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State-of-charge optimising control approach of battery energy storage system for wind farm

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Abstract: In recent years, configuring battery energy storage system (BESS) in wind farm has become the most popular method to smooth wind power fluctuation. The effectiveness of wind power fluctuation smoothing relies on the charging/discharging power control and state of charge (SOC) regulation of BESS. This study proposed a novel optimising SOC control approach for BESS in wind farm which could regulate wind power fluctuation in a suitable level and maintain SOC in an optimal range by utilising the wind power prediction information. A wind power prediction-based optimal SOC calculation module is designed to obtain an optimal range of SOC which makes BESS have enough capacity to smooth wind power fluctuation in a finite future period of time. It takes minimising over-charging and over-discharging time as optimisation objectives and biggest variations of wind farm outputting power within 1 and 10 min as restraint. A fuzzy self-adjusting of filter-based real-time control module is designed to smooth the wind power fluctuation in real time and regulate SOC to the optimal range. Finally, the effectiveness of the proposed approach was demonstrated through implementing it in wind power smoothing control simulation experiments.

1 Introduction

Since the randomness and intermittence characteristics of wind power, the outputting power of wind farm alone would fluctuates with the wind changing. The wind power fluctuation would seriously affect the stability and security of power grid operation [1]. Recently, configuring battery energy storage system (BESS) in wind farm has become the most popular method to smooth wind power fluctuation [2, 3]. The BESS could be used to smooth wind power fluctuation by absorbing the excess wind power or filling up the power outputting, which makes wind farm connecting into the power grid as a stabilised power supply.

In wind farm configuring with BESS, BESS is prone to be over-charging or over-discharging for the irregular charging or discharging with wind power fluctuation [4, 5]. It is that state of charge (SOC) of BESS is out of normal working range, which would cause adverse effects, such as loss of battery life, losing ability of wind power fluctuation smoothing for insufficient capacity. Currently, most existing BESS control approaches utilize the principle of low-pass filter to compensate wind power fluctuation. However, they do not consider the limitation of SOC of battery [6–8], they only limit charging or discharging power of BESS when the SOC is out of its normal working range [9–13].

Recently, some researchers have started to study the control approach for BESS, which would maintain SOC of BESS in a normal working range. In [14], a SOC limitation strategy is utilised in low-pass filter-based BESS control to avoid overcharging and discharging. In [15], a variable time constant filtering-based BESS control approach is proposed, which makes SOC tend to a limited range by adjusting time constant. In [16], a modified time constant adjusting strategy is proposed, which adjusts the time constant piecewise according to SOC in real time to maintain SOC in a limited range. In [17], a SOC-based smoothing control approach is proposed, which adds an adjusting power when the SOC is too low or too high, to control SOC into normal working range. In [18], a fuzzy control based smoothing control approach is proposed to avoid over-charging or over-discharging, which uses a fuzzy controller to adjust charging or discharging power calculated by a low-pass filter. All the above control BESS approaches try to limit the SOC of BESS in a fixed working range, and they could avoid over-charging and over-discharging of BESS in some extent. However, a fixed working range may not be a suitable SOC range, which would cause that BESS has inefficient capacity to smooth wind power fluctuation in a finite period of time in future. With the development of wind power prediction technology [19, 20], it is possible to calculate an optimal SOC to smooth wind power fluctuation and avoid over-charging or over-discharging in a finite period of time in future.

This paper proposes a novel SOC optimising control approach of BESS for the wind farm, which utilises wind power prediction information to calculate an optimal SOC range and utilises a fuzzy self-adjusting filter to regulate SOC in the optimal range. An objective optimisation-based optimal SOC calculation module (OSCM) is introduced, which takes minimising over-charging and over-discharging time of BESS in a finite period of time as optimising objective and takes biggest variations of wind farm outputting power as constraints. A SOC real-time control module (SRCM) is designed based on fuzzy self-adjusting filter, which smoothes wind power fluctuation in real time and regulates the SOC of BESS into the optimal range gradually with maintaining the biggest variations of outputting power of wind farm in power grid standard level. In this way, the BESS will not only smooth the current power fluctuations, but also has enough ability to smooth the future power fluctuations in the long term without the over-charging or over-discharging of BESS.

