Research on All-Vanadium Redox Flow Battery Energy Storage Device Based on Energy-Saving and Environmentally-Friendly New Energy Power Station Interface Technology

Yanan Wang *
College of Electrical Engineering, Xi’an Traffic Engineering Institute, Xi’an 710300, China

*Corresponding author e-mail: 563787999@xjtu.edu.cn

Abstract. In the context of energy conservation and environmental protection, new wind energy power generation has obvious random, intermittent, uncontrollable and anti-peak-shaving characteristics. The large-scale grid connection of wind power has brought grid peaking and stable and safe operation the huge pressure has caused more serious wind curtailment and power rationing, which has seriously affected the effective use of wind resources and economic benefits. Under the dispatch of the energy management system, the all-vanadium redox flow battery energy storage power station smooths the output power of wind power generation, and cooperates with the wind farm power forecast system to improve the wind farm tracking planned power generation capacity and improve the grid-connected power quality of the wind farm. Based on this, the thesis studied the external operating characteristics of the all-vanadium flow battery (VFB) energy storage system, and carried out the modeling and simulation of the energy storage system (ESS) based on the electrochemical properties of the VFB. Systematically analyse the actual operating data of the energy storage system and evaluate the impact of its overload operation on dispatch control, and fit key parameters such as state of charge (SOC), electromotive force and equivalent resistance, and obtain functional relationships.

Keywords: Energy saving and environmental protection, new energy technology, all vanadium flow battery, energy storage system, simulation modeling.

1. Introduction
With the development of renewable new energy power generation technologies, especially the vigorous promotion of photovoltaic power generation and wind power generation and the rise of smart grids, energy storage technology as a supporting technology for new energy utilization has also been rapidly developed. All vanadium redox flow battery VRB has the advantages of large capacity, high efficiency, long life, fast response speed, independent design of power and capacity, etc., not only can be used for photovoltaic power generation, wind power generation and other intermittent power sources to smooth
the power fluctuations, but also independently used for large-scale capacity energy storage. VRB has received widespread attention, especially in the field of large-capacity energy storage. Currently, a number of VRB energy storage system application demonstration projects have been established worldwide, with broad development prospects.

In view of the large fluctuations in output power of direct-drive permanent magnet synchronous wind turbines with changes in wind speed, the article proposes to combine the advantages of all-vanadium redox flow batteries and super capacitor energy storage methods, and super capacitors can suppress high peaks and high frequencies caused by sudden changes in wind speed. Wind power output changes, the all-vanadium redox flow battery compensates for relatively smooth, low-frequency wind power output fluctuations, and makes full use of the characteristics of dynamic absorption and timely release of energy in hybrid energy storage systems [1]. The two complement each other and overcome the shortcomings of single energy storage. The smooth dynamic fluctuation of the output power of the wind turbine. The research results verify the effectiveness of the proposed hybrid energy storage system to stabilize wind power output.

2. Power generation principle and structure of vanadium redox flow battery

The all-vanadium flow battery (VRB) was proposed by analysis in 1984. Compared with other energy storage, it has the characteristics of independent design of power capacity, safety, long life, and low life cycle cost, as shown in Table 1.

| Energy storage method | Super capacitor | Lead-acid batteries | lithium batteries | All vanadium flow battery | Pumped storage |
|-----------------------|-----------------|---------------------|------------------|---------------------------|----------------|
| Power/MW              | - 0.1           | 0.1 - 10            | 0.1 - 1          | 1 - 100                   | >100           |
| Specific energy/(Wh/kg) | 3 - 5          | 30 - 50             | 75 - 200         | 15 - 20                   | 0.5 - 1.5      |
| Energy efficiency/%   | 85 - 95         | 60 - 70             | 90 - 95          | 75 - 80                   | 70 - 75        |
| Cycle life / ten thousand times | 5              | 0.05 - 0.1          | 0.1 - 1          | 2                         | 1.46           |
| Depth of discharge/%  | > 90            | < 70                | > 90             | 100                       | 100            |
| Environmental protection / safety / site selection | Good / medium / easy | Poor/low/easy | Medium/low/easy | Good/high/easy | Poor/medium/difficult |
| Total investment cost/ (ten thousand yuan/kW5h) | 15              | 0.5                 | 1.5              | Pile 0.8 electrolyte      | 0.6            |
| Total lifetime cost/(yuan/(kWh/d))       | 0.6             | 1                   | 3                | 0.18                      | 0.06           |

