Flow Batteries for Future Energy Storage: Advantages and Future Technology Advancements

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Abstract. For sustainable development, finding a clean energy storage technology for the future is necessary. The main technology for promoting the evolution of the energy structure and popularizing the use of renewable energy sources, including wind and solar energy, is high-power and high-capacity energy storage. Flow batteries is one of the most promising technologies in the industrial energy storage technology, owing to their unique features such as long cycling life, reliable design, high safety, and relative mature development. Nevertheless, the high cost and low energy density problems restrict its further development. This paper first introduces the working principles and characteristics of flow batteries that have been industrialized. Secondly, the advantages and the research status of the new flow battery (FB) systems are summarized. Finally, the main challenges that hinders the large-scale application of the flow batteries are emphatically analyzed, and the suggestions regarding the further technologies required for the development of advanced flow batteries are put forward, which points out the direction for the progress of new high-performance FB systems.

Keywords: Flow batteries, Vanadium-based flow batteries, Energy storage systems.

1. Introduction

Sustainable development is one of the most popular and important features of future developments - United Nations divides sustainable goals into 17 different parts. Clean and affordable energy is one of the goals. The energy storage system is a mandatory part of the future clean energy system. Since most of the clean energy is hard to control its output, the energy got made which is above people's needs to be stored in the energy storage system. Or they are going to be wasted. A FB is a good choice among all those different energy storage technologies. A FB has the characteristic of rechargeability. The typical FB realizes the mutual conversion of electrical energy and chemical energy through the reversible redox reaction, which relies on the reversible change of valence state of the active material in the electrolytes. When the flow batteries are discharging, the liquid electrolyte is pumped through electrodes to extract the electrons and generate electricity [1]. Energy in the FB energy storage system is converted between electrical energy and chemically stored energy. The key for the FB system to generate electricity is the ion exchange membrane which divides two cells. It allows for high-efficiency ionic conduction in the system and reduces the loss of electroactive species created in the half cells, both of which contribute to the system's ability to maintain a high coulombic efficiency.

2. The Advantages and characteristics of flow batteries

2.1. Properties of flow batteries

Decoupling, the feature of flow batteries, can make the design and use of the battery very convenient. It means that the increase in the energy capacity in the FB system is irrelevant to the power resources. In other words, means that there would be no size limit for the FB storage capacity. With the tanks getting larger, the energy storage capacity would increase. This means that theoretically, the flow of battery energy storage can reach infinite.

Flow batteries also have the characteristics of fast electricity generation. In practical applications of energy storage technology, the responding time for the system is really important. Because of its special structure, with the pumps working, the FB can give respond in a very short time. The FB system can convert between charging and discharging in 0.02 seconds. This could make the people using it feel no lagging and able to make the FB system convenient to use [2].

Furtherly, the structure of this system is special but also simple. The whole system consists of two big tanks for the electrolyte, two pumps to make the liquid flow, and, most importantly, an ion exchange membrane. All of those make FB energy storage easy to be manufactured. Also, it doesn't have too many requirements on the location. The only thing it needs is just the space to put some huge tanks. This is one of the reasons why the FB system is convenient to use.

2.2. Advantages of flow batteries

Flow batteries usually have very low stand-by loss compared with other energy storage technologies. The energy lost is quantified by the self-discharge, capacity loss, and energy efficiency. Since the electrolyte in the FB system is housed in separate tanks, there is almost no self-discharge during periods of inactivity. Clean energy institute did an estimation in 2022, showing that the self-discharge is very low for most kinds of flow batteries.

The FB system is also unaffected by changing power demand due to its unique structural differences from other batteries. Some kinds of flow batteries, such as the vanadium-based, and iron-chromium-based ones, are the ones getting most commercialized among all kinds of flow batteries and can suffer more than 10000 full charge-discharge cycles. All kinds of different flow batteries can normally, on average, reach at least 2000 cycles before maintenance [3].

Flow batteries have stable storage of energy. The electrodes in the FB energy storage system do not alter physically or chemically while it is operating. Performance would improve and become more dependable as a result. For instance, the Mitsubishi Chemicals (1996) at Kashima-Kita Electric Power, Japan, for load-leveling has been working for more than a decade, and it is still working as how it was expected [4].

The safety and recyclability of flow batteries are high. There is cross-contamination in the FB system. The safety of storing the active components apart from the reactive point source is a built-in feature of the FB.

3. FB research and development status and future application prospects

3.1. Challenges of flow batteries from larger application

FB energy storage systems also urgently require considerable advancements in power density, stability and dependability, cost reductions, and the development of workable business models in order to meet the demands of practical and industrial applications.

In terms of the cost, the most expensive part of a stack is the membrane, with prices for currently in-use membranes ranging from $200 to $600 per square meter. However, the costs for the new membranes/separators being developed are around $50 per square meter [5].