The rest of this paper is organised as follows. The structure of a wind farm with BESS is described in Section 2. In Section 3, the proposed control approach is presented in details, including the design of optimal SOC calculation module and SOC real-time control module. In Section 4, the implementation of the proposed control approach to wind power fluctuation smoothing simulation

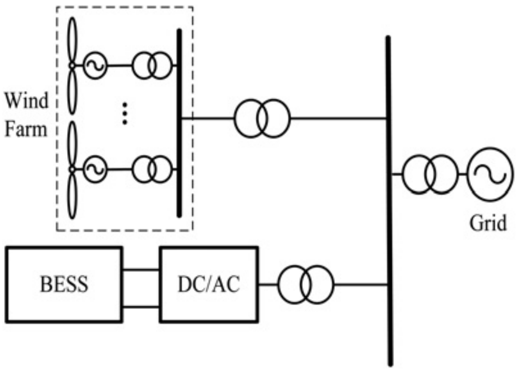

Fig. 1 *Wind farm with BESS*

experiment is described, where the results are discussed. The conclusions are drawn in Section 5.

2 Optimising SOC control of BESS for wind farm

2.1 Wind farm configuring with BESS

The wind farm configuring with BESS is shown in Fig. 1. It mainly consists of wind farm, BESS and DC/AC converter. It always configures BESS with a wind farm in a centralised way. The BESS is connected to the grid through a DC/AC converter at parallel port where wind farm connects into the power grid. The charging or discharging operation of BESS is controlled to smooth the outputting power of wind farm.

2.2 Optimising SOC control approach of BESS for wind farm

The control scheme of the proposed approach for wind farm is shown in Fig. 2, where P_W is the outputting power of wind farm, P_pre is the predictive power of wind farm, $P_\mathrm{out\_exp}$ is the expected power transmitted to the grid, $P_\mathrm{B\_ref}$ is the reference power of BESS and T is the filter time constant.

As seen in Fig. 2, the control scheme consists of OSCM and SRCM. The OSCM adopts an objective-optimisation model to calculate the optimal SOC range according to the predictive power of wind farm, rated power, capacity and normal working SOC rang of BESS. The OSCM will calculate the optimal SOC range in a period of SOC regulation, which will be used as the objective of SOC regulation for SRCM. The SRCM consists of a fuzzy logic-based filter time constant adjuster and a low-pass filter. The fuzzy logic-based filter time constant adjuster is utilised to regulate SOC of BESS to the optimal range by adjusting the time constant of the low-pass filter. The low-pass filter is utilised to smooth wind power fluctuation in real time.

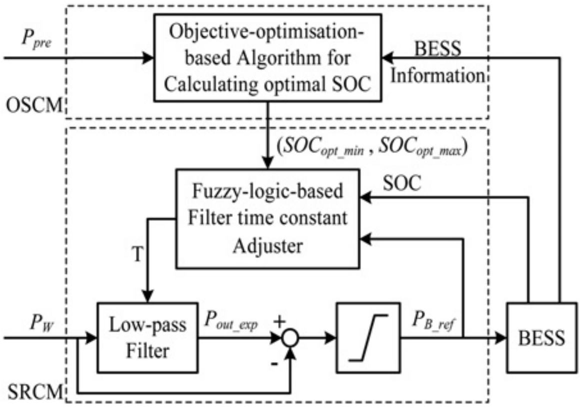

Fig. 2 *Control structure of the optimal method of SOC*

3 Design of optimal SOC calculation module

The design objective of the optimal SOC calculation module is designing an objective optimisation model to calculate the optimal range of SOC of BESS. By using the capacity, the reference power and the limitation of normal working SOC range, the objective optimisation model takes minimises over-charging and over-discharging time of BESS as optimisation objective. By using the wind power prediction information, rated power of wind farm expected power of wind farm and limitation of normal working SOC range, constraints of the objective optimisation model is deduced according to the constraints of the biggest variations of wind farm outputting power and limitation of the optimal range of SOC.

The objective functions and constraint conditions of objective optimisation model will be given in following subsection.

