Design and Performance Testing of Lead-acid Battery Experimental Platform in Energy Storage Power Station

Wen-Hua Cui, Jie-Sheng Wang, and Yuan-Yuan Chen

***Abstract*—The lead-acid battery experimental testing platform in energy storage power station is composed of the WEBEST valve-controlled sealed colloid lead-acid battery and the bidirectional high-precision programmable DC power supply so as to control the battery charge and discharge, which can realize the information collection, data processing and signal control. Based on the established experimental testing platform, the performance testing experiments on the lead-acid battery are carried out in details. The charge and discharge experiments under the different working conditions of lead-acid batteries are carried out to analyze the characteristics of charge and discharge of lead-acid battery. On the other hand, according to the above discussed battery charge and discharge characteristics, the remaining power of the situation of the energy storage power station under the complicated working conditions is estimated. Through the related performance testing experiments, the established accurate cell model can effectively improve the accuracy of estimating the remaining power of the battery.**

***Index Terms*—energy storage power station, lead-acid batteries, performance measurement**

I. Introduction

With the progress of modern society, the electrical energy consumption will continue to increase, but other energy, such as coal, oil and other non-renewable energy sources is decreasing. Thus prompting the development of renewable energy power generation and solving the problem of environmental pollution have become the research focus in China and the world. With the development of renewable energy, more and more researchers focus their attention on energy storage technology. Energy storage technology in a certain extent can effectively regulate the grid connected power generation with renewable energy caused by the changes of network voltage and frequency change, the large-scale and distributed power generation in reliable incorporated into the power grid, improve power grid stability [1-2].

The storage of energy in batteries is a cause of the failure and loss of reliability in PV systems. In order to validate two general lead acid battery models (Monegon and CIEMAT), the behavior of different battery cycling currents has been simulated [3-4]. A framework that employs real-time operating data to estimate jointly the SOC and parameters performs statistical analysis to derive quantitative diagnostic procedures with error analysis. Simulated case studies and experimental data are used to illustrate the diagnosis algorithms and their capabilities [5]. Behavior modeling and experimental validation of a lead-acid battery integrated in a hybrid solar-wind power generation (HSWPG) system are presented and discussed. The simulation results have been compared to experimental measurements during both the charging and discharging of the system, under the same operation and environmental conditions [6]. It is considered a simplified model of the lead-acid battery discharge, based on simulation of electrolyte diffusion process in space between a positive and negative electrode. The correctness of model and influence of various boundary conditions are investigated [7]. Battery discharging behavior is one of the most important parts of the dynamic battery-model. Through regression analysis of experimental data, the nonlinear behavior is verified and a nonlinear dynamic Thevenin model is developed [8]. Open-circuit voltage (OCV) is one of the most important parameters in determining state of charge (SoC) of power battery. The scheme only uses the measurable input (terminal current) and the measurable output (terminal voltage) signals of the battery system and is simple enough to enable online implement [9]. The performance of the self-discharged gel cell has been studied [10]. Although the gel valve-regulated lead-acid batteries were shelved for nearly 3 years, the active mass structure of the positive plate, its resistance and the corrosion layer of the grid are not much affected. The capacity of the long self-discharged gel cell can be completely restored by recharging. Electrical tests were performed on two valve-regulated lead-acid (VRLA) batteries to compare the effects of several design improvements, evaluate their applicability to stationary

Manuscript received January 24, 2017; revised April 9, 2017. This work was supported by the Project by National Natural Science Foundation of China (Grant No. 21576127), the Program for Liaoning Excellent Talents in University (Grant No. LR2014008), the Project by Liaoning Provincial Natural Science Foundation of China (Grant No. 2014020177), the Program for Research Special Foundation of University of Science and Technology of Liaoning (Grant No. 2015TD04) and the Opening Project of National Financial Security and System Equipment Engineering Research Center (Grant No. USTLKFGJ201502 and USTLKEC201401).

Wen-Hua Cui is with the School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan, 114051, PR China; National Financial Security and System Equipment Engineering Research Center, University of Science and Technology Liaoning. (e-mail: cwh@ustl.edu.cn).

Jie-Sheng Wang is with the School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan, 114051, PR China; National Financial Security and System Equipment Engineering Research Center, University of Science and Technology Liaoning. (phone: 86-0412-2538246; fax: 86-0412-2538244; e-mail: wang_jiesheng@126.com).

Yuan-Yuan Chen is a postgraduate student in the School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan, 114051, PR China (e-mail: chenyuanyuan@mail.iee.ac.cn).

applications, and determine their service lives [11]. As partial-discharge techniques require temporarily shutting-down of the system and also degrade battery life, manual testers based on ohmic techniques have become popular. Accordingly, the Battery Condition Watcher (BCW) has been developed and commercialized, which is an automatic monitoring system with remote communication capabilities to measure the internal impedance, voltage and temperature of individual cells or batteries with high accuracy [12].

In order to accumulate the experimental data to establish the cell model and estimate the remaining power of the battery. The WEBEST valve control sealed colloid lead-acid battery and the bidirectional high-precision programmable DC power supply to control the charge and discharge are used to construct the lead-acid storage battery power station test experiment platform and the performance tests are carried out to provide the technical support for establishing the accurate cell model and improving the accuracy of estimating the remaining power of the battery. The paper is organized as follows. In Section 2, the experimental testing platform for lead-Acid battery in energy storage power station is established. The performance test of lead-acid battery in storage power station is described in details in Section 3. The conclusion illustrates the last part.

II. Experimental Testing Platform for Lead-Acid Battery in Energy Storage Power Station

A. System Architecture of Photovoltaic Energy Storage Integrated Power Generation

The photovoltaic energy integrated power generation system is consisted of the reservoir power plant and the photovoltaic power station. Wherein, the energy storing power plant is mainly used to help to stabilize the photovoltaic power fluctuation and real-time improve the response intermittent of the power generation system. It can increase the stability and reliability of the new energy power generation and network and improve the economic benefit. In addition, the power storage power plant in the power grid can also achieve many function applications, such as cut peak and fill valley, isolated network operation, power compensation, make up the line loss, load regulation, new energy access, improvement of electric energy quality, et al. Thus, it can be seen the importance of power plants in the power system of the reservoir. The photovoltaic energy generation system architecture is shown in Fig. 1, which includes photovoltaic power generation, energy storage power station, user load parts and the energy management system.

