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Analysis of Influence of Electrochemical Battery Energy Storage Regulation Technology on Stable Operation of Power System

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This paper studies the energy storage technology of all-vanadium redox flow battery (VRB), analyzes the energy storage mechanism of VRB, builds an energy storage system model for VRB, and validates the validity of the relevant parameters of the model, on these basis, a new charge-discharge strategy for battery energy storage systems is proposed. The research results show that the multi-VRB energy storage system designed in this paper can effectively suppress the maximum power fluctuation in the wind power plant power grid. The active power curve in the power grid is smoother than the traditional energy storage system. The power converter is designed as a double-closed-loop control, which can control the voltage in the DC bus to a greater extent and suppress over-charge and over-discharge. The upper and lower limits of the working voltage of the battery energy storage system are respectively set to 610V and 400V. The power distribution of the multi-VRB energy storage system can greatly reduce the cycle charge-discharge times of the battery pack and increase the working life of the energy storage system.

1. Introduction

With the rapid development of society, the traditional fossil energy reserves in the worldwide have been declining rapidly every year. The search for a new type of energy that can be recycled without pollution has become a research hotspot. Among them, wind power and hydropower generation are currently the major new energy utilization methods (Chen and Ding, 2016). Wind power generation and hydropower generation have typical volatility and randomness, which are manifested in: uncontrollable power generation volatility; uncontrollable power generation output; difficult transmission cost control (Luo and Ooi, 2006; Gjengedal, 2010; Xie et al., 2011).

Electrochemical energy storage technology is an effective means to solve the above-mentioned defects. Generally, the electrochemical energy storage system is configured on the power supply side or the load side, so as to improve the control ability of the power system (Hall and Bain, 2008; Cao and Yang, 2012; Chen and Guo, 2015). Electrochemical batteries are one of the most used containers in current energy storage systems. They have the advantages of structural modularization, product commercialization, and long cycle life (Nithya and Gopukumar, 2015; Muddappa and Kumar, 2014). Researchers have conducted research on electrochemical batteries in the energy storage, charge-discharge strategies of renewable energy generation, and achieved some results (Chang et al., 2009).

VRB is a new type of electrochemical battery, which has the great advantage of maintaining original capacitance after repeated charging and discharging, now it has been gradually applied to practical power engineering (Kear, Shah and Walsh, 2012; Zhao et al., 2009; Huang et al, 2008; Li et al., 2011; Ding et al., 2013). Researchers studied the advantages of the VRB energy storage system in the charging and discharging mechanisms, fluctuating control, smoothing and controlling of electric field frequency fluctuations (Shah et al., 2011; Wei et al., 2014). However, the above studies are all under ideal laboratory state, at present, there is no literature that has considered constraints of practical engineering applications and the safety of external converters (Joerissen et al., 2004).

This paper studies the energy storage technology of VRB, analyzes the energy storage mechanism of VRB,

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builds an energy storage system model for VRB and validates the validity of related parameters of the model. Based on these, it proposes a new charge-discharge strategy for battery energy storage systems. Finally, the dynamic response capabilities of the proposed VRB energy storage system and the traditional constant-power energy storage system are compared and analyzed.

2. Introduction of VRB energy storage system

Figure 1 shows the composition and working principle of the VRB used in this paper. The system consists of positive and negative electrolyte storage tanks, an electric energy inverter, a load, an ion membrane, pressure pumps, a battery with positive and negative electrodes, etc. The pressure pumps transport the vanadium solutions in the positive and negative electrodes into the battery stack respectively to realize the relevant chemical reactions of the battery energy storage. The active materials in the system are recycling all the time so as to achieve the charge-discharge process of the VRB.
In order to facilitate analysis of the electrochemical characteristics of the battery system during charging and discharging, the system of Figure 1 is equivalent to Figure 2. The state of charge (SOC) in the figure can be expressed as:

$$\mathrm{SOC}_{t+1} = \mathrm{SOC}_t + \Delta\mathrm{SOC}_t \tag{1}$$

$$\Delta\mathrm{SOC}_t = \frac{P_{\mathrm{stack}} T_{\mathrm{step}}}{P_{\mathrm{n}} T_{\mathrm{rated}}} \tag{2}$$

In the formula, P_{stack} and P_n are the actual output power and rated output power of the system respectively; T_{step} is the number of iterations; T_{rated} is the actual working time.

