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Effective power dispatch capability decision method for a wind-battery hybrid power system

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Abstract: With integration of a battery energy storage system (BESS) into the wind power system, the wind power variation can be mitigated to dispatch a constant power to the grid. To effectively supply the constant power dispatch to the grid with a limited BESS, the power dispatch capability should be defined primarily at beginning of each dispatching interval to cooperate with the transmission system operator. This study introduces a method to determine the power dispatch capability of a wind-battery hybrid power system with the minimal battery capacity. The power dispatch capability is decided under the condition that the battery power is maintained below its rating and that the state of charge of the battery is guaranteed within a safe range. For economic BESS operation, the battery capacity, including the power and energy ratings, is also determined cost-effectively to obtain the constant power dispatch. Based on the long-term wind power profile, the authors develop the determination process to minimise the battery capacity which ensures that the BESS sufficiently mitigates wind power variation to dispatch the constant power into grid under all wind conditions. To evaluate the proposed determination method, a case study is carried out with a 3-MW wind turbine generator and real wind speed data measured on Jeju Island in Korea.

1 Introduction

The intermittent characteristic of wind causes wind farms (WFs) to be non-dispatchable energy sources and limits the potential penetration of wind generation into the electric power system. Wind power sources are a leading candidate among renewable energy conversion systems [1], which have grown rapidly in recent years to resolve critical global problems such as environmental pollution and diminishing fossil energy sources. In [2], the grid frequency deviation caused by wind power fluctuation was investigated to show that wind power variations over second-long to minute-long periods can result in significant grid frequency deviation. The other severe impacts caused by wind power variation on the power system affect the grid connection, the power quality, and the system reliability. These factors are examined in [3]. Therefore, the problems related to the intermittency of wind generation must be overcome to dispatch high wind power into the grid.

There are two concepts that can be used to mitigate wind power fluctuation. The first includes power smoothing methods, without using energy storage systems, such as pitch angle control [4] and wind generator rotor inertia regulation [5]. Although these methods require low investment costs, they do not ensure that wind turbines (WTs) will capture the maximum available wind power [6]. In the second concept, wind power is smoothed by an energy storage system such as a battery, super-capacitor, superconducting magnetic energy storage, or flywheel. The application of these types of energy storage enables renewable energy conversion systems to be dispatchable and harness the maximum power available in wind [7]. As a result, the use of energy storage systems in wind generation systems has been actively researched as a feasible solution to enable high penetration of wind power into the electric power market.

Among the energy storage systems available, batteries are the most widely utilised because of their well-developed technology and their sufficient power and energy density [8]. Integrating batteries with WFs results in a wind-battery hybrid power system (WBHPS), in which the system cost and the power control must be taken into account. Related to the system cost, finding methods to minimise the battery capacity has attracted increased attention in recently published literatures [9–11]. Nguyen and Lee [9] suggested the use of a zero-phase low-pass filter to remove the phase-delay between the power dispatch and wind power, which results in the minimum required battery capacity. To control the power flow effectively, a new power dispatch control method has been proposed based on the state of charge (SOC) of the battery [10]. In addition, a two-time-scale coordination control was presented in [11] to minimise the battery capacity while simultaneously limiting the power dispatch fluctuation within an allowable range.

When the penetration level of wind power into electric power systems becomes comparable with conventional power sources, such as hydroelectric and nuclear power plants, the transmission system operator (TSO) requires that WFs supply a constant power in each dispatching interval [12]. To meet this requirement, the constant power dispatch control method was introduced in [13] by averaging the available wind power in each dispatching interval. Another interesting method is based on the maximum and minimum levels of the wind power that enable the battery to operate with full charge-discharge cycles; the battery lifetime can be prolonged significantly [14]. To cooperate with the TSO, the power dispatch capability of the WBHPS, which implies the maximum and minimum power dispatch levels, must be defined primarily at the beginning of each dispatching interval. Based on such levels, the TSO can command a suitable power dispatch to the WBHPS; this helps the WBHPS meet the commands of the TSO successfully. Therefore, the determination of the power dispatch capability is an essential step for managing the WBHPS.

In this paper, we define the battery capacity for the wind power system required to obtain a constant power dispatch based upon the long-term wind power profile and the averaged WT output. The proposed determination process makes it simple to determine the minimal battery capacity. Then, we introduce a method for determining the power dispatch capability of the WBHPS according to the wind power availability and the battery capacity status. To guarantee that the WBHPS operates properly, two crucial constraints are applied: the battery power should be kept lower than its rating, and the SOC of the battery should be kept within a safe operation range. In addition, the availability of the wind power in each dispatching interval is evaluated by forecasting the wind power.

