International Journal of Smart Grid and Clean Energy

Investigation on SOC Estimation Algorithms for VRFB

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Abstract

Increasing the use of renewable energy based distributed generation (DG) embedded with energy storage systems (ESS) and smart grids are the recent development trend in power and energy systems. Considering the nature of power fluctuation in the DG systems, certain ESS are necessary in realizing optimal energy management and control of power systems. Of the known batteries, the all vanadium redox flow battery (VRFB) is a chemical energy storage device with many merits, e.g., high application flexibility, high efficiency, re-scalability, fast response, long life, and low maintenance requirements. In practice, the real-time estimation of battery's state of charge (SOC) plays a very important role in operating smart grid with DG systems. In this paper, a novel SOC estimation method based on neural networks (NN) and the electrochemical impedance spectroscopy (EIS) analysis is proposed for the VRFB. Basic principles of VRFB and existing SOC estimation methods are firstly reviewed, followed by a set of test results demonstrating the feasibility and effectiveness of the proposed NN based on-line detecting algorithm.

Keywords: Distributed Power Generation (DG), Energy Storage System (ESS), all Vanadium Redox Flow Battery (VRFB), State of Charge (SOC)

1. Introduction

In recent years, technologies related to DG, microgrid and smart grid have developed rapidly [1]. DG is attractive because it can help in moderating the carbon emissions. However, DG has some intrinsic problems of intermittent power and irregular fluctuations. When the penetration of DG increases, voltage of the connected grid is more likely to be disturbed, resulting in poor power quality (PQ). Solving this problem requires the addition of proper ESS. At present, VRFB has been widely recognized as a highly promising large-scale ESS technology having the following features: 1) long-term storage and low self-discharge rate, 2) wide output range, 3) high efficiency, 4) low maintenance requirements, 5) long life, and 6) fast response [2]. When the VRFB is in operation, how to quickly and accurately monitor its SOC supporting optimization functions for the system has become a new focus of research in this field. This paper firstly introduces the VRFB system and reviews commonly used detection methods of VRFB's SOC in open literature. Then, a new real-time VRFB SOC detection scheme based on NN is proposed, which uses VRFB cell impedance parameters obtained from EIS tests to analyze the characteristic parameters required for training the NN. The goal is to enable the trained NN to correctly estimate the SOC of VRFB. The feasibility and validity of the proposed scheme are verified with simulation results.

2. Working Principle of VRFB

VRFB is a flow battery using vanadium ions in different oxidation states to store chemical potential energy, as shown in Fig. 1 (a). It consists of a cell stack, positive/negative electrolytes stored in separate reservoirs, two sets of pumps, and some peripheral systems such as piping and controllers required for the electrolyte flow. The positive/negative active materials of are vanadium ions dissolved in sulfuric acid, and the charge/discharge mechanisms are activated by the valence change of the vanadium ions.

* Manuscript received May 10, 2020; revised March 30, 2021.
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doi: 10.12720/sgce.10.2.162-166

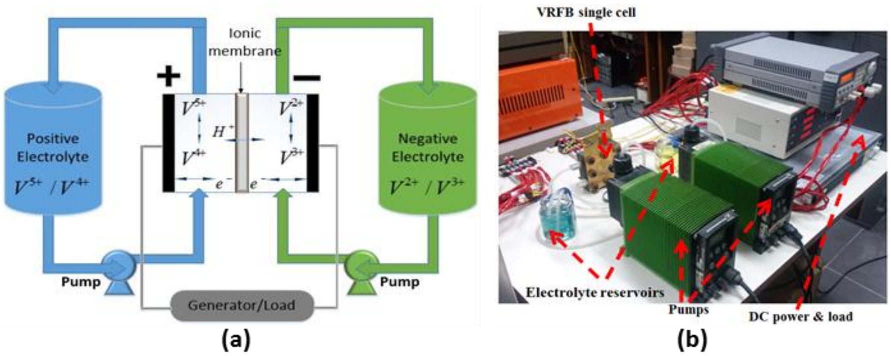

Fig. 1. (a) VRFB operation principle, (b) VRFB single cell experimental system.

VRFB is unique because 1) the redox reaction occurs between two electrolytes and 2) the electrolytes are stored in external reservoirs. When the battery is repeatedly charged/discharged, the active material undergoes no electroplating or loss, and the system capacity is both expandable and flexible. V^{2+}/V^{3+} and V^{4+}/V^{5+} ion pairs act as the electrolytes in negative/positive electrolyte reservoirs, respectively. Once an electrochemical reaction occurs, the carbon electrode causes a flow of electrons through the load, and hydrogen ions maintain charge balance by moving through the ion exchange membrane. Since the products of the electrochemical reaction remain dissolved in the electrolytes, the reverse process causes the solutions to return to their original states [3]. The total stored energy of VRFB is related to the SOC and chemical reaction of the system, and its total power is related to the electrode area of the stack. Fig. 1 (b) shows a simple VRFB cell experiment system built in the Electrical Power Technology Laboratory of the Department of Electrical Engineering, National United University. The following is the process of electrochemical reaction.