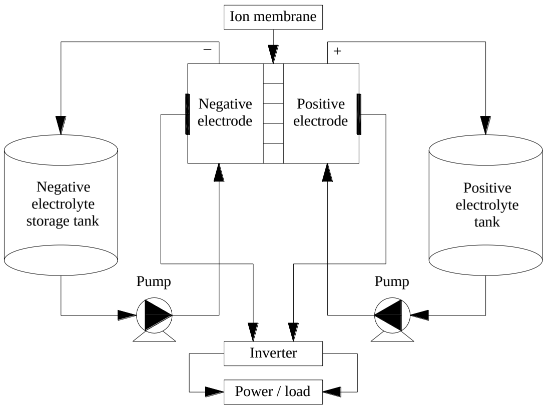


Figure 1: Working principle of VRB system

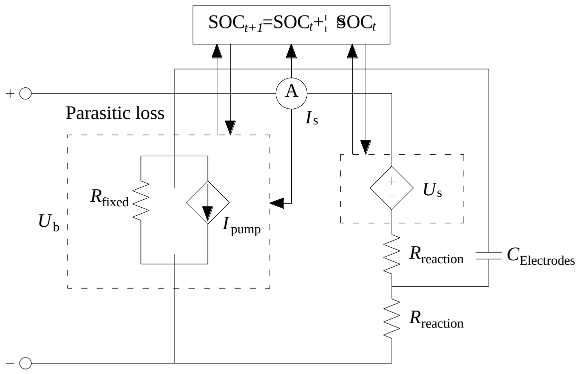


Figure 2: Equivalent circuit of VRB

In actual work, multiple VRB are connected in series to form a battery pack, thereby increasing its maximum working voltage. The voltage of the battery pack can be expressed as:

$$U_{\mathrm{s}} = n\left[V_{\mathrm{equilibrium}} + 2\frac{RT}{F}\ln\left(\frac{\mathrm{SOC}}{1-\mathrm{SOC}}\right)\right] \tag{3}$$

n, T are the number of batteries and battery operating temperature; R and F are relevant constants. The internal electrochemistry of the battery will cause the current loss I_s in charging and discharging, and the loss of the pressure pump in the transmission of the reaction solution I_{pump} is:

$$I_{\mathrm{pump}} = \frac{k_{\mathrm{T}}\dfrac{I_{\mathrm{s}}}{\mathrm{SOC}}}{U_{\mathrm{b}}} \tag{4}$$

3. Electric field power control based on energy storage technology of VRB

After comprehensive consideration of multiple factors such as economic efficiency, safety, and power transmission efficiency of the electrochemical battery energy storage systems, an improved voltage pulsewidth modulation converter is used as a transit hub for the energy conversion between electrochemical battery energy storage system and the large-scale power grid, its schematic diagram is shown in Figure 3.