In the realization of the above functions, the energy storage power station is mainly used to cut peak and fill the valley on the power grid. The photovoltaic energy storage integrated power generation system can access the energy storage power station in to the user power supply system, which mainly realizes the effective management of the users' demands. The storage energy power plants can absorb the power grid harmonics generated by the grid connected photovoltaic power generation, smooth the load of power grid, peak shaving and valley filling, greatly improve the local electric energy quality, reduce the cost of power supply, improve the response time of the system, and improve the stability and reliability of the whole power system operation. The structure of the energy storage power station is shown in Fig. 2.

The power station is composed of battery pack, battery management unit, grid connected control unit PCS, power station distribution unit and monitoring unit of the power station, where the total capacity of storage battery group is 1MWh and the total power of the grid connected control unit is 2MW. Because of the larger PCS capacity, the system selects two grid control units connected in parallel. Then it is connected with battery pack. This structure can improve the safety of energy storage power station.

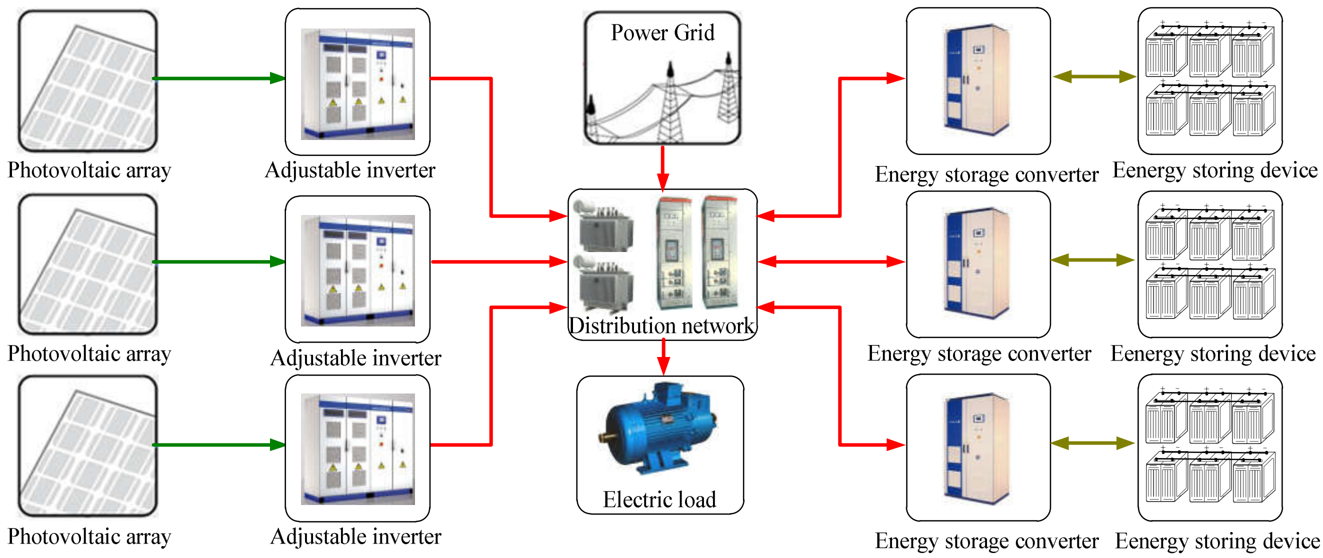

Fig. 1 Energy storage power station (with grid-connected PV applications) architecture diagram.

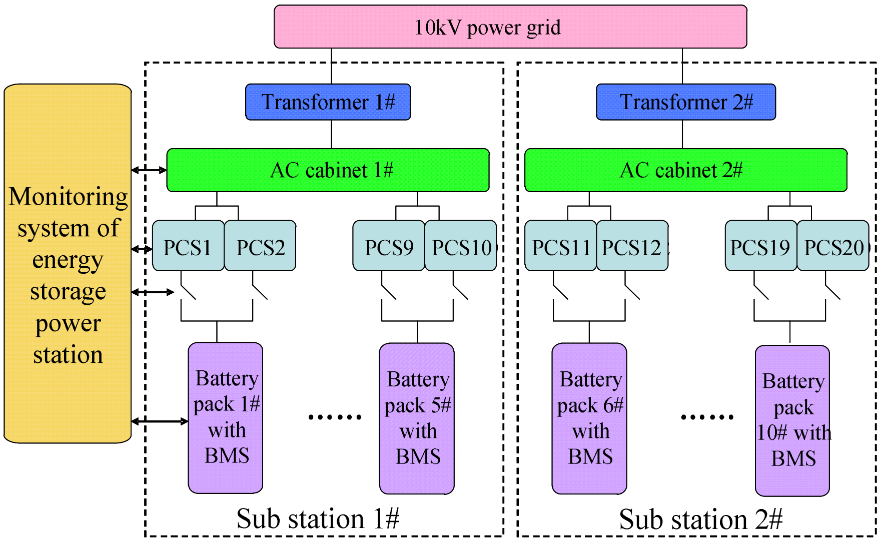

Fig. 2 Energy storage power station system structure.

B. Lead-acid Battery Experiment Testing Platform

The battery testing platform is mainly composed of batteries, two high precision programmable DC power supply, battery monitoring system and the host computer. The battery test chart and the battery experiment platform are respectively shown in Fig. 3.

The lead-acid battery experimental testing platform mainly uses the WEBEST valve-controlled sealed colloid lead-acid battery, whose model is DFS12-65. The structure of the experimental platform is composed of a battery pack composed of 28 12V65AH batteries connected in series. The technical parameters of the cell are shown in Table 1. The DFS12-65 valve-controlled lead-acid battery used in this experiment platform is shown in Figure 4.

Battery Pack

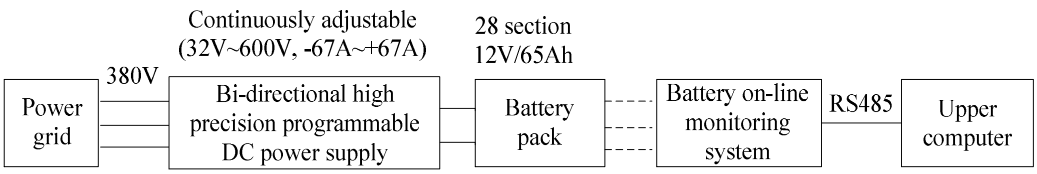

Fig. 3 Block diagram of battery test structure.

