal modelling

The thermal behaviour of the 5 kW/10 kWh VRFB system is modelled based on the energy conservation law presented in [10]. The model of the electrolyte temperature in the stack consid-

ers the self-discharge reactions, entropy variations, internal heat generation, and electrolyte heat exchange, and its derivation is given by:

$$C_p \rho V_s \frac{dT_s}{dt} = Q_s C_p \rho (T_p - T_s) + Q_s C_p \rho (T_n - T_s) + I^2 r_s + I T_s \frac{dE}{dT} + P_{self} \quad (28)$$

The electrolyte temperature in the positive/negative tanks can be determined from the equations:

$$C_p \rho V_p \frac{dT_p}{dt} = Q_s C_p \rho (T_s - T_p) + U_t A_t (T_{air} - T_p) \quad (29)$$

$$C_p \rho V_n \frac{dT_n}{dt} = Q_s C_p \rho (T_s - T_n) + U_t A_t (T_{air} - T_n) \quad (30)$$

Note that in this study, the minor heat friction by the electrolyte is not considered following the assumption made by Tang et al. in [8] to reduce the complexity of the thermal model. Furthermore, the difference in the electrolyte volume between the positive/negative tanks may result in a difference in the results of the electrolyte temperature in these two tanks. However, from the experimental results of Trovo et al. in [20], it can be seen that the electrolyte temperature difference between the two tanks is negligible. In this work, considering the difficulties of modelling the electrolyte heat exchange across the membrane because of the electrolyte temperature difference between the half-cells, the small volume difference between the tanks is ignored in the thermal model, which results in a uniform electrolyte thermal distribution. This assumption is reasonable considering that the 5 kW/10 kWh VRFB system used in this study has a hydraulic shunt to rebalance the electrolyte volume. This will minimise the electrolyte volume difference in the two half-systems. More details and explanations of the thermal model can be found in [10].

2.3. Electrochemical model

In this section, an electrochemical model of VRFB is developed to simulate the stack voltage performance of the 5 kW/10 kWh VRFB system. The open circuit voltage (OCV) of a single cell can be formulated as [21]:

$$E^{OCV} = E^{0'} + \frac{RT}{zF} \ln \left(\frac{c_2^s c_5^s}{c_3^s c_4^s} \right); E^{0'} = 1.40 \text{ V} \quad (31)$$

The total stack voltage can be represented as the sum of the overpotentials and the OCV, as indicated below for charging [21]:

$$E_s = N \left[E^{0'} + \frac{RT}{zF} \ln \left(\frac{c_2^s c_5^s}{c_3^s c_4^s} \right) + I r' - \frac{RT}{zF} \ln \left(1 - \frac{I}{k_m F L_e H_e c_3^s} \right) - \frac{RT}{zF} \ln \left(1 - \frac{I}{k_m F L_e H_e c_4^s} \right) \right] \quad (32)$$

The stack voltage during discharging is:

$$E_s = N \left[E^{0'} + \frac{RT}{zF} \ln \left(\frac{c_2^s c_5^s}{c_3^s c_4^s} \right) - I r' + \frac{RT}{zF} \ln \left(1 - \frac{I}{k_m F L_e H_e c_5^s} \right) + \frac{RT}{zF} \ln \left(1 - \frac{I}{k_m F L_e H_e c_2^s} \right) \right] \quad (33)$$

$$k_m = 1.6 \times 10^{-3} \left(\frac{Q_c}{10 L_e W_e} \right)^{0.4} \quad (34)$$

Note Eq. (34) is used to derive the mass transfer coefficient k_m in dm s^{-1} [12], and in this form the units for Q_c , L_e and W_e are L s^{-1} , dm and dm , correspondingly. The SOC is estimated

Table 1: Model parameters and their definitions of the 5 kW/10 kWh VRFB system [12, 22, 16, 23, 24, 25, 26]

Symbol	Definition	Value
N	Number of cells in the stack	37
c	Total concentration of vanadium ions in mol L^{-1}	1.5
V_n	Volume of the electrolyte in the negative tank in L	240
V_p	Volume of the electrolyte in the positive tank in L	240
H_e	Height of the electrode in m	0.3
L_e	Length of the electrode in m	0.7
W_e	Width of the electrode in m	2.5×10^{-3}
A_m	Membrane area in m^2	0.21
D	Thickness of the membrane in m	1.27×10^{-4}
T	Ambient temperature in K	298.15
R	Gas constant in $\text{J mol}^{-1} \text{K}^{-1}$	8.314
ρ	Electrolyte density in kg m^{-3}	1300
F	Faraday's constant in C mol^{-1}	96,485
r'	Overall cell resistance in Ω	1.3×10^{-3}
k_2	Diffusion coefficient of V^{2+} in $\text{m}^2 \text{s}^{-1}$	8.768×10^{-12}
k_3	Diffusion coefficient of V^{3+} in $\text{m}^2 \text{s}^{-1}$	3.222×10^{-12}
k_4	Diffusion coefficient of V^{4+} in $\text{m}^2 \text{s}^{-1}$	6.825×10^{-12}
k_5	Diffusion coefficient of V^{5+} in $\text{m}^2 \text{s}^{-1}$	5.897×10^{-12}
k_{H^+}	Diffusion coefficient of H^+ in $\text{m}^2 \text{s}^{-1}$	3.35×10^{-9}
A	Cross sectional area of the porous electrode in m^2	7×10^{-4}
d_f	Fibre diameter in m	1.76×10^{-5}
ε	Electrode porosity	0.93
λ_{KC}	Kozeny-Carman constant	4.28
κ_m	Membrane hydraulic permeability in m^2	2×10^{-19}
κ_φ	Membrane electro-kinetic permeability in m^2	1.13×10^{-20}
μ_w	Mean viscosity of the bulk electrolyte in $\text{Pa} \cdot \text{s}$	4.2×10^{-3}
c_f	Fixed acid concentration in mol L^{-1}	2.5
C_p	Specific heat capacity of electrolyte in $\text{J g}^{-1} \text{K}^{-1}$	3.2
A_t	Surface area of the tank in m^2	2.8
U_t	Overall heat transfer capability of the tank in $\text{J K}^{-1} \text{s}^{-1} \text{m}^{-2}$	3.67
ρ	Electrolyte density in g cm^{-3}	1.354

1 considering the imbalance between the half-systems, by the following equation [27]:

$$SOC = \min\left(\frac{c_2^t}{c_2^t + c_3^t}, \frac{c_5^t}{c_4^t + c_5^t}\right) \quad (35)$$

2 3. Model validation

3 This study uses an industrial-scale 5 kW/3 kWh VRFB system and extends into a 5 kW/10
4 kWh VRFB system for case studies and validation. This is done to verify the effectiveness of
5 VRFB-BMS in actual residential settings, as 10 kWh is a common battery size for residential
6 BESSs. Because VRFB systems allow for independent power and energy ratings, increasing the
7 rated energy can be easily accomplished by adding more electrolyte to the tanks. The schematic
8 of the original VRFB system is shown in Fig. 2 (a), where each half tank contains 70 L of
9 electrolyte from the measurement. Although the electrolyte volume in each half tank of the
10 5 kW/10 kWh system is increased to achieve higher energy capacity, other parameters of the

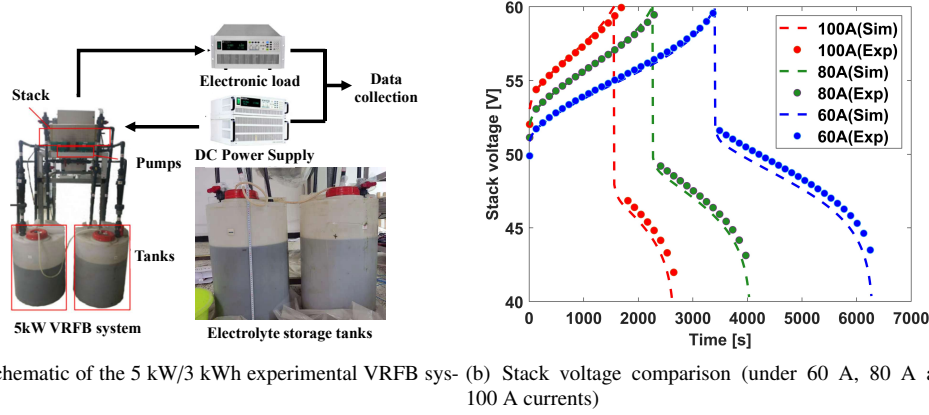


Figure 2: Schematic of the 5 kW/3 kWh experimental VRFB system and model validation results under three different currents [12]

original 5 kW/3 kWh VRFB system remain the same, as reported in Table 1. With an identical stack design, the hydraulic pressure drop and pump power consumption profile will also be consistent with those reported in [22].