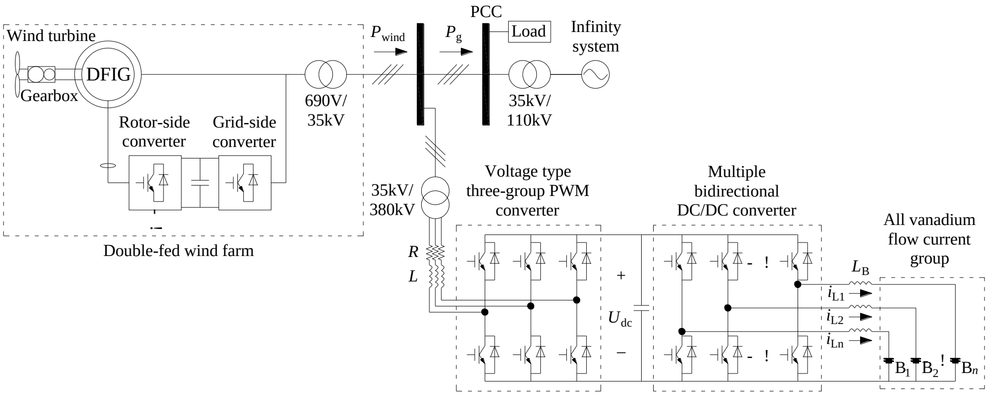


Figure 3: Architecture of wind power plant based on VRB energy storage technology

The energy conversion channel of the energy storage system and the large-scale power grid is on the DC bus side, and the feedforward algorithm is used to control the constant power conversion voltage.

$$\begin{cases} u_{gd}^{*} = u_{gd} - Ri_{gd} - L\dfrac{\mathrm{d}i_{gd}}{\mathrm{d}t} + \omega Li_{gq} \\ u_{gq}^{*} = -Ri_{gq} - L\dfrac{\mathrm{d}i_{gq}}{\mathrm{d}t} - \omega Li_{gd} \end{cases} \tag{5}$$

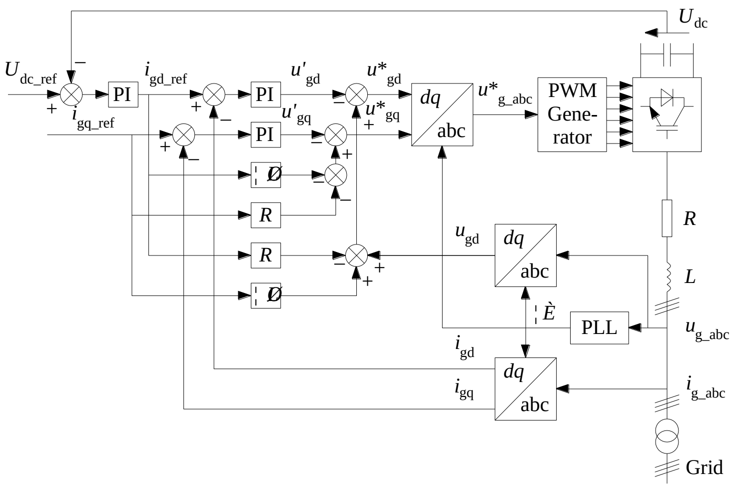


Figure 4: AC and DC power converter control system

AC and DC voltage conversion control system diagram is shown in Figure 4. Real-time adjustment of active/reactive power is achieved by controlling the d-axis and q-axis components of the current of AC side.
On the basis of Figure 4, the multiple AC/DC voltage conversion control system shown as Figure 5 is established so as to realize bi-directional transmission between electrochemical battery energy storage system and large-scale power grid, and can effectively enhance the safety of the battery energy storage system during charge and discharge switching. Define the maximum threshold for charge and discharge:

$$\begin{cases} P_{\mathrm{charge}} = P_{\mathrm{B\_ref}}, & 0.2<\mathrm{SOC}<0.8 \\ i_{\mathrm{charge}} = i_{\mathrm{L\_ref}} = i_{\min}, & \mathrm{SOC} \geq 0.8 \end{cases} \tag{6}$$

$$\begin{cases} P_{\text{discharge}} = P_{\text{B\_ref}}, & 0.2<\text{SOC}<0.8 \\ i_{\text{discharge}} = i_{\text{L\_ref}} = i_{\min}, & \text{SOC} \le 0.2 \end{cases} \tag{7}$$

