Advanced Battery Management System for Standalone VRFB Applications

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***Abstract*-- The rapid increasing of renewable energy installations across the globe demands the integration of a reliable storage technology like vanadium redox flow battery (VRFB) for stationary applications. Due to the inherent advantages like ultra-long life (>10,000 cycles), great depth of discharge and excellent recyclability, VRFB still outperforms its storage alternatives. Effective utilization of the VRFB for a commercial application necessitates the integration of a dedicated battery management system (BMS). Majority of the existing BMS for conventional batteries are incompatible for the flow batteries, resulting in the deterioration of the battery performance and lifetime. In this context, the current study presents a simple and cost-effective BMS to interface with a given VRFB for standalone usage. The BMS consists of an integrated online monitoring [IoT based] and protection system that supervise and control the battery in the optimal range. The simulation and hardware results depict the effectiveness of the designed BMS over a wide operating range.**

***Index Terms*--Battery state estimation, BMS, DC-DC converter, IoT, Power electronics, Renewable energy storage, VRFB.**

I. Introduction

Renewable energy is a crucial component in creating a more sustainable future. It provides a clean and renewable alternative to fossil fuels. To integrate sustainable energy into the grid, energy storage is essential to ensure excess energy generated from renewable sources can be stored and used as needed [1]. Among the various types of energy storage, batteries play a crucial role. Researchers have been continuously improving battery technology and performance to meet the increasing demand for renewable energy [2].

The integration of renewable energy sources into the grid requires energy storage systems to balance supply and demand. Lithium-ion batteries are currently the most widely used battery technology, offering high energy density, long cycle life, and low self-discharge rates [4] [5]. However, safety and environmental concerns related to their use of toxic materials and the potential for thermal runaway have led to the development of alternative battery technologies such as flow batteries and lead-acid batteries [6].

Flow batteries are scalable and offer advantages such as long cycle life and safety, making them suitable for large-scale energy storage applications [7]. Research and development in energy storage technologies continue to advance, leading to improved battery technology and performance [8].

A. Vanadium Redox Flow Battery

The VRFB was initially developed in the late 1980s by Professor Maria Skyllas-Kazacos and her team [9]. Since then, VRFB technology has undergone continuous improvement, making it increasingly suitable for large-scale energy storage applications. In a VRFB, energy is stored in two solutions of chemically active species, each held in separate tanks, while electricity is generated in a separate device where electrochemical reactions occur. This separation of energy storage and electricity generation provides several advantages over traditional battery technologies [10]. Significant benefits of VRFBs are their scalability. The power output of a VRFB can be increased simply by adding more cells to the electrochemical stack. Additionally, the energy storage capacity can be increased by using larger tanks to store more electrolyte solution. As a result, VRFBs are suitable for a wide range of applications, from small-scale residential energy storage to large-scale grid-level applications [11]. Another significant advantage of VRFBs is their ability to provide long-duration energy storage. Since the electrolyte solution is stored in separate tanks, the energy capacity of a VRFB can be easily scaled up without affecting the power output [12]. This makes VRFBs ideal for storing energy from sources such as solar and wind, which have intermittent power output [13].

In a VRFB, energy is stored in two separate electrolyte solutions containing vanadium ions with different valence states. The two solutions are kept in separate tanks and are circulated through the electrochemical stack via a pumping system [14]. Reaction while charging and discharging is shown in (1),(2) and (3).

$$\textbf{Anode} \quad V^{3+} + e^- \underset{Discharging}{\overset{Charging}{\rightleftarrows}} V^{2+} \qquad E^0=-0.25V \tag{1}$$

$$\textbf{Cathode} \quad VO^{2+} + H_2O \underset{Discharging}{\overset{Charging}{\rightleftarrows}} VO_2^+ + 2H^+ + e^- \qquad E^0=1.00V \tag{2}$$

$$\textbf{Overall} \quad VO^{2+} + H_2O + V^{3+} + \underset{Discharging}{\overset{Charging}{\rightleftarrows}} VO_2^+ + 2H^+ + V^{2+} \qquad E^0=1.25V \tag{3}$$

The flow of the electrolyte solutions through the stack is regulated to maintain a constant voltage and current output. Since the vanadium ions are dissolved in a liquid electrolyte, the amount of stored energy can be easily increased by adding more electrolyte solution to the tanks [15], making VRFBs an ideal solution for large-scale energy storage applications. A typical single-cell VRFB is shown in Fig. 1.