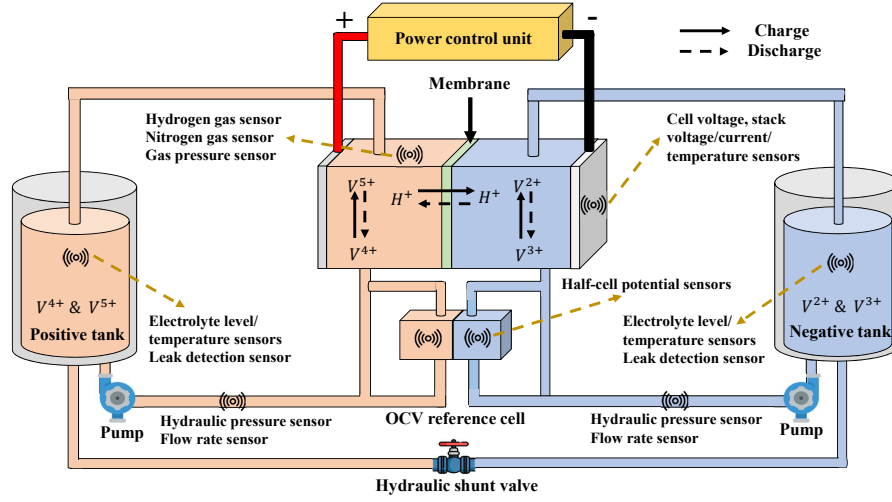
Experimental data for the initial 5 kW/3 kWh VRFB stack were obtained from a VRFB setup experiment employing LabView at a room temperature of 25°C under constant operational currents of 60 A, 80 A and 100 A [22]. The cut-off voltage limit was 40-60 V, the initial SOC in each operational current regime was 10% and the electrolyte flow rate was 1 m³/h. The data has then been used in [22] to validate the accuracy of the proposed model. Note in this study, the value of membrane hydraulic permeability is increased compared with the value in [12] to exhibit a more rapid electrolyte volume transfer rate for electrolyte volume rebalance validation in the later section. Fig. 2 (b) presents the model validation results in this work, which demonstrate accurate estimations with mean absolute error (MAE) and mean absolute percentage error (MAPE) less than 1 V and 2%, correspondingly for these three different current regimes.

4. Battery management system functionalities and design

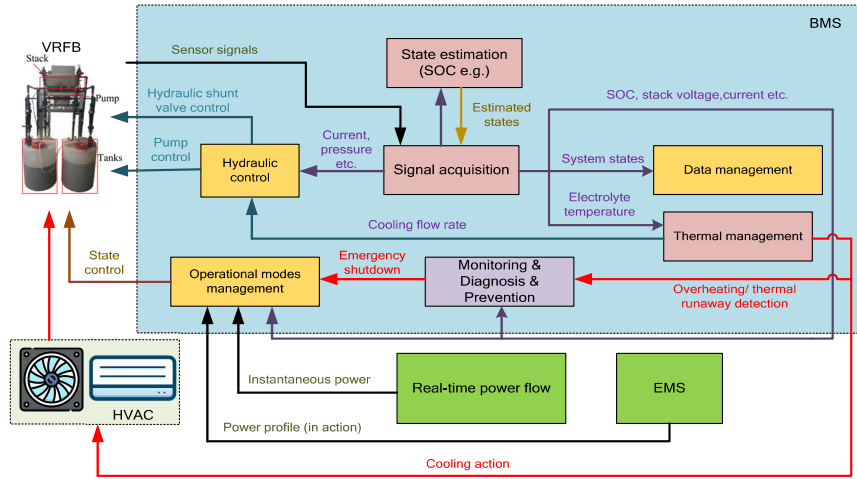
4.1. Systematic VRFB-BMS design

The primary objective of a BMS is to protect, manage and optimise battery operation to satisfy the energy demand of end users. At the same time, an efficient and functional VRFB-BMS design should avoid computationally intensive algorithms or methods to ensure rapid and cost-effective performance in industrial or commercial VRFB systems, as indicated by Trovo et al. [3].

To effectively and efficiently manage VRFBs, sensors are crucial as they offer real-time measurements of various key states, thus aiding in the monitoring and control during battery operation. In our VRFB-BMS design, we propose installing different sensors to monitor critical systems state parameters, including SOC, voltage, current, and pressure drop. The type and location of these sensors proposed to be embedded in the 5 kW/10 kWh VRFB system are shown in the schematic diagram of Fig. 3 (a). More details on the types of sensors and their functionalities



(a) The proposed location of sensors used in the VRFB system design



(b) Proposed VRFB-BMS scheme integrated within an EMS

Figure 3: The illustration of the proposed sensors placement in the VRFB-BMS design and their intended functionalities

1 in contemporary VRFB systems are given in Table 2. Building on [1], an advanced VRFB-BMS
 2 framework with seven main functionalities was proposed. This study integrates these critical
 3 functionalities into the proposed VRFB-BMS architecture, providing concrete technical speci-
 4 fications.

5 In applications such as energy arbitrage, the operational decisions of BESSs are determined
 6 by an upper-level EMS. Usually, an EMS gathers information from the current state of the power
 7 systems, e.g., electricity prices, end-user load demand, renewable energy generation, and their

Table 2: Typical sensors used in the design of a VRFB-BMS and their functionalities

Sensors	Functionality	Ref.
Stack		
Flow channel pressure drop	Measure the pressure drop in the stack	[28]
Stack voltage	Measure the overall stack voltage.	[3]
Stack current	Measure the stack current.	[3]
Stack temperature	Measure the electrolyte temperature in the stack.	[28]
Cell voltage	Measure the cell voltage.	[28]
Tanks		
Hydraulic pressure	Measure the pressure drop on the half-systems.	[3]
Flow rate	Measure the flow rates on the half-systems.	[3]
Electrolyte level	Measure the electrolyte level of the two tanks.	[3]
Electrolyte temperature	Measure the electrolyte temperature inside the two tanks.	[3]
Half-potential	Measure the half-cell potentials for SOC estimation.	[3]
Leak detection	Detect the electrolyte leakage.	[29]
Hydrogen/nitrogen gas	Detect the gas generation.	[29]
Gas pressure sensor	Measure the gas pressure.	[29]

future forecasts. Using these crucial pieces of information, typically an optimisation problem is solved, and the optimal decisions are communicated to other different system components. In the case of a BESS, the commands go through the inverter for implementation in connection with the BMS. The primary task of the BMS is to perform localised management to ensure safe and stable battery operation. Despite the predominant focus on localised online management in most current BMS designs, the emerging trend emphasises that a cooperative strategy between the BMS and an EMS can improve the economic benefits of BESSs in different applications.

A block diagram of the VRFB-BMS design with these functionalities is shown in Fig. 3 (b). As indicated in this figure, it is designed to manage and process the power schedule from the upper-level management system, while it also achieving local management in real-time operation. The primary objective of a VRFB-BMS is to detect and control operational modes according to the scheduled power profile or the real-time power flow to decide when the VRFB system should be charged, discharged, in standby mode, or shut down. During operation, the BMS in Fig. 3 first collects sensor data and processes it to estimate certain system state parameters that are not directly observable, such as SOC. The measured and estimated system states are transmitted to different functional modules via the signal acquisition unit for battery management. Note that some BMSs have a data management module to save and process historical data for analysis, and this data is typically stored in the cloud for future research and product development by the manufacturers. To avoid unnecessary complexity, we do not show the data management unit in the block diagram. The hydraulic control module and thermal management module receive these transmitted signals from the BMS to control the flow rate, rebalance the electrolytes, and detect/prevent thermal issues. Addressing issues of overheating and thermal runaway is crucial to mitigate capacity fading in VRFB systems caused by thermal precipitation. The thermal management system can effectively regulate cooling flow rates during standby periods or use the heating, ventilation, and air conditioning (HVAC) system throughout charging and discharging periods. If the monitored battery state reaches the predefined cut-off limits, the BMS will switch to standby mode to prevent overcharging or over-discharging. However, if severe incidents occur that exceed the emergency limits, the VRFB system will immediately shut down the battery. Such urgent situations may include instances of system-wide overheating or the detection of electrolyte leakage by the electrolyte level sensors.