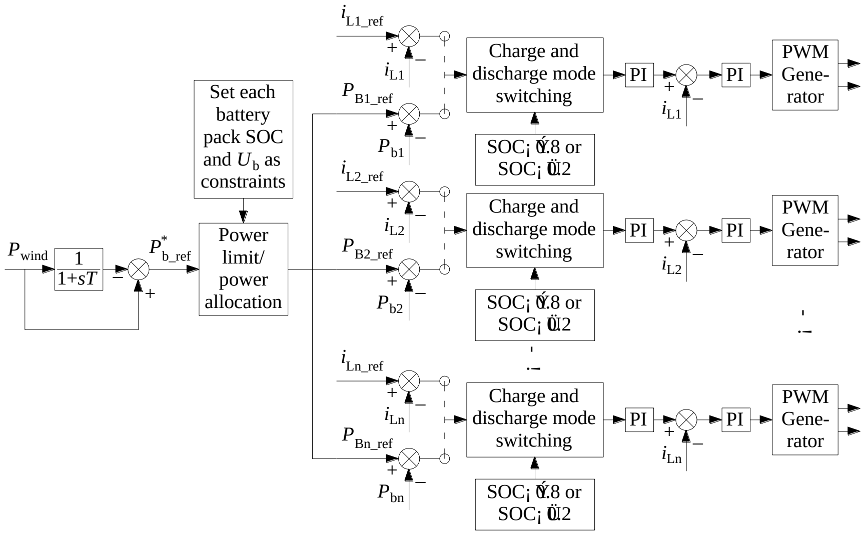


Figure 5: Control architecture of multiple AC and DC voltage converter

4. Optimal allocation scheme of multi-VRB energy storage

Figure 6 shows the optimal allocation scheme for the energy storage of multi-VRB. The maximum charging power of the electrochemical energy storage system can be expressed as:

$$P_{\text{bx\_charge}}^{\max} = \frac{U_{\text{high}}^2 - U_{\text{s}} U_{\text{high}}}{R_{\text{reaction}} + R_{\text{resistive}}} + \frac{U_{\text{high}}^2}{R_{\text{fixed}}} + \frac{k_{\text{T}} I_{\text{s}}}{\text{SOC}} \tag{8}$$

The maximum discharge power is:

$$P_{\text{bx\_discharge}}^{\max} = \frac{U_{\text{s}} U_{\text{low}} - U_{\text{low}}^2}{R_{\text{reaction}} + R_{\text{resistive}}} - \frac{U_{\text{low}}^2}{R_{\text{fixed}}} - \frac{k_{\text{T}} I_{\text{s}}}{\text{SOC}} \tag{9}$$

Through the process of Figure 6, the real-time and accuracy of the system's energy storage can be achieved, damage of related equipment caused by overcharge and over-discharge can be avoided.

5. Verification of simulation model

The smoothing power fluctuation and overall optimization strategy of the electrochemical energy storage system proposed in this paper are validated. A simulation model is established to simulate the operation of the battery energy storage system under wind power plant conditions. Figure 7 shows the total output power of the smoothing wind power and battery energy storage system. It can be seen from the figure that the transmission power of the original wind power is very volatile and the maximum instantaneous amplitude is 0.9 MW. The maximum instantaneous amplitude after the stabilization of the system designed by this paper has dropped to 0.42 MW, which proves the superiority of the design system in this paper.

Figure 8 shows the change of charge and output power of a level-2 VRB energy storage system. Figure 9 shows the terminal voltage of each group of the level-2 VRB energy storage system. When the maximum DC bus voltage is below 800V, the transmission power of the grid and battery energy storage system can work normally. Using the power allocation strategy proposed in this paper, the level-2 VRB energy storage system is always performing charge and discharge operations. While using traditional power distribution, the state of charge of different battery packs is more volatile. According to the actual calculation results, the upper and lower limits of the working voltage of the battery energy storage system are 610V and 400V respectively.