Positive electrode half reaction:

$$VO_2^+ + 2H^+ + e^- \underset{charge}{\overset{discharge}{\Leftrightarrow}} VO^{2+} + H_2O \tag{1}$$

Negative electrode half reaction:

$$V^{2+} + \underset{charge}{\overset{discharge}{\Leftrightarrow}} V^{3+} + e^- \tag{2}$$

3. VRFB SOC Real-time Estimation Algorithm

The SOC value of a VRFB is a parameter for measuring the usable capacity, evaluating its performance, and determining the amount of energy stored in the electrolytes. The SOC of VRFB can be defined as the percentage of V^{5+} to total vanadium concentration of the positive electrode, or V^{2+} to total vanadium concentration of the negative electrode. VRFB uses H_2SO_4 solution containing V(IV)/V(V) and V(II)/V(III) redox couples as the positive/negative half-cell electrolytes, respectively. The proportion of each ion in the mixed solution is different depending on the SOC, as described in the following:

$$SOC = \frac{V(V)}{V(IV)+V(V)} \times 100\% = \frac{V(II)}{V(II)+V(III)} \times 100\% \tag{3}$$

The VRFB's SOC detection methods that have been proposed in open literature are introduced below:

- Fuzzy logic algorithm [4]: fuzzy modeling based on input and output test data of the system.
- Kalman filter algorithm [5]: using signal state space model of previous and current states.
- Coulomb counting algorithm [6]: accumulating the amount of energy flow.
- Open circuit voltage method [7]: relating the SOC with the terminal voltage of the VRFB.

- Potentiometric titration method [8]: quantitative analysis of vanadium ions of each valence.
- Spectrophotometry method [9]: using the spectrophotometric principles.
- Electric conductivity method [10]: monitoring different conditions of electrolyte conductivity.

4. The Proposed VRFB Real-time SOC Detection Algorithm

It has been well known that the electrical conductivity (or impedance characteristics) of VRFB electrolyte has a correlation with its SOC and the state of health (SOH). This section presents a modified EIS on-line measurement technique to obtain instantaneous impedance parameters of VRFB's electrolytes and used for estimating the VRFB's SOC value. It can also be used to detect positive/negative electrolyte balance statuses and the overall SOH. In practice, the real-time measurement of VRFB's EIS and electrolyte conductivity can be performed by using one or more single cells.

In this study, the proposed modified EIS measurement technique and the NN estimation of the real-time SOC include the following steps: 1) performing the EIS measurement through frequency sweep from 0 kHz to 100 kHz and with voltage of 0.01V; 2) recording the measurement of voltage, current and SOC values of each frequency test point; 3) calculating the VRFB impedance or conductivity of each frequency on each test point; 4) selecting several SOC test points for the calculation of impedance or conductivity; 5) off-line training of the NN SOC estimator. The successfully trained NN SOC estimator can then be used online or assisted by other detecting schemes described above to obtain a more accurate and reliable SOC estimation.

4.1. Neural network

After the VRFB EIS measurement tasks are completed, the NN suitable for this application case must be determined and the related training algorithms should be decided before NN training parameters are chosen. The multilayer back propagation neural network (BPNN) is adopted here as the NN structure and training algorithm. BPNN is known as the most common ways of online learning. Its detailed architecture is shown in Fig. 2 (a). A set of different NN topologies tested in this study is shown in Table 1.

Table 1. NN topology.

NN topology	Num. of hidden layers	Num. of hidden nodes	Num. of output nodes
5_1	1	5	1
6_1	1	6	1
7_1	1	7	1
8_1	1	8	1
9_1	1	9	1
5_5_1	2	5, 5	1
6_5_1	2	6, 5	1
7_5_1	2	7, 5	1
8_5_1	2	8, 5	1
9_5_1	2	9, 5	1

4.2. EIS measurement on VRFB

The VRFB's SOC detection method proposed in this paper is based on the understanding that the equivalent impedance parameter of VRFB changes with its SOC, and thus the real-time measured impedance parameters can be used for analysis and estimating the VRFB's SOC via NN learning and online real-time measurement. EIS method is an electrochemical measurement method that uses a small sine wave as a disturbance signal. Since the VRFB is disturbed only by just a small signal, a large influence on the VRFB system can be avoided; on the other hand, the disturbance and system response are closer to a linear relationship and the subsequent quantization processing of the measurement result can be simplified.

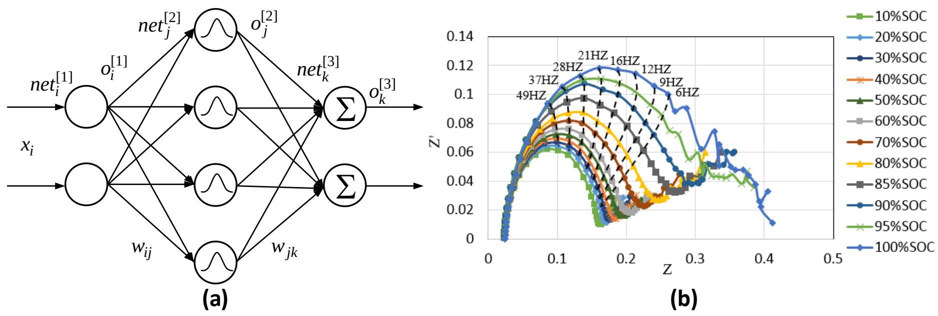

Fig. 2. (a) BPNN architecture, (b) EIS data obtained from the VRFB cell system in Fig. 1 (b).