VRB consists of a stack, positive and negative liquid storage tanks, circulation pumps and control systems. Among them: the stack is composed of multiple single VRBs in series, and the single battery is composed of electrodes, baffles, graphite felt electrodes, and graphite conductive plates, ionic diaphragm combination; the positive electrode electrolyte is composed of V(V) and V(IV) ion solutions, and the negative electrode electrolyte is composed of V(III) and V(II) ion solutions; the circulating pump is the power part of the entire system, To complete the transportation of the electrolyte; the role of the control system is to complete the charge and discharge control and protection of the vanadium battery [2] . The working principle of VRB is shown in Figure 1.
The chemical reaction equation of VRB is as follows:

\[
\text{positive electrode: } V^{4+} - e^- \xleftrightarrow{\text{Recharge/Discharge}} V^{5+} \tag{1}
\]

\[
\text{negative electrode: } V^{3+} + e^- \xleftrightarrow{\text{Recharge/Discharge}} V^{2+} \tag{2}
\]

The general reaction equation is

\[
VO^{2+} + H_2O + V^{3+} \xleftrightarrow{\text{Recharge/Discharge}} VO_2^+ + V^{2+} + 2H^+ \tag{3}
\]

The potential difference between the electrodes of the single VRB and \( V^{4+} / V^{5+}\) and \( V^{3+} / V^{2+}\) is about 1.26V. When charging, the positive electrode \( VO_2^+\) loses electrons to form \( VO_2^{2+}\), the negative electrode \( V^{3+}\) gets electrons to form \( V^{2+}\), and the electrons pass through the external circuit from the positive electrode to the negative electrode to form a current, and \( H^+\) passes through the ion-conducting membrane transfers charge from the positive electrode to the negative electrode, forming a closed circuit [3].

3. Equivalent circuit model of vanadium battery

The equivalent circuit of a vanadium battery is shown in Figure 2. Among them: the state of charge (SOC) represents the amount of active chemical substances in the battery, which is equivalent to a change; the potential of the battery stack is affected by the change of SOC and is equivalent to a controlled voltage source; the pumping loss is equivalent to a controlled current The source is controlled by the pump loss current \( I_{\text{pump}}\), and \( I_{\text{pump}}\) is determined by the current \( I_{\text{stack}}\) and SOC. The power loss of vanadium batteries is mainly divided into equivalent internal resistance loss (respectively the loss of resistance \( R_{\text{reaction}}\) due to reaction kinetics and the loss of resistance \( R_{\text{resistive}}\) due to solution,
membrane, bipolar plate, and electrode) and external parasitic resistance loss $P_{\text{parasitic}}$ (divided into fixed Resistance loss $P_{\text{fixed}}$ and pump loss $P_{\text{pump}}$).

In Figure 2, the SOC is equivalent to a variable; the battery stack is equivalent to a controlled voltage source; the pumping loss is equivalent to a controlled current source, which is controlled by the pump loss current $I_{\text{pump}}$, and $I_{\text{pump}}$ is determined by the current $I_{\text{stack}}$ and SOC together; VRB Power loss is mainly divided into equivalent internal resistance loss (including $R_{\text{reaction}}$ loss caused by dynamics and $R_{\text{resistive}}$ loss caused by solution, membrane, bipolar plate, and electrode) and parasitic loss $P_{\text{parasitic}}$ (including fixed resistance loss $P_{\text{fixed}}$ and pump loss $P_{\text{pump}}$). When VRB is discharged to 20% SOC, the estimated loss is 21%, of which the internal resistance loss is 15% and $P_{\text{parasitic}}$ is 6%, the VRB equivalent circuit parameter value can be calculated. From the Nernst equation:

$$V_{\text{cell}} = V_{\text{equilibrium}} + 2k \log \left( \frac{SOC}{1 - SOC} \right)$$

Among them, $V_{\text{cell}}$ represents the voltage of the single battery, $k=(RT/F)\ln10=0.059$, $R=8.314$J/K·mol; $T=298$K; $F=96500$C/mol; $V_{\text{equilibrium}} = 1.25$V (single VRB potential difference).

4. VRB SOC simulation analysis
This article models and simulates VRB. VRB simulation parameters are shown in Table 2.

| rated power | Rated Capacity | Output voltage range | Output current | $R_{\text{reaction}}$ | $R_{\text{resistive}}$ | $R_{\text{fixed}}$ | $C_{\text{electrodes}}$ |
|-------------|----------------|---------------------|----------------|----------------------|----------------------|---------------------|----------------------|
| 5kW         | 20kWh          | 42V-56V             | 112A           | 0.045Ω               | 0.03Ω               | 13.889Ω            | 0.15F                |

The discharge process of the rechargeable battery VRB (SOC=80%) at a rated output power of 5kW is shown in Figure 3. Set the output current of the DC power supply according to the output voltage to keep its power at 5kW.
We use MATLAB/Simulink to simulate VRB for three hours with a step length of 100 microseconds. The results are shown in Figure 4. Theoretically, during the charging and discharging process of a vanadium battery, the terminal voltage of the vanadium battery changes linearly between 20% and 80% SOC. As shown in Figure 4, the battery model meets the configuration requirements of discharge voltage and SOC.