3.1 Objective functions

The objective of calculating the optimal SOC is obtaining an optimal SOC range, which could ensure the capacity of BESS to smooth the wind power fluctuation without over-charging or over-discharging in a finite future period of time. So, the first objective is obtaining an optimal SOC range, which could minimises over-charging and over-discharging time of BESS, whose function is given as follows

$$\min f = \sum_{i=1}^{N} u(t_i)\Delta t \tag{1}$$

where Δt is the calculating step size, N is the step size number of finite coming period of times in future, $u(t_i)$ is a representing function whether the BESS is over-charging or over-discharging at t_i, which is given as follows

$$u(t_i) = \begin{cases} 0 & \mathrm{SOC}_\mathrm{min} \le \mathrm{SOC}(t_i) \le \mathrm{SOC}_\mathrm{max} \\ 1 & \mathrm{SOC}(t_i) < \mathrm{SOC}_\mathrm{min} \text{ or } \mathrm{SOC}(t_i) > \mathrm{SOC}_\mathrm{max} \end{cases} \tag{2}$$

where $\mathrm{SOC}_\mathrm{max}$ and $\mathrm{SOC}_\mathrm{min}$ are the upper and lower limits of the normal working range of BESS respectively, $\mathrm{SOC}(t_i)$ is SOC of BESS at t_i.

The relationship of SOC at two adjacent time step is as follows

$$\mathrm{SOC}(t_i) = \mathrm{SOC}(t_{i-1}) - \frac{P_\mathrm{B\_ref}(t_i)\Delta t}{E_\mathrm{cap}} \tag{3}$$

where $P_\mathrm{B\_ref}\,(t_i)$ is the reference power of the BESS at t_i and E_cap is the capacity of BESS.

As the optimal SOC range could be represented by optimal upper limit $\mathrm{SOC}_\mathrm{opt\_max}$ and optimal lower limit $\mathrm{SOC}_\mathrm{opt\_min}$, the objective function in (1) could be rewritten as follows

$$\min f_1 = \sum_{i=1}^{N} u_{\mathrm{optSOC\,min}}(t_i)\Delta t \tag{4}$$

$$\min f_2 = \sum_{i=1}^{N} u_{\mathrm{optSOCmax}}(t_i)\Delta t \tag{5}$$

where $u_\mathrm{optSOCmin}(t_i)$ is a function represents whether BESS is overcharging or over discharging at t_i when $\mathrm{SOC}(t_0) = \mathrm{SOC}_\mathrm{opt\_min}$, $u_\mathrm{optSOCmax}(t_i)$ is a function represents whether BESS is over-charging or over-discharging at t_i when $\mathrm{SOC}(t_0) = \mathrm{SOC}_\mathrm{opt\_max}$ ($u_\mathrm{optSOCmin}(t_i) = 0$, $u_\mathrm{optSOCmax}(t_i) = 0$ represents no over-charging and over-discharging, $u_\mathrm{optSOCmin}(t_i) = 1$, $u_\mathrm{optSOCmin}(t_i) = 1$ represent overcharging or over-discharging).

To enhance achievability of the optimal range of SOC, the second objective is set to minimise the distance between $\text{SOC}_{\text{opt\_min}}$ and SOC_{min} and the distance between $\text{SOC}_{\text{opt\_max}}$ and SOC_{max}. It could be written as follows

$$\min f_3 = \left|\text{SOC}_{\text{opt\_min}} - \text{SOC}_{\text{min}}\right| \tag{6}$$

$$\min f_4 = \left|\text{SOC}_{\text{opt\_max}} - \text{SOC}_{\text{max}}\right| \tag{7}$$

3.2 Constraint conditions

Power grid always takes biggest variations of wind farm outputting power within 1 and 10 min as grid connected operation standard of wind farm [21]. Thus, two constraint conditions for the power fluctuation within 1 and 10 min of a finite coming period of time in future are presented as follows

$$\max_{j=1,2,\ldots,N_1} P_{\text{out}}(t_{i-j}) - \min_{j=1,2,\ldots,N_1} P_{\text{out}}(t_{i-j}) \le \frac{1}{10} P_{\text{rated}} \tag{8}$$

$$\max_{j=1,2,\ldots,N_{10}} P_{\text{out}}(t_{i-j}) - \min_{j=1,2,\ldots,N_{10}} P_{\text{out}}(t_{i-j}) \le \frac{1}{3} P_{\text{rated}} \tag{9}$$

where N_1 is the step time numbers within 1 min, N_{10} is the step time numbers within 10 min, P_{rated} is the rated power of wind farm and $P_{\text{out}}(t_i)$ is the expected power transmitted to the grid at t_i.

The expected power $P_{\text{out}}(t_i)$ could be calculated as follows

$$P_{\text{out}}(t_i) = P_{\text{w\_pre}}(t_i) + P_{\text{B\_ref}}(t_i) \tag{10}$$

where $P_{\text{w\_pre}}(t_i)$ is the predictive power of wind farm at t_i and $P_{\text{B\_ref}}(t_i)$ is the reference power of BESS t_i.