4.2. Battery operational modes control

The switching of battery modes is the key to achieving its function based on the requirements of site operations. In Fig. 4, the systematic control of the operational mode within the BMS is presented. The VRFB system starts operation either when the scheduled start-up time is reached or through manual activation. Note that, because of the different designs of VRFB, the electrolytes in some of these VRFB systems will be stored in two separate storage tanks before shutdown. For VRFB systems with this particular design, it is necessary to have a pre-startup sequence by activating pumps on both ends to fill the stacks with electrolytes. For VRFB designs in which the electrolyte remains in the stack, it is still essential to use a high electrolyte flow rate to quickly circulate the electrolyte when a load is applied. This is designed to prevent gas evolution and other side reactions that could lead to capacity fading and subsequent issues with overcharging or over-discharging. Once the VRFB system is activated by the start command, the monitoring and surveillance systems are initialised to manage battery operation. Meanwhile, the signal acquisition and state estimation modules start to continuously monitor or estimate battery states and communicate the results to other modules for use.

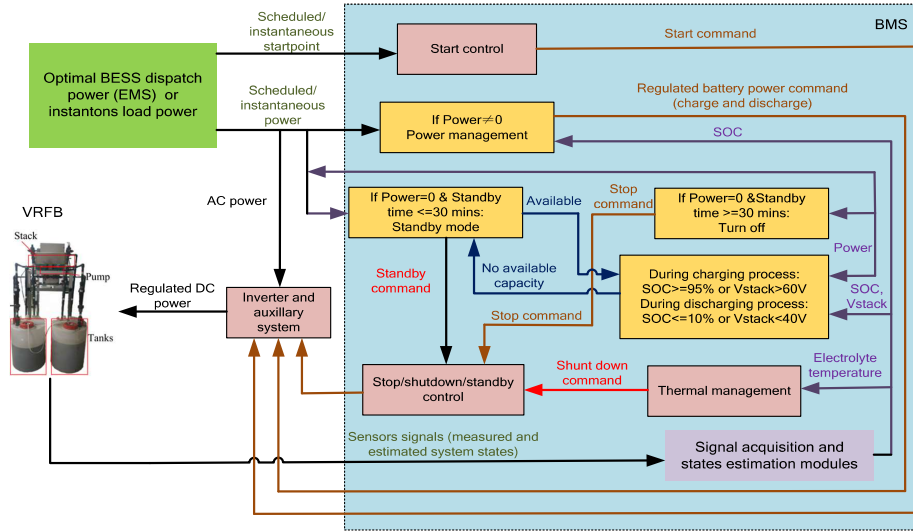


Figure 4: The mode control flow chart for the 5 kW/10 kWh VRFB system integrated with EMS or other external high-level control platforms

After the BMS is activated, the power management function begins to control the battery's operational modes in real-time. For instance, if the scheduled/instantaneous power is negative/positive/zero, the battery will go into charge/discharge/standby mode, respectively. However, due to the cut-off thresholds designed to protect the VRFB system from overcharging and over-discharging that could threaten the lifespan and thermal stability of the VRFB, the power flow will stop and the battery will go into standby mode once the stack voltage (40-60 V) and SOC (10-95%) reach cut-off limits. In this design, the BMS shuts the system down and, if appropriate, discharges the electrolytes inside the stack into separate tanks if there is a scheduled standby period of over 30 minutes. This is to avoid rapid self-discharge by the ion crossover

inside each cell. Note that the thermal management unit will shut down the VRFB system once the electrolyte temperature in the stack or tank reaches 50°C in this design.

4.3. State of charge monitoring

The SOC is a vital indicator used in the BMS to estimate the remaining battery capacity and knowledge of this parameter is critical to ensure safe and efficient battery operation [30]. In order to achieve highly accurate SOC estimation, a significant amount of effort has been focused on the development of SOC observers, mainly using the Kalman filter and its extensions. However, two significant obstacles hinder the advancement of these observer-based methods in VRFB-BMS and other BMS applications. The first obstacle is that SOC observers must be designed on a relatively accurate state-space model. However, some critical parameters in the VRFB models, such as the membrane permeability and electrode porosity dimensions, are sensitive to the operating conditions (e.g., temperature variations, degradation levels, etc.) or difficult to measure or obtain from the manufacturer's datasheets. Furthermore, SOC observers are designed based on relatively simple 0-D models without considering vanadium ion crossover mechanisms (the crossover driven by the electric field and membrane osmotic pressure) [31, 32]. As a result, they offer limited accuracy in a large number of operational cycles. Although some adaptive filters have been proposed to handle the limitations mentioned above, these advanced observer-based methods normally require substantial computational capacity, which is not available in commercial- or industrial-scale BMS systems. In conclusion, a simple and efficient method is needed to accurately estimate the remaining capacity of positive and negative half cells in VRFB systems.

Moreover, the proposed method for SOC estimation must be robust enough to mitigate electrolyte imbalances arising from extended operational periods and to accurately estimate the SOC in both the negative and positive half-cells. Currently, methods based on coulombic counting (CC) and OCV observation are the most widely used in existing BMS. In the only article that addressed VRFB-BMS [3], a simple OCV-based derivation method was used for SOC estimation, as:

$$SOC = \frac{\exp\left(\frac{zF}{2RT} (E^{OCV} - E^{0'})\right)}{1 + \exp\left(\frac{zF}{2RT} (E^{OCV} - E^{0'})\right)} \quad (36)$$

where z , F , R and T are the number of electrons transferred, Faraday's constant, gas constant and electrolyte temperature, respectively. E^{OCV} and $E^{0'}$ are the open-circuit voltage of a single cell and its equilibrium open-circuit potential (OCP) measured at 50% SOC [13]. The value of $E^{0'}$ in this study is 1.40 V, obtained from the experimental results by Li et al. [13]. This equation is based on the assumption that there is no concentration imbalance between the positive and negative sides (e.g., $SOC = SOC_n = SOC_p$). In this scenario, the Nernst equation can be formulated as follows:

$$E^{OCV} = E^{0'} + \frac{2RT}{zF} \ln\left(\frac{SOC}{1 - SOC}\right) \quad (37)$$

During the operation of the VRFB system, the imbalance of electrolyte concentration on the positive and negative sides becomes more significant. Simultaneously, the concentration of each vanadium ion on both sides tends to become more disproportional to SOC variations due to their different crossover capabilities, as indicated by the results in [33]. To overcome this problem, Corcuera et al. [34] designed a reference electrode to measure the half-cell potentials.

