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Comprehensive Calculation of Vanadium Redox Flow Battery Capacity For 5kW Lighting Applications

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***Abstract*— Vanadium Redox Flow Batteries (VRFB) have emerged as a potential solution for renewable energy storage due to their scalability and long lifetime. However, optimizing their operational efficiency and addressing the issue of parameter accuracy for the right load pose significant challenges. This paper aims to quantify the critical parameters of VRFBs and analyze their performance in powering the system under various flow rate operating conditions. Simulations are performed using MATLAB software and unit blocks to evaluate the behavior of VRFBs during discharge and charge conditions at three electrolyte flow rates: 10, 5, and 1 liter per minute (lpm). The analysis focuses on key parameters, including operating duration, charge/discharge time, and state of charge. The results show that higher flow rates increase the discharge duration, while lower flow rates lead to shorter operating times and more pronounced ripples caused by pump control instability and electrolyte density variations. Therefore, designing appropriate parameters in VRFB systems is critical to developing sustainable energy storage solutions and supporting the implementation of clean energy technologies.**

Keywords—Energy Storage, Battery, Vanadium Redox Flow Battery, Flowrate

I. INTRODUCTION

Electrical energy plays a vital role in meeting the needs of modern society due to technological developments, increasing population, and increasing industrial activity. This increase has resulted in an increase in electricity demand in Indonesia of up to 4% per year [1]. The development of new methods to produce clean energy storage technology is urgently needed along with the increasing demand for electrical energy and to reduce environmental pollution [2].

Environmentally friendly batteries include various technologies designed to reduce negative impacts on the environment. One of the conventional batteries used is the lithium-ion battery type because it has high energy density, fast charging, and low price. However, this conventional battery also has many disadvantages such as the risk of fire or explosion, short life cycle and sensitivity to extreme temperatures [3].

One of the most promising technologies for energy storage other than existing conventional batteries is the vanadium redox flow battery (VRFB) [2]. One study shows that VRFB can achieve energy efficiency of up to 85%, much higher than several other types of batteries [4]. This battery works by utilizing vanadium-based electrolytes stored in an external tank, allowing energy capacity to be adjusted to the volume of electrolyte, regardless of the size of the battery cell [5].
VRFBs have been used in a variety of applications, including grid stabilization to address renewable energy fluctuations, energy storage in remote areas not connected to the main grid, and as energy backup for critical infrastructure such as hospitals and data centers. This demonstrates the ability of VRFBs to support large-scale renewable energy integration [6].

In a more specific application context, VRFBs are also very suitable for use in lighting systems that require stable and continuous power, such as street lighting, public lighting, or lighting in remote areas. The VRFB efficiency value is around 85%, the required storage capacity must be greater to compensate for energy losses during the charging and discharging process. Simulations using the *Simscape* Battery Block from MATLAB allow further analysis to determine the optimal VRFB capacity reliably and efficiently support 5kW lighting applications under real conditions. This research aims to make a significant contribution to the development of efficient energy storage solutions for medium-scale lighting applications, while supporting wider adoption of renewable energy technologies and sustainable development [7].

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II. METHOD

A. Previous Research

First introduced as a flexible and long-lasting energy storage solution, the Vanadium Redox Flow Battery (VRFB) combines the advantages of conventional battery technology with flow systems. As explained by Skyllas-Kazacos et al., VRFBs are identified as batteries designed to overcome some of the limitations of lithium-ion batteries and other energy storage battery technologies, such as cycle life and capacity instability [8]. With their ability to support large-scale energy storage, VRFBs have emerged as an attractive option in renewable energy storage systems, especially in the context of integrating intermittent renewable energy sources such as wind and solar power. As energy storage technology advances, VRFBs have effectively competed with other types of batteries, including lithium-ion and other flow batteries. According to Wang et al. (2023), the advantages of VRFBs lie in their longer cycle life, lower maintenance costs, and better stability under various operating conditions [9]. Research shows that VRFBs are not only able to compete in performance, but also offer a more environmentally friendly solution by utilizing safer and more recyclable materials. This makes a significant contribution to the sustainability goals and future use of clean energy.