5. All vanadium redox flow battery energy storage control after being connected to a new energy power station

Distributed energy storage refers to the energy storage device connected to the DC bus of the micro power source or the feeder of the important load; the central energy storage refers to the energy storage device connected to the AC bus of the micro grid. Central energy storage is used for centralized control and has the advantages of convenient maintenance, simple control, high reliability, and reasonable use of energy storage capacity [4]. In this paper, the vanadium battery energy storage device is connected to the AC bus of the microgrid and belongs to the central energy storage method. The functions of the energy storage system are different under different operation modes of the microgrid. In the grid-connected operation mode, the system requires that the energy storage device can stabilize the grid-connected power of distributed power sources and further reduce the impact of power fluctuations on the microgrid system. At this time, PQ control is generally used; in the island operation mode, it is required Energy storage devices can provide voltage and frequency references for the microgrid system, and can reasonably share the load power and maintain the power balance of the entire microgrid system.
Therefore, V/f control is usually adopted [5]. The vanadium battery adopts PQ control when the microgrid is connected to the grid; when the island is running, it adopts V/f control. The VRB energy storage system is controlled by a two-way DC/DC converter, and its control strategy is shown in Figure 5.

**Figure 5.** The control strategy adopted by the vanadium battery DC/DC converter

In Figure 5, the voltage $U_{b} = 150V$ of the vanadium battery at SOC=0.5=150V, after boosting, a DC voltage of 750V can be obtained. $U_{bd}$ is the boosted DC side bus voltage, $I_{b}$ is the vanadium battery current, using the control strategy of voltage outer loop and current inner loop. By comparing the input voltage of 750V and $U_{bd}$, the voltage deviation $\Delta U$ can be obtained, and then the voltage deviation $\Delta U$ can be adjusted by PI, and the given value of the battery charging current $I_{b}^{*}$ can be obtained through the output of the FPI regulator [6]. The actual charging current $I_{b}$ of the battery is compared with $I_{b}^{*}$, and the on-duty ratio D is generated by the PI regulator, and then compared with the triangle wave to generate PWM1 and PWM2 pulse signals, and then to trigger the switching devices of the bidirectional DC/DC converter to affect the battery Perform charge and discharge.

In this simulation, at 0s-0.5s and 2s-3s, the microgrid runs in parallel; at 0.5s-2s, the microgrid runs on islands. In the simulation, the rated voltage of the vanadium battery is $U_b = 150v$, and the rated capacity is $s=500kwh$. Soc characteristics are not considered for the time being [7]. The simulation results are shown in Figure 6 below.

**Figure 6.** Active power emitted by vanadium batteries

6. **Conclusion**

In this paper, vanadium ion diffusion is introduced into the equivalent circuit of VRB, an equivalent circuit simulation model considering ion diffusion is established, and the corresponding operating characteristic simulation method is proposed. Through the simulation of the model under the three states of open circuit, charge-discharge cycle and transient process, the influence of ion diffusion on the change
of ion concentration, battery capacity and battery operating characteristics is systematically studied. The simulation analysis results prove that the model proposed in this paper can realize more accurate VRB operating characteristics simulation, can provide accurate real-time prediction results for VRB operation management and control, and can provide accurate theoretical basis for VRB production process control.

Acknowledgments
Fund Projects: Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No.20JK0749).

7. References
[1] Gandomi, Y. A., Aaron, D. S., Zawodzinski, T. A., & Mench, M. M. In situ potential distribution measurement and validated model for all-vanadium redox flow battery. Journal of The Electrochemical Society, 163(1) (2016) A5188-A5201.
[2] Reed, D., Thomsen, E., Li, B., Wang, W., Nie, Z., & Koeppel, B., et al. Performance of a low-cost interdigitated flow design on a 1 kw class all vanadium mixed acid redox flow battery. Journal of Power Sources, 306(2) (2016) 24-31.
[3] Wang, S., Huang, Y., Huo, J., Dou, S., & Hu, K. Graphitic c3n4 as a powerful catalyst for all-vanadium redox flow batteries. RSC Adv., 6(70) (2016) 66368-66372.
[4] Chen, Y. S., Ho, S. Y., Chou, H. W., & Wei, H. J. Modeling the effect of shunt current on the charge transfer efficiency of an all-vanadium redox flow battery. Journal of Power Sources, 390(6) (2018) 168-175.
[5] Kumar, S., & Jayanti, S. Effect of flow field on the performance of an all-vanadium redox flow battery. Journal of Power Sources, 307(3) (2016) 782-787.
[6] Huang, Y., Deng, Q., Wu, X., & Wang, S. N, o co-doped carbon felt for high-performance all-vanadium redox flow battery. International Journal of Hydrogen Energy, 42(10) (2016) 7177-7185.
[7] Yang, D. S., Lee, J. Y., Jo, S. W., Yoon, S. J., & Hong, Y. T. Electrocatalytic activity of nitrogen-doped cnt graphite felt hybrid for all-vanadium redox flow batteries. International Journal of Hydrogen Energy, 43(3) (2017) 15-26.