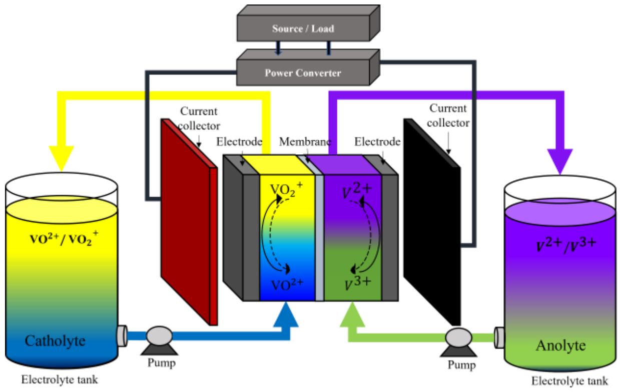

Fig. 1. Single cell vanadium redox flow battery

However, ensuring efficient and reliable VRFB operation requires integration of a dedicated BMS [16]. In addition to monitoring and protection, a VRFB BMS must accurately estimate the battery's SoC and control the battery's charge/discharge process to prevent overcharging or over-discharging, which could significantly affect the battery's lifespan and performance [17]. Furthermore, since VRFB can operate under a wide range of temperatures and current densities, the BMS must be capable of monitoring and controlling the battery under these varying conditions. The complex and dynamic behavior of VRFB poses unique challenges for BMS design.

B. *Conventional Battery Management System*

Conventional BMS are designed to ensure that batteries are charged and discharged within safe limits. They monitor the battery's SoC, voltage, and temperature to optimize performance and ensure safety [18]. BMS for conventional batteries is usually equipped with voltage and temperature

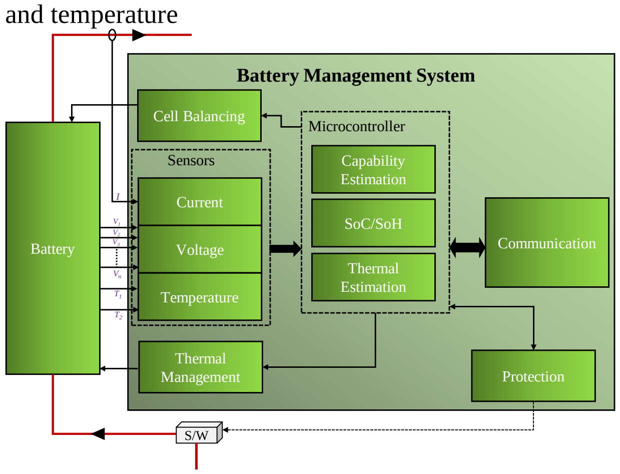

Fig. 2. Conventional battery management system

sensors, charge, and discharge control circuits, as well as communication and protection circuits (Fig. 2) [19]. The voltage sensor measures the battery voltage and controls the charging and discharging process to avoid overcharging and over-discharging, which can damage the battery. The temperature sensor measures the temperature of the battery to prevent overheating, which can cause thermal runaway and fire [20]. The BMS also has communication and protection circuits that allow the user to monitor the battery's performance and protect it from overcurrent, overvoltage, and short circuits [21].

II. ARCHITECTURE

As mentioned earlier complex and dynamic behavior of VRFB poses unique challenges for BMS design. In this section, advance BMS is proposed, a comprehensive description of the design of each part of the proposed BMS and the corresponding battery specifications are presented.