The upper and lower limitations of the optimal range of SOC should be limited in the normal working range. Thus, the constraint conditions for them are given as follows

$$\text{SOC}_{\text{min}} \le \text{SOC}_{\text{opt\_min}} \le \text{SOC}_{\text{max}} \tag{11}$$

$$\text{SOC}_{\text{min}} \le \text{SOC}_{\text{opt\_max}} \le \text{SOC}_{\text{max}} \tag{12}$$

The reference power of BESS $P_{\text{B\_ref}}(t_i)$ should be limited between the biggest charging power $P_{\text{ch\_max}}$ and discharging power $P_{\text{disch\_max}}$ of BESS. Thus, its constraint condition is given as follows

$$-P_{\text{ch\_max}} \le P_{\text{B\_ref}}(t_i) \le P_{\text{disch\_max}} \tag{13}$$

3.3 Analysis and solution of the objective optimisation model

Linear weighted function method [22] is adopted to solve above multi-objective optimisation problem, which could convert the multi-objective optimisation problem into single optimisation problem. And then, particle swarm algorithm [23] is adopted to solve the single optimisation problem. The evaluation function for the multi-objective optimisation problem is given as follows

$$\min F = \lambda_1 f_1 + \lambda_2 f_2 + \lambda_3 f_3 + \lambda_4 f_4 \tag{14}$$

where λ_1, λ_2, λ_3, λ_4 are the weight coefficients of the corresponding objective functions.

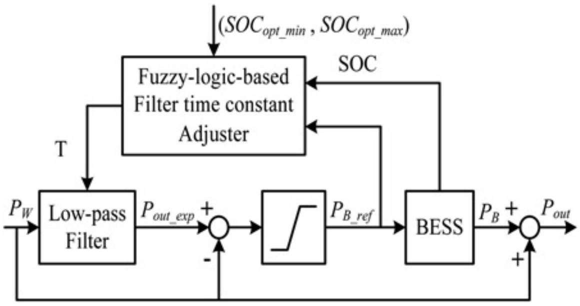

Fig. 3 *Control structure of SOC real-time control module*

According to (1)–(14), the objective functions and constraint conditions of the objective optimisation model are written as follows

$$\min F = \lambda_1 \sum_{i=1}^{N} u_{\text{optSOC min}}(t_i)\Delta t + \lambda_2 \sum_{i=1}^{N} u_{\text{optSOC max}}(t_i)\Delta t + \lambda_3\left|\text{SOC}_{\text{opt\_min}} - \text{SOC}_{\text{min}}\right| + \lambda_4\left|\text{SOC}_{\text{opt\_max}} - \text{SOC}_{\text{max}}\right| \tag{15}$$

s.t.

$$\begin{cases} \max\limits_{j=1,2,\ldots,N_1} P_{\text{out}}(t_{i-j}) - \min\limits_{j=1,2,\ldots,N_1} P_{\text{out}}(t_{i-j}) \le \dfrac{1}{10} P_{\text{rated}} \\ \max\limits_{j=1,2,\ldots,N_{10}} P_{\text{out}}(t_{i-j}) - \min\limits_{j=1,2,\ldots,N_{10}} P_{\text{out}}(t_{i-j}) \le \dfrac{1}{3} P_{\text{rated}} \\ -P_{\text{ch\_max}} \le P_{\text{B\_ref}}(t_i) \le P_{\text{disch\_max}} \\ \text{SOC}_{\text{min}} \le \text{SOC}_{\text{opt\_min}} \le \text{SOC}_{\text{max}} \\ \text{SOC}_{\text{min}} \le \text{SOC}_{\text{opt\_max}} \le \text{SOC}_{\text{max}} \\ \text{SOC}(t_i) = \text{SOC}(t_{i-1}) - \dfrac{P_{\text{B\_ref}}(t_i)\Delta t}{E_{\text{cap}}} \\ P_{\text{out}}(t_i) = P_{\text{B\_ref}}(t_i) + P_{\text{w\_pre}}(t_i) \end{cases} \tag{16}$$

4 Design of SRCM

The design objective of SRCM is designing a fuzzy self-adjusting filter which could regulate the SOC of BESS to the optimal range and smoothes wind power fluctuation in real time with maintaining the biggest variations of wind farm outputting power in power grid standard level. The control structure and principle of SRCM are given in following.

