International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0058

LONG-TERM STABLE OPERATION CONTROL METHOD FOR DUAL-BATTERY ENERGY STORAGE SYSTEM FOR SMOOTHING WIND POWER FLUCTUATIONS

Li Lin[1*], Xin Jin[1], Shasha Wang[1], Hao Luo[1], Liyun Zhu[2]

1 State Key Laboratory of Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 40044, PR China

2 State Grid Xiamen Power Supply Company, Xiamen 361004, PR China

ABSTRACT

Wind power output shows obvious fluctuations characteristics, and direct grid-connection will bring great challenges to the safe and stable operation of power system. This paper adopts the dual-battery energy storage operation mode which performs charge-discharge tasks separately based on the consideration of the effect of discharge depth and frequent charge-discharge conversion on battery life and energy utilization. In addition, this paper proposes charge-discharge operational stability index for characterizing the operation of DBESS, according to the real-time operating conditions of the energy storage system and wind power fluctuations. In order to solve the extreme operation problems caused by the unbalance of charge and discharge energy during the long-term operation of the dual-battery energy storage system, this paper uses the two proposed indicators as input, and presents a control strategy to adaptively fine-tune the first-order low-pass filtering time constant. Purpose of the above work is to change the battery throughput power in real time and optimize the state of charge of the two battery packs. The effectiveness of the proposed control strategy is verified from two aspects: optimization control effect on SOC and power fluctuations smoothing effect using MATLAB/Simulink software.

Keywords: DOD, DBESS, status assessment indicator, unbalanced charge and discharge energy; control strategy

NONMENCLATURE

Abbreviations

DBESS	dual-battery energy storage system
SOC	state of charge
DOD	depth of discharge
ESS	energy storage system
BESS	battery energy storage system
EMS	energy management system

Symbols

P_w	actual output power of wind farm (MW)
P_b	charge-discharge power of the battery (MW)
P_g	grid-connected wind power (MW)
P_{gref}	the reference value of grid-connected wind power (MW)
s	differential operator
T	filter time constant (s)
P_{bref}	the reference value of the power fluctuations required for DBESS (MW)
D_{ref}	DOD of optimal operating status
$S_A(t)$	SOC of battery pack A at time t
$S_B(t)$	SOC of battery pack B at time t
E_{rate}	the rated energy of the battery packs A and B (MWh)
η_c	the charging efficiency
η_d	the discharging efficiency
η_{inv}	the conversion efficiency of the converter
$P_b(t)$	the actual charging and discharging power of battery at time t (MW)

w_c	indicate whether ESS are performing charging tasks at time *t*, with which 1 for Yes and 0 for No
w_d	indicate whether ESS are performing discharging tasks at time *t*, with which 1 for Yes and 0 for No
P_{rate}	the rated power of battery packs A and B (MW)
$E_{\max}$	the maximum allowable residual energy value of the battery during operation (MWh)
$E_{\min}$	the minimum allowable residual energy value of the battery during operation (MWh)
$E_A(t-1)$	the remaining energy of battery packs A at time *t-1* (MWh)
$E_B(t-1)$	the remaining energy of battery packs B at time *t-1* (MWh)
$S_{\max}$	the maximum SOC values of battery during the optimal operating mode
$S_{\min}$	the minimum SOC values of battery during the optimal operating mode
$\varepsilon_{ch}(t-1)$	the ability of the rechargeable battery pack to absorb energy after the last moment
$\varepsilon_{dis}(t-1)$	the ability of the rechargeable battery pack to release energy after the last moment
$\vartriangle S_{AB}(t-1)$	the deviation between the two packs capacity after the last stage(limited by the remaining capacity) (MWh)
ΔT	filter time constant adjustment (s)
P_{total}	the total battery charge and discharge power (MW)

1. INTRODUCTION

In recent years, wind energy technologies are receiving widespread acceptance as an eco-friendly energy source regarding its pollution-free, sustainability, mature and other characteristics. However, the output power fluctuates due to the strong randomness, intermittent and inaccurate predictability of wind energy, which will bring huge safety and stability challenges to the operation of the power system with directly grid-connected. ESS can adjust the power balance of the system flexibly and apace with its rechargeable operating characteristics, to smooth the fluctuations of wind power output and reduce the possible damage of wind power integration on the system. Since the energy storage technology has not yet become mature at this stage, the economics of the wind storage combined system are influenced greatly by the relatively high equipment cost [1]. For the BESS, an important factor in the economics of the operation process is the cycle life, including the depth of discharge, the number of charge-discharge conversions [2].