A. *Proposed Battery Management System*

In the case of VRFBs, the BMS unit plays a critical role in maintaining the battery's SoC and preventing any chemical imbalances that can damage the battery. Unlike conventional batteries, VRFBs store energy in two separate electrolyte solutions that are pumped through a series of cells to generate electricity. The VRFB BMS unit is designed to monitor the voltage and current flowing through each cell, ensuring that they are operating within safe limits. It also controls the flow rate of the electrolytes, ensuring that the battery remains in a SoC and preventing any chemical imbalances. Additionally, the BMS unit is capable of detecting any faults or anomalies in the system and alerting the user to take appropriate action. The VRFB BMS unit's real-time data monitoring and predictive analytics capabilities enable the users to optimize the battery's performance and extend its lifespan. This making it a crucial component in the integration of VRFBs into the grid. The overview of proposed BMS for VRFB is shown in Fig. 3.

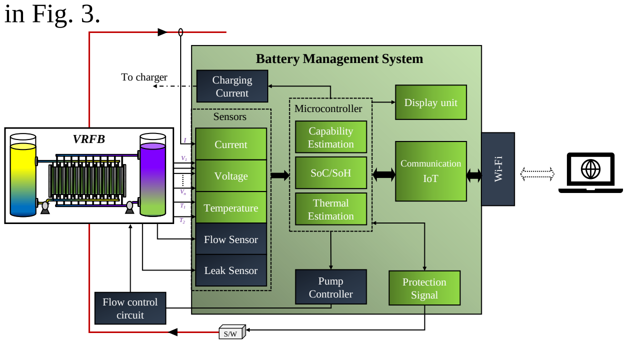

Fig. 3. Proposed BMS block diagram for VRFB

In addition, VRFBs eliminate the need for cell balancing due to their utilization of a solitary electrolyte solution, which is circulated through two half-cells separated by a membrane. This constant circulation and mixing of the electrolyte solution facilitate the homogenization of the vanadium ion concentration in the solution. Thus, cell balancing technique is not required in BMS for VRFB.

B. *Sensors and Microcontroller*

The voltage is sensed using optically isolated amplifiers, followed by an op-amp-based differential amplifier with an RC filter to reduce noise. The current is detected through the application of ACPL7195 fully integrated Hall-effect-based isolated linear current sensors that are specifically for sensing AC or DC current. A ±50A DC current is measured by the current sensor. The temperature is measured using DS18B20 and it is connected to the electrolyte tank. DS18B20 has a sensing temperature range of -55°C to +125°C. A leakage sensor is attached to the basement where the battery, electrolyte tank, and pump are located. If a leakage is detected, 5V will be applied to the ADC pin of the microcontroller, which will then turn off the relay and notify the user.

The PIC18F4550 is a versatile and low-cost microcontroller that offers a wide range of connectivity options and peripherals for embedded applications. Its low power consumption, integrated oscillator, and clocking options make it an efficient choice for controlling battery-powered and portable devices.

C. Electrolyte Flow Controller

Flow control of a VRFB can be achieved using Sinusoidal Pulse Width Modulation (SPWM) based inverter [22]. The SPWM is a commonly used modulation technique that can effectively control the speed of the pump. This modulation technique generates a series of voltage pulses with varying widths to control the flow rate of the electrolyte. The SPWM technique provides a high level of accuracy in regulating the electrolyte flow and also improves the efficiency of the VRFB.