In the context of energy storage, VRFBs are identified as an efficient solution to support the transition towards a more sustainable energy system. Previous studies have also highlighted that VRFB technology can store large amounts of energy and releasing it as needed, making it ideal for applications such as peak load management and grid balancing [10]. With the ability to operate in a wide temperature range and high electrolyte stability, VRFBs offer advantages in supporting grids integrated with renewable energy.

However, despite the many advantages of VRFBs, the challenge of battery sizing remains a major concern. Research [8] identified that proper battery sizing is critical to ensure system efficiency and effectiveness in the desired application. This research suggests the need for a better approach in designing VRFB systems to adapt to specific energy needs and optimize space and cost usage. These challenges must be overcome for VRFBs to be more widely adopted across various industrial sectors and energy infrastructure.

B. Battery

A battery is an electrochemical device that functions to store energy in the form of chemical energy and convert it into electrical energy. In general, a battery consists of two electrodes, namely the anode (negative electrode) and the cathode (positive electrode), and a membrane that functions to conduct ions between the two electrodes so that there is a flow of power or voltage from the battery that is supplying (anode to cathode) or vice versa. Batteries are used for various applications, from small to large scale. Based on the working principle, batteries are divided into 2 types, namely primary (disposable) and secondary batteries (rechargeable). Primary batteries, such as alkaline batteries, Zinc-Carbon, Lithium, Silver Oxide, and so on are batteries that cannot be recharged because the chemical reaction is nonreversible. Meanwhile, secondary batteries, such as Lithium-Ion (Li-ion), Lithium Polymer (Li-Po), Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Lead-Acid, and Vanadium Redox Flow (VRFB) batteries are batteries that work with reversible chemical reactions during the charging and discharging process, so they can be used repeatedly [11].

C. Vanadium Redox Flow Battery

Battery is a tool or device that functions to collect and generate electric current. Redox Flow is an electrical energy storage scheme using electrochemical materials contained in two solutions consisting of different redox pairs where the performance flows continuously and circulates. The term "redox" is derived from the contraction of the words "reduction" and "oxidation" that occur in its chemical fluid [17].

Vanadium is one of the chemical elements in the periodic table that has the symbol V and atomic number 23. In short, the Vanadium Redox Flow Battery (VRFB) is a vanadium ion device that functions as a storage generation of electrical energy with circulated performance [15].

The Vanadium Redox Flow Battery (VRFB) has two tanks that function as electrolyte solution storage, one for