In [3], an equivalent charging cycle method for the battery life estimation, to explicitly analysis the life depreciation when ESS operates at different DODs, is proposed. Two sets of batteries are used to match the short-term scheduling of wind power in [4-5], one set is only responsible for storing the output power of wind farm, and the other set is barely in charge of releasing the required power to the grid. While the specified charge or discharge status reaches, their respective tasks will exchange. This operation mode reduces the battery life loss since the number of each battery's charge-discharge conversions has been reduced. However, all the output power of wind farm is transferred through ESS and then sent to power grid, this process will require higher cost undoubtedly. In [6], a model of DBESS connected to a wind farm on the PSCAD/EMTDC platform is built, and a coordinated operation control strategy for DBESS at a given discharge depth is proposed. Based on measured data, an application model of DBESS is built with independent execution of charge and discharge tasks in [7]. From the perspective of reducing the life loss, the economics of adopting this operating mode is analyzed.

Though the coordinated operation mode of the dual-battery pack can extend the battery service life to a certain degree, the current literature do not consider the stability of the long-term operation of ESS. On the basis of existing research, this paper discusses the extreme operating conditions when the charge or discharge capacity is insufficient caused by the unbalanced charge and discharge energy of DBESS in the long-term operation process. According to the real-time operation conditions of battery and power fluctuations characteristics, the charge-discharge saturation capability indicators and charge-discharge operation stability indicators are proposed, to characterize the operating conditions of DBESS. Besides, a control strategy is also presented to adjust the low-pass filter time constant adaptively. In this way, the SOC of DBESS can be optimized and controlled in real time to ensure the long-term stable operation of DBESS.

2. DBESS USED FOR SUPPRESSING WIND POWER FLUCTUATIONS

The structure diagram of a wind farm with DBESS is elaborated in Fig.1. The EMS determines the charge-discharge tasks of the battery pack A and the pack B based on the output power of wind farm and the operating condition of the battery packs. If the AC-DC converter works in the rectified state, ESS will store the remaining energy of wind farm. On the contrary, ESS will releases energy to compensate deficit power of wind farm when the AC-DC converter operates in the inverter state.

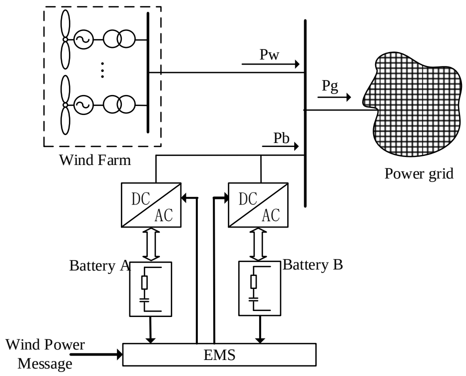

Fig 1 Wind farm structure containing DBESS

2.1 First-order low-pass filtering method

Practically, the value of P_{gref} can be obtained by wind power after first order low-pass filtering:

$$\begin{cases} P_{gref} = P_w \dfrac{1}{1+sT} \\ P_{bref} = P_{gref} - P_w = -\dfrac{s\tau P_w}{1+sT} \end{cases} \tag{1}$$

2.2 Operation principle of DBESS

To solve the problem of reduced service life caused by frequent charge-discharge conversion of the battery, we divide the battery into A and B two packs, and the operation mode that charge and discharge tasks execute separately, to make the battery operate at a given optimal DOD to extend the battery's actual service life. Whether the two packs battery have a charge and discharge state transition depends on their SOC.

Assuming that in the initial operation, rechargeable battery pack, A only performs the charging task and its SOC is $S_{A0} = \left(1 - D_{ref}\right)/2$, while pack B as discharge battery and only performs the discharging task with SOC is $S_{B0} = \left(1 + D_{ref}\right)/2$. In the mode of best discharge depth, when the SOC of battery A reaches at $S_A(t) = S_{\max}$ and battery B reaches at $S_B(t) = S_{\min}$, the operation modes of the two batteries will be exchanged. However, due to the uncertainty of the wind power fluctuations and inconformity of the two packs' power during operation, which lead to the total energy of each pack are unbalanced, it is difficult to achieve the critical state where exchange the operating simultaneously in most cases. In order to prevent the battery from over-charging and over-discharging, ESS will exchange charging and discharging operation modes when the SOC of one of the two battery packs reach the critical conversion value, as shown in Fig. 2.