To evaluate the proposed decision method, a case study is carried out using a 3-MW WT generator with real wind speed data measured on Jeju Island, Korea.

2 Integration of the battery into the wind power system

Fig. 1*a* shows a schematic diagram of a battery energy storage system (BESS) that has been applied to a WF to mitigate the wind power fluctuation. The WT generator is connected to the point of common coupling (PCC) via a power converter system (PCS1) that regulates the WT generator to capture the maximum available wind power. The BESS is connected to the PCC via the PCS2 that controls a bidirectional power flow: when the storage is charged, its power is a positive value (i.e. $P_b > 0$) and vice versa. Under the assumption that power losses in the system are negligible, the WBHPS output power P_d dispatched to the grid can be calculated from the BESS power, P_b, and the wind power, P_w, as

$$P_d = P_w - P_b. \tag{1}$$

The power management system (PMS) controls the WBHPS by determining a suitable power reference, P_b^*, for the PCS2 to successfully commit the power dispatch command, P_d^*, that is defined by the TSO of the electric power system. With the assumption that the PCS2 is capable of tracking the power reference, P_b^*, the PMS can determine the power reference for the PCS2 as follow:

$$P_b^* = P_w - P_d^*. \tag{2}$$

Therefore, the power dispatch command, P_d^*, is firmly associated with the WBHPS operation. To effectively manage the overall system, the PMS must submit the power dispatch capability to the TSO. Based on the information of the power dispatch capability, the TSO is aware of the WBHPS status. This enables the TSO to order a power dispatch command properly. As shown in Fig. 1*a*, P_d^{cap} denotes the power dispatch capability that includes the minimum and maximum levels represented by P_d^{min} and P_d^{max}, respectively. When the PMS sends the power dispatch capability to the TSO, the TSO can order the power dispatch command arbitrarily, but it must satisfy the following constraint

$$P_d^{min} \le P_d^* \le P_d^{max}. \tag{3}$$

To determine the power dispatch capability, P_d^{cap} (i.e. P_d^{min} and P_d^{max}), the PMS requires information about the wind power and SOC of the battery, as shown in Fig. 1*a*.

3 Determination of battery capacity

To mitigate the wind power variation, the battery capacity including the power and energy ratings must be sufficient. However, it is necessary to minimise the battery capacity to reduce the system cost. To determine the battery capacity, the wind power dispatching strategy should be defined primarily. In [15], several power dispatching strategies were overviewed and compared in terms of the battery capacity and the ability to cooperate with the TSO. Among the power dispatch strategies, the averaged method requires the smallest battery capacity and is able to cooperate with the TSO. Therefore, we apply this dispatching method to define the power dispatch of WBHPS.

3.1 Averaged power dispatch method

In the modern electric power market, the power dispatch of all generation systems must be constant in each dispatching interval. One of the most effective ways to achieve this requirement is to define the power dispatch by means of averaging the wind power. In the *k*th dispatching interval, the power dispatch is defined as follows

$$P_d(t) = \frac{1}{T_d}\int_{kT_d}^{(k+1)T_d} P_w(\tau)\,d\tau, \tag{4}$$

where T_d denotes one dispatching interval, which is generally set in hour-scale periods by the TSO [16, 17]. It is noted that we use the power dispatch defined in (4) is to determine the battery capacity. Once the battery capacity is defined, the overall system is managed to regulate the power and SOC of the battery by varying the power dispatch around the averaged value in (4).

The averaged power dispatch strategy is illustrated in Fig. 1*b*. This shows the 3 MW WT output power and the power dispatch. By averaging the available wind power, the power dispatch of the WBHPS is constant in each dispatching interval despite the fact that the wind power fluctuates significantly.

3.2 Determination of the minimum battery capacity

When the battery capacity is small, the system cost is reduced. However, a small capacity may not be sufficient to compensate for the wind variation to dispatch a constant power into the grid. Therefore, the battery capacity that is defined at the minimum required volume is the optimal solution.