TAB. 1 WEIBO（WEBEST）VRLA GEL LEAD-ACID BATTERIES DFS12-65

Technical parameter		Value				
Rated voltage (v)		12V				
Rated capacity (AH)		65AH				
Dimension(mm)		High: 176mm		Length: 351mm		Width: 167mm
Weight (kg)		22.0kg				
Battery characteristics	Capacity 25℃	20 hours discharge（3.25A）65AH	10 hours discharge（6.05A）60.5AH	5 hours discharge（11.06A）55.3AH	1 hour discharge（39A）39AH	15 minutes discharge（113.6A）28.4AH
	Internal resistance	Factory new battery temperature: 25℃＜7.5mΩ				
	Effect of temperature on capacity	104℉ (40℃) 102%	77℉(25℃) 100%		32℉ (0℃) 85%	5℉ (-15℃) 65%
	Capacity preservation rate (25℃)	Capacity after 6 months of storage 94%	Capacity after 12 months of storage 88%			Capacity after 24 months of storage 76%
	Maximum discharge current	77℉ (25℃), 975A(5S)				
	Charging voltage cycle (Constant voltage charging)	Maximum charge current: 19.5A 14.4V～15.0V/77℉ (25℃)		Floating charge use 13.5V～13.8V/77℉ (25℃)		
Terminal type	Standard configuration	Copper thread terminal				
	Optional configuration	Lead terminal				

Fig. 4 Valve Regulated Lead Battery.

Bidirectional High-precision Programmable DC Power Supply

The bidirectional high-precision programmable DC power supply used in this experimental platform is a digital operation power supply equipment, which can also provide two energy flows, that is to say the output is fed to the load and the load can receive the feedback from energy. So it can be used to control the charging and discharging of the battery pack. This bi-directional high-precision programmable DC power supply has three operating modes: voltage regulation, current regulation and power regulation. The operation modes include the constant voltage, the constant current and the constant power.

The bidirectional high-precision programmable DC power supply is mainly used in the operation mode of constant voltage or constant current charging. Generally in the experiments, the constant current is initialized and the maximum voltage for the input battery pack is initialized under the given voltage. After a period charging, with the increase of the output voltage of the battery pack, the voltage reaches the preset value and remains the constant, so the current can be reduced. Then the operation mode of the bidirectional high-precision programmable DC power supply will autocratically and fast switch from the constant current operation mode to the constant pressure operation mode. Similarly, when carrying out the discharging experiments, the negative constant current is initialized and the cut-off voltage that the battery can drop to initialized under the given voltage. After a period discharging, as the voltage drops to the cut-off voltage, its operation mode will autocratically and fast switch from the constant current operation mode to the constant pressure operation mode. This advantage of intelligent switch can protect the battery and meet the requirements of the experiments.

The preset power value should be larger than the product value of preset voltage and preset current. The small preset power will cause the power supply work under the constant power operation mode in that the power limit will be automatically opened once the power supply reaches the preset limits. The bi-directional high precision programmable DC power supply used in this experiment is shown in Figure 5, whose voltage is 32V~600V and continuously adjustable, and current is -67A~+67A and continuously adjustable. The LCD screen in the front panel can be operated through the select button in order to provide a high accuracy, repeat-ability and stability for the charging and discharging control.

Fig. 5 Two-way high-precision programmable DC power supply.

C. Battery Monitoring System Software

The software part of this experiment is the key part of the experimental platform operation, which includes the battery information collection unit, the battery data processing unit, the signal control unit and the battery information display part. The battery information collection unit is to collect the battery monomer voltage, battery current, battery temperature and battery group pressure. This collected information will be uploaded through the data processing and signal control units and the RS485 communication interface with the battery. Then the residual energy is estimated based on the related control algorithm and mathematical model. The battery monitoring system software is mainly used to realize the estimation of residual power and the remote computer interaction. It has many functions, such as battery operation monitoring, capacity testing, recording inquiries and data communication. The battery information display unit is mainly used as the interface display of the host computer.

Data Acquisition Unit of Battery Monitoring System

The information collection unit mainly realizes the on-line monitoring function of single voltage, the environment temperature (battery temperature) monitoring, the group pressure monitoring and the charge discharge current monitoring. For the general battery acquisition unit, generally the voltage acquisition line and the monitored battery are directly connected. But it will cause the phenomenon of self-discharge of the battery and the cable short circuit. For having no any interference on the charge-discharge system and working circuit, the voltage acquisition line is not directly connected with the monitored battery. These two parts are connected with an ohmic resistance. All detection channels of the acquisition unit adopt the mode with the high input impedance so that the current in the detection circuit can reach less than microamp so as to further improve the precision of data acquisition.

Figure 6 is a schematic diagram of the acquisition unit. The charge-discharge current, single voltage, group pressure, ambient temperature (cell temperature) was obtained by the acquisition unit. The data exchange is realized through the RS485 communication interface with the control unit. The remaining power is estimated by using the collected data through the Kalman filter algorithm and displayed on the monitoring interface.

Control Unit of Battery Monitoring System

In the control unit of the whole monitoring system, the main control unit is mainly to realize data storage and communication, intelligent analysis, residual capacity estimation, record query, alarm indication, parameter setting and self check function. In these functions, the most important is to estimate the residual capacity of the battery. The general battery monitoring system can only monitor the charged and released electricity quality of the battery. Because the remaining power of the battery cannot simply obtained by subtracting of the charged electricity quality and the released electricity quality, it cannot be monitored in real time for each battery. The proposed monitoring system is mainly to solve how to realize the on-line monitoring of the residual quantity of each battery and the battery. Figure 7 is a schematic diagram of the control unit, which mainly uses the data from the information acquisition unit to establish the related equivalent circuit mathematical model, adopts the Kalman estimation algorithm to estimate the residual capacity and output the estimated value on the monitoring interface.