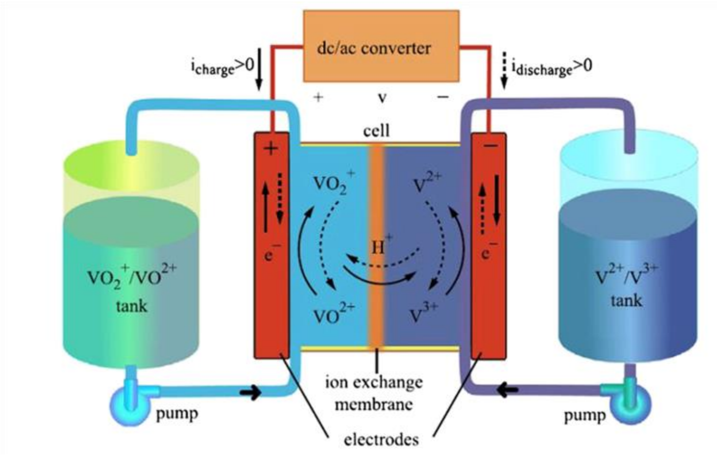

Figure 1. Redox flow battery scheme

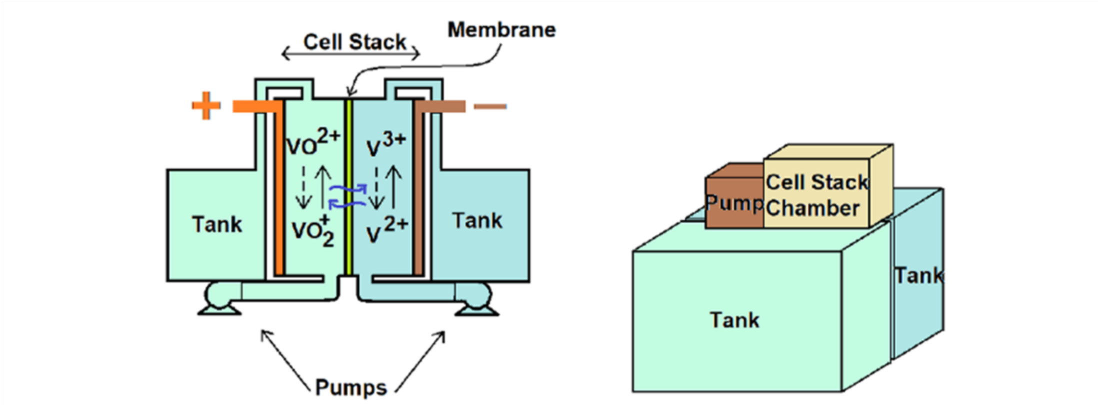

Figure 2. VRFB in MATLAB

positive electrolyte and one for negative electrolyte. Between these two tanks, there is a stack of electrochemical cells consisting of electrodes, separator membranes, bipolar plates, and current collectors. In the working process, the electrolyte solution is pumped from each tank to the stack of cells using two pumps that work in a coordinated manner. As electrolyte flows through the stack of cells, redox reactions occur within the cells, producing or absorbing electrical current that can then be used for a variety of energy storage applications.

Figure 1. is the structural scheme of the vanadium flow battery where there are 2 external tanks containing electrolytes that contain vanadium ions in a sulfuric acid solution. During the charging process, the positive side is oxidized from VO2+ (V4+) to VO2+ (V5+) and the negative side is reduced to V2+. This reaction will reverse during the discharge process. The complete chemical reaction is written in the equation below [12]

Positive Side: $VO^{2+} + H_2O \leftrightarrow VO_2^+ + 2H^+ + e^-$

Negative Side: $V^{3+} + e^- \leftrightarrow V^{2+}$

Total: $VO^{2+} + H_2O + V^{3+} \leftrightarrow V^{2+} + VO^{2+} + 2H^+$

In addition to capacity flexibility, VRFB has a very long cycle life, which can achieve more than 10,000 charge and discharge cycles without significant degradation in its capacity. This is due to the properties of the vanadium electrolyte which does not cause degradation in the electrodes due to the redox process that occurs entirely in the form of vanadium ions. In addition, VRFB has high energy storage efficiency and good thermal stability, making it a safe and reliable choice for energy storage applications [13].

D. Vanadium Redox Flow Battery Design

In the MATLAB R2023b software, VRFB is presented to calculate the state of charge (SOC) and assess the impact of the electrolyte flow rate on battery performance by solving ordinary differential equations (ODE) equations and using special components in *Simscape*. In the available scheme, the VRFB is composed of a series connected cell stack and a refilled electrolyte liquid from a large electrolyte tank as shown in Figure 2.

To design a resistor-capacitor pair-based equivalent circuit (RC pair-based), the open-circuit equation is defined as:

$$V_{oc} = V_{elecPot} + \frac{\mathrm{RT}}{\mathrm{nF}}\log\left(\frac{\mathrm{SOC}}{1 - SOC_p} \cdot \frac{\mathrm{SOC}_n}{1 - SOC_n}\right)$$

Where,

$V_{elecpot}$ = Electrode potential value, E+ −E−~1.3V

R = Universal gas constant value (8.314 J K^{-1} mol^{-1})

T = Battery Temperature

F = Faraday Constant (96485 C mol^{-1})

By determining the SOC value through calculations

$$SOC_p = \frac{c_5^{tank}}{c_4^{tank} + c_5^{tank}}$$

$$SOC_n = \frac{c_2^{tank}}{c_2^{tank} + c_3^{tank}}$$

$$SOC_{overall} = \frac{\mathrm{SOCp} + \mathrm{SOCn}}{2}$$

E. Sizing Vanadium Redox Flow Battery

Determining the capacity of a Vanadium Redox Flow Battery (VRFB) is an important process in designing an energy storage system that fits the specific load requirements. The crucial thing in this study is the calculation of tank size and cell stack size.