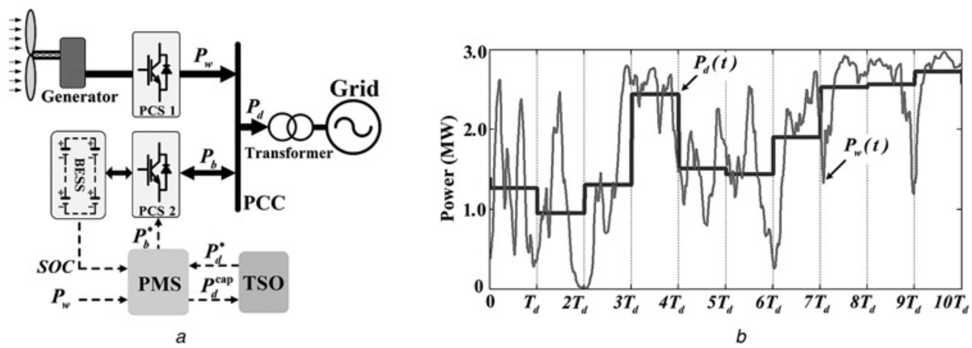

Fig. 1 *WBHPS and the power dispatch strategy*

a WBHPS configuration
b Illustration of the averaged power dispatch strategy

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To determine the battery capacity, the required battery capacity must be defined primarily. The required battery capacity, which is normally specified in terms of the energy rating, $E_{\rm b}^{\rm rat}$, and power rating, $P_{\rm b}^{\rm rat}$, is stated based on the battery power flow. From (1), the battery power can be expressed as

$$P_{\rm b}(t) = P_{\rm w}(t) - P_{\rm d}(t). \tag{5}$$

For a system operating over the time period, T, the required battery power rating is

$$P_{\rm b}^{\rm rat} = \underset{0 \le t \le T}{\rm MAX}\big(|P_{\rm b}(t)|\big) = \underset{0 \le t \le T}{\rm MAX}\big(|P_{w}(t) - P_{\rm d}(t)|\big). \tag{6}$$

The net energy either injected into or drawn out of the battery up to time t can be calculated as follows

$$E_{\rm b}(t) = \int_0^t P_{\rm b}(\tau)\,{\rm d}\tau = \int_0^t [P_{\rm w}(\tau) - P_{\rm d}(\tau)]\,{\rm d}\tau. \tag{7}$$

Similar to the power rating, the energy rating is defined as

$$E_{\rm b}^{\rm rat} = \frac{\underset{0 \le t \le T}{\rm MAX}\,(E_{\rm b}(t)) - \underset{0 \le t \le T}{\rm MIN}\,(E_{\rm b}(t))}{D}, \tag{8}$$

where D represents the depth of discharge of the battery. For example, if the SOC of the battery is regulated between 20 and 100%, then $D = 0.8$.

In this paper, we propose a process to define the battery capacity that is required to dispatch a constant power for the system. During the design and planning of the WBHPS, it is assumed that a historical wind power profile has been acquired; the WF owner must collect the historical wind profile to examine the wind power availability before making any investment decisions. To make sure that the defined battery capacity can handle the wind power variation, the wind power should be measured in long-term of several months up to several years. For example, the authors in [7] used one year wind data to design their own system, and another project reported in [14] utilised two years wind data to determine the BESS capacity. Based on the measured wind power profile in T, the following steps are suggested to determine the optimal battery capacity:

Step 1: Divide the wind power profile into N sets, where each set contains the wind power for the time interval $T_{\rm d}$. In the kth set, the wind power is denoted $P_{\rm w}^{k}(t)$, where $1 \le k \le N$ and $(k-1)T_{\rm d} \le t < kT_{\rm d}$. Note that $T = NT_{\rm d}$.

Step 2: For the $k$thinterval, the dispatched power and battery power are computed from (9) and (10), respectively

$$P_{\rm d}^{k} = \frac{1}{T_{\rm d}} \int_{(k-1)T_{\rm d}}^{kT_{\rm d}} P_{\rm w}^{k}(t)\,{\rm d}t, \tag{9}$$

$$P_{\rm b}^{k}(t) = P_{\rm w}^{k}(t) - P_{\rm d}^{k}. \tag{10}$$

Because the dispatched power is the average wind power in $T_{\rm d}$, the total charged energy is equal to the discharged energy. In the kth interval, the energy stored in the battery with respect to time is calculated as follows

$$E_{\rm b}^{k}(t) = \int_{(k-1)T_{\rm d}}^{t} P_{\rm b}^{k}(\tau)\,{\rm d}\tau, \tag{11}$$

During kth dispatching interval, the maximum variation of the battery energy response is defined as

$$\Delta E_{\rm b}^{k} = \underset{(k-1)T_{\rm d} < t \le kT_{\rm d}}{\rm MAX}\,(E_{\rm b}^{k}(t)) - \underset{(k-1)T_{\rm d} < t \le kT_{\rm d}}{\rm MIN}\,(E_{\rm b}^{k}(t)). \tag{12}$$