III. Performance Test of Lead-acid Battery in Storage Power Station

A. Voltage Characteristics of Battery under Constant Current Charge and Discharge Current

The battery constant current charging and discharging experiments are carried out to obtain the basic knowledge for the lead-acid battery. Through the analysis on the experiments results, the voltage characteristics of battery under the constant current charging and discharging are obtained. The testing method of the constant current charging is to charge the battery with constant current 13A (0.2C) and the the charging termination voltage is limited as 15V. When the voltage is charged to 15V, the battery is charged under the constant pressure. When the current drops to 6A under the constant voltage charging, the charging process is stopped (this constant voltage charging stage is named as the floating charging stage). Under the room temperature, the battery is charged to 15V with the constant current 13A (0.2C). The tested object is a set of 28 65Ah series connected lead-acid batteries.

After the constant current charging and discharging process is ended, the battery need to be remained static, whose function is mainly to make the battery output voltage be the stable open circuit voltage. After 3 hours static state, the constant current discharging experiment is performed test. The method is to discharge the battery under the constant current 13A (0.2C) and limit the discharge cut-off voltage to 11.2V. The battery charging and discharging characteristic curves are shown in Figure 8 and Figure 9 (the horizontal axis is time and the vertical axis is the current and voltage, respectively). It can be seen from Figure 8 the battery charging characteristics. In the charging process, the voltage rising gradually tends to be gentle and the voltage in the float charging stage has a slight downward trend. The discharge characteristics of the battery can be seen from Figure 9. When proceeding the constant current discharging, the voltage has a steep drop process, and then enters a voltage drop process.

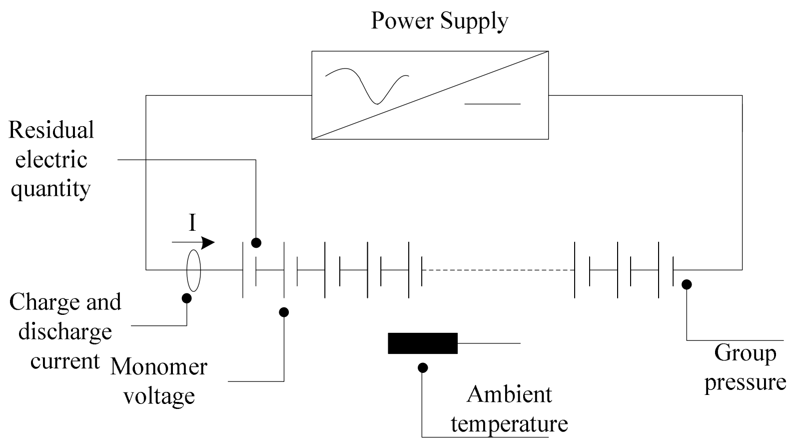

Fig. 6 The acquisition unit.

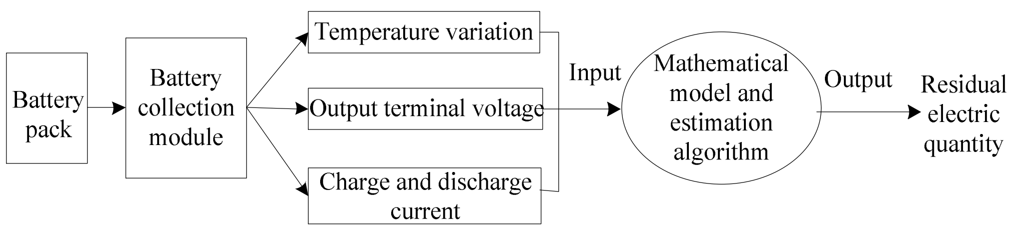

Fig. 7 Control unit.

B. Voltage Characteristics of Battery under Complex Operating Conditions

The main function of the energy storage power station is to make the power supply system realize the peak clipping and valley filling, which can effectively manage the demand side, smooth the load, reduce the cost of power supply, and improve the stability of power system operation. Because the energy working condition of power supply system is complex, it not only needs the good control strategies to achieve the peak clipping and valley filling, but also the accurate prediction on the remaining power of the battery.

The charging and discharging experiments are carried out under the complex working conditions of the battery in the storage battery so as to simulate the working conditions of power plant. Through analyzing the battery voltage characteristics under different working conditions, the the in-depth understanding on the battery can be realized. The battery testing experiments results shown in Figure 10 to Figure 12 under different working conditions for the battery show that the battery voltage has the resistance capacitance characteristics. The current-voltage diagram under the interval continuous charging and discharging with the same charge-discharge current is shown in Figure 10. It can be seen form Figure 10 that the voltage response is similar to the first order RC circuit response. Figure 11 shows the current-voltage diagram under non-equidistance continuous charging and discharging with the same charge-discharge current. Figure 12 shows the current-voltage diagram under interval charging and discharging with the different charge-discharge current.

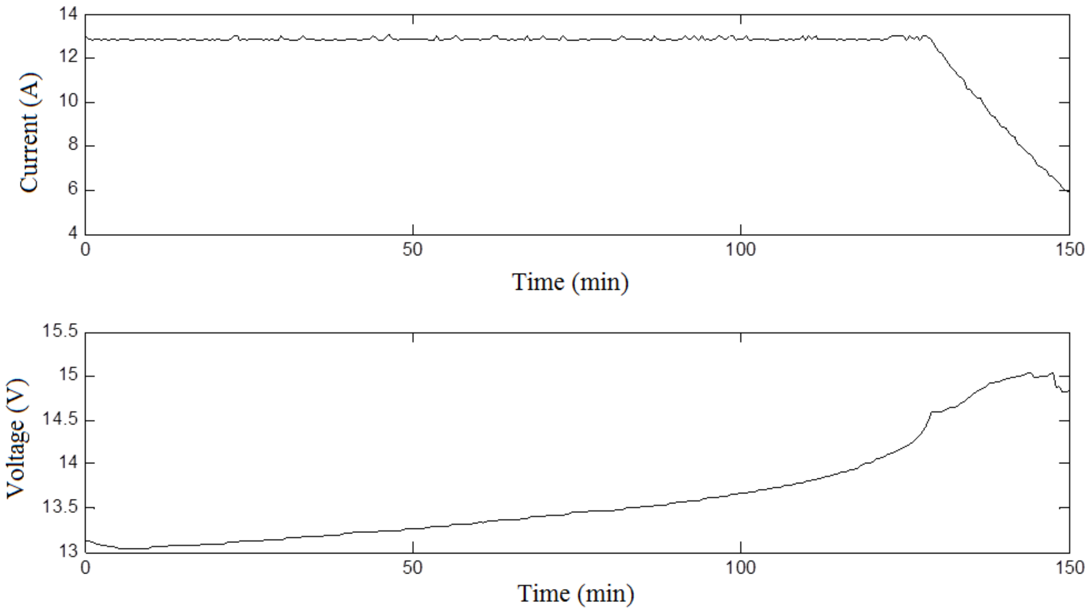

Fig. 8 The current and voltage of constant current charging.