To obtain the size of the tank, it is necessary to have a maximum power value, energy density value, and atomic mass density

$$V_{tank} = \frac{\text{Maxpower}}{\text{Energy Dencity} \times \text{Atom mass}}$$

The volume of the tank is expected to store at least one month of power consumption. With the parameter of energy density value in VRFB is 35 Wh/kg and the atomic mass density value of Vanadium is 6110 kg/cm3 [14]. Meanwhile, to calculate the number of cell stacks that can meet the load needs is by dividing the stack voltage and the cell voltage.

$$n = \frac{\mathrm{E}_{stack}}{\mathrm{E}_{cell}}$$

III. RESULTS AND DISCUSSION

In this section, the research results are presented in a structured manner to answer the research questions formulated previously. The data obtained are analyzed using the methods described previously, with a focus on measurement and validation of the results. The analysis is carried out to evaluate the performance of the system under study and identify significant patterns or trends with the results of the parameters that have been calculated such as the number of cells, tank volume and other parameters that follow the default model so that this VRFB model is able to supply a load of 5kW. The first calculation is related to the calculation of the size of the tank which is calculated from the equation:

$$V_{tank} = 2 \cdot 10^4\ Wh\ \times \frac{kg}{25\ Wh} \times \frac{m^3}{6110 kg}$$

$$V_{tank} =\ 0.2\ m^3$$

Then the calculation is continued by determining the number of cells connected in series, with the calculation

$$\text{n} = \frac{E_{Stack}}{E_{cell}}$$

$$\text{n} = \frac{65\ \text{V}}{1.65\ \text{V}}$$

$$\text{n}\ \approx 40\ Cell$$

So in this study, the basic parameters were determined as in table 1.

This simulation is carried out with 2 conditions, charging, discharging conditions. where in each condition there are several scenarios to see the performance of the VRFB in different conditions according to the scenarios that have been created.

Under discharge conditions, the VRFB is connected to a specific load, as shown in Figure 3. At the beginning of the discharge process, this battery can produce a substantial amount of power, approximately 5000Watt, indicating that the energy stored in the system is still in optimal condition. Over time, the power output of the battery begins to show a gradual decline. Around 5.5 hours into the process, the power output remains

TABLE 1.
PARAMETER VRFB 5KW

Parameter	Value
Number of series connected cells in the battery stack	40
Single cell electrode potential	1.65 V
Cell ohmic resistance	0.025 Ohm
Cell 1st RC pair resistance	0.5 Ohm
Cell 1st RC pair time constant	1 s
Cell initial state of charge	0.9
Length of porous electrode	0.4 m
Width of porous electrode	025 m
Thickness of porous electrode	3e-3 m
Electrode porosity	0.9
Membrane thickness	1e-3 m
Vanadium molarity	2 mol/l
Va(II) diffusivity through membrane	0.877e-9 m^2/s
Va(III) diffusivity through membrane	0.322e-9 m^2/s
Va(IV) diffusivity through membrane	0.682e-9 m^2/s
Va(V) diffusivity through membrane	0.589e-10 m^2/s
Tank volume	0.2 m^3
Temperature	298 K
Flowrate	10 lpm
External Resistance as system load	1 Ohm