Later, Ngamsai et al. developed a new middle half-cell inside the conventional OCV reference cell [35]. Rigorous validations are given in [35] to highlight the feasibility of these proposed half-cell designs to measure the system imbalance. In recent studies, exemplified by the work of Li et al. [13], it is evident that the design of reference OCV half-cells has been successfully implemented in a laboratory-scale VRFB system which is a practical solution from the hardware design perspective. The open-circuit potentials for negative and positive half-cells are given below [13]:

$$E_{oc,n} = E_n^{0'} + \frac{RT}{zF} \ln \left(\frac{1 - SOC_n}{SOC_n} \right) \quad (38)$$

$$E_{oc,p} = E_p^{0'} + \frac{RT}{zF} \ln \left(\frac{1 - SOC_p}{SOC_p} \right) \quad (39)$$

where $E_{oc,n}$ and $E_{oc,p}$ are half-cell OCP for the negative/positive half-systems, and $E_n^{0'}$ and $E_p^{0'}$ are the equilibrium OCP for the negative and positive half-cells measured separately at 50% SOC [13], respectively (0.43 V and -0.97 V from [13]). As a result, the SOC of the negative and positive sides can be derived as [36]:

$$SOC_n = \frac{1}{1 + \exp \left(\frac{zF}{RT} (E_{oc,n} - E_n^{0'}) \right)} \quad (40)$$

$$SOC_p = \frac{\exp \left(\frac{zF}{RT} (E_{oc,p} - E_p^{0'}) \right)}{1 + \exp \left(\frac{zF}{RT} (E_{oc,p} - E_p^{0'}) \right)} \quad (41)$$

To validate the performance of the proposed half-cell potential for SOC estimation, an optimal BESS power profile is used, which fluctuates considerably due to load demand and rooftop solar variations. This profile is derived from real residential user data in the Australian Capital Territory (ACT), Australia [37]. The variable flow rate, which reduces overall losses, increases the complexity of the VRFB system operation. Additionally, during that day of operation, the 5 kW/10 kWh VRFB system undergoes stop, standby, charge, and discharge modes to replicate real-world conditions. The initial concentration of V^{2+} , V^{3+} , V^{4+} and V^{5+} was set to 0.2, 1.45, 1.25, 0.1 mol/L, respectively, to simulate a severe electrolyte concentration imbalance ($c^{2+} + c^{3+} \neq c^{4+} + c^{5+}$) between these two half-cells and vanadium species concentration imbalance ($\frac{c^{2+}}{c^{2+}+c^{3+}} \neq \frac{c^{5+}}{c^{4+}+c^{5+}}$) in each half-cell. The performance of the proposed method is evaluated and compared with other mainstream SOC estimation methods in the IS-VRFB system (enhanced CC [36] and full-cell potential estimation method [3]), where the results are given in Fig. 5.

As indicated in Figs. 5 (a) and (b), a varying power profile and optimised flow rates are applied to the 5 kW/10 kWh VRFB system using the proposed 0-D VRFB model in [12] to simulate on-site operation. The actual SOC is obtained using Eq. 5, which considers the concentration imbalance of vanadium species. The results in Fig. 5 (c) indicate that the proposed half-potential SOC measurement technique shows excellent accuracy in estimating the SOC of half-cells with a mean absolute percentage error (MAPE) of less than 0.6%. Moreover, the performance of two popular VRFB SOC estimation methods at the system level is shown in Fig. 5 (d). The two methods are

1. **Enhanced CC method:** Considers the charge/discharge coulombic efficiency from the CC-CV/CC tests [36, 38].

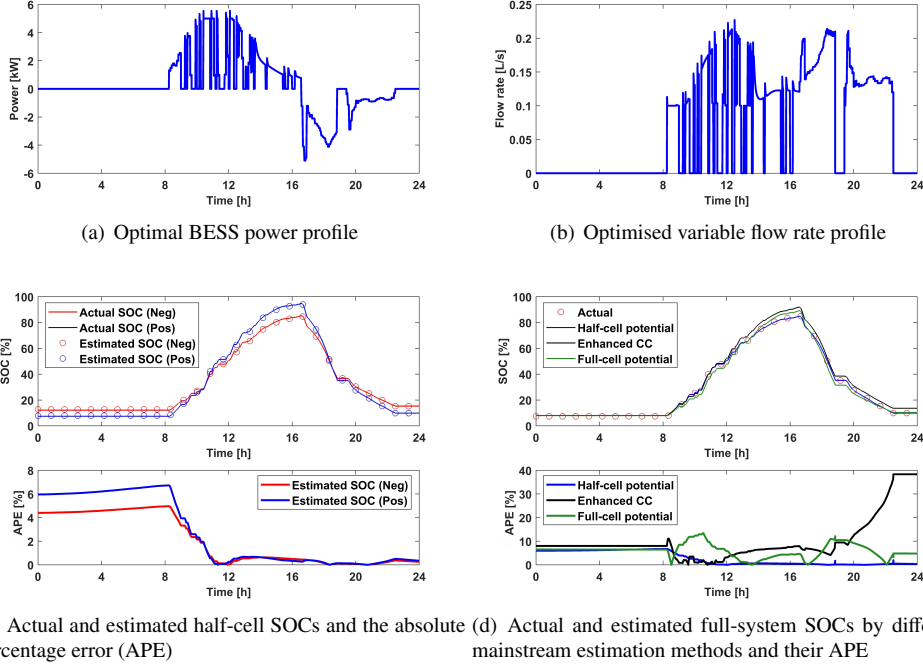


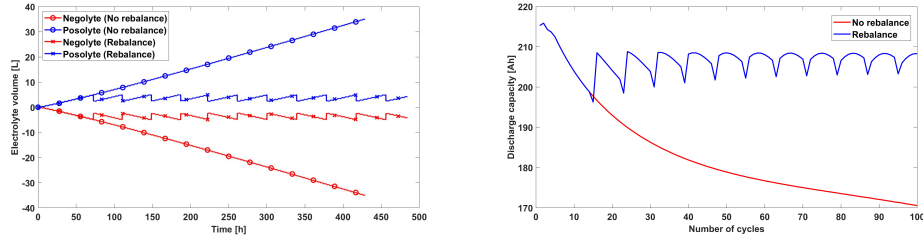
Figure 5: The performance of the proposed half-cell potential SOC measurement method and other existing methods under the varying BESS power and flow rate profiles over a day

2. **Full-cell potential method:** Another universal open-circuit potential-based method for system SOC estimation measured by the half-cell potential [3].

The results in Fig. 5 (d) show that our proposed method achieves high accuracy compared to the other two methods. The enhanced CC and full-cell potential methods neglect the dynamic ion crossover process during VRFB operation, leading to more significant errors in the SOC estimation outcomes. However, in this study, the variations of the degree of acidity or alkalinity of the electrolyte are neglected due to the relatively high concentration of hydrogen ions in the electrolyte design. For some VRFB electrolyte designs with low acid concentrations, variations in hydrogen ions may result in a lower SOC estimation accuracy using this proposed half-cell potential SOC estimation method. In this case, a more comprehensive exploration of how hydrogen ion concentration influences the cell OCV is essential. Detailed experimental analysis is required to clarify its impact, thereby enhancing the accuracy of the suggested SOC estimation technique.

4.4. Hydraulic shunt control for electrolyte rebalancing

The most competitive and attractive advantage of VRFBs compared to other battery technologies is their long life, as they have almost no degradation over 20-30 years. However, this is only achievable by preventing the oxidation and precipitation of vanadium ions in the electrolyte and ensuring the balance of positive electrolyte (posolyte) and negative electrolyte (negolyte) volumes. For industrial and commercial-scale VRFB systems, sealed tanks with gas bubbler



(a) The positive/negative electrolyte volume variation profiles

(b) The actual battery capacity during discharge

Figure 6: The half-system electrolyte volume variation and discharge capacity profile of the 5 kW/10 kWh VRFB system over 100 cycles with a constant operational current of 100 A over 100 cycles with/without automatic rebalancing using hydraulic shunt

systems are the most effective solution to significantly reduce the oxidation of vanadium species [39]. The thermal precipitation of vanadium species is less likely to occur because the electrolyte has a high tolerance to ambient temperature (around 40°C for most VRFB systems) and effective thermal management procedures are carried out to manage ambient temperature.

To restore the capacity by electrolyte volume rebalance, several practical methods have been proposed including remixing of electrolytes [40], electrolyte reflow [41], continuous electrolyte overflow [42] and hydraulic shunts [39]. The hydraulic shunt emerges as the most promising technological solution, which only requires switchable connections at the bottom of the tanks [39]. In this study, the hydraulic shunt is considered using a simple pipe connecting the two electrolyte storage tanks and an automatic valve in the pipe that is controlled by the BMS for periodic rebalancing. Considering the complexity of simulating the density of the negolyte and posolyte due to the concentration variations of different ions, simulating the hydraulic pressure at the two ends of the electrolyte feeding pipe is challenging. Therefore, in this work, it is assumed that upon valve opening, the electrolyte flow rate through the electrolyte feeding pipe is 0.1 L/s. Upon detection of a volumetric disparity exceeding 10 L by electrolyte level sensors within the tanks, the BMS automatically opens the valve in the electrolyte feeding pipe to initiate equilibrium. In contrast, when the volume differential decreases below 5 L, the automatic balancing valve will be closed. In Fig. 6, the simulated performance of the electrolyte rebalance design is given, in which a high constant pump flow rate of 0.8 L/s is used to show a more significant electrolyte volume transfer over 100 cycles. As indicated in Fig. 6 (a), the electrolyte volumes can periodically be rebalanced from the positive to the negative side. Thus, the capacity of the 5 kW/10 kWh VRFB system can be recovered compared to the results without the electrolyte shunt design, as shown in Fig. 6 (b).