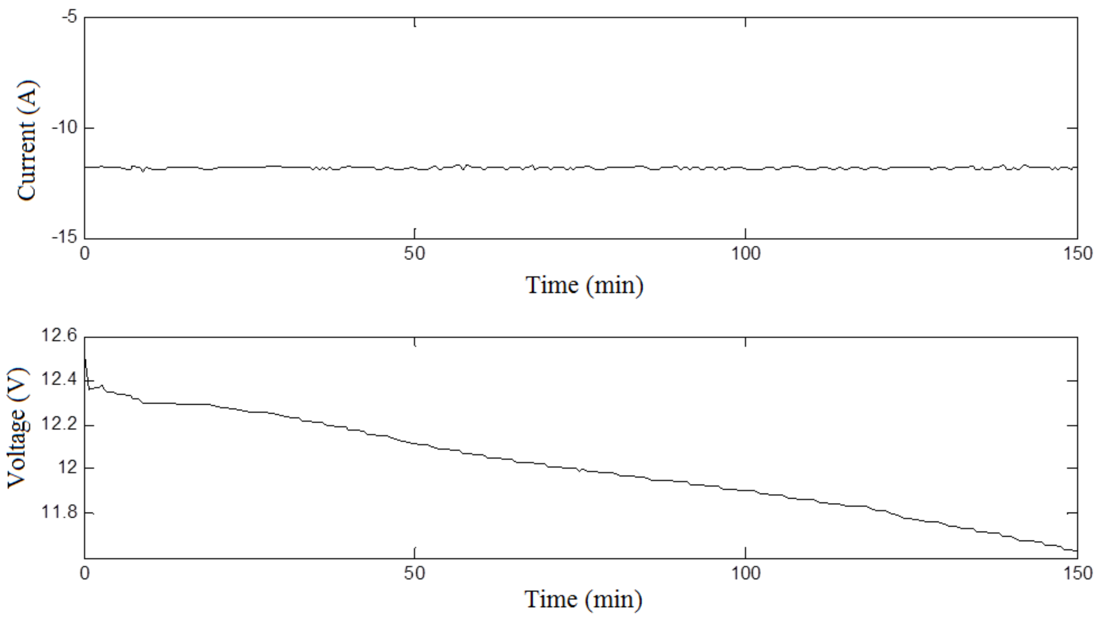

Fig. 9 The current and voltage of constant current discharging.

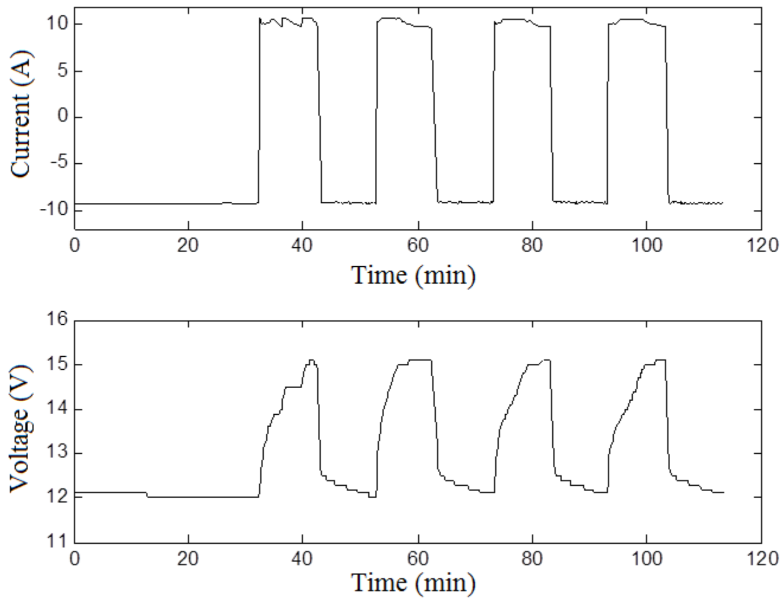

Fig. 10 The voltage and current of equal interval continuous charging and discharging.

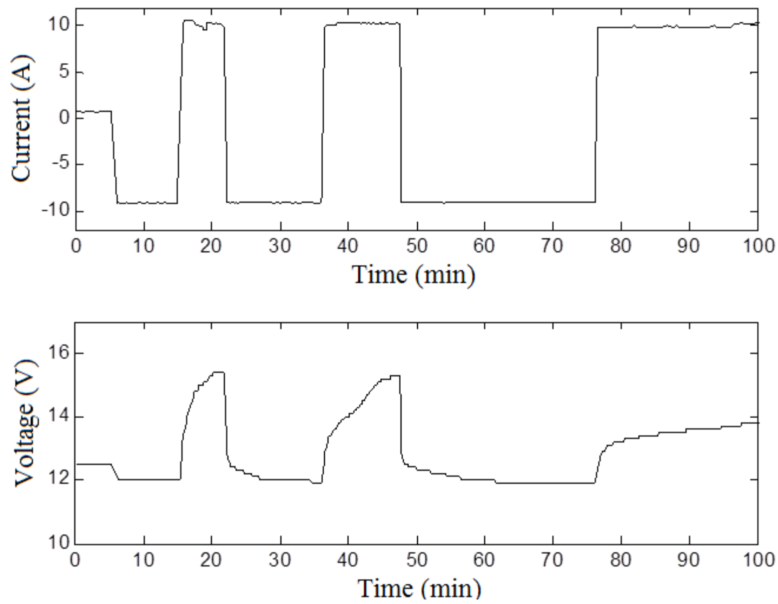

Fig. 11 The voltage and current of not-equal interval continuous charging and discharging.

