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The study of dynamic response model and energy optimization management process for the application of vanadium redox flow battery in microgrid

Jing-Wei Ni[1], Ming-Jia Li[1*], Teng Ma[1]

1 Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy & Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

ABSTRACT

In order to realize the reasonable configuration and efficient operation of vanadium redox flow battery (VRB) in microgrid containing renewable energy and the traditional power system such as supercritical carbon dioxide coal-fired power generation system, an advanced dynamic response model of VRB is constructed and a feasible energy optimization process is proposed in this paper. First, the U_{battery}-I_{battery}-SOC curves are obtained based on the improved electrochemical mode. Key parameters for the simplified equivalent circuit model of VRB are further analyzed to refine the dynamic response model of VRB with fast computational capabilities. Second, the optimized configuration design method of microgrid is proposed with the consideration of investment costs, operation costs, economic benefits and rates of renewable energy utilization. Finally, the energy optimization management process for microgrid is proposed combining with the load distribution algorithm aiming at efficiency. The results are presented as follow. First, the combination of the fitted curve and the experimental data can be used to calculate the key parameters of the simplified equivalent circuit model of VRB. In the state of charge, the maximum U_{battery} of VRB of 86.14 V is obtained at the I_{battery} of 10A and SOC of 0.99. Second, with the lowest average daily cost as the optimization target, the optimal rated power and rated capacity of VRB are 891 kW and 7344 kWh, respectively. Finally, the change frequency of load distribution results for grid, VRB and S-CO_2 in microgrid matches their dynamic response characteristics. The VRB energy storage system is operating at an efficient level with a time average efficiency of 82.50%. The time average efficiency of S-CO_2 generation system is up to 43.53%. The study can provide a theoretical reference for the optimal operation of the VRB energy storage system.

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Keywords: vanadium redox flow battery, dynamic response model, optimized configuration design method, load distribution algorithm, energy optimization management process, microgrid

NONMENCLATURE

Symbols	
AC	Average daily cost of energy abandonment, CNY
a	Scaled capacity costs of cell stacks, CNY/kW
B	Average daily benefits of VRB, CNY
b	Scaled capacity costs of electrolytes, CNY/kWh
C_i	The concentration of vanadium ions, mol/L
c	Loss factor of energy abandonment, CNY/kWh
FC	Fixed costs, CNY
I_{battery}	Current of the battery, A
P_{c}	Output power of VRB while charging, kW
$P_{\text{VRB,c}}$	Actual power of VRB while charging, kW
P_{d}	Output power of VRB while discharging, kW
$P_{\text{VRB,d}}$	Actual power of VRB while discharging, kW
P_{PV}	Output power of photovoltaic power generation, kW
P_{Wind}	Output power of wind power, kW
$P_{\text{S-CO}_2}$	Output power of the S-CO_2 coal-fired power generation system, kW
P_{grid}	Power purchased from the grid, kW
P_{Load}	Real-time user load power in microgrid, kW
U_{battery}	Voltage of the battery, V
U_{stack}	Stack voltage of VRB, V
TC_{VRB}	Total costs of VRB, CNY
VC	Variable cost of VRB, CNY
η_{c}	Charging efficiency of VRB
η_{d}	Discharging efficiency of VRB

1. INTRODUCTION

To develop the clean and low-carbon energy, to build a safe and efficient modern energy system are important strategic layouts for national energy development [1]. In response, the Chinese government has taken a responsible and proactive approach by setting targets to achieve "peak carbon and carbon neutrality" by 2030 and 2060, respectively. Renewable energy sources with disadvantages such as uncertainty and intermittency are being rapidly developed [2]. Their direct connection to the grid will cause large impacts, which including transmission line blockage and grid destabilization, on the stability of the grid and the quality of energy supply. The configuration of stable, reliable, efficient and large-scale energy storage system in microgrid can achieve the goals of load smoothing and flexible access to renewable energy.

Energy storage systems have been classified into mechanical energy storage, chemical energy storage, thermal energy storage, electromagnetic energy storage and electrochemical energy storage by He et al. according to the form of stored energy combined with the mechanism of the storage process [3]. Electrochemical energy storage systems have been widely concerned by scholars at home and abroad because of its high conversion efficiency, short response time and high energy density. The vanadium redox flow battery (VRB) has been one of the current frontiers and thermoelectricity in the field of electrochemical research due to its outstanding advantages including the long service life and low overall cost of electricity [4].