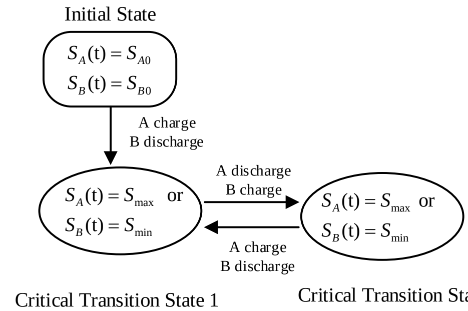

Fig.2 The critical condition of charging and discharging operation mode conversion

2.3 The mathematical model of DBESS charge and discharge operation

The rated capacity of each pack is half of the entire BESS. Besides, the power of suppressing fluctuations should be limited, which meet a certain constraint as follows at time *t*:

$$P_{\text{xumaxch}}(t) \le P_b(t) \le P_{\text{xumaxdis}}(t) \tag{2}$$

According to the operating principle of DBESS, the SOC of battery packs are shown in (3) to (6). When battery A works as a charge battery pack, battery B as a discharge battery pack:

$$\begin{cases} S_A(t) = S_A(t-1) - \dfrac{w_c P_b(t) \eta_c \eta_{inv} \vartriangle t}{E_{rate}} \\ S_B(t) = S_B(t-1) - \dfrac{w_d P_b(t) \vartriangle t}{E_{rate} \eta_d \eta_{inv}} \end{cases} \tag{3}$$

In order to prevent the battery from over-charging and over-discharging, the actual power $P_b(t)$ of each battery should be limited, as shown in equation (4).

$$\begin{cases} P_{\text{xumaxch}}(t) = -\min\{\dfrac{P_{rate}}{\eta_c \eta_{inv}}, [E_{\max} - E_A(t-1)]/(\eta_c \eta_{inv} \vartriangle t)\} \\ P_{\text{xumaxdis}}(t) = \min\{P_{rate} \eta_d \eta_{inv}, [E_B(t-1) - E_{\min}] \eta_d \eta_{inv} / \vartriangle t\} \end{cases} \tag{4}$$

When battery A as a discharge battery pack, battery B as a charge battery pack:

$$\begin{cases} S_A(t) = S_A(t-1) - \dfrac{w_d P_b(t) \vartriangle t}{E_{rate} \eta_d \eta_{inv}} \\ S_B(t) = S_B(t-1) - \dfrac{w_c P_b(t) \eta_c \eta_{inv} \vartriangle t}{E_{rate}} \end{cases} \tag{5}$$

and the constraints are as follows:

$$\begin{cases} P_{\text{xumaxch}}(\text{t}) = \min\{P_{rate} \eta_d \eta_{inv}, [E_A(t-1) - E_{\min}] \eta_d \eta_{inv} / \vartriangle t\} \\ P_{\text{xumaxdis}}(\text{t}) = -\min\{\dfrac{P_{rate}}{\eta_c \eta_{inv}}, [E_{\max} - E_B(t-1)]/(\eta_c \eta_{inv} \vartriangle t)\} \end{cases} \tag{6}$$

To ensure long-term stable operation of DBESS, the power of the two battery packs should be adjusted in real time according to the operating conditions of DBESS.

3. DBESS OPERATING STATUS AND EVALUATION INDICATORS

3.1 DBESS extreme operating range

For avoiding over-charging and over-discharging of the battery, the state of two packs should exchange, as long as one set of batteries reaches the state transition threshold. Nevertheless, long-term operation may lead DBESS enters an extreme operating range where exists insufficient discharge capacity or charge capability, as shown in Fig. 3.

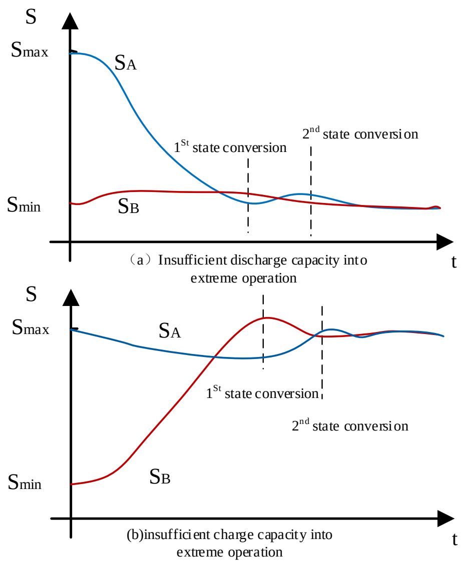

Fig.3 Unstable operation of DBESS

3.2 DBESS operating status assessment indicators

The SOC of the two battery packs are the key parameter affecting the conversion of the operating state of DBESS. Based on the real-time operation, this paper proposes the charge-discharge saturation capability indicator that can reflect the operating conditions of DBESS and is available to measure the ability of DBESS to smooth wind power output when DBESS operates at the optimal discharge depth.