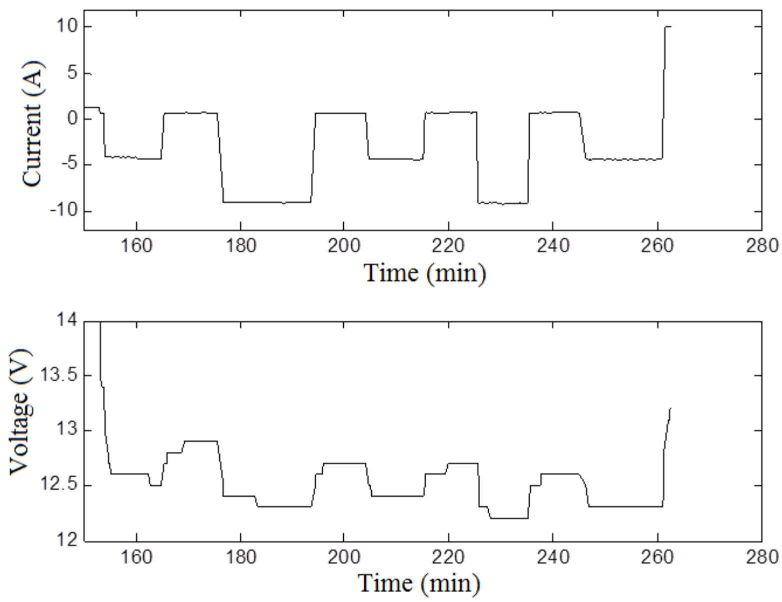

Fig. 12 The voltage and current of equal interval but not-equal current charging and discharging.

C. Voltage Characteristics of Battery under Different Charge and Discharge Rate

In order to obtain the accurate battery model, the voltage characteristics of the battery under the different discharge rates need be studied. An important factor of the SOC estimation algorithm is the charge discharge rate. The experiment method under the different charging rate in this experiment is the constant current and constant voltage charging, where 4 different charging currents (6.5A (0.1C), 9.75A (0.15C), 13A (0.2C) and 16.25A (0.25C)) are used for charging. After the charging to the cut-off voltage, the float charging process is carried out for 1 hour so as to ensure that the battery is in full state. The procedure of this experiment is shown in Figure 13. The discharge rate experiment is similar to the charging experiment. In the discharging experiment process, 4 different discharging currents (6.5A (0.1C), 9.75A (0.15C), 13A (0.2C) and 16.25A (0.25C)) are used for discharging. After the discharging to the cut-off voltage, the discharging process is over so as to prevent the battery form over-discharge and ensure to vent the battery power. The procedure of this experiment is shown in Figure 14.

Tables 2 and Table 3 show the estimation of the battery charging and discharging efficiency. Because the limited conditions of the adopted experimental platform, only 4 kinds of charging and discharging currents are used. Then the each current charging electricity and releasing electricity can be calculated by using the current integration method. It can be seen form Table 2 and Table 3 that the current 13A in the battery charging and discharging process is maximum power. At this point, the charging and discharging efficiency under other currents relative to the current 13A can be calculated. At the same time, the least square method can be used to simulate the relationship between the charging and discharging efficiency and the current. The calculation on the charging and discharging efficiency η can provide parameters for the adopted prediction model on the battery residual electricity.

It can be seen from Table 2 and Table 3 that there is a direct relationship between the battery charge-discharge efficiency and the charge-discharge current. So the relation between on the charge-discharge efficiency η and the charge-discharge current is fitted by adopting the least squares method. So the relationship between charging efficiency and current is described as:

$$\eta = p1 \cdot i^2 + p2 \cdot i + p3 \tag{1}$$

where $p1$=-0.0055, $p2$=0.1362, and $p3$=0.0757.

The relationship between discharging efficiency and current is described as:

$$\eta = p1 \cdot i^2 + p2 \cdot i + p3 \tag{2}$$

where $p1$=-0.004899, $p2$=0.1189, and $p3$=0.1874.

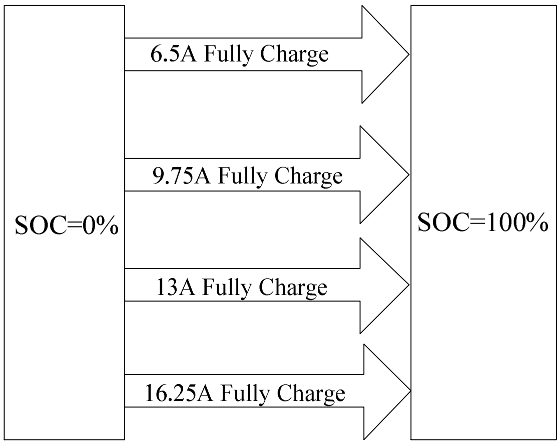

Fig. 13 The charging experimental procedure.

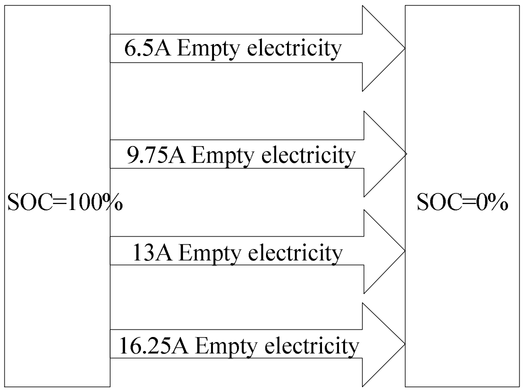

Fig. 14 The discharging experimental procedure.

TAB. 2 CHARGING EFFICIENCY UNDER DIFFERENT MAGNIFICATIONS

Current (A)	Charging capacity (Ah)	Charging efficiency
6.5	30.07	0.776
9.75	30.28	0.781
13	38.75	1
16.25	30.75	0.794

TAB. 3 CHARGING EFFICIENCY UNDER DIFFERENT MAGNIFICATIONS

Current (A)	Discharge capacity (Ah)	Discharge efficiency
6.5	30.3	0.785
9.75	30.38	0.787
13	38.6	1
16.25	30.69	0.795

D. Relationship between Battery Voltage Characteristics and SOC

A lot of literatures show that the open circuit voltage of lead-acid battery can reflect the actual remaining capacity of the battery. So the open circuit voltage is an important feature of the battery. In order to find the relationship between the open circuit voltage and the residual capacity of the battery, the charging and discharging experiments under the interval pulse are carried out to obtain the relationship between the open circuit voltage and SOC under the different SOC conditions.