Current research on VRB is mainly focused on the performance enhancement of battery, with little research involving the application of VRB in microgrid, including its dynamic modeling and energy management. Particularly in dynamic response model of VRB, the effects of the pump have not been fully considered on the system efficiency [5][6]. The system efficiency is significantly influenced by the electrolyte flow rate and the flow state in the pipe. In the energy optimization management of VRB, studies have focused on the economic analysis based on the steady-state system model [7]. In some scenarios the efficiency of VRB is considered to be constant, while in others the instantaneous charge/discharge efficiency is obtained by fitting an equivalent circuit model. Furthermore, the dynamic response characteristics of each subsystem in microgrid and the impact of user load changes on the system have not been fully considered in the existing research on the energy management of microgrid.

Therefore, an improved electrochemical model of VRB considering the electrolyte flow rate and the corresponding flow state is primarily developed in this paper to obtain the U_{battery}-I_{battery}-SOC curve. The simplified equivalent circuit model is further constructed and combined with the model of energy storage converter. Second, the dynamic response model that enable the application of VRB in microgrid containing renewable energy and the supercritical carbon dioxide coal-fired power generation is refined. Finally, the energy optimization management process of the VRB is proposed with the objective of the economy of microgrid and dynamic efficiency of each subsystem. The research results can provide a theoretical reference for the application of the VRB energy storage system in microgrid.

2. DYNAMIC RESPONSE MODEL OF VRB

The dynamic response model of VRB is composed of the improved electrochemical model, the simplified equivalent circuit model and the energy storage converter model. First, the U_{battery}-I_{battery}-SOC curves are fitted based on the improved electrochemical model. Second, key parameters of the simplified equivalent circuit model are obtained based on the curve data and computational equations. Finally, combining the simplified equivalent circuit model and energy storage converter model, a response model that can characterize the dynamic efficiency of VRB can be constructed.

2.1 The improved electrochemical model of VRB

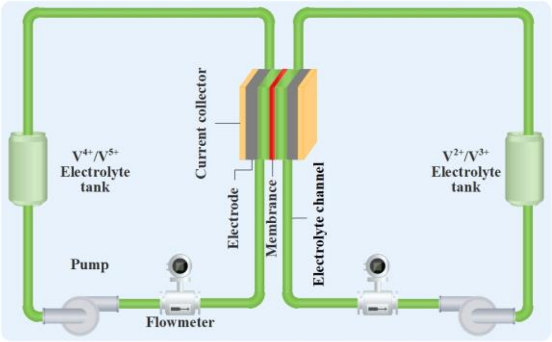

Fig. 1. System structure of the vanadium redox flow battery

The system structure of VRB is shown in Fig. 1. The improved electrochemical model of VRB is specifically composed of a hydrodynamic model and a basic electrochemical model. COMSOL Multiphysics is used for modeling in this paper. The improved electrochemical model and corresponding conclusions have been discussed in the author's another article under review. In this paper, the model is only used to obtain relevant data for the calculation of the following simplified equivalent circuit model.

First, in the hydrodynamic model section, the electrolyte flow field is calculated using the classical laminar and the turbulent flow model in hydrodynamics. Second, the electrolyte flow velocity distribution results are passed to the electrochemical model section for calculation. Finally, the U_{battery}-I_{battery}-SOC curves are fitted based on the simulation results and used to calculate the relevant parameters of the simplified equivalent circuit model.

The electrolyte circulation in the system requires shaft work provided by the pump. There are various pressure losses during its flow. Therefore, the pump work considering the electrolyte flow losses needs to be calculated to evaluate its effect on the performance of VRB. The flow state of the electrolyte in the pipe is considered as well.

The electrochemical model is established based on the classic VRB model, in which the electrode reaction, battery self-discharge reaction, and sulfuric acid dissociation reaction are considered.

The state of charge (SOC) of VRB is defined by Eq. (1).

$$\mathrm{SOC}=\frac{C_2+C_5}{C_2+C_3+C_4+C_5} \tag{1}$$

Where C is the ionic concentration of vanadium ions in each valence state.