$$\begin{cases} \varepsilon_{ch}(t-1) = S_{\max} - S_{ch}(t-1) \\ \varepsilon_{dis}(t-1) = S_{dis}(t-1) - S_{\min} \end{cases} \tag{7}$$

Particularly, when battery A works as a charge battery, and battery B works as a discharge battery, the formula (7) could be written as:

$$\begin{cases} S_{ch}(t-1) = S_A(t-1) \\ S_{dis}(t-1) = S_B(t-1) \end{cases} \tag{8}$$

otherwise:

$$\begin{cases} S_{ch}(t-1) = S_B(t-1) \\ S_{dis}(t-1) = S_A(t-1) \end{cases} \tag{9}$$

$$\Delta S_{AB}(t-1) = \varepsilon_{ch}(t-1) - \varepsilon_{dis}(t-1) \tag{10}$$

If the optimal discharge depth is given as *d*, that is to say, $\Delta S_{AB}(t-1) \in [-d,d]$. When $\Delta S_{AB}(t-1)$ is greater than 0, it means the total energy that discharge battery pack has released, which used to smooth the fluctuations of wind power, is relatively more than the total energy that charge battery pack has absorbed. If it is not deal with in time, the discharge battery pack will reach the critical conversion value before the charge battery pack. Meanwhile, the larger the value is, the more unfavorable the coordinated and stable operation of DBESS will be. Conversely, when $\Delta S_{AB}(t-1)$ is below 0, it means the total energy that the charge battery pack has absorbed is relatively more than the total energy that the discharge battery pack has released. If it does not be solved in time, the charge battery pack will reach the critical conversion value before the discharge battery pack. Similarly, the larger the value is, the more unfavorable the coordinated and stable operation of DBESS will be.

4. REAL-TIME OPTIMIZATION AND CONTROL OF SOC BASED ON VARIABLE FILTER TIME CONSTANT

The method devised in this paper divides the charge and discharge stability of DBESS into *2n* operation intervals (as shown in the figure.4).

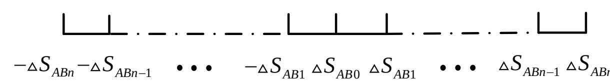

Fig.4 charging and discharging stability interval division of DBESS

The stability of charge and discharge reflects whether DBESS has the tendency to enter the insufficient charging or insufficient discharging status caused by the imbalance energy between charge and discharge process. Therefore, when the charge battery pack is working at this time and the absolute value of $\Delta S_{AB}(t-1)$ (negative) is relatively large, the filter time constant T value should reduce to speed up the tracking process of P_{gref} to P_w. Otherwise, if the value of $\Delta S_{AB}(t-1)$ is positive, constant value should increase to slow down the tracking speed of P_{gref} to P_w, also relatively increase the charging power of DBESS. It helps speed up the SOC of the charge battery pack and narrow the difference between two types of battery. When the discharge battery pack replace the charge battery to work at this time, the regulation is similar to the one just mentioned. Dividing the charge and discharge stability values into different sections by their sizes facilitate adjust the filter time constant.

According to the charge and discharge stability value and state of DBESS, the rules for adjusting the filter time constant T are derived in Table 1.

Table.1 Filter time constant adjustment rules

$\Delta S_{AB}(t-1)$	w_c	w_d	ΔT	P_{total}

$[-\vartriangle S_{ABn},$	1	0	$-C_n T_d$	↑
$-\vartriangle S_{ABn-1}]$	0	1	$C_n T_d$	↓
$[-\vartriangle S_{ABn-1},$	1	0	$-C_{n-1} T_d$	↑
$-\vartriangle S_{ABn-2}]$	0	1	$C_{n-1} T_d$	↓
$\vdots$	1	0	$\vdots$	$\vdots$
	0	1	$\vdots$	$\vdots$
$[-\vartriangle S_{AB1}, \vartriangle S_{AB0}]$	1	0	$-C_1 T_d$	↑
	0	1	$C_1 T_d$	↓
$[\vartriangle S_{AB0}, \vartriangle S_{AB1}]$	1	0	$C_1 T_d$	↓
	0	1	$-C_1 T_d$	↑
$\vdots$	1	0	$\vdots$	$\vdots$
	0	1	$\vdots$	$\vdots$
$[\vartriangle S_{ABn-2}, \vartriangle S_{ABn-1}]$	1	0	$C_{n-1} T_d$	↓
	0	1	$-C_{n-1} T_d$	↑
$[\vartriangle S_{ABn-1}, \vartriangle S_{ABn}]$	1	0	$C_n T_d$	↓
	0	1	$-C_n T_d$	↑