4.1 Control structure and principle

The control structure of SRCM is shown in Fig. 3, where P_{B} is the output power of BESS and P_{out} is the practical power transmitted to the grid.

As seen in Fig. 3, SRCM mainly consists of a low-pass filter and a fuzzy-logic-based filter time constant adjuster. Low-pass filter calculates the reference charging power or discharging of BESS according to outputting power of wind farm in real time. Fuzzy-logic-based filter time constant adjuster adjusts the filter time constant to regulate charging and discharging power of BESS, so as to regulate the SOC of BESS.

4.2 Design of Low-pass filter

The most used wind power smoothing control approaches always utilise low-pass filter to reject the wind power fluctuation. Thus, a first-order low-pass filter as in [6] is adopted in SRCM, which

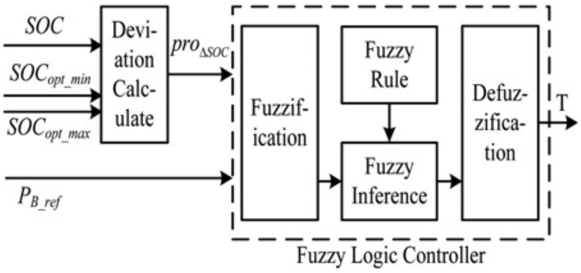

Fig. 4 *Structure of the fuzzy-logic-based filter time constant adjuster*

could be given as follows

$$P_{\text{out}} = \frac{1}{1+sT}P_{\text{W}} \tag{17}$$

where T is the time constant.

4.3 Design of fuzzy-logic-based filter time constant adjuster

Fuzzy-logic-based filter time constant adjuster is designed based on fuzzy control theory, which adjusts filter time constant according to according to SOC of BESS, the optimal range of SOC and the charge–discharge state of BESS. The structure of fuzzy-logic-based filter time constant adjuster is shown in Fig. 4.

As seen in Fig. 4, fuzzy-logic-based filter time constant adjuster consists of deviation calculation module and fuzzy logic controller. In Fig. 4, $\text{pro}_{\Delta\text{SOC}}$ is the deviation proportion of SOC of BESS in real time, which is calculated by deviation calculation module. Its calculation algorithm is given as follows.

(1) When $\text{SOC}_{\text{opt\_min}} \le \text{SOC} \le \text{SOC}_{\text{opt\_max}}$, the deviation calculate module uses following equation to calculate $\text{pro}_{\Delta\text{SOC}}$, when –50% $\le \text{pro}_{\Delta\text{SOC}} \le 50\%$

$$\text{pro}_{\Delta\text{SOC}} = \frac{\text{SOC} - (1/2)\left(\text{SOC}_{\text{opt\_min}} + \text{SOC}_{\text{opt\_max}}\right)}{\text{SOC}_{\text{opt\_max}} - \text{SOC}_{\text{opt\_min}}} \tag{18}$$

(2) When $\text{SOC} \ge \text{SOC}_{\text{opt\_max}}$, $\text{pro}_{\Delta\text{SOC}} = 50\%$.
(3) When $\text{SOC} \le \text{SOC}_{\text{opt\_min}}$, $\text{pro}_{\Delta\text{SOC}} = -50\%$.

The fuzzy controller is a two input–one output structure. The input variables to the fuzzy logic controller are $\text{pro}_{\Delta\text{SOC}}$ and $P_{\text{B\_ref}}$. The first input $\text{pro}_{\Delta\text{SOC}}$ varies between -50 and 50%, and its fuzzy sets is {NB, NM, NS, ZO, PS, PM, PB}, which means the SOC is {negative big, negative middle, negative small, zero, positive small, positive middle positive big}. The second input is reference power of BESS. When the $P_{\text{B\_ref}}$ is less than 0, the BESS is being charged, and its fuzzy variable is *N*. When $P_{\text{B\_ref}}$ is greater than 0, BESS is being discharged, and its fuzzy variable is *S*. The output variable of fuzzy logic controller is *T*, which ranges from 0 to 3000 s, and its fuzzy sets is {ES, VS, SM, M, BM, VB, EB}, which means {extremely small, very small, small middle, middle, big middle, very big, extremely big}.