2.2 The simplified equivalent circuit model of VRB

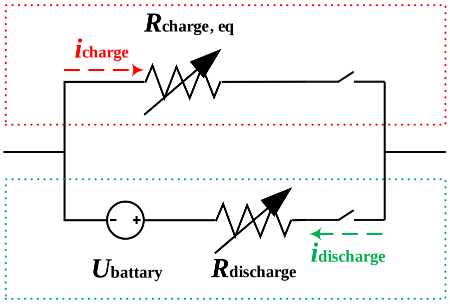

Fig. 2. Simplified equivalent circuit model

A simplified equivalent circuit model constructed based on the calculation results of multi-physical field coupling model is shown in Fig. 2. Based on the U_{stack} data in the literature [8] and the above calculation results, the equivalent resistance can be calculated based on Eq. (2)-(4). When charging, the VRB is equated to a variable resistor. When discharging, the VRB can be equated to a series connection of a voltage source and a variable resistor.

$$U_{\text{stack}}=N_{\text{cell}}\times E_{\text{cell}}-U_{\text{loss}} \tag{2}$$

$$U_{\text{stack,charge=}}U_{\text{battery,charge}}-I_{\text{battery}}\times R_{\text{charge,eq}} \tag{3}$$

$$U_{\text{stack,discharge=}}U_{\text{battery,discharge}}+I_{\text{battery}}\times R_{\text{discharge}} \tag{4}$$

Where U_{stack} is the stack voltage of VRB, U_{battery} is the voltage of the battery.

2.3 The model of energy storage converter

The DC/DC energy storage converter based on a phase-shifted full-bridge circuit used in the literature [9] is chosen in this paper.

2.4 The definition of efficiency of VRB

The efficiency of VRB can be divided into real-time charging efficiency and discharging efficiency，in which the effect of pump work is considered. The two efficiencies can be defined by Eq. (5)-(6).

$$\eta_{\mathrm{c}}=\frac{P_{\mathrm{VRB,c}}}{P_{\mathrm{c}}+P_{\mathrm{Pump}}} \tag{5}$$

$$\eta_{\mathrm{d}}=\frac{P_{\mathrm{d}}-P_{\mathrm{Pump}}}{P_{\mathrm{VRB,d}}} \tag{6}$$

Where η_c is the charging efficiency of VRB, η_d is the discharging efficiency of VRB, P_{VRB} is the actual power of VRB, P_c and P_d are the output power of VRB.

3. ENERGY OPTIMIZATION MANAGEMENT PROCESS

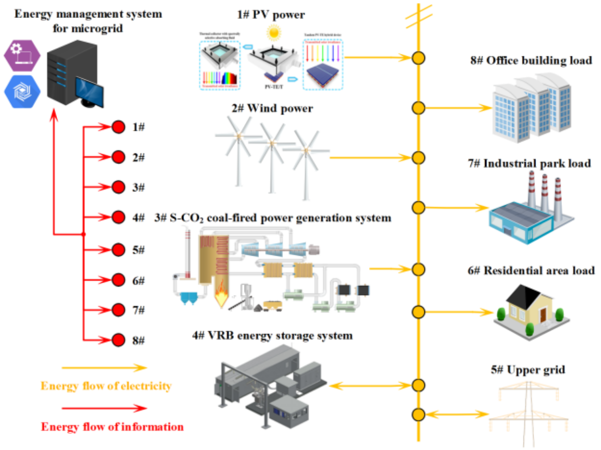

Fig. 3. System structure of the microgrid

In the microgrid with energy storage system, the large-scale access of distributed power sources and renewable energy can be fully realized. The constructed VRB energy storage system is applied to a microgrid shown in Fig. 3, in which the solar photovoltaic (PV) power, wind power and supercritical carbon dioxide (S-CO_2) coal-fired power generation system are combined. Among them, the user load scenario contains the residential area, industrial park, and office building.

Due to the complex composition of the microgrid, it is a key challenge to allocate the power output of each generation system and VRB in real time to efficiently balance the power supply and demand of microgrid. In this section, an energy optimization management process incorporating the configuration optimization design method and the load distribution algorithm is presented.