To effectively comply with the average dispatching method, the SOC of the battery at the beginning of each dispatching interval is usually maintained at the middle range of the operational SOC level. In other word, the battery energy at the beginning of kth dispatching interval is

$$E_{\rm b}^{k}(0) = \frac{{\rm SOC_U} + {\rm SOC_L}}{2} E_{\rm b}^{\rm rat}, \tag{13}$$

where $\rm SOC_L$ and $\rm SOC_U$ are the upper and lower SOC limits, respectively. To ensure that the WBHPS operates functionally, the battery energy must be kept within the allowable maximum and minimum ranges. Therefore, the following constraints are defined during the system operation

$$E_{\rm b}^{k}(0) + \Delta E_{\rm b}^{k} \le {\rm SOC_U} E_{\rm b}^{\rm rat} \tag{14}$$

$$E_{\rm b}^{k}(0) - \Delta E_{\rm b}^{k} \ge {\rm SOC_L} E_{\rm b}^{\rm rat} \tag{15}$$

By substituting (12) and (13) to (14) and (15), we can derive the constraint of the required battery energy rating

$$E_{\rm b}^{\rm rat} \ge 2\,\frac{\underset{(k-1)T_{\rm d} < t \le kT_{\rm d}}{\rm MAX}\,(E_{\rm b}^{k}(t)) - \underset{(k-1)T_{\rm d} < t \le kT_{\rm d}}{\rm MIN}\,(E_{\rm b}^{k}(t))}{{\rm SOC_U} - {\rm SOC_L}}. \tag{16}$$

Likewise, the battery power rating must be greater than the maximum value of the battery power in the kth interval

$$P_{\rm b}^{\rm rat} \ge \underset{(k-1)T_{\rm d} < t \le kT_{\rm d}}{\rm MAX}\,\{|P_{\rm b}^{k}(t)|\}. \tag{17}$$

Step 3: After determining the required battery capacity in each dispatching interval, the largest value is defined as the battery capacity for the WBHPS. The proposed flowchart to find the battery capacity is summarised in Fig. 2. By increasing the index k by one after a searching step, the minimum battery capacity in each interval $T_{\rm d}$ is calculated based on (16) and (17). When the index k reaches N, all of the wind power data sets are evaluated and the battery capacity is eventually determined.

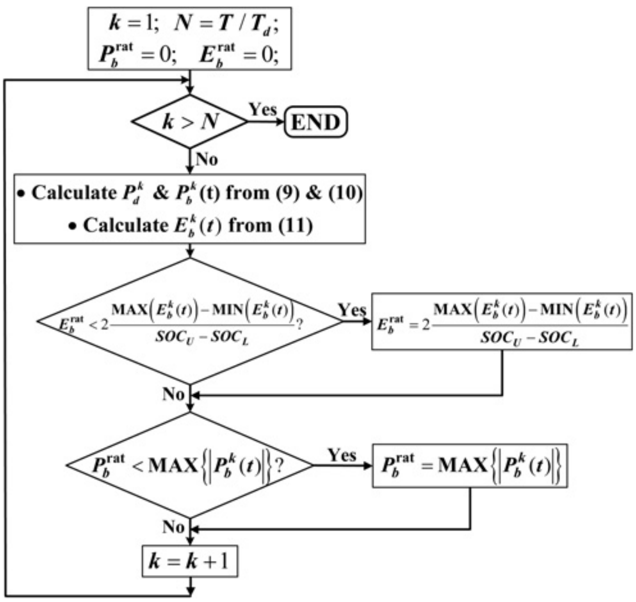

Fig. 2 *Proposed flowchart for determining the battery capacity*

4 Power dispatch capability

After determining the battery capacity, cooperation between the PMS and TSO is considered to effectively integrate the WBHPS output power into the grid. The TSO requires information about the power dispatch capability in each dispatching interval to appropriately command the power dispatch to the PMS. As mentioned in Fig. 1*a* and the constraint defined in (3), the PMS should submit the power dispatch capability (including the maximum and minimum levels of the power dispatch) to the TSO. Because the power dispatch capability is clearly dependent on the availability level of wind power, we must the forecast the wind power to examine the potential available wind power range. So far, several wind power forecast methods have been introduced to improve the forecasting accuracy. However, forecast error is inevitable, hence it is necessary to analyse the forecast error before determining the power dispatch capability.

4.1 Determination of the wind power range

In [18, 19], several advanced forecasting techniques have been developed to predict wind speeds accurately. However, error in the wind forecast data is inevitable and highly dependent on the time period of the forecast. The authors in [20] came to the conclusion that when the forecast horizon is less than half a day long, the probability of error in the wind speed forecast can be described in the form of a normal distribution with a constant mean μ and a standard deviation σ. Therefore, the real wind speed is bounded by the upper limit $v_f^u(t)$ and the lower limit $v_f^l(t)$ from the forecasted data $v_f(t)$ as follows

$$v_f^u(t) = v_f(t) + (\mu + \ell\sigma)V_r, \quad (18)$$

$$v_f^l(t) = v_f(t) - (\mu + \ell\sigma)V_r, \quad (19)$$

where V_r is the rated wind speed and ℓ is a constant specifying the forecast certainty level. For example, the probability that the real wind speed is within the upper and lower limits is 68.27% and 99.73% if $\ell = 1$ and $\ell = 3$, respectively.