4.5. Efficient and robust pump flow rate control

Dynamic control of the electrolyte flow rate is critical to improving the efficiency of VRFB systems [22]. To do so, various studies have been reported in the literature to investigate the optimal flow rates for VRFB systems. Wang et al. [1] summarised several model-based methods for optimisation of flow rates. These methods are proposed to achieve point-based or dynamic optimisation through the operation based on different local minimum searching algorithms. However, these model-based optimisation methods lack robustness which needs a highly accurate

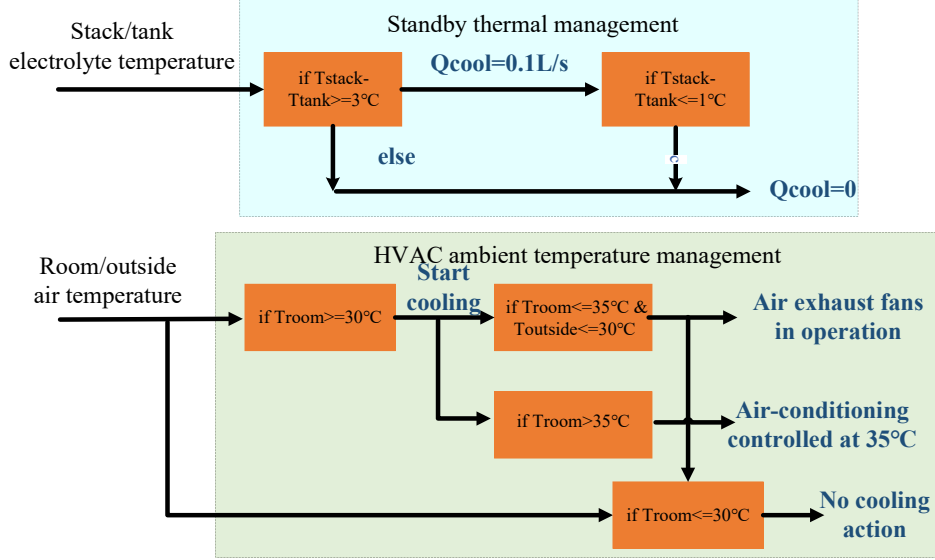


Figure 7: A conceptual thermal management design using cooling flow rate and HVAC air exchange and cooling methods

1 model to provide the state information in real-time. Most importantly, solving these dynamic
2 optimisation problems is computationally demanding, making this an impractical approach for
3 commercial-scale VRFB-BMS with constrained resources. For example, gradient-based search
4 methods and evolutionary algorithms are used to solve the optimisation problem [43, 44].

5 To overcome these issues, Wang et al. [22] proposed an approach that involves two stages.
6 In the first stage, which occurs offline, a model-based nonlinear dynamic optimisation (MNDO)
7 is solved to obtain optimal flow rate under different currents when the VRFB system is fully
8 balanced. The proposed MNDO method uses an iterative optimisation framework to find the
9 optimal flow rate at each time step. Once the optimal flow rate values are obtained, in the second
10 stage, certain solutions are chosen to generate a 2D look-up table using the cubic spline interpo-
11 lation/extrapolation technique. The look-up table is then used in the VRFB BMS for rapid and
12 accurate online flow rate control. A 100 cycles constant charge/discharge test was carried out to
13 validate the effectiveness of the proposed online flow rate control method with electrolyte imbal-
14 ance in the VRFB system. The results proved that the proposed look-up table method achieves
15 almost the same performance in reducing the overall losses of the VRFB system compared to the
16 MNDO method. Moreover, the proposed approach is more computationally efficient compared
17 to other dynamic flow rate optimisation methods without the need to have an accurate state esti-
18 mation of the VRFB system. In this study, we use the identical stack design as described in [22],
19 allowing the use of the optimal 2D look-up table in this paper. Both pumps are designed to main-
20 tain a steady flow rate of 0.4 L/s for 1 minute following the conclusion of the standby period,
21 preparing the VRFB system for charge and discharge activities. This is to provide a moderate
22 initial electrolyte flow rate to prevent overcharging/discharging issues due to the self-discharge
23 reactions that lead to low electrode surface concentration.

4.6. Thermal management

Thermal management is important in reducing the thermal precipitation of vanadium ions that causes a non-reversible capacity loss in VRFB systems. Tang et al. [8] revealed the significance of using a cooling flow rate to reduce the thermal imbalance of the electrolyte within the stack and tank due to the high heat generation from the crossover during the standby period. The electrolyte flow rate is critical for absorbing self-discharge heat because of the low heat-exchange capability of the VRFB stack. However, because of the large volume of the electrolyte in the half-system, it is not practical to cool the entire VRFB system via electrolyte circulation alone. Employing an HVAC system to maintain a cooler ambient temperature is the most feasible method for achieving adequate heat dissipation from the VRFB system through passive thermal management. Note that in most literature, the thermal precipitation threshold for the electrolyte is defined as 40°C at high SOC levels [6, 8, 10]. However, from the experimental validation results in [45], V^{5+} tends to precipitate above 35°C. In current VRFB electrolyte designs, different stabilising additives are added during the electrolyte preparation stage to increase the thermal stability of vanadium ions [46]. For commercial-scale VRFB systems, the thermal threshold is normally set to 35-50°C for ambient operating temperatures [47, 48, 49].

In this study, it is assumed that the maximum ambient temperature is 35°C to prevent the stack electrolyte temperature from reaching 40°C to have thermal precipitation [8, 14]. The thermal management strategy in this BMS design involves integrating multiple VRFB systems within a confined space, modelled after the practical example of the Roseworthy solar farm and battery at the University of Adelaide [50]. An HVAC system is integrated with the BMS to control the room temperature after measuring the room and outside air temperature using sensors. The design of the thermal management system is presented in Fig. 7. The standby thermal management is achieved using a small cooling flow rate of 0.1 L/s. If the stack and tank electrolyte temperature disparity exceeds 3°C, the cooling flow rate will start and stop only when this disparity is reduced to 1°C. The HVAC system will be activated when the room temperature exceeds 30°C. In addition, air exhaust fans are used as soon as the outside air temperature drops below 30°C. Furthermore, when the room temperature exceeds 35°C, the air conditioning system will be used to maintain the room temperature at 35°C. Once the room temperature is lower than 30°C, the exhaust fans and air conditioners will be turned off to save energy.

5. Performance of the proposed BMS

In this section, the performance evaluation of the proposed BMS design is reported based on the optimal BESS power scheduling profile using real PV/load/temperature data of several unique residential profiles from Australian Capital Territory (ACT) using the NextGen dataset [37]. The time of use (ToU) tariff and the solar feed-in tariff (FiT) are obtained from Origin Energy for the same location [51].