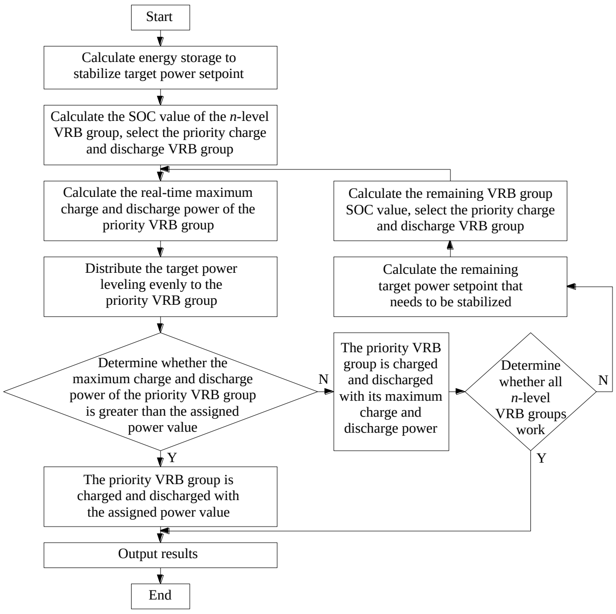
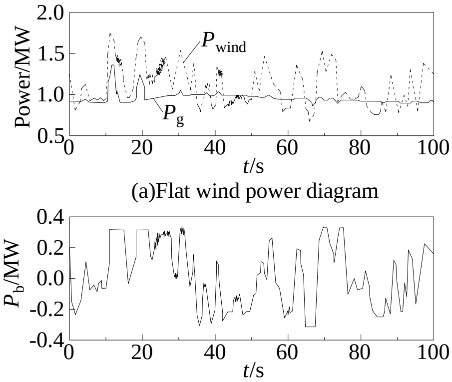


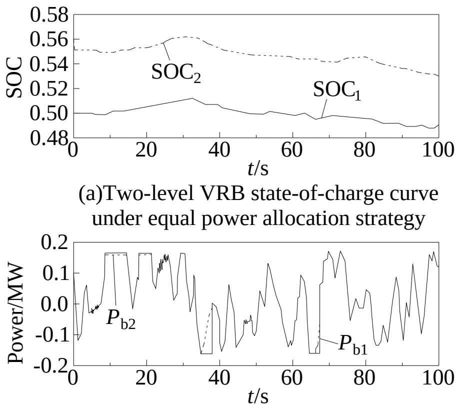
Figure 6: Optimal allocation scheme of multi-VRB energy storage



(a)Flat wind power diagram

(b)VRB Energy storage system total output power curve

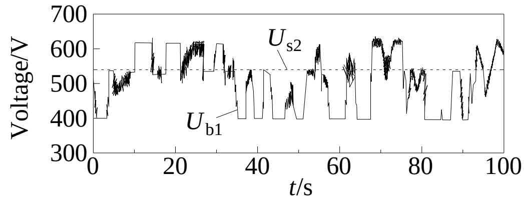
Figure 7: Total output power of smoothing wind power and battery energy storage system



(a)Two-level VRB state-of-charge curve under equal power allocation strategy

(b)Two-level VRB output power curve under average power allocation strategy

Figure 8: Change of charge and output power of level-2 VRB energy storage system



Level 2 VRB voltage response characteristics

Figure 9: Group terminal voltage of level-2 VRB energy storage system

6. Conclusion

This paper studies the energy storage technology of VRB, analyzes the energy storage mechanism of VRB, builds an energy storage system model for VRB, and validates the validity of the related parameters of the model. Based on these, it proposes a new charge-discharge strategy for battery energy storage systems. The research conclusions are as follows:

(1) The multi-VRB energy storage system designed in this paper can effectively suppress the maximum power fluctuation in the wind power plant power grid. The active power curve in the power grid is smoother than the traditional energy storage system. The power converter is designed as a double-closed-loop control, which can control the voltage in the DC bus to a greater extent and suppress overcharge and over-discharge.

(2) The upper and lower working voltages of the battery energy storage system designed in this paper are 610V and 400V, respectively. The power distribution of the multi-VRB energy storage system can greatly reduce the cycle charge-discharge times of the battery pack and increase the working life of the energy storage system.

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