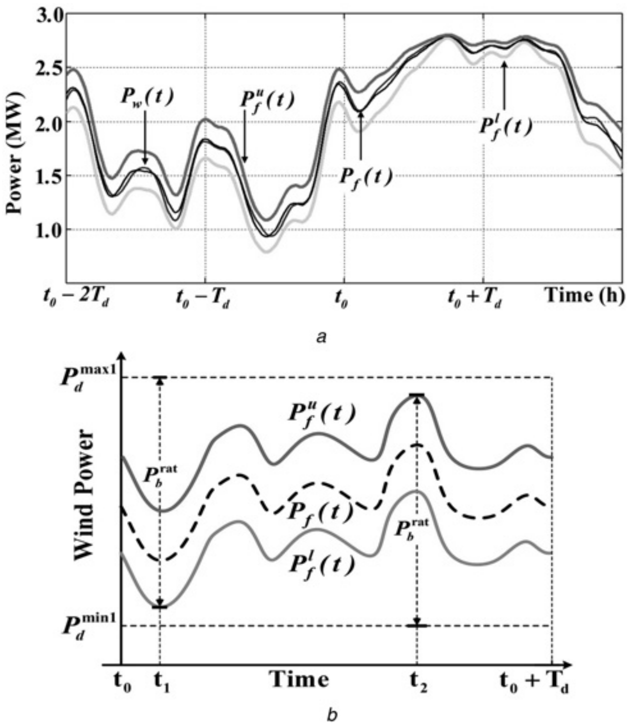

Fig. 3 *Wind power range and the capability of power dispatch*
a Forecasted wind power $P_f(t)$, the upper range $P_f^u(t)$, the lower range $P_f^l(t)$, and the real wind power $P_w(t)$
b Power dispatch capability related to the wind power availability

The relationship between wind speed $v(t)$ and the WT output power $P_w(t)$ is givens as follows

$$P_w(t) = \frac{1}{2} C_p(\lambda, \beta)\rho\pi R^2 v^3(t), \quad (20)$$

where ρ is the air density, R is the radius of the WT, and $C_p(\lambda, \beta)$ is the power coefficient, which is a function of the tip-speed ratio λ and the pitch angle β [21]. To capture the maximum available wind power, the PCS1 regulates the WT generator to obtain the maximal power coefficient C_p as shown in Fig. 1*a*. This power coefficient is usually given in the WT specification. As a result, the WT power range including the upper and lower power limits ($P_f^l(t)$ and $P_f^u(t)$) can be determined by using the upper and lower limits of wind speed. Fig. 3*a* shows an example of the wind power range with a zero mean error, a forecast confidence level of 99.73%, and a standard deviation of 3%. Despite the fact that the real wind power is likely to be different from the forecasted value, it is still bounded by the upper and lower power ranges.

4.2 Power dispatch capability of WBHPS

The power dispatch capability depends on the wind power availability and the battery capacity status. Based on the upper and lower wind power ranges, the wind power availability can be evaluated. The other technical consideration during WBHPS operation is to ensure that the battery stays below its power rating and that its SOC is maintained within a safe range. Therefore, determining the power dispatch capability means the maximum and minimum levels of the power dispatch are defined to meet the constraints associated with the wind power availability and the battery capacity status.

The first constraint is to keep the battery power lower than the battery power rating, P_b^{rat}, at all times. This can be expressed as

$$P_b(t) \le P_b^{rat}. \quad (21)$$

At the beginning of a new dispatching interval, which is denoted by t_0, the wind power range in one dispatching interval T_d is estimated using the process discussed previously. Based on the upper and lower ranges of the wind power and the relationship between the power dispatch and battery power defined in (1), the maximum and minimum levels of the power dispatch can be made to satisfy the first constraint as follows

$$P_d^{max1} = \underset{t_0 \le t \le t_0 + T_d}{\text{MIN}} \{P_f^l(t)\} + P_b^{rat}. \quad (22)$$

$$P_d^{min1} = \underset{t_0 \le t \le t_0 + T_d}{\text{MAX}} \{P_f^u(t)\} - P_b^{rat}. \quad (23)$$

Fig. 3*b* demonstrates the power dispatch capability determined from (22) and (23). At time t_1, the lower range of the wind power is minimal; the maximum level of the power dispatch is defined at this moment with (22). In addition, at time t_2 when the upper range of the wind power is at a maximum, the minimum level of the power dispatch is defined by (23).