where exists the following equation:

$$C_1 < C_2 < \cdots < C_n \tag{11}$$

Filter time constant adjustment is:

$$T(t) = T(t-1) \pm C_x T_d \tag{12}$$

where $x = 1, 2, \cdots n$, its value depends on Table 1.

5. RESULTS AND DISCUSSIONS

In order to verify the effectiveness of the control strategy mentioned above, we perform a simulation using MATLAB/Simulink software. The total installed capacity of the wind farm is 32MW; DBESS is composed of battery A and battery B. To avoid the impact of insufficient rated power on the control strategy, the rated capacity of the two battery packs are set to 30MWh/10MWh, and the optimal DOD is given as 0.6. Initially, battery A and battery B work as the chargeable battery and the dis-charge battery with the SOC are 0.2 and 0.8, respectively, and the efficiency of both packs is 0.9, and the conversion efficiency of converter is 0.95. The filter time constant during normal operation is set to 160s; As well as, the maximum time constant is set to 200s, and the minimum limit is set to 120s. Besides, *n* is set to 3, $C_1 = 0$, $C_2 = 1$, $C_3 = 2$; $\vartriangle S_{AB0} = 0$, $\vartriangle S_{AB1} = 0.2$, $\vartriangle S_{AB2} = 0.4$, $\vartriangle S_{AB3} = 0.6$.

This simulation mainly takes the situation that ESS enters the extreme operation due to insufficient discharge capacity as an example, while the analysis of the system entering the extreme operation state due to insufficient charging capacity is similar to this. This paper will not elaborate.

5.1 Analysis of SOC optimization control effect

Fig.5 shows the differences of two battery packs' SOC with the proposed control strategy changing time constant and without control strategy respectively in DBESS.

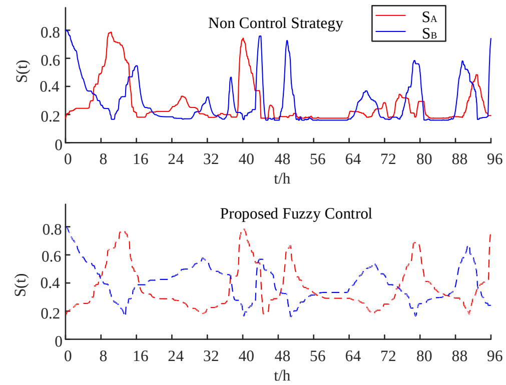

Fig.5 The SOC curves of battery A and battery B with/without proposed control strategy

In Fig. 5, when DBESS does not adopt the proposed control strategy, there exists the unbalanced charge and discharge energy of two battery packs during operation. During each charge-discharge cycle of simulation period, the discharge battery pack A vulnerably reaches to the next critical conversion value owing to insufficient remaining capacity. As a result, the charge battery pack B fails to be fully charged, thus the remaining capacity of charge battery pack B is relatively less when it starts to undertake the discharge task in the next stage, that's the reason the operating mode exchange quickly. With this cycle continues, the remaining capacity of two battery packs are seriously insufficient and the discharge ability of DBESS is extremely weak during part of operation condition, such as 81h -88h.

Fig.6 shows the actual charging and dis-charging power of DBESS with and without proposed control strategy respectively during 81h-88h.

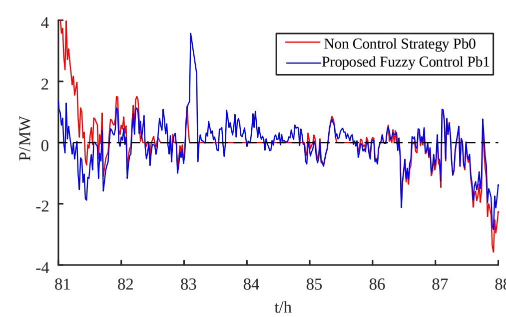

Fig.6 The actual charging and discharging power with/without proposed control strategy during 81*h*-88*h*

In Fig.6, if DBESS is required to release energy to smooth the wind power fluctuations during 82h to 86h, the two battery packs will never work limited by the given operating mode. It is difficult for DBESS to ensure the stability of long-term operation in extreme operating range due to insufficient discharge capacity. However, with the proposed control strategy, the SOC of the two battery packs are optimized in real time to maintain equal operating capabilities of the two battery packs as possible, even though it could not guarantee that each battery pack operates at the given optimal DOD. Ultimately, the extreme operating caused by insufficient charge and discharge capacity of DBESS are avoided.