3.1 The introduction of microgrid

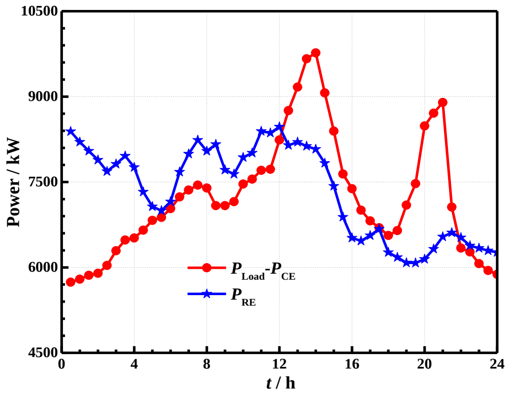

Fig. 4. Real-time power in the microgrid

The real-time power in the microgrid for a typical day is shown in Fig. 4. The installed power of solar power is 3 MW, and the installed power of wind power is 10 MW. The conventional power generation system in the microgrid is selected as the S-CO$_2$ coal-fired power generation system with high power generation efficiency at present, and its power generation is stable at 17.95 MW.

3.2 Configuration optimization design method for microgrid

The configuration optimization design method for microgrid based on the economic model is constructed according to the technical and economic indicators of VRB. Factors such as the investment cost, operation cost, economic benefits and renewable energy utilization are comprehensively considered in the constructed cost function of microgrid, which can be expressed as Eq. (7)-(10). The calculation of the investment cost and operating cost of VRB is based on the previous work of our team [11].

$$f(P_{\text{VRB}}^{\text{rated}}, E_{\text{VRB}}^{\text{rated}}) = TC_{\text{VRB}} - B + AC \tag{7}$$

$$TC_{\text{VRB}} = VC + FC = (P_{\text{VRB}}^{\text{rated}} \times a + E_{\text{VRB}}^{\text{rated}} \times b) + FC \tag{8}$$

$$B = \int_{t_1}^{t_2} P_{\text{VRB,d}} C_{\text{e}} dt \tag{9}$$

$$AC = \begin{cases} \int_{t=0}^{24} c \times \left(P_{\text{PV}} + P_{\text{Wind}} - P_{\text{VRB,c}} + P_{\text{S-CO}_2} + P_{\text{Grid}} - P_{\text{LOAD}} \right) dt, & \text{charging} \\ \int_{t=0}^{24} c \times \left(P_{\text{PV}} + P_{\text{Wind}} + P_{\text{VRB,d}} + P_{\text{S-CO}_2} + P_{\text{Grid}} - P_{\text{LOAD}} \right) dt, & \text{discharging} \end{cases} \tag{10}$$

Where $P_{\text{VRB}}^{\text{rated}}$ is rated power, $E_{\text{VRB}}^{\text{rated}}$ is rated capacity, TC_{VRB} is total costs, B is average daily benefits, AC is average daily cost of energy abandonment.

Based on the objective function constructed by Eq. (7), the lowest average daily cost is selected as the optimization objective. And the configuration optimization design is carried out using genetic algorithm.

3.3 Load distribution algorithm of the system

A modified moving average filter algorithm is used in the system load distribution algorithm. The frequency of the load distribution results corresponds to the dynamic response characteristics of each equipment.

The moving average filtering method is often used for signal noise reduction and data smoothing, and is calculated as Eq. (11).

$$Y(n) = \frac{1}{2m+1} \sum_{k=n-m}^{n+m} y(n-k) \tag{11}$$

Where $2m+1$ is the filter width, $Y(n)$ is the target sequence for filter, $y(n-k)$ is the original data sequence.

Depending on the response time of each distributed generation system and VRB, different filter widths are selected to obtain the corresponding filtering results. The adopted load distribution algorithm that can guarantee the full consumption of renewable energy is shown in Fig. 5. For the difference between real-time user power and renewable energy output, different filter widths are selected to obtain high, medium and low frequency components, corresponding to the load instructions of the electricity grid, VRB and S-CO$_2$, respectively. The ratio of the three filter widths is 1:5:50. The algorithm also calibrates the SOC of VRB to ensure that the battery power is in a suitable state after 24 hours of operation.