The second constraint is to maintain the SOC within a safe range

$$\text{SOC}_L \le \text{SOC}(t) \le \text{SOC}_U. \quad (24)$$

At the beginning of a new dispatching interval (i.e. at t_0), the SOC of the battery is SOC_0. Using the energy conservation law, the constant power dispatch can be expressed as follows

$$P_d = \frac{E_w - \{\text{SOC}(t_0 + T_d) - \text{SOC}_0\}E_b^{rat}}{T_d}, \quad (25)$$

where E_b^{rat} is the battery energy rating and E_w is the wind power energy in the dispatching interval from t_0 to $t_0 + T_d$. The wind power energy is bounded by the lower limit E_f^l and the upper limit

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E_f^u, which are computed based on the wind power range $P_f^l(t)$ and $P_f^u(t)$. From (25), the maximum and minimum levels of the power dispatch can be defined to meet the second constraint as

$$P_d^{\max 2} = \frac{E_f^l - (\mathrm{SOC_L} - \mathrm{SOC_0})E_b^{\mathrm{rat}}}{T_d}, \quad (26)$$

$$P_d^{\min 2} = \frac{E_f^u - (\mathrm{SOC_U} - \mathrm{SOC_0})E_b^{\mathrm{rat}}}{T_d}. \quad (27)$$

It is recognised that the power dispatch capability defined in (26) and (27) not only relates to the wind power availability but also depends on the battery energy capacity. To ensure the validity of this system, the maximum power dispatch must be kept above the minimum power dispatch, that is, the following constraint must be satisfied

$$P_d^{\max 2} \geq P_d^{\min 2}. \quad (28)$$

From (18)–(20) and (26)–(28), the lower bound of the battery energy rating must be

$$E_b^{\mathrm{rat}} \geq \frac{2(\mu + \ell\sigma)P_r T_d}{\mathrm{SOC_U} - \mathrm{SOC_L}}, \quad (29)$$

where P_r is the WT output power rating. The relationship shown in (29) demonstrates that the requirements of the battery capacity are clearly related to the accuracy of the wind forecast. When the error of the wind forecast is reduced (i.e. both μ and σ are small), the system requires less battery capacity. Fig. 4 shows an example that illustrates the impact of the wind power forecast on the battery capacity. In this case, we consider the system where $P_r = 1$ MW, $T_d = 1$ h, $\mathrm{SOC_L} = 0.2$, $\mathrm{SOC_U} = 1.0$, and the forecast certainty level is 99.73%. The lower bound of the battery capacity is linearly enlarged when the mean error and the standard deviation are increased. It is noted that if the wind power is exactly forecasted (i.e. $\mu = 0$ and $\sigma = 0$), the lower bound is zero. This means that any battery capacity determined based on the long-term wind power history can be utilised to obtain constant power dispatch. However, when the wind power is not forecasted exactly, the battery capacity must be higher than the limit defined in (29).

Finally, to ensure that the power dispatch capability satisfies both constraints, the maximum and minimum levels of power dispatch are defined by (30) and (31)

$$P_d^{\max} = \mathrm{MIN}(P_d^{\max 1}, P_d^{\max 2}), \quad (30)$$

$$P_d^{\min} = \mathrm{MAX}(0, P_d^{\min 1}, P_d^{\min 2}). \quad (31)$$

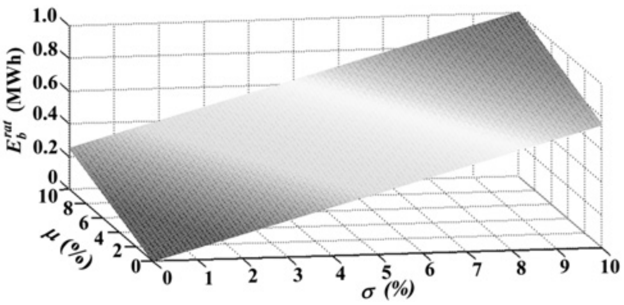

Fig. 4 *Lower bound of the battery capacity with respect to the wind forecast accuracy level*

5 Numerical examples

To demonstrate the proposed determination method of the battery capacity and the power dispatch capability, we investigate a 3-MW WT model [22] using MATLAB/Simulink with real wind speed data measured on Jeju Island in 2012 and 2013. The wind speed is sampled in 30 s periods and the dispatching interval is set to be 1 h (i.e. $T_d = 1$ h). In this study, we regulate the battery with the SOC between 20 and 100%, such that $\mathrm{SOC_L} = 0.2$, $\mathrm{SOC_U} = 1.0$, and $D = 0.8$.