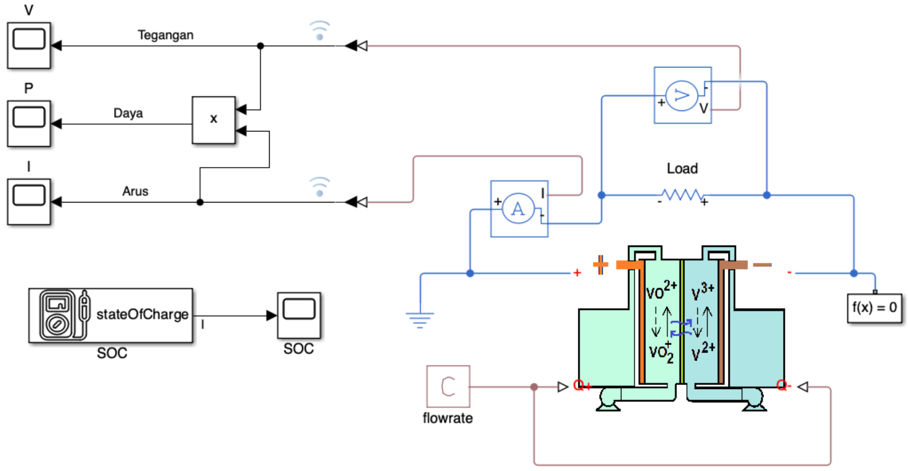

Figure 3. Discharge Configuration

significant but starts to gradually decrease as the stored energy depletes. This process continues until the power output drastically drops to near zero after 12.5 hours. This power decline is a natural phenomenon during the discharge process, where the energy stored in the electrolyte is gradually released to meet the demands of the connected load. This process illustrates how the battery operates effectively at the start of the discharge cycle, with performance gradually decreasing as its capacity nears depletion. This phenomenon also highlights the importance of proper energy management to maximize the battery's power usage, particularly in applications requiring consistent power supply over a specific period.

At a flowrate of 5 lpm, the VRFB can deliver energy for approximately 12.5 hours, with a stable decline in power throughout the discharge process. This duration indicates that at a lower flowrate, the VRFB can sustain the stored energy longer before the power is completely depleted. This is due to the gradual and more controlled release of energy, allowing the system to provide consistent energy supply over a longer period. On the other hand, at a flowrate of 10 lpm, the total duration of energy delivery also reaches around 12.5 hours, but the decline in power occurs more rapidly compared to the 5 lpm flowrate. As a result, the effective energy delivery time at 10 lpm is shorter due to the higher power consumption at the beginning of the discharge cycle.

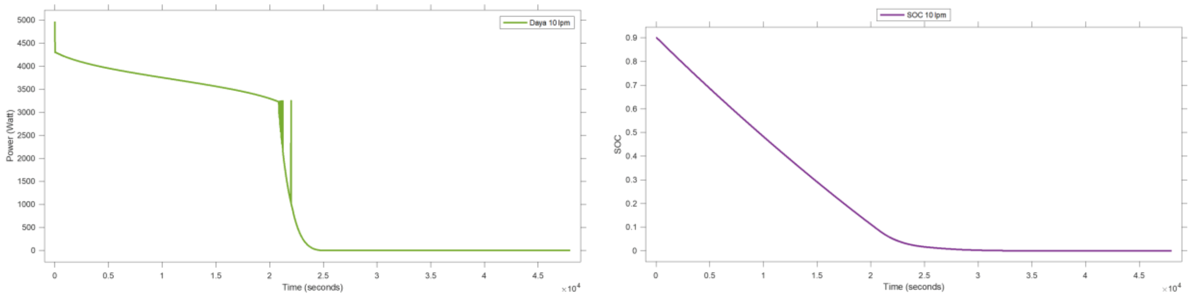

Figure 4. VRFB power output and SOC at 10 lpm while discharge

Figure 7 is the comparison of VRFB output power at various flowrates, namely 1 lpm (green line) in Figure 6,