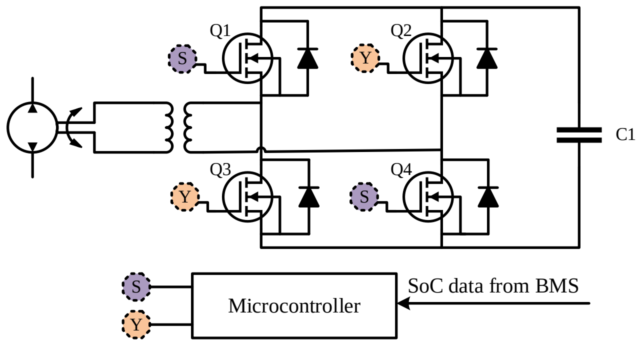

Fig. 4. Full bridge inverter for pump control

To control the pump flow rate in the VRFB system, a sinusoidal pulse width modulation (SPWM) based inverter employing a voltage control method was used. The modulation index of SPWM was varied to adjust the terminal voltage and, consequently, the flow rate of the pump. The two 40W induction motor-based pump is used to control the flow of electrolyte. The resulting data was arranged into a lookup table and programmed into PIC18F4550 microcontroller that could vary the pump flow rate based on the SoC. The full bridge inverter for pump flow control is shown in Fig. 4. The stoichiometric factor (*SF*), which is used to calculate the pump flow rate, is determined by the current (*I*) and the concentration of vanadium ions (*C*), which is fixed at 1.5M. The Faraday constant (F), which has a value of 96485 C/mol, is also included in the calculation, as demonstrated in (4).

$$Flow\ (Q) = \frac{SF \cdot I}{C \cdot F} \tag{4}$$

D. Internet of Things

Incorporating IoT-based microcontrollers can assist in monitoring standalone VRFB systems deployed in remote areas on a regular basis. VRFB batteries are utilized in a variety of applications, including household energy storage, telecom towers etc. Continuously monitoring the battery's parameters is necessary to ensure optimal performance. With the assistance of IoT-based microcontrollers, real-time data monitoring and cloud platform updating can be facilitated, allowing remote access to critical performance metrics and early detection of system faults. This results in prompt corrective actions. Overall, the utilization of IoT-based microcontrollers can enhance VRFB system efficiency and reliability, making them a more viable energy storage option. ESP32 based microcontroller board having Wi-Fi feature is used in this project.

E. Control Architecture

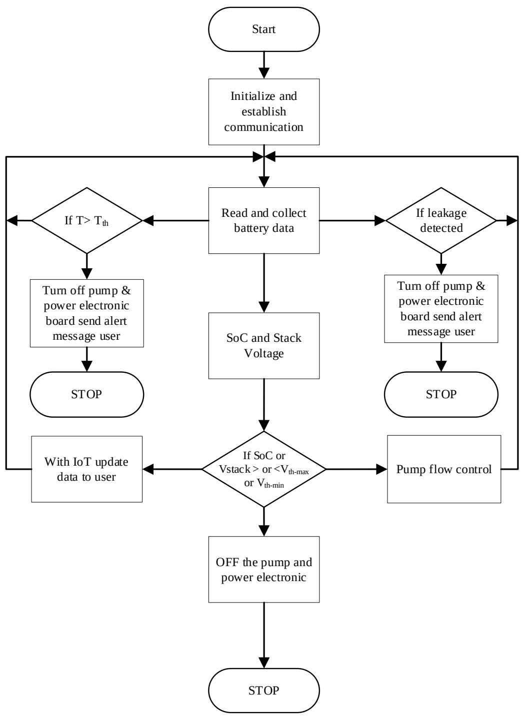

Fig. 5. Flow chart for the proposed BMS

The proposed BMS flow chart is shown in Fig. 5. The overall system is initialized and communication with the VRFB is established. Battery data, such as voltage, current, temperature, and SoC, is collected and analyzed. The battery's performance is compared to pre-determined thresholds, and maintenance procedures are activated if necessary. Battery data and performance trends are recorded for future reference. These steps are repeated at regular intervals.