5.1 Determination of battery capacity

For simply explaining the steps to decide the battery capacity, we only consider the wind power within the first 12 h of a day, as shown in Fig. 5. The wind power and power dispatch are shown in Fig. 5*a*. We can see that the power dispatch is constant in each dispatching interval despite the fact that the wind power is highly fluctuated. To obtain such constant power dispatch, the battery must respond to the power and energy, as shown in Figs. 5*b* and *c*, respectively. Based on 12 sets of battery power and energy values, we can define the battery power rating and energy rating to meet the required power response. Among these 12 sets of battery power, the battery power rating is defined by the first set as 1.8 MW. Similarly, the battery energy rating is specified by the fifth set because the maximum battery energy variation is 0.48 MWh in this set. Based on the constraints of the required battery energy

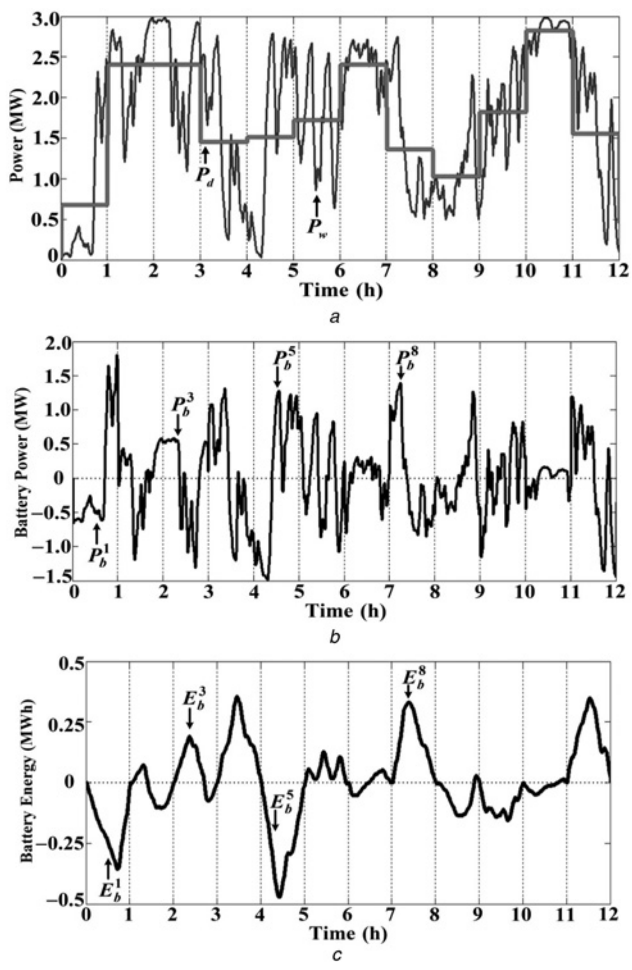

Fig. 5 *Determination of battery capacity*

a Wind power P_w and power dispatch P_d
b Battery power response
c Battery energy response

Table 1 Lower bound of the battery capacity (MWh)

σ(%)	μ(%) 0	1	2	3	4	5	6	7	8	9	10
0	0	0.075	0.15	0.225	0.3	0.375	0.45	0.525	0.6	0.675	0.75
1	0.225	0.3	0.375	0.45	0.525	0.6	0.675	0.75	0.825	0.9	0.975
2	0.45	0.525	0.6	0.675	0.75	0.825	0.9	0.975	1.05	1.125	1.2
3	0.675	0.75	0.825	0.9	0.975	1.05	1.125	1.2	1.275	1.35	1.425
4	0.9	0.975	1.05	1.125	1.2	1.275	1.35	1.425	1.5	1.575	1.65
5	1.125	1.2	1.275	1.35	1.425	1.5	1.575	1.65	1.725	1.8	1.875

Table 2 Battery capacity required for the different methods

	Proposed method	Low-pass filter method [11]	Min–max method [17]	Ramp-rate limit method [23]
power rating (MW)	2.10	2.24	2.92	2.03
energy rating (MWh)	1.75	1.98	2.76	2.15

rating defined in (16), the required battery energy rating in these intervals is at least 1.2 MWh.