Fig. 2 (a) shows the BPNN architecture and (b) shows the EIS data obtained from the experimental VRFB cell system shown in Fig. 1 (b) with frequency span of 0~100 kHz and voltage of 0.01V.

5. Case Study and Results

Analysis of EIS data of the VRFB single cell as shown in Fig. 2 (b) reveals that the frequency range suitable for NN training falls roughly between 6 Hz and 49 Hz. In this study, three frequencies points, 12 Hz, 16 Hz and 28 Hz, are taken as main training parameters. In this study, the detailed arrangement is shown in Table 2, having 6 cases of training parameters, where R/X are the real/imaginary parts of the AC impedance measured by EIS, and θ is the impedance angle. The frequency points used are 12 Hz and 12 Hz + 16 Hz + 28 Hz. The parameters required to train the NN are based on the combination of different impedance parameters, frequency points and the corresponding SOC values. After appropriate training and testing, the overall performance of the proposed NN based on-line SOC estimation algorithm can be discussed and analyzed.

Table 2. Training parameter combinations for the case study.

Case	Input parameter(s)	Frequency point(s)	Output parameter
1	R+X+θ	12Hz	SOC
2	R+X+θ	12Hz+16Hz+28Hz	SOC
3	θ	12Hz	SOC
4	θ	12Hz+16Hz+28Hz	SOC
5	|Z|	12Hz	SOC
6	|Z|	12Hz+16Hz+28Hz	SOC

In the above six training cases, according to the SOC values of VRFB, 10 sets of data are taken as the training values (SOC = 10%, 20%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, and 100%), and 2 sets of data are taken as the testing values (SOC = 30% and 85%). For demonstration purposes, typical test results on different NN network structures of the above six cases are graphically presented in Fig. 3.

6. Conclusion

The SOC detection function of an ESS plays a very important role in advanced DG applications. This paper has briefly introduced the basic principle of VRFB and reviewed the reported SOC detection methods. The design concepts and implementation issues of the proposed method utilizing online EIS and NN for real-time VRFB's SOC estimation has been addressed. Based on the test results, the trained NN is able to appropriately determine the VRFB's SOC on the test points which are indeed new set of input parameters to the NN system. Therefore, it can be concluded that the dynamic characteristics of VRFB has been learned by the trained NN. From the presented test results, it can be found that different training values combined with different NN topologies will result in different testing errors. Therefore, the selection of VRFB parameters is extremely important in practical applications.

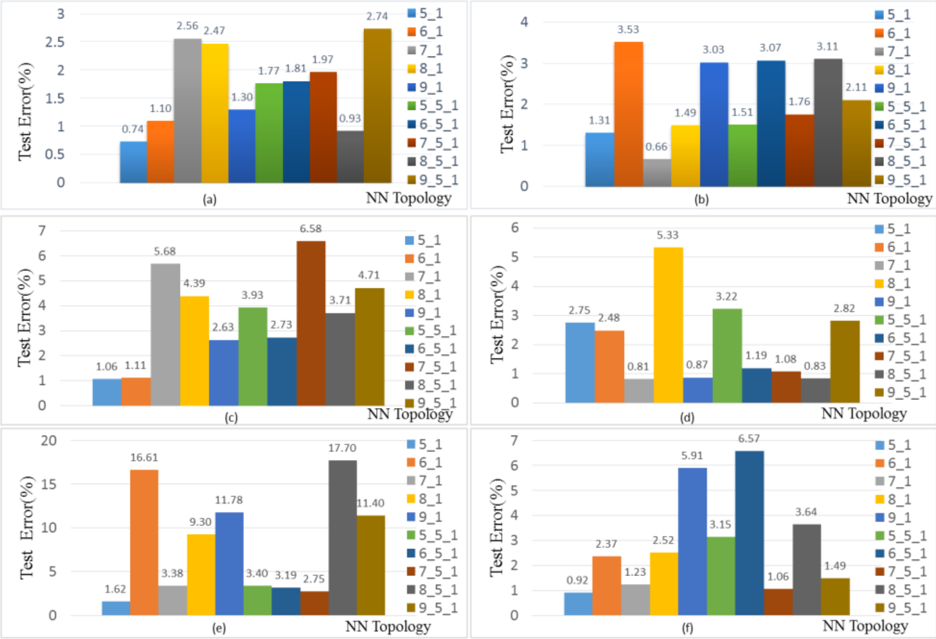

Fig. 3. (a) - (f): Average test errors under different NN topologies in cases 1-6 (Table 2).

Acknowledgements

This work was supported in part by the Ministry of Science and Technology, Taiwan R.O.C. under Grant MOST 107-2221-E-239-036.

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