F. State of Charge Estimation

In the current state of research, multiple techniques have been investigated to determine the state-of-charge of VRFB electrolyte (SoC_e). These techniques include the usage of an equivalent circuit modeling approach or the physical properties of the electrolyte, such as viscosity, potential, among others. The SoC_e can be expressed mathematically using (5).

$$SoC_e = \frac{C_{VO_2^+}}{C_{VO_2^+} + C_{VO^{2+}}} = \frac{C_{V^{2+}}}{C_{V^{2+}} + C_{V^{3+}}} \tag{5}$$

$$SoC_e = \frac{e^{19.34(OCV-\alpha)}}{1+e^{19.34(OCV-\alpha)}} \quad (6)$$

By applying the Nernst equation to the reaction in (3), a mathematical relationship between the open circuit voltage (OCV) and SoC_e was derived using (6), where α signifies the formal potential. Furthermore, the OCV of known SoCe solutions was experimentally determined utilizing the SoC cell, and this data was fitted into (6), with α=1.375 [11] as the resultant fitted parameter.

G. *Battery Specifications*

The VRFB stack used in the study consisted of ten cells, with each cell featuring an active area of 228 cm^2, graphite felt electrodes treated with sulfuric acid, and a Nafion 117 membrane separator sourced from DuPont (USA). The stack's electrolyte solution was composed of 1.5 M total vanadium with 4 M total sulfate, which were continuously circulated between the stack and the electrolyte tanks using flow-controlled pumps.

III. REALIZATION AND EXPERIMENTAL RESULTS

The proposed VRFB BMS and the realization of the experiment is tested using 500W hardware setup as shown in Fig. 6. The proposed BMS included additional sensors, such as a leak sensor and an overflow sensor, along with pump control based on SoC and charging current. Insufficient charging current and flow rate could degrade the battery's graphite felt. The system updated data and alert messages to the user and automatically shut down in case of a fault or an undesirable condition. The cut-off window for voltage, current, and temperature, as well as the controller designed for electrolyte flow, all these significantly influenced the VRFB performance.

In detail, if any malfunction occurs, the BMS issues a control signal to the relay, which turns off the pumps, power converters and an alert mail will send to the registered account. If the SoC reaches 100%, the BMS turns off the charger, and the discharge circuit gets activated. If the SoC is below 10% the battery charger circuit get activated. In Fig. 7, the blue dot represents the cutoff point based on battery SoC and shows the measurement of charging voltage and current obtained using the BMS. During the charging process, the battery is charged at a constant current of 8A, and the voltage is regulated to remain within the range of 9V to 17V.

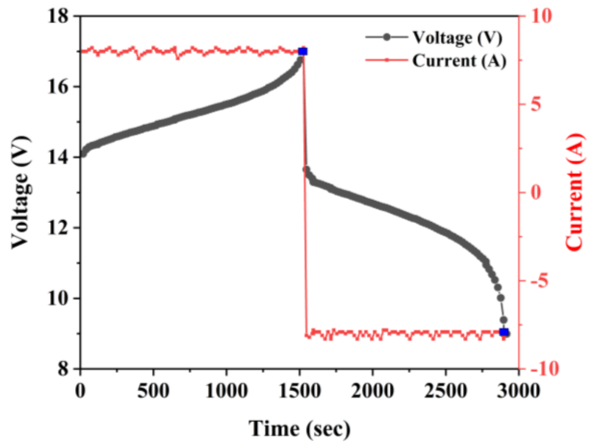

Fig. 7. Battery charging and discharging controlled using BMS

The battery is charged and discharged using a bidirectional synchronous buck-boost converter. During the charging process, the converter operates in buck mode and regulates a constant current of 8A. Conversely, during discharging, the DC-DC converter functions as a boost converter and maintains a regulated output voltage of 24V. The flow rate is regulated by referring to the lookup table that is based on the SoC of the battery.