The process of the pulse charging experiments is described as follows. Firstly, the battery electricity is vented, where the default remaining battery power is 0%. Then the constant current charging on the battery is carried out under 10 certain interval pulses, with the 13A (0.2C) charging current, where each charging time is 15 minutes for obtaining the remaining power with the 10% interval. The batter after each pulse charging is remained fully static for half an hour. The procedure of the pulse charging experiment is shown in Figure 15. Similarly, the process of the pulse discharge experiment is described as follows. Firstly, the battery is full of electricity, where the battery residual capacity is 100%. Then the battery is carried out the constant current discharge under 10 certain interval pulses, where the discharge current was 13A (0.2C) and each discharge time is 15 minutes. The batter after each pulse discharging is remained fully static for half an hour. The procedure of the pulse discharging experiment is shown in Figure 16. The relationship between the SOC under the charge-discharge state and the open circuit voltage are shown in Figure 17 and Figure 18.

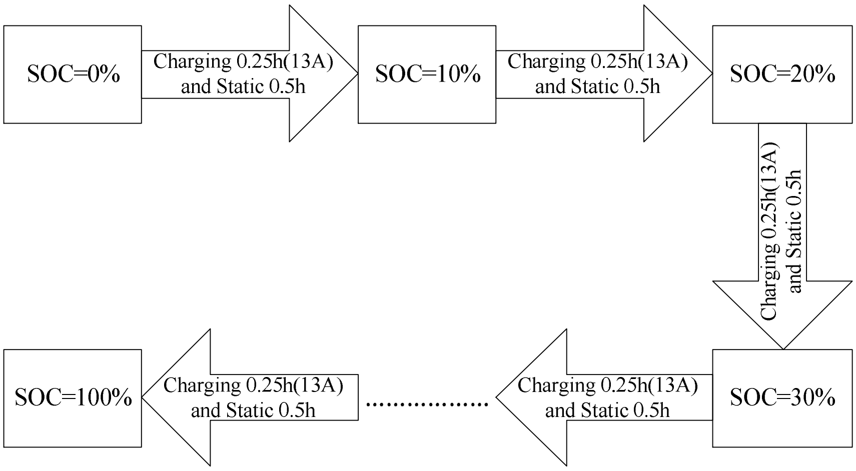

Fig. 15 Pulse charging experimental procedure.

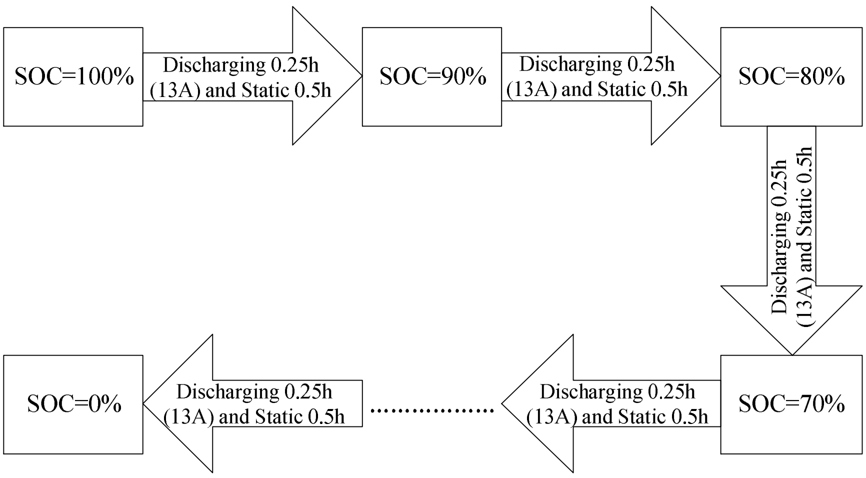

Fig. 16 Pulse discharging experimental procedure.

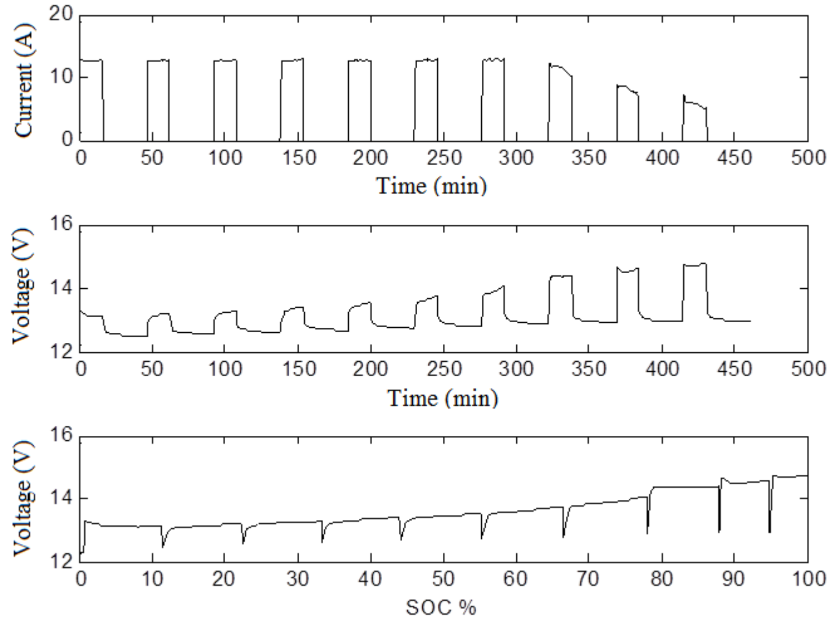

Fig. 17 The relationship between the SOC and the open circuit voltage under charging.