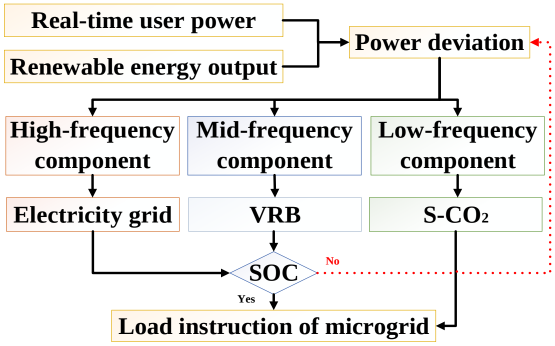

Fig. 5. Load distribution algorithm

3.4 The energy optimization management process for microgrid

The energy optimization management process is mainly composed of configuration optimization design method and load distribution algorithm, which correspond to the economy and efficiency optimization objectives, respectively. The energy optimization management process for the microgrid is shown in Fig. 6. The dynamic response model of S-CO_2 used is based on the previous research results of our team [10].

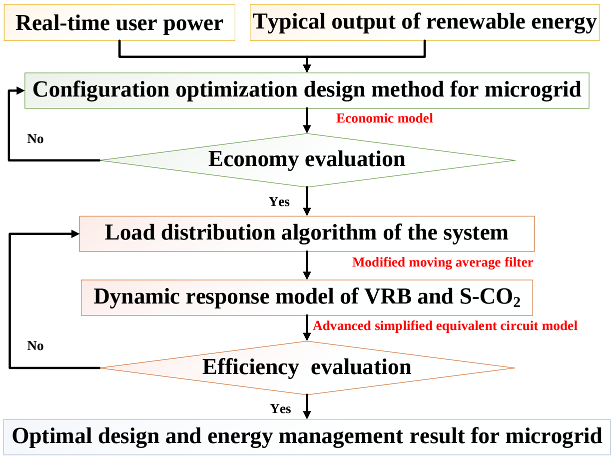

Fig. 6. Energy optimization management process

4. RESULTS AND DISCUSSION

By combining the dynamic response model of VRB and the energy optimization management process of microgrid, the optimal design plan and energy optimization management results of microgrid can be obtained.

4.1 *Results of* the dynamic response model of VRB

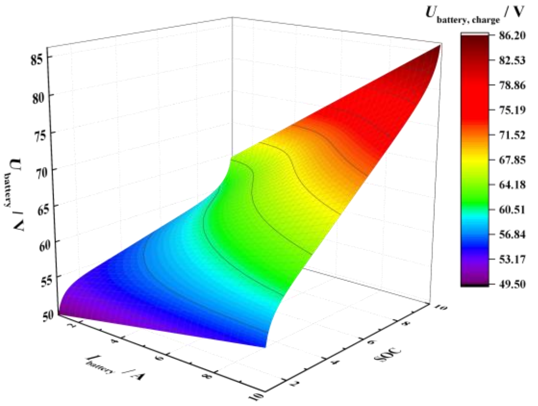

Fig. 7. The Performance curve at the state of charge

In the dynamic response model section, the $U_{battery}$-$I_{battery}$-SOC curves and key parameters for the simplified equivalent circuit model are obtained.

The $U_{battery}$-$I_{battery}$-SOC curves of VRB at the state of charge are shown in Fig. 7. The $U_{battery}$ of VRB increases with the increase of the $I_{battery}$ and SOC. In the state of charge, the maximum $U_{battery}$ of VRB of 86.14 V is obtained at the $I_{battery}$ of 10A and SOC of 0.99.

The key parameters for the simplified equivalent circuit of VRB are shown in Fig. 8. The $R_{charge,eq}$ of VRB decreases with the increase of $I_{battery}$ and SOC, and the corresponding trend of change is fast and then slow.