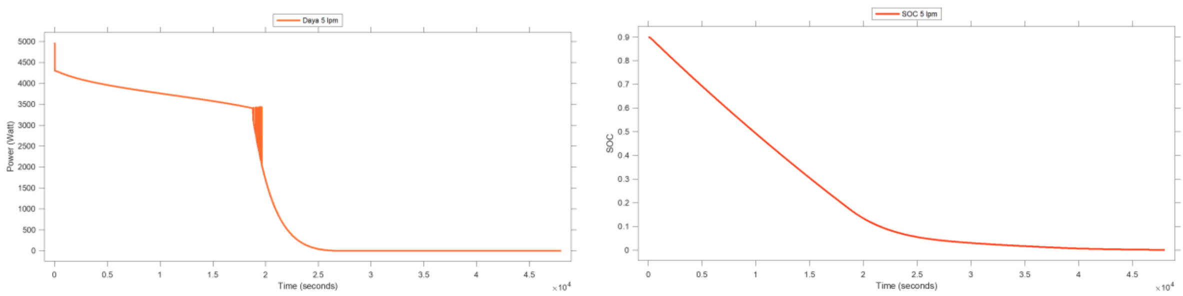

Figure 5. VRFB power output and SOC at 5 lpm while discharge

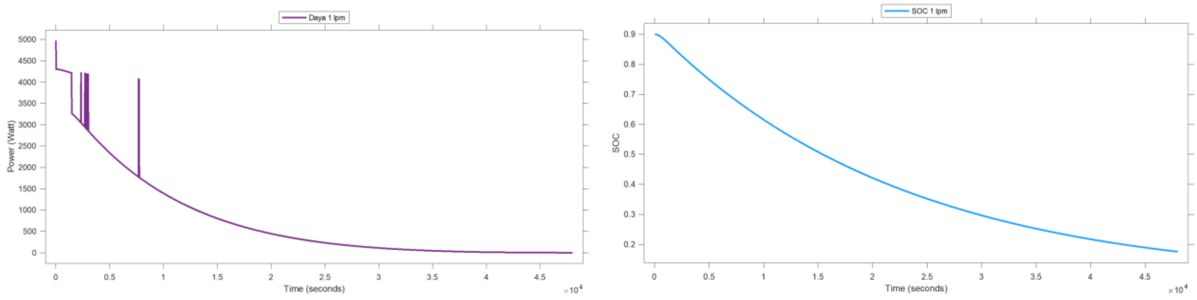

Figure 6. VRFB power output and SOC at 1 lpm while discharge

5 lpm (blue line) in Figure 5, and 10 lpm (black line) in Figure 4. At a flowrate of 1 lpm, the initial power produced is relatively lower, around 3000 Watts, and the power drop takes place slowly, allowing energy to be channeled for about 12.5 hours. This flowrate indicates the longest discharge duration with a very stable power drop pattern, signaling maximum energy release efficiency for applications requiring a continuous power supply.

initial power remains in the range of 4000 Watts, but the power drop occurs at a faster rate than the flowrate of 5 lpm. The significant drop started at 4.2 hours, and the power was completely depleted at 12.5 hours.

This flowrate indicates that the energy release takes place faster, making it more suitable for applications that require high power in a short period of time, although the overall energy release efficiency is lower than that of lower flowrates. Overall, this graph shows that a lower

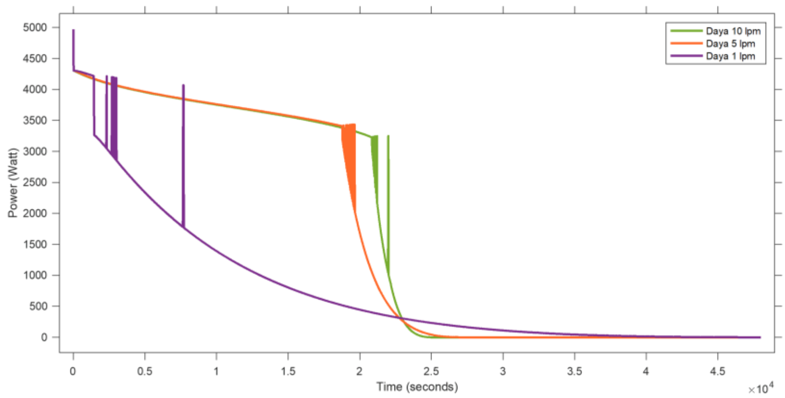

Figure 7. VRFB power output while discharge comparison

At a flowrate of 5 lpm, the initial power increases to about 4000 Watts, with a faster power drop pattern than 1 lpm. A significant drop in power began at 5.5 hours, before finally the power dropped to near zero at 12.5 hours of operation. Although the total duration is equal to a flowrate of 1 lpm, the effective energy channeled at this flowrate is slightly shorter due to the faster power drop in the final phase of discharge. For a flowrate of 10 lpm, the

flowrate, such as 1 lpm, provides a longer duration of energy dissipation with a more stable power drop, while a higher flowrate, such as 10 lpm, results in a high initial power but with a shorter energy dissipation effective time.