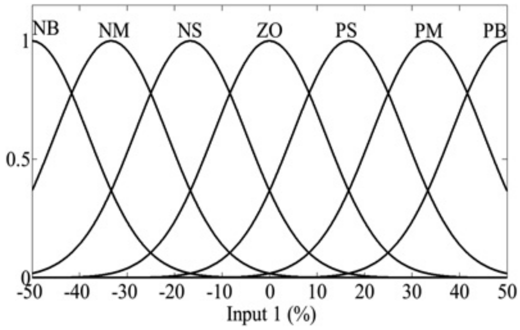

Fig. 5 *Membership function of the input 1*

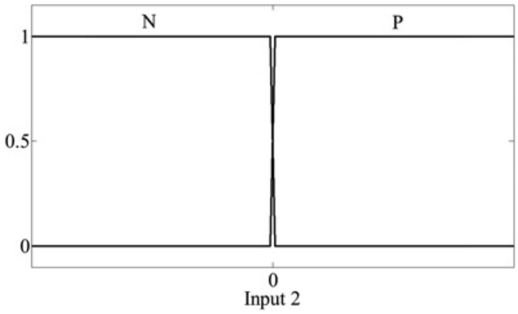

Fig. 6 *Membership function of the input 2*

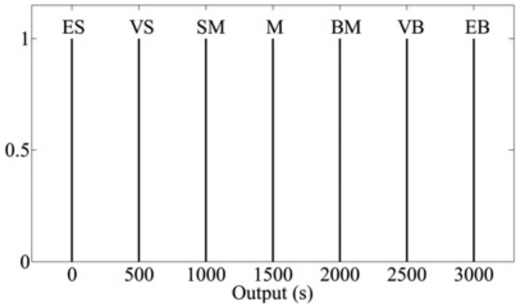

Fig. 7 *Membership function of the output*

The membership function of the two inputs and output of the fuzzy logic controller are shown in Fig. 5–7. Table 1 shows the fuzzy control rule. The weighted average method is used for defuzzification.

5 Simulation experiments

In this section, the proposed control approach will be illustrated by implementing it in wind power fluctuation smoothing control simulation experiment.

A wind farm with 20 1.5 MW wind turbines and Vanadium Redox Battery (VRB)-based BESS whose SOC could be easily measured [24], were used for in simulation experiments, whose parameters are shown in Table 2. The actual outputting power and predictive power of wind farm used in the simulation are shown in Fig. 8, which are collected from the wind farm in inner Mongolia in China [25] and predictive power of the wind farm is obtained by using wind power prediction method based on modified grey model [26].

The optimal range of SOC was calculated by solving the proposed optimal SOC calculation module designed in MATLAB, according to the predictive power of the wind farm in the future 10 min, and the calculation for the optimal SOC range was updated in every 10 min. The simulation model of the SOC real-time control

Table 1 Fuzzy control rule

U		E1						
		NB	NM	NS	ZO	PS	PM	PB
E2	N	EB	VB	BM	ZO	SM	VS	ES
	P	ES	VS	SM	ZO	BM	VB	EB

Table 2 Simulation parameters

Wind farm	
number of wind turbines	20
rated power of wind turbine	1.5 MW
total installed capacity	30 MW
BESS based on VRB	
number of VRBs	35
rated power of single VRB	420 kW
capacity of single VRB	70 kW·h
rated power of BESS	14.7 MW
capacity of BESS	2.45 MW·h
normal working range	0.2–0.8

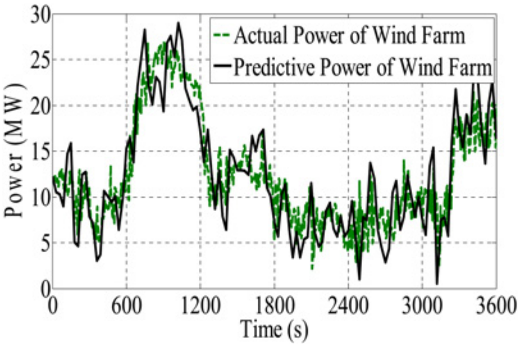

Fig. 8 *Actual and predictive outputting power of wind farm*

module was established in PSCAD, and the optimal range of SOC calculated in MATLAB was taken as the objective of SOC regulation.

Two experiments were conducted to demonstrate the effectiveness of the proposed control approach. For comparison, the proposed control approach which takes the optimal range of SOC as the objective of SOC regulation was used in experiment 1, low-pass filter-based smoothing control approach with a fixed SOC range limitation was used in experiment 2.