To establish an appropriate relationship between the flow rate and SoC of the battery, we assessed various flow rates at a fixed current for a single cell. According to the results, the battery's coulombic variation, voltage, and energy efficiencies exhibited an increasing trend as the

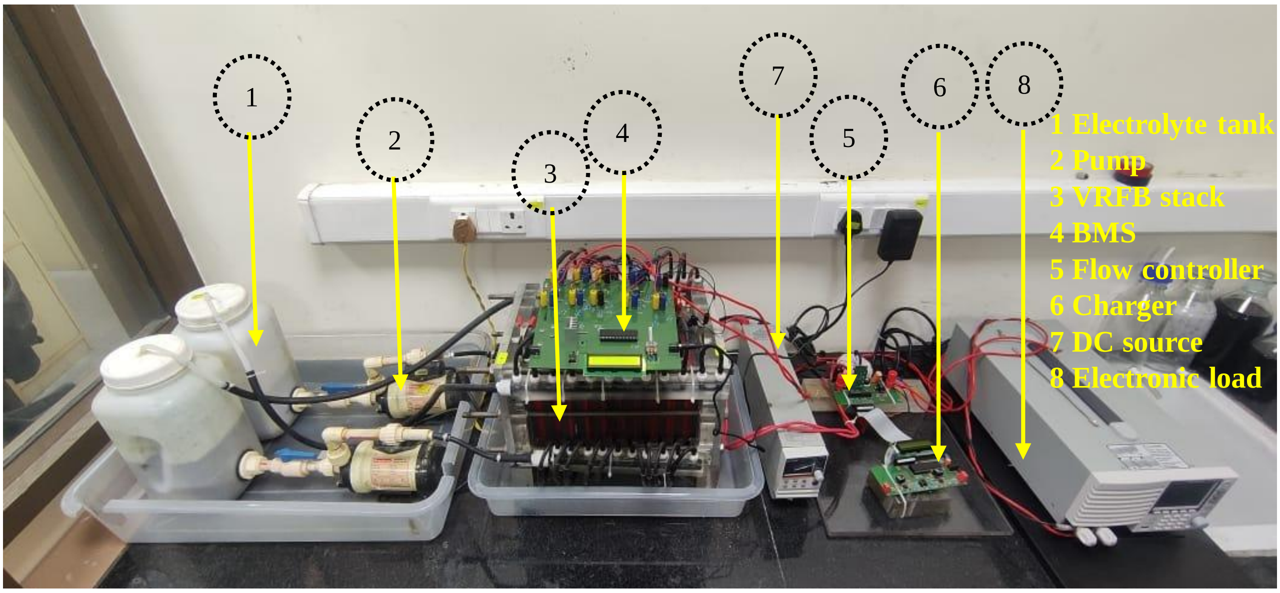

Fig. 6. 500W VRFB integrated with power electronics and BMS

non-dimensional stoichiometric number increased from 4 to 16, followed by a decreasing trend. The highest efficiencies were observed at a stoichiometric number range of 6 to 9. It has been observed that increasing the flow rate of the battery leads to an improvement in its charge and discharge capacities. However, this improvement becomes relatively smaller beyond a stoichiometric number of 10. The results of this analysis are presented in Fig. 8.

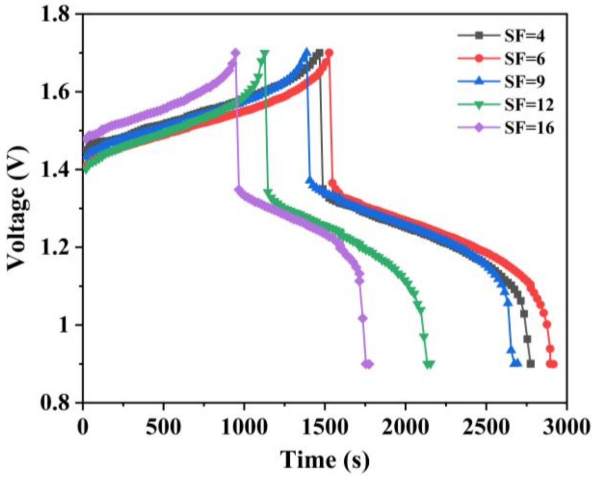

Fig. 8. Charging and discharging VRFB at different flow rate.