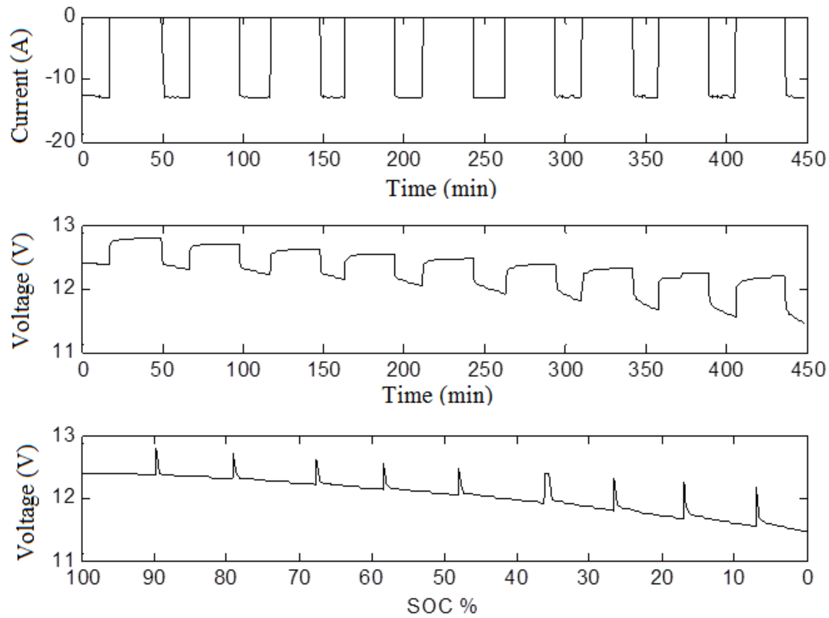

Fig. 18 The relationship between the SOC and the open circuit voltage under discharging.

It can be seen form Figure 17 that the current after 3 pulses gradually decreases in that the battery is mainly in the float charge stage under the constant voltage charge. Seem from the voltage response under pulse current shown in Figure 17 and Figure 18, the voltage response is similar to the first-order circuit voltage response. In this case, the output terminal voltage is regarded as the open circuit voltage of battery. That is to say that the relationship between the open circuit voltage of lead-acid battery and SOC is a one-to-one corresponding, which can be used to predict the residual capacity of battery.

IV. Conclusion

Based on the established lead-acid storage battery testing platform in power plant, a various properties are tested through a series of experiments so as to study the performance of the battery pack so as to accumulate the experimental data and provide a basis for predicting the remained power after setting up the cell model in the energy storage power station. Firstly, the basic characteristics of charge and discharge are obtained by carrying out the constant current charge and discharge experiments to understand the characteristics of the battery. Then, on the basis of the characteristics of the micro grid energy storage power station, the charge and discharge characteristics of battery under the complicated working conditions are simulated to obtain that the battery has the resistance capacitance characteristics. The voltage characteristics of battery under the different charge and discharge magnification are analyzed so as to estimate the relationship between efficiency of the charge and discharge with the current. The relationship between SOC and the terminal voltage is analyzed in details to provide the basis for the determination and identification of model parameters and initial SOC value.

References

[1] G. L. Plett, "Extended kalman filtering for battery management systems of LiPB-based HEV battery packs," *Journal of Power Sources*. vol. 134, no. 2, pp. 262–276, 2004.
[2] D. Dennis, and A. Suleiman, "A critical review of using the peukert equation for determining the remaining capacity of lead-acid and llithium-ion batteries," *Power Sources*, vol. 155, no. 2, pp. 395–400, 2006.
[3] N. Achaibou, M. Haddadi, and A. Malek, "Lead acid batteries simulation including experimental validation," *Journal of Power Sources*, vol. 185, no. 2, pp. 1484–1491, 2008.
[4] N. Achaibou, M. Haddadi, and A. Malek, "Modeling of lead acid batteries in PV systems," *Energy Procedia*, vol. 18, no. 2, pp. 538–544, 2012.
[5] Z. Chen, L. Y. Wang, and G. Yin, "Accurate probabilistic characterization of battery estimates by using large deviation principles for real-time battery diagnosis," *IEEE Transactions on Energy Conversion*, vol. 28, no. 4, pp. 860–870, 2013.
[6] A. M. Yahya, A. Mellit, and A. K. Mahmoud, "Lead-acid battery behavior modelling and experimental validation under a specific climatic condition for a hybrid solar-wind system," *International Review on Modelling & Simulations*, vol. 4, no. 4, pp. 1751–1759, 2011.
[7] M. G. Semenenko, "Research of the simplified model of lead-acid battery discharge," *Journal of Power Sources*, vol. 160, no. 1, pp. 681–683, 2006.
[8] S. Tian, M. Hong, and M. Ouyang, "An experimental study and nonlinear modeling of discharge I–V, behavior of valve-regulated lead–acid batteries," *IEEE Transactions on Energy Conversion*, vol. 24, no. 2, pp. 452–458, 2009.
[9] Y. Zhang, C. Zhang, and N. Cui, "An adaptive estimation scheme for open-circuit voltage of power lithium-ion battery," *Abstract & Applied Analysis*, vol. 2013, no. 2, pp. 1–6, 2013.
[10] Y. Guo, J. Hu, and M. Huang, "Investigations on self-discharge of gel valve-regulated lead–acid batteries," *Journal of Power Sources*, vol. 158, no. 2, pp. 991–996, 2006.
[11] J. Crow, I. Francis, and P. Butler, "Summary of electrical test results for valve-regulated lead-acid (VRLA) batteries," *Journal of Power Sources*, vol. 95, no. 1-2, pp. 241–247, 2001.
[12] S. Nagashima, K. Takahashi, and T. Yabumoto, "Development and field experience of monitoring system for valve-regulated lead–acid batteries in stationary applications," *Journal of Power Sources*, vol. 158, no. 2, pp. 1166–1172, 2006.
[13] A. K. Leros, V. C. Moussas, "Performance analysis of an adaptive algorithm for DOA estimation," *IAENG International Journal of Computer Science*, vol. 38, no. 3, pp. 309–313, 2011.
[14] T. O. Ting, K. L. Man, C. U. Lei, C. Lu, "State-of-charge for battery management system via Kalman filter," *Engineering Letters*, vol. 22, no. 2, pp. 75–82, 2014.

Wen-Hua Cui is with the School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan, 114051, PR China; National Financial Security and System Equipment Engineering Research Center, University of Science and Technology Liaoning. (e-mail: cwh@ustl.edu.cn).

Jie-Sheng Wang received his B. Sc. And M. Sc. degrees in control science from University of Science and Technology Liaoning, China in 1999 and 2002, respectively, and his Ph. D. degree in control science from Dalian University of Technology, China in 2006. He is currently a professor and Master's Supervisor in School of Electronic and Information Engineering, University of Science and Technology Liaoning. His main research interest is modeling of complex industry process, intelligent control and Computer integrated manufacturing.

Yuan-Yuan Chen is a postgraduate student in the School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan, 114051, PR China (e-mail: chenyuanyuan@mail.iee.ac.cn).