5.2 Analysis of smoothing effect of wind power

Fig.7 shows the smoothing effect of wind power fluctuations at different operating time periods.

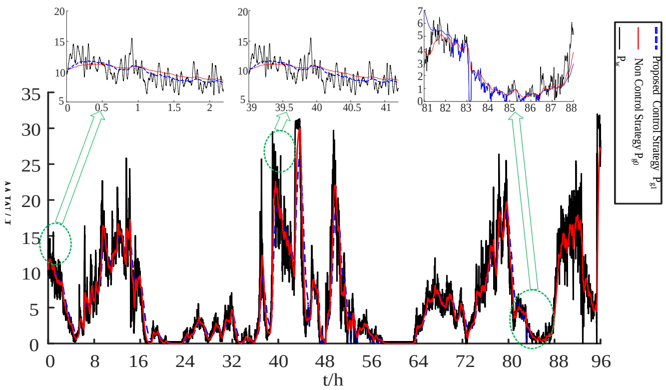

Fig.7 Wind power output P_w and grid-connected power P_{g1} / P_{g0} with/without control strategy during different periods Wind power under different situations during 0h -96h

In Fig.7, during normal operating range of DBESS, whether the proposed control strategy applied or not, does not exert an influence on smoothing the fluctuations of wind power effectively. Nevertheless, during some operation periods (e.g., 81h-88h), DBESS without the strategy has a significantly poorer effect on smoothing fluctuations of wind power, even completely loses its ability. The reason is that both battery packs are over-discharged to reach the given minimum limit, and the system lose the ability to take the discharge task, also to meet the energy requirement to smooth power fluctuations. After adopting the proposed control strategy, the optimization of the operating state of the system ensures that the charging and discharging capability of DBESS is comparable during the operation. The situation where the chargeable or discharge capacity is insufficient, only barely exist in the extreme short period, like approaching the transition range of state.

6. CONCLUSIONS

In this paper, the charge-discharge smoothness index which characterizes the system operation status is proposed considering the unbalanced energy between charging and discharging process of DBESS. Meanwhile, to optimize the SOC of each pack, a controller is designed to fine-tune the first-order low-pass filter time constant in real time. The simulation results have shown that the proposed method make DBESS operate at the given optimal DOD as far as possible, and the extreme operating conditions have been avoided in which the system lacks sufficient capacity to ensure the feasibility of long-term stable operation of DBESS. What's more, it improves the effect of DBESS on smoothing wind power fluctuations.

REFERENCE

[1] HAMEER S, NIEKERK J L. A review of large scale electrical energy storage, International Journal of Energy Research, 2015; 39(9): 1179-1195.

[2] YE Y, SHI Y, TAY AAO. Electro-thermal cycle life model for lithium iron phosphate battery, Journal of Power Sources, 2012; 217(11): 509-518.

[3] Ke X, Lu N, Jin C. Control and Size Energy Storage Systems for Managing Energy Imbalance of Variable Generation Resources, IEEE Transactions on Sustainable Energy, 2017; 6(1):70-78.

[4] Yao D L, Choi S S, Tseng K J, et al. Determination of Short-Term Power Dispatch Schedule for a Wind Farm Incorporated With Dual-Battery Energy Storage Scheme, IEEE Transactions on Sustainable Energy, 2011; 3(1): 74-84.

[5] A Statistical approach to the design of a dispatchable wind power-battery energy storage system. IEEE Transactions on Energy Conversion, 2009; 24(4): 916-925.

[6] LI Junhui, JI Li, CUI Xinzhen, et al. Coordination operating characteristics analysis of dual battery energy storage system based on PSCAD/EMTDC, Journal of Chinese Electrical Engineering Science, 2015; 30(14): 434-441.

[7] ZHANG Hua, ZHANG Bin, JI Tianming, et al. Control strategy and economic analysis of energy storage system based on bidirectional complementary, Electric Power Construction, 2016; 37(8): 96-101. (in Chinese)