5.1. Case 1: A 15-day study without thermal management issues

In Case 1, the 5 kW/10 kWh VRFB system is used in residential applications to reduce the electricity costs for residents. In this study, the load demand and PV generation profiles of a single user in the ACT, Australia, during summer are considered [37]. Fig. 8 (a) illustrates the deployment of the VRFB system in a residential setting with an EMS. The consumer is connected to the grid and can purchase electricity from a retailer when needed. The EMS is assumed to have access to a perfect forecast of load demand and PV generation to determine the optimal charge

and discharge power of the VRFB system for one day ahead. The objective is to minimise the electricity cost of the consumer. The EMS design in this paper is identical to the work by Wang et al. in [52], which used a linear state of energy (SOE) model for remaining energy estimation, similar to the majority of battery energy management studies. Moreover, the EMS applied in this study bears similarity to some commercial residential EMS or smart solar inverter architectures, while necessitating minimal computational resources. The battery power of 1 kW-5 kW for charging and 0.2-5 kW for discharging, the rated energy capacity of 10 kWh and the round-trip efficiency of 70% are assumed for the VRFB system. The optimisation problem solved by the EMS is given below [52]:

$$\min \sum_{t \in \mathcal{H}} (C_t^{im} P_t^{im}) \Delta t - (C_t^{ex} P_t^{ex}) \Delta t \quad (42a)$$

$$\text{s.t. } SOE_t = SOE_{t-1} + \eta_{rt} \frac{P_t^{ch} u_t^{ch} \Delta t}{E_n} - \frac{(P_t^{dis} - P^{aux}) u_t^{dch} \Delta t}{E_n} \quad \forall t \in \mathcal{H}, \quad (42b)$$

$$SOE_0 = 10\%, \quad (42c)$$

$$SOE_{t_f} = SOE_0, \quad (42d)$$

$$0 \leq SOE_t \leq 1 \quad \forall t \in \mathcal{H}, \quad (42e)$$

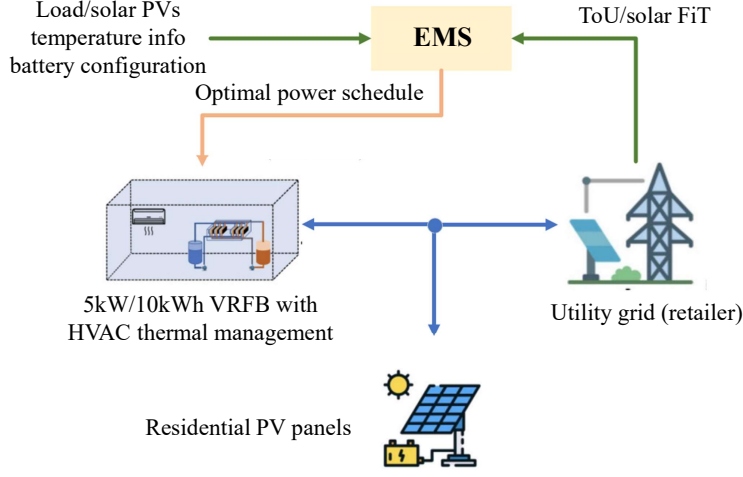
$$0 \leq u_t^{ch} + u_t^{dch} \leq 1 \quad \forall t \in \mathcal{H}, \quad (42f)$$

$$P_{min}^{ch} + P^{aux} \leq P_t^{ch} \leq \min(\alpha_{ch} + \beta_{ch} P_{max}^{ch}, P_{max}^{dch}) + P^{aux} \quad \forall t \in \mathcal{H}, \quad (42g)$$

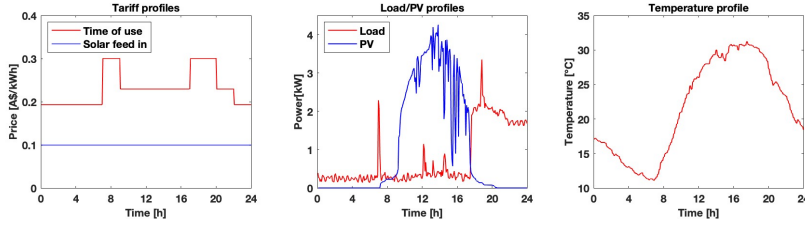
$$P_{min}^{dch} + P^{aux} \leq P_t^{dch} \leq \min(\alpha_{dch} + \beta_{dch} P_{max}^{dch}, P_{max}^{dch}) + P^{aux} \quad \forall t \in \mathcal{H}, \quad (42h)$$

$$P_t^{pv} + (P_t^{dis} - P^{aux}) u_t^{dch} \eta_{inv} - P_t^{ch} u_t^{ch} / \eta_{inv} = P_t^{ex} - P_t^{im} + P_t^{load}, \quad \forall t \in \mathcal{H} \quad (42i)$$

The definitions, values, and types of symbols in the EMS optimisation formulation are presented in Table 4 in Appendix A. The ToU tariff and solar FiT profiles, as well as sample load, PV, and temperature profiles, are shown in Fig. 8 (a) for an anonymous user. The optimal BESS power dispatch profile is obtained by solving this optimisation problem in MATLAB using the Gurobi solver [53] on a desktop with Intel^(R) Core^(TM) i7-10700 CPU @ 2.90 GHz and 16 GB RAM. Using 5 days of distinct load demand and PV generation data, the battery operation is simulated over a total of 15 days by repeating these profiles three times. This is because the original data exhibits data loss during certain complete days. Another factor contributing to this issue is that many users have minimal electricity consumption at night, rendering the battery system operation unnecessary. This situation is not ideal for demonstrating the results of BMS design. The electrolyte concentration of the VRFB system is assumed to be completely balanced. A minor imbalance in electrolyte volume (244 L in the positive tank and 236 L in the negative tank) is introduced to assess the auto-rebalancing mechanism within the BMS using a hydraulic shunt. The simulation results for battery operation are shown in Fig. 9 (a) for 15 days. The optimal values are then sent to the BMS for action, where a detailed dynamic model of VRFB is used to calculate SOC and temperature profiles. These profiles are shown in Figs. 9 (b) and (c). The results presented in Fig. 9 (c) reveal that the VRFB system rarely encounters thermal management issues. This is attributed to its effective heat exchange capability and the low heat production rate resulting from its large scale. In practical scenarios, thermal management for industrial or commercial-scale VRFB systems is generally unnecessary if the systems are not operated under intensive conditions and the ambient temperature remains below 35°C.



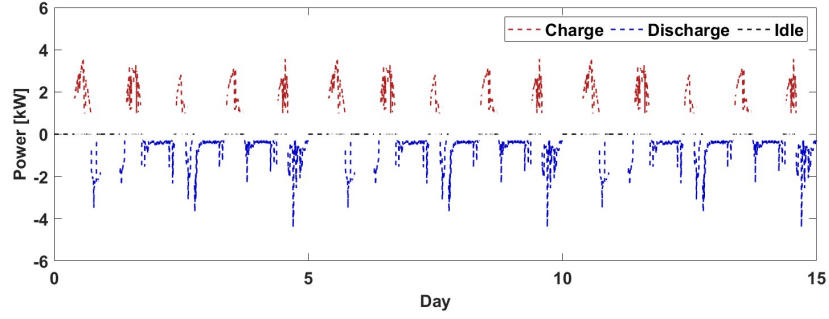
(a) The schematic of a VRFB BMS-EMS system in residential application



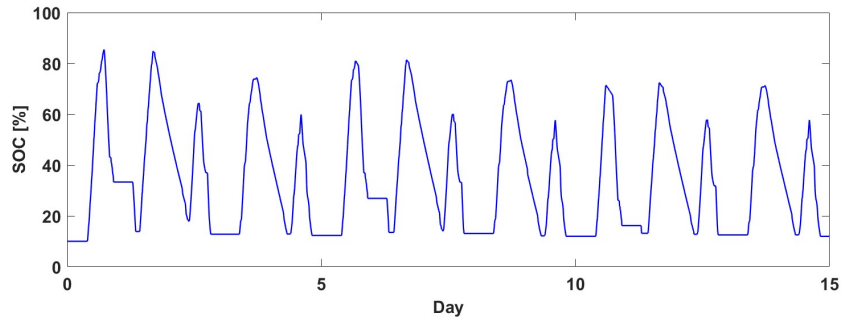
(b) Sample tariffs, load, PV, and temperature profiles for a random user

Figure 8: VRFB BMS-EMS system used in Case 1 with a sample load, PV, and temperature profiles, as well as ToU and solar FiT.