FB also has the problem of storage power density. In order to lower cell resistance, especially ohmic resistance, it is necessary to lessen the anode-cathode separation without raising the pressure drop. Scientists are implementing fuel cell stack topologies that use serpentine flow fields. According to cell architecture, ohmic losses account for 50–80% of total cell resistance. More conducting electrodes and membranes, as well as shorter inter-electrode distances, can lessen this. In flow-through cells using porous carbon felt electrodes, activation polarization losses account for less than 20% of total cell resistance, but they account for a much higher percentage in "zero-gap" designs using thin carbon paper electrodes in conjunction with serpentine or interdigitated flow fields [6]. The capital cost of the different kinds of vanadium flow batteries is shown in Figure 1 and Figure 2.

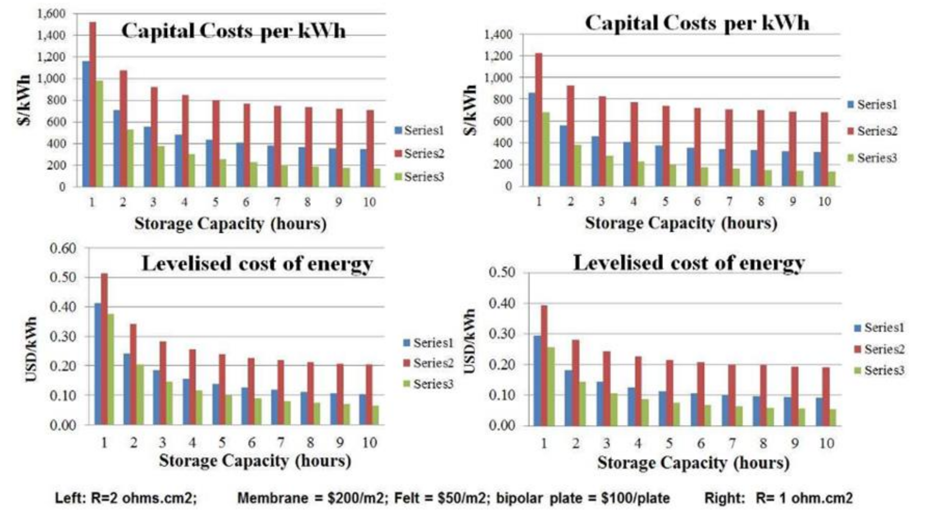

Figure 1. Simulated capital and levelized costs for 100kW VFB as a function of storage capacity based on the effect of electrolyte leasing and cell resistance [7]

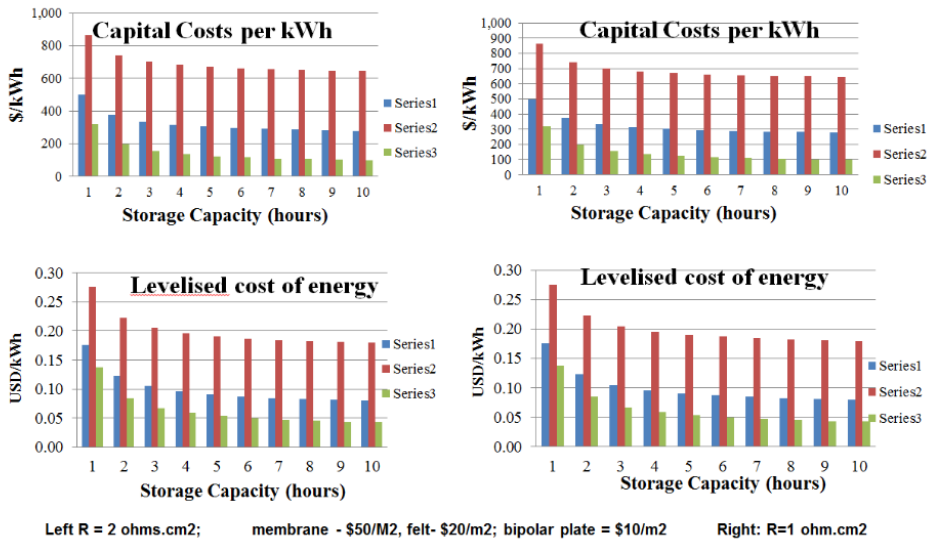

Figure 2. Simulated capital and levelized costs for 100kW VFB as a function of storage capacity effect of electrolyte leasing and cell resistance [7]

3.2. Future technology advancements for flow batteries

The stability of the active components in non-aqueous FB systems still has to be improved, and the organic solvents utilized in these systems are typically flammable. Non-aqueous FB technologies also have a working current density that is comparably low and insufficient for practical application. High-performance and inexpensive flow batteries must have electrodes, bipolar plates, ion-conducting membranes, and electrolytes. The ideal electrolytes used in flow batteries should have high solubility and great stability, and affordably priced in order to increase the energy density of flow batteries [8]. A crucial part of the FB, the membrane separator serves to isolate electrolytes while still transmitting ions to complete the circuit. Although these membranes exhibit great proton conductivity and chemical durability, their limited commercialization has been hampered by their astronomically high cost and poor ion selectivity. As a result, different ion exchange membrane (IEM) materials are being looked for [9].