In our study, we have developed an IoT cloud data monitoring system for the VRFB using the Arduino cloud. The system enables remote monitoring of the battery parameters and gives real-time updates on the performance of the VRFB, independent of its location. The system architecture is based on the Arduino IoT Cloud platform, which is an easy-to-use and scalable IoT platform that enables seamless integration with various IoT devices.

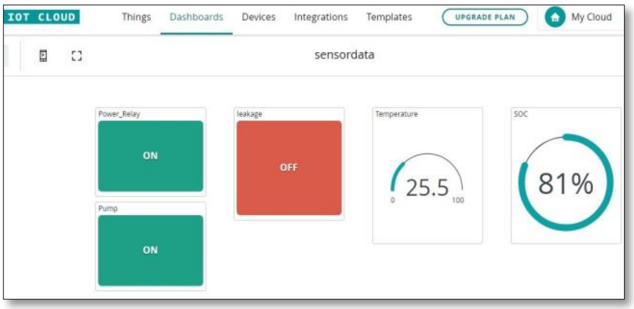

Fig. 9. IoT cloud data monitoring and storage system

The Fig. 9 shows the IoT cloud data monitoring system developed using the Arduino cloud. The microcontroller which is used to collect data from the VRFB sensors and transmit it to the cloud. The cloud platform is used to process the data and display the battery parameters on a web-based dashboard. The dashboard provides a real-time view of the VRFB performance, including SoC, temperature, control relay and leakage indicator. With this system, users can remotely monitor the VRFB performance and receive alerts in case of any anomalies, enabling proactive maintenance and troubleshooting. In addition to its primary functions, the BMS also incorporates a 16x2 display module that provides easily accessible data, alerts, and warning notification. The display notification is shown in Fig. 10.

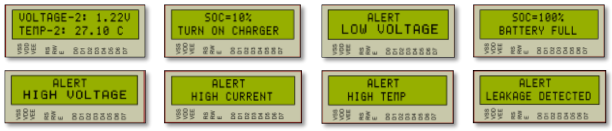

Fig. 10. Display alert and data monitoring on BMS hardware.

According to observations, conventional battery management systems (BMS) have resulted in several issues in vanadium redox flow batteries (VRFB). These issues include graphite precipitation due to overcharging and dehydration of graphite felt caused by overheating due to improper flow-based state-of-charge (SoC) control, as illustrated in Fig. 11. The aforementioned cases highlight

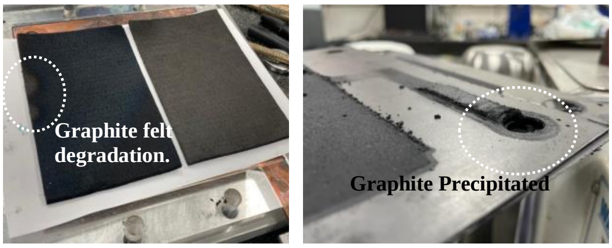

Fig. 11. Graphite precipitation and degradation of graphite felt due improper BMS

the need for advanced BMS, which can significantly enhance battery performance and prolong battery life.

IV. Conclusions

In conclusion, the development of a 500-Watt BMS for VRFB systems for standalone application has proven to be a significant contribution to the field. BMS is an essential component of VRFB systems that ensures the battery's optimal performance. The research has demonstrated that traditional BMS cannot be implemented in VRFB systems to achieve better results. To further enhance the performance of the VRFB system, a separate flow controller based on the SoC of the battery has been incorporated into the BMS. This additional feature allows for better regulation of the VRFB system, ensuring that the battery is performing at its best. Furthermore, the IoT cloud platform integrated with the BMS ensures regular monitoring and control of the battery. This system detects any battery malfunction and initiates the appropriate action to protect the battery. With the aid of IoT-based microcontrollers, real-time data monitoring and cloud platform updating can be facilitated, allowing remote access to critical performance metrics and early detection of system faults.

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