The second condition is the charging condition where the VRFB is connected to the DC Current Source as a driver so that the VRFB enters the charging state as shown in Fugure 7. In the VRFB charging process, not only the

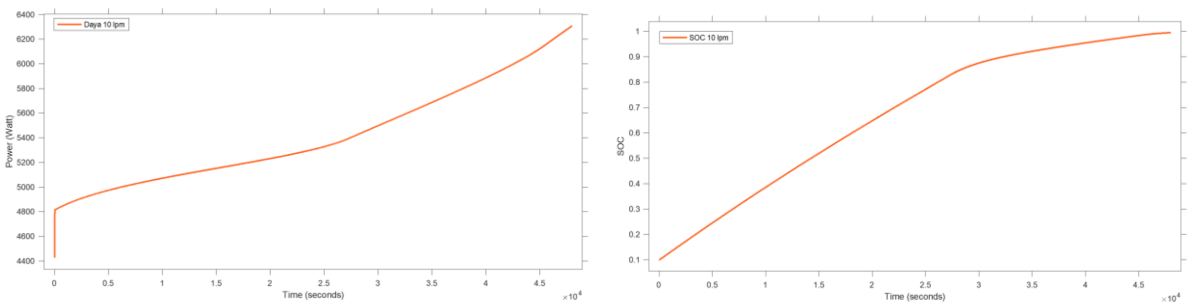

Figure 8. VRFB power output and SOC at 10 lpm while charging

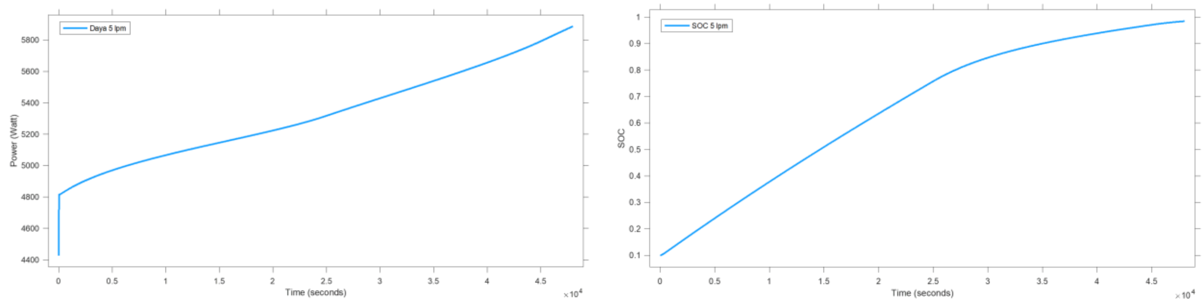

Figure 9. VRFB power output and SOC at 5 lpm while charging

speed of SOC increase is important, but also the time it takes to reach full capacity and the power coming out of the system during charging. Based on the SOC and power graphs that have been presented in Figure 11, we can see a significant difference between the flowrates of 1 lpm, 5 lpm, and 10 lpm in terms of charge time and output power.

A t a flowrate of 1 lpm, the filling takes place more slowly but steadily. Its output power starts at about 4800 Watts and gradually increases until it reaches 5400 Watts. Although the power generated is not as high as the higher flowrate, the charging process is more controlled. The SOC also increased slowly from 0.1 to nearly 1.0 over a longer period, reflecting charging that took longer to reach full capacity. The advantage of this flowrate is the stability of the power generated, which is especially important for applications that require a continuous power supply over a long period of time, even with longer charging times. With a lower flow, the battery can avoid sharp power fluctuations, although the total time it takes is longer compared to a higher flowrate.

At a flowrate of 5 lpm, the output power starts at around 4400 Watts and increases faster compared to a flowrate of 1 lpm, by reaching 5400 Watts in a shorter time. Charging times are also faster, with the SOC increasing faster towards full capacity, although not as fast as at a 10 lpm flowrate. The 5 lpm flowrate provides a balance between charging time and power stability. Charging takes place faster but still quite stable in generating power. This makes it suitable for applications that require faster charging without losing excessive control over energy distribution. The power output is stable throughout the charging process, but with a shorter time to achieve full SOC compared to a flowrate of 1 lpm.