The electrolyte of the all-vanadium redox FB has a strong oxidizing property and is easy to permeate and cause a decrease in the battery capacity, which means that the ion exchange membrane should have a unique structure and performance. The ion exchange membrane is the key component of the all-vanadium redox FB. It not only isolates the positive and negative electrolytes but also provides proton conduction channels for the positive and negative electrolytes. The ion exchange membrane with high cross-linking and good permeability will be the future all-vanadium redox FB separator development trend.

At the same time, it also provides proton conduction channels for the positive and negative electrolytes. V^{2+}, V^{3+}, V^{4+}, and V^{5+} vanadium ions were successfully separated from protons by the porous membranes because of their disparity in radius, charge density, and particular interactions with the electrolyte and membranes. The thermal precipitation of V^{5+} ions in the vanadium battery electrolyte is the main factor affecting the concentration of the vanadium electrolyte and an important factor affecting the normal operation of the vanadium battery. Adding additives to the electrolyte is an effective method to improve the thermal stability of V^{5+} ions in the electrolyte. The organic additives are not suitable as electrolyte additives because they will be oxidized by the V^{5+} ions and lose their effect. Some metal ions, such as titanium, antimony can improve the performance of the electrolyte. In addition, the mixed-use of inorganic additives also has a good stabilization effect [10].

Compared with the vanadium FB, the zinc-bromine batteries have inherent advantages in cost, because from the perspective of the general cost of energy storage batteries, the cost of electrolyte accounts for 30% of the total cost, so the price of electrolyte components determines the cost of the battery to a large extent. overall cost. The electrolyte components of zinc-bromine batteries are zinc and bromine. Zinc is a very common metal, which is easy to obtain in large quantities and has a low price, while another component, bromine, is more common and can even be extracted from sewage. This innate characteristic determines the cost advantage of zinc-bromine batteries. According to industry estimates, the cost per kWh of sodium-sulfur batteries and vanadium batteries is basically around US$500, while the corresponding cost of zinc-bromine batteries is around US$100, which is comparable to the cost of common lead-acid batteries. It can be seen that the price advantage of zinc-bromine batteries is very obvious, which lays a good foundation for the large-scale and wide-scale application of zinc-bromine batteries [10]. Furtherly, the zin deposition is the main problem in zinc-bromine batteries. The morphology of zinc deposition is related to various factors such as electrolyte system and working current density, so it can be controlled by optimizing the above conditions. In addition, the accumulation of zinc caused by the imbalance of charge consumed by side reactions can be suppressed by inhibiting the side reactions of anode, enhancing the negative side reactions and preparing composite positive materials to reduce the accumulation problem. Also, the polarization phenomenon is related to the current density, and the electrode polarization can be reduced by optimizing the electrolyte flow field structure and using porous electrode materials. Finally, the development of new electrode materials can reduce battery cost and improve the area capacity of the electrodes on both sides.

4. Conclusion

Due to its low cost and excellent performance characteristics, the FB is a promising technology, which is expected to be widely used in new energy power generation, power grid peak cutting and grain filling, power storage at different peaks for large power users, electric vehicle charging, and other fields in the future. However, in view of its current development status, it still needs the joint participation and efforts of the national government, research institutions and other forces to rapidly develop and grow.

Nowadays, more research institutions are engaging in the research of energy storage batteries, especially the flow batteries. The development is the large-scale, high-efficiency, low-cost, long-life FB system is the future direction of research. Therefore, it is necessary to research on the flow energy storage materials, including the electrolyte, ion exchange membrane, electrode plates. At the same time, the mass production technology development of key materials to reduce costs is necessary in future production of flow energy storage batteries for industrialization.

References

[1] Dincer I, Erdemir D. Heat Storage Systems for Buildings [M]. Elsevier, 2021.

[2] Kwabi D G, Ji Y, Aziz M J. Electrolyte lifetime in aqueous organic redox flow batteries: a critical review [J]. Chemical Reviews, 2020, 120(14): 6467-6489.

[3] Letcher T M. Storing electrical energy [M]. Managing Global Warming. Academic Press, 2019: 365-377.

[4] Park M, Ryu J, Wang W, et al. Material design and engineering of next-generation flow-battery technologies [J]. Nature Reviews Materials, 2016, 2(1): 1-18.

[5] Wei Z, Bhattarai A, Zou C, et al. Real-time monitoring of capacity loss for vanadium redox FB [J]. Journal of Power Sources, 2018, 390: 261-269.

[6] Zhang H, Lu W, Li X. Progress and perspectives of FB technologies [J]. Electrochemical Energy Reviews, 2019, 2(3): 492-506.

[7] What is a FB? - The International FB Forum, 2022. Retrieved 15 August 2022 from: Flowbatteryforum.com

[8] Zhao Z, Zhang C, Li X. Opportunities and challenges of organic FB for electrochemical energy storage technology [J]. Journal of Energy Chemistry, 2022, 67: 621-639.

[9] Ding C, Zhang H, Li X, et al. Vanadium FB for energy storage: prospects and challenges [J]. The journal of physical chemistry letters, 2013, 4(8): 1281-1294.

[10] Garg, Bhaskar. "Introduction to Flow Batteries: Theory and Applications." Introduction to Flow Batteries: Theory and Applications [R], Stanford University, 22 Mar. 2012.