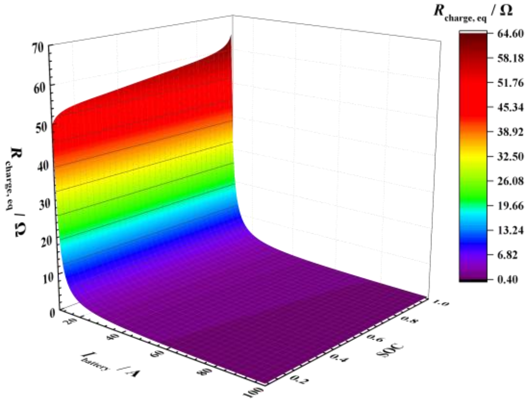

Fig. 8. key parameters of the equivalent circuit model

4.2 *Results of* the energy optimization management

In the energy optimization management section, the load distribution results, performance parameters change of VRB and S-CO_2 are analyzed. With the lowest average daily cost as the optimization target, the optimal rated power and rated capacity of VRB are 891 kW and 7344 kWh based on the configuration optimization design method for microgrid. At this point, the average daily cost of the microgrid decreases to 5192 CNY.

The load distribution results of microgrid are shown in Fig. 9. When applying the energy optimization management process, the change frequency of load distribution results for grid, VRB and S-CO_2 in microgrid matches their dynamic response characteristics.

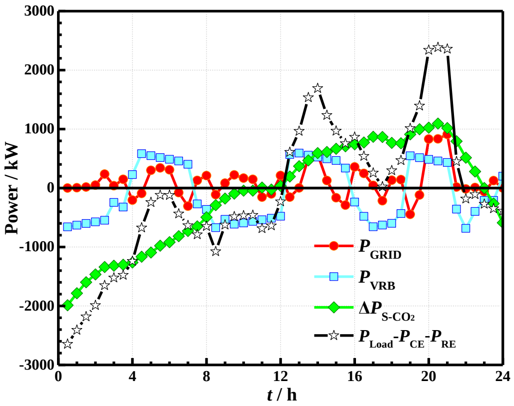

Fig. 9. Load distribution results of microgrid

Performance parameters change of VRB and S-CO_2 are shown from Fig. 10. The results show that the time average efficiency of VRB is operating at a time average efficiency of 82.50%, and the time average efficiency of S-CO_2 generation system is up to 43.53%. Its SOC basically returns to near the initial value after completing 24 hours of operation. Due to the lower variable load frequency, the higher time average efficiency of S-CO_2 is obtained. Efficient and economical operation of microgrid can be achieved by using the proposed energy optimization management process.

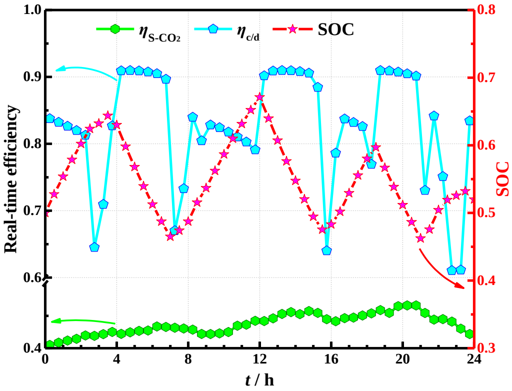

Fig. 10. Change of performance parameters of the vanadium redox flow battery and S-CO_2 power generation

5. CONCLUSIONS

In this paper, a dynamic response model of VRB is established, and key parameters for the simplified equivalent circuit model are obtained. In addition, an energy optimization management process composed of the configuration optimization design method and load distribution algorithm is proposed. The specific conclusions are as follows.

(1) The U_{battery} of VRB increases with the increase of the I_{battery} and SOC. In the state of charge, the maximum U_{battery} of VRB of 86.14 V is obtained at the I_{battery} of 10A and SOC of 0.99. The $R_{\mathrm{charge,eq}}$ of VRB decreases with the increase of I_{battery} and SOC, and the corresponding trend of change is fast and then slow.

(2) With the lowest average daily cost as the optimization target, the optimal rated power and rated capacity of VRB are 891 kW and 7344 kWh based on the configuration optimization design method for microgrid.

(3) Based on the energy optimization management process, the time average efficiency of VRB is operating at a time average efficiency of 82.50%, and the time average efficiency of S-CO_2 generation system is up to 43.53%. In this microgrid, the change frequency of load distribution result and the dynamic response characteristic of each equipment can be well matched.

This work can provide guidance in two aspects. It develops the easily computable dynamic response model of VRB. Furthermore, it provides a feasible idea for the energy optimization management for the application of vanadium redox flow battery in microgrid.

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