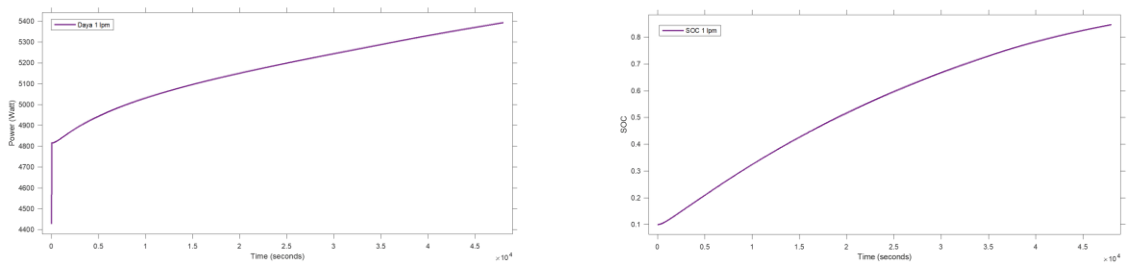

Figure 10. VRFB power output and SOC at 1 lpm while charging

At a flowrate of 10 lpm, the output power starts at around 4800 Watts and increases more sharply, reaching 5900 Watts in a shorter time compared to the other two

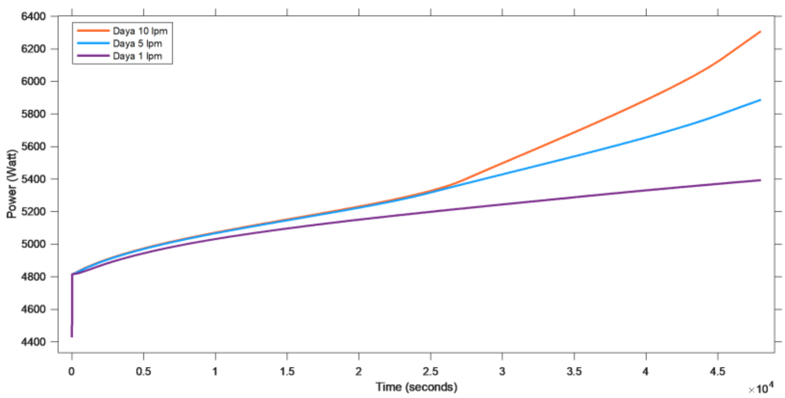

Figure 11. VRFB power output while charging comparison

flowrates. The charging process is very fast, with the SOC increasing faster towards full capacity in less time. This high charging speed makes it ideal for applications that require fast charging in a short period of time. However, the power generated at the initial stage is higher, which can affect the stability of the system if it is not properly controlled. Although the power generated is high, faster charging can lead to greater fluctuations in battery capacity, which can affect long-term efficiency if not closely monitored.

Overall, the higher flowrate results in greater power at the beginning of charging and speeds up the time it takes to reach the full capacity of the battery. A flowrate of 10 lpm indicates the greatest power in the early stages and the fastest charging, but with a higher risk of power fluctuations. In contrast, a flowrate of 1 lpm provides a more stable charge but takes longer to reach full SOC. The 5 lpm flowrate provides a good balance, allowing for faster filling than 1 lpm with better stability than 10 lpm.

The selection of the optimal flowrate depends on the specific needs of the application. If fast fill times are a priority, a flowrate of 10 lpm is the way to go. However, for applications where power stability and more controlled charging are prioritized, a flowrate of 1 lpm or 5 lpm would be more suitable, with a flowrate of 5 lpm offering the best compromise between speed and stability.

IV. CONCLUSION

The results of this study evaluate the performance of the system in meeting the requirements outlined in the results. with parameters mainly regarding the number of cell stacks required, which is 40 cells and a tank volume of 0.2 m3. VRFB is capable of being an energy storage that supplies a load of 5 kW which in this study was made for lighting but can also be used for other daily loads that are in accordance with the same parameters as this paper. The results of the data analysis show that the system efficiently supplies a load of 5 kW. In addition, the identified patterns and trends indicate the potential for further development to increase the capacity of vanadium redox flow batteries (VRFBs) in energy storage applications. This study also reveals certain limitations, such as the lack of comprehensive testing in all aspects. Nevertheless, the findings provide a strong foundation for future studies, especially in advancing redox flow battery technology for energy storage. Overall, this study makes a significant contribution to the development of VRFBs, which have substantial promise as a reliable and efficient solution for future energy storage needs.

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