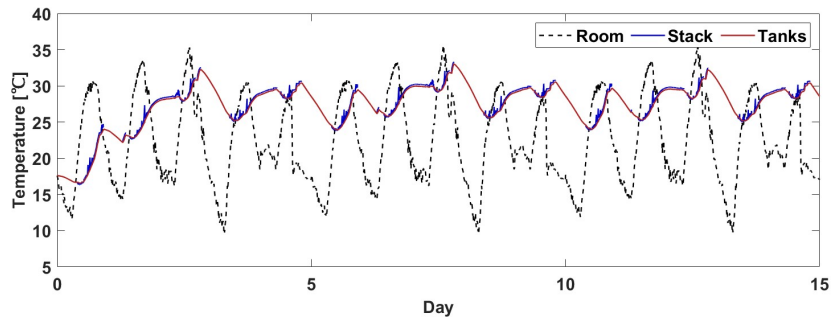
More simulation results are presented in Fig. 10 to further demonstrate the efficacy of the proposed VRFB-BMS design. Firstly, the results of automatic electrolyte rebalancing using a hydraulic shunt, shown in Fig. 10 (a), indicate that electrolyte volume rebalancing is achieved on day 9 using hydraulic shunt valve control. Secondly, the results depicted in Fig. 10 (b) reveal that the use of a simple half-cell potential method with reference cells leads to highly precise half-system SOC estimation over a 15-day simulation period. Additional results are shown in Fig. 10 (c) over the same 15-day period, assuming the VRFB system had an electrolyte imbalance issue prior to operation, as mentioned in Section 4.3. The results show that the proposed method continues to deliver exceptional performance even when the VRFB system exhibits significant imbalance issues. Most importantly, the proposed computationally efficient and robust flow rate control method achieves a significant round-trip efficiency improvement to 64.4% from 56.3% obtained with a constant flow rate of 0.4 L/s.



(a) The battery power profile (positive values represent charging)



(b) The system SOC profile

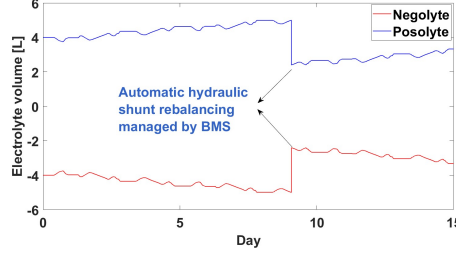


(c) Electrolyte thermal dynamics and ambient temperature profiles

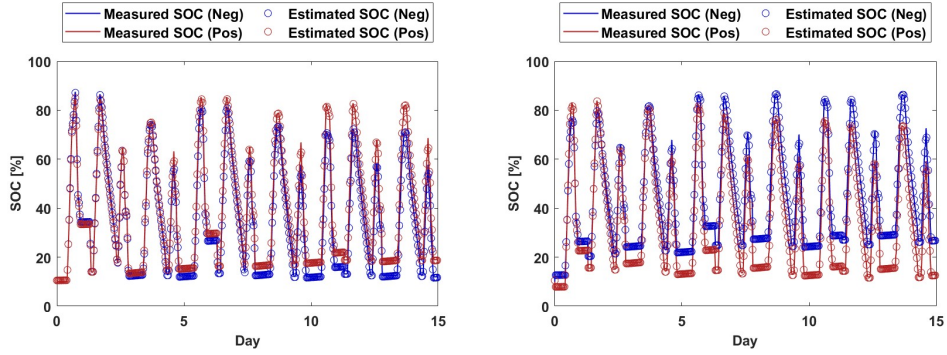
Figure 9: The power profile, system SOC and temperature profiles of the 5 kW/10 kWh VRFB system over 15 days

5.2. Case 2: A 15-day test using real residential profiles with thermal management issues

In the simulation study presented in Section 5.1, there are no problems related to thermal management because the ambient temperature remains within acceptable limits. However, when the VRFB system is placed in an environment with limited heat exchange capacity and added heat produced by the pump and inverter, the room temperature is likely to exceed the acceptable limits. This could be exacerbated by hot summer days in many places and areas close to the equatorial with high solar radiation rates, where the inside temperature can easily exceed 35°C.



(a) Electrolyte volume variations over the half-systems (assume a 8 L electrolyte volume imbalance occurred in day 1)



(b) Half-system SOC profiles assumed the system concentration is fully balanced (c) Half-system SOC profiles assumed the system concentration is not balanced as the case in Section 4.3

Figure 10: The electrolyte volume and half-system SOC profiles over 15 days of simulation

As a result, active cooling using an HVAC system is necessary to guarantee effective thermal management. This section presents the results of a simulation aimed at validating the proposed thermal management approach using an HVAC system. It assumes that the outside air temperature oscillates between 25°C and 40°C in a sinusoidal pattern, as described in [10], to model the uninterrupted operation of a single VRFB system over a span of 15 days, as detailed below:

$$T_{\text{air}} = (T_{\text{max}} - T_{\text{min}}) \cdot \sin^2(\omega t + \varphi) + T_{\text{min}} \quad (43)$$

where T_{min} and T_{max} are the minimum/maximum ambient air temperature within a day. ω and φ are the angular frequency and phase in rad/s and rad, respectively. Moreover, the 5 kW/10 kWh VRFB system will continue to operate in standby mode when there is no power applied to simulate the rapid rise in stack electrolyte temperature. In this case, the 5 kW/10 kWh VRFB system is installed in a small room with a dimension of 5 m × 4 m × 3 m. In addition, it is assumed that 5% of the inverter's power losses and 20% of the hydraulic pump's power losses from their electric circuits contribute to heat generation. The air mass flow through the air exhaust fan is 0.90 kg s⁻¹, and the exhaust fan power consumption is 140 W. The formulation of the room temperature model and the power consumption of the air-conditioning system is extended based

on the model from [10]:

$$\frac{d\dot{Q}_{cool}}{dt} = (T_{room} - T_{out}) \cdot M_{fan} \cdot C_{air} + \frac{d\dot{Q}_{ac}}{dt} \quad (44)$$

$$\frac{d\dot{Q}_{loss}}{dt} = (T_{out} - T_{room}) \cdot h \cdot A_{wall} \quad (45)$$

$$\frac{dT_{room}}{dt} = \frac{1}{M_{air} \cdot C_{air}} \cdot \left(\frac{d\dot{Q}_{loss}}{dt} + \frac{d\dot{Q}_{heat}}{dt} - \frac{d\dot{Q}_{cool}}{dt} \right) \quad (46)$$

$$\frac{d\dot{Q}_{heat}}{dt} = (T_n + T_p - 2 \cdot T_{room}) \cdot U_t \cdot A_t + \alpha_{pump} \cdot P_{pump} + \alpha_{inv} \cdot P_{VRFB} \quad (47)$$

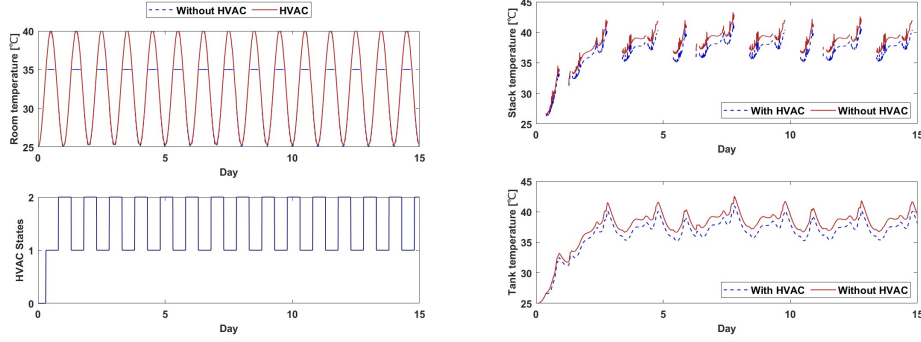
$$P_{ac} = \frac{d\dot{Q}_{ac}}{dt} / EER \quad (48)$$

Table 3: Parameters specifications of the room thermal model

Symbol	Definition	Value
A_{wall}	Total surface of walls in m^2	94
h	Heat transfer coefficient of concrete in $W m^{-2} K^{-1}$	5.32
M_{fan}	Air mass flow through fan in $kg s^{-1}$	0.90
C_{air}	Heat capacity of air in $J kg^{-1} K^{-1}$	1020
α_{pump}	Heat loss percentage during pump operation in %	20
α_{inv}	Heat loss percentage during inverter operation in %	5
M_{air}	Air mass inside the room in kg	77
EER	Energy efficiency ratio	3