The experimental results are shown in Figs. 9–11. The simulation results of SOC and smoothing effectiveness by using above two control approaches are shown in Figs. 9 and 10. In Fig. 9, the red dashed lines are the optimal range of SOC calculated by the optimal SOC calculation module. As seen in Fig. 9, SOC in experiment 1 has a less variation than that in experiment 2, the SOC could be maintained in the optimal range. As seen in Figs. 9 and 10 both, the output power P_W of wind farm increases from 600 to 1200 s and from 3000 to 3600 s, which causes BESS over-charging around 1200 s and over-discharging around 3000 s in experiment 2. However, in experiment 1, the proposed control approach could regulate the SOC into the optimal SOC range in real time and maintain SOC in 0.2–0.8 which is a smaller range than that by using a low-pass filter-based smoothing control approach with a fixed SOC range limitation.

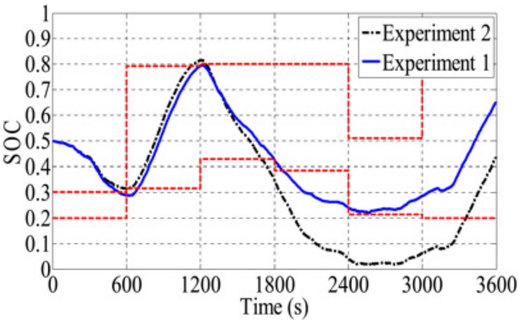

Fig. 9 *Simulation results of SOC of BESS*

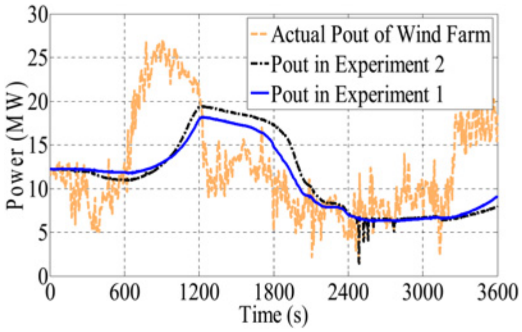

Fig. 10 *Smoothing control experiments results*

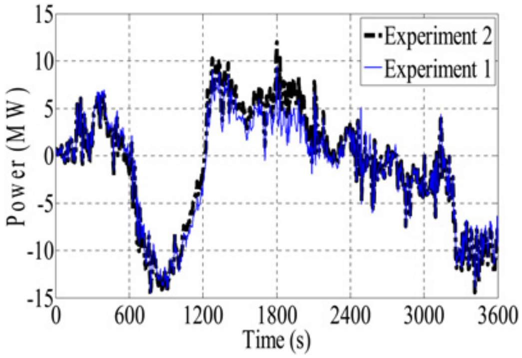

Fig. 11 *Simulation results of outputting power of BESS*

Table 3 Biggest variations of P_{out}

Experiment	1	2	Requirements
biggest variations in 1 min, MW	1.6425	5.4690	3
biggest variations in 10 min, MW	9.1524	14.6973	10

As seen in Fig. 10, the two control approaches have nearly the same smoothing performance before 2400 s. However, between 2400 and 3000 s, the power P_{out} transmitted to the grid in experiment 2 has violent fluctuation, and P_{out} in experiment 1 keeps smooth. Table 3 shows the biggest variations of P_{out} in 1 and 10 min. It is obvious that the biggest variations of P_{out} in experiment 1 are smaller than that in experiment 2.

The simulation results of outputting power BESS are shown in Fig. 11. As seen in Fig. 11, from 1200 to 2400 s, the discharging power is obviously higher in experiments 2 than experiment 1. Thus, SOC in experiment 2 decreases very fast, which causes BESS over-charging. The output power of BESS in experiment 2 becomes zero for several times, which makes the BESS has no capacity to fill up the wind power and makes P_{out} has a violent fluctuation. While the BESS in experiment 1 always has enough capacity to be charged or discharged to smooth wind power fluctuation, which keeps P_{out} smooth.

6 Conclusions

A novel SOC optimising control approach of BESS for wind farm was proposed in this paper. An objective optimisation-based optimal SOC calculation model is developed by using wind power prediction information, which could calculate the optimal range of SOC to avoid over-charging and over-discharging in a finite period of time in future. A fuzzy self-adjusting filter-based SOC real-time control module is designed to regulate SOC into the optimal range and keep outputting power of wind farm smooth in real time. The implementation of the proposed control approach in wind power smoothing control simulation experiments demonstrated its effectiveness.

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