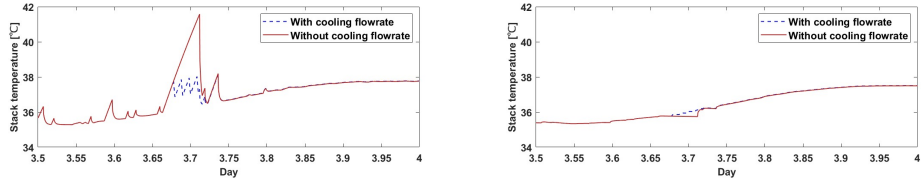
Note the parameters specifications of the room thermal model are given in Table 3. Figs. 11 (a) and (b) illustrate the simulation results for 15 days with and without the proposed thermal management scheme using an HVAC. In particular, Fig. 11 (a) clearly shows that employing HVAC keeps the maximum room temperature at 35°C, meeting the thermal management goal. The design of the individual operation using air exhaust fans is to ensure that the outside air temperature is adequate to provide heat exchange through the ventilation operation as the results given in Fig. 11 (a). For example, the air exhaust fan operates when the outside air temperature is below 30°C, and the air-conditioning is designed to regulate the temperature inside the battery room once the internal air temperature exceeds 35°C in the absence of enough cooling capacity. Further results in Fig. 11 (b) indicate that room temperature control is effective in decreasing the electrolyte temperature in the stack and tank to prevent the electrolyte temperature from being exposed above the thermal precipitation limit (40°C) for a long period of up to 3 hours. The power usage for a 15-day period is approximately 103.5 kWh, demonstrating the efficiency of the thermal management design in conserving energy.

More results are shown in Figs. 11 (c) and (d) to demonstrate the effectiveness of using a cooling flow rate in reducing the accumulated crossover heat inside the stack. In Fig. 11 (c), rapid reductions in stack electrolyte temperature to prevent overheating that could cause thermal precipitation can be observed on the third day during the standby period to prevent overheating that can cause thermal precipitation. However, the cooling flow rate cannot improve the overall heat exchange capacity of the entire VRFB system. The results presented in Fig. 11 (d) reveal that there is negligible variation in the tank electrolyte temperature, underscoring the critical role



(a) The room temperature and HVAC status profiles over 15 days with and without HVAC operation for thermal management (HVAC status: 1 stands for air-conditioning operation and 2 stands for ventilation operation by using air exhaust fans)

(b) The stack and tank electrolyte temperature profiles over 15 days with and without HVAC operation for thermal management



(c) The stack electrolyte temperature profiles in a day with and without cooling flowrate

(d) The tank electrolyte temperature profiles in a day with and without cooling flowrate

Figure 11: Temperature and HVAC system operational profiles for a single 5 kW/10 kWh VRFB system inside a small room

of HVAC operation in the regulation of room air temperature.

6. Conclusion

In this paper, an advanced VRFB-BMS scheme is designed and validated using a newly proposed zero-dimensional model that incorporates all vanadium ion crossover and electrolyte transfer mechanisms. Additionally, a genuine 5 kW VRFB stack design is employed in the model development, and several case studies are provided next. Detailed explanations are subsequently provided to illustrate the BMS scheme design in terms of operational mode control, hydraulic regulation, SOC estimation, and thermal management. In this study, real residential user profiles are used to validate the design of the VRFB-BMS to accurately estimate SOC, and to perform operational mode control, capacity recovery, auxiliary energy savings, and thermal management. The key findings of this paper are:

- An efficient and practical VRFB-BMS has been developed that can be integrated with an EMS to meet economic and various other objectives for users.

- 1 • A highly accurate SOC estimation method is proposed and comprehensively evaluated
2 in comparison with other mainstream methods. Effective and efficient hydraulic control
3 methods are proposed to achieve energy saving and capacity recovery.
- 4 • This study suggests that an effective design would include a hybrid thermal management
5 system that combines electrolyte circulation with an HVAC system to effectively manage
6 thermal conditions and reduce capacity loss.
- 7 • Long-term operational simulations over 15 days are conducted for further validations. En-
8 ergy savings and thermal management performance are reported using the proposed ad-
9 vanced VRFB-BMS design.

10 For future work, an in-depth analysis of the precipitation level of different vanadium species
11 is crucial to designing a more sophisticated thermal management system that can help reduce
12 HVAC energy consumption considering different designs of the VRFB system and its long-term
13 impact. Additional evaluation of hydraulic flow rate control is necessary to avoid overpressure on
14 the membrane that could cause damage. Furthermore, the selection of sensor configurations in
15 the advanced VRFB-BMS design requires in-depth cost-benefit analysis to balance the accuracy
16 and cost requirements in industrial and commercial applications. Above all, it would be valuable
17 to implement this advanced VRFB-BMS scheme design on the hardware for better assessment
18 and model refinement.

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25 **Declaration of Generative AI and AI-assisted technologies in the writing process**

26 During the preparation of this work, the authors used Writefull/Grammarly for grammar
27 checking. After using these tools, the authors reviewed and edited the content as needed and take
28 full responsibility for the content of the publication.

29 **CRedit authorship contribution statement**

30 **Hao Wang:** Conceptualization, Investigation, Methodology, Software, Validation, Formal
31 analysis, Writing – original draft, Writing – review & editing, Visualization. **S. Ali Pour-**
32 **mousavi:** Conceptualization, Writing – review & editing, Supervision, Project administration.
33 **Wen L. Soong:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Xi-**
34 **nan Zhang:** Writing – review & editing, Methodology, Supervision. **Aleksandar N. Nikoloski:**
35 Writing – review & editing, Methodology. **Nesimi Ertugrul:** Writing – review & editing.

1 Appendix A:

Table 4: The definition of symbols, their value and type in the HEMS formulation for optimal energy dispatch of the 5 kW/10 kWh VRFB system [52] (The DV in the table stands for decision variable and the coefficients for battery charging/discharging power regulation are designed to fully charge or discharge the VRFB system)

Symbol	Definition	Type
C_t^{im}	Cost of imported electricity at timestep t (Time of use tariff in A\$/kWh)	Variable
C_t^{ex}	Revenue of exported electricity to the grid at timestep t (Solar feed-in tariff in A\$/kWh)	Variable
P_t^{im}	Residential imported power from the grid at timestep t in kW	Real number DV
P_t^{ex}	Residential exported power to the grid at timestep t in kW	Real number DV
SOE_t	Estimated remaining energy in the battery at timestep t in %	Variable
u_t^{ch}	Battery status indicator during charging at timestep t (1: in charging, 0: idle)	Binary DV
u_t^{dch}	Battery status indicator during discharging at timestep t (1: in discharging, 0: idle)	Binary DV
P_t^{ch}	Battery charge power at timestep t in kW	Real number DV
P_t^{dch}	Battery discharge power at timestep t in kW	Real number DV
P_t^{pv}	PV power generation at timestep t in kW	Variable
P_t^{load}	Load power at timestep t in kW	Variable
P_{min}^{ch}	Minimum charge power (1 kW)	Constant
P_{min}^{dch}	Minimum discharge power (0.2 kW)	Constant
P_{max}^{ch}	Maximum charge power (5 kW)	Constant
P_{max}^{dch}	Maximum discharge power (5 kW)	Constant
P_{aux}	Auxiliary power of the VRFB (0.1 kW)	Constant
α^{ch}	Coefficient in Eq. (42g) for battery charging power regulation (10 kW)	Constant
β^{ch}	Coefficient in Eq. (42g) for battery charging power regulation (-9 kW)	Constant
α^{dch}	Coefficient in Eq. (42h) for battery discharging power regulation (1 kW)	Constant
β^{dch}	Coefficient in Eq. (42h) for battery discharging power regulation (6 kW)	Constant
E_n	Nominal (rated) energy capacity of the VRFB system (10 kWh)	Constant
SOE_{min}	Minimum SOE level during the operation (0)	Constant
SOE_{max}	Maximum SOE level during the operation (100%)	Constant
η_{inv}	DC-AC Inverter/AC-DC battery charger efficiency (95%)	Constant
η_{rt}	Round-trip efficiency of the 5 kW/10 kWh VRFB system (70%)	Constant

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