By executing the proposed process, as depicted in Fig. 2 for two years of wind data, the battery capacity can be determined. It is noted that the battery power rating is defined at the time when the wind speed suddenly changes from the cut-in to the cut-out speed of the WT; we recognise that the system requires a battery power rating of up to 2.1 MW based on two years of wind data. In addition, the energy rating is 1.75 MWh. The other constraint on the battery capacity is related to the wind forecast accuracy level during the

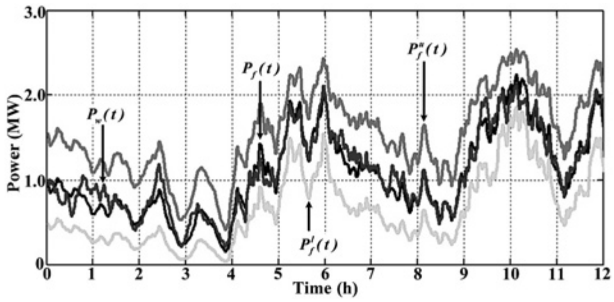

Fig. 6 *Forecasted wind power$P_f(t)$, the upper range$P_f^u(t)$, the lower range$P_f^l(t)$, and the real wind power*$P_w(t)$

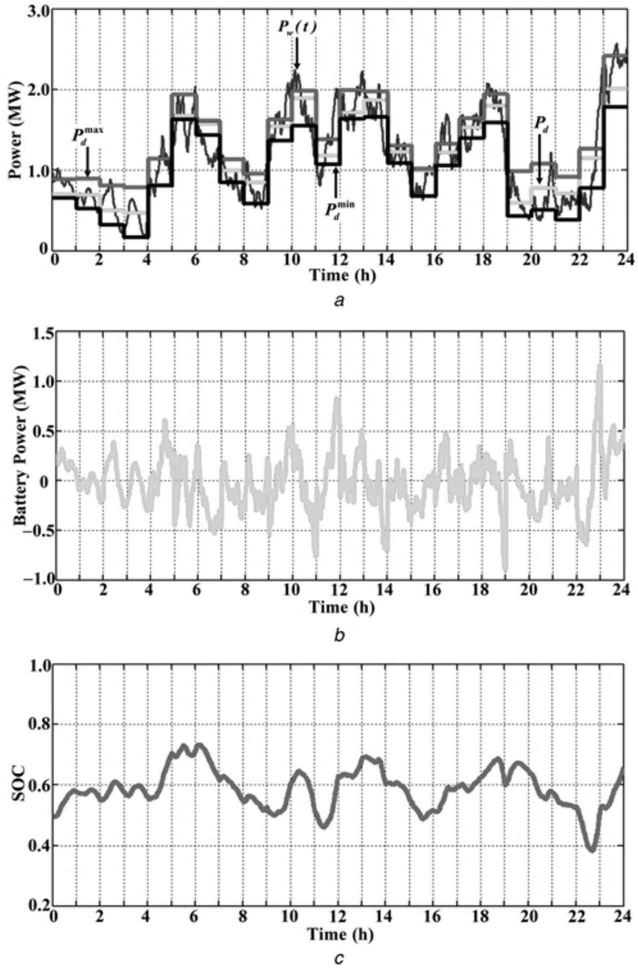

Fig. 7 *Power dispatch capability and battery power response*

a Wind power, maximum and minimum power dispatch levels, and power dispatch
b Battery power response
c SOC of the battery

Table 3 Determination of power dispatch capability (MW)

	Time, h 1	2	3	4	5	6	7	8	9	10	11	12
SOC	0.50	0.578	0.552	0.578	0.561	0.702	0.713	0.62	0.55	0.525	0.6	0.524
$P_d^{max\,1}$	2.309	2.244	2.142	2.128	2.303	2.796	2.604	2.340	2.298	2.596	2.750	2.506
$P_d^{min\,1}$	−0.37	−0.67	−0.53	−0.84	−0.10	0.40	0.314	−0.27	−0.34	0.449	0.489	0.366
$P_d^{max\,2}$	0.882	0.894	0.810	0.787	1.140	1.938	1.612	1.131	0.956	1.627	1.979	1.380
$P_d^{min\,2}$	0.654	0.519	0.319	0.167	0.805	1.624	1.434	0.848	0.584	1.366	1.553	1.073
P_d^{max}	0.882	0.894	0.810	0.787	1.140	1.938	1.612	1.131	0.956	1.627	1.979	1.380
P_d^{min}	0.654	0.519	0.319	0.167	0.805	1.624	1.434	0.848	0.584	1.366	1.553	1.073
P_d	0.696	0.694	0.497	0.465	0.812	1.677	1.572	0.995	0.845	1.546	1.889	1.182

control of the power dispatch, as mentioned in (29). Table 1 shows the lower bound of the battery capacity corresponding to several wind forecast accuracy levels, in terms of μ and σ. In this study, the forecast accuracy level is defined as $\mu = 5\%$ and $\sigma = 3\%$. In this case, the battery capacity must be higher than 1.05 MWh. For the battery capacity that satisfies the long-term wind power profile, 2.1 MW and 1.75 MWh are defined as the battery power rating and energy rating, respectively.

To ensure that the battery capacity has been determined effectively, three well-known dispatching methods are compared in Table 2. These methods include the method that is based on a low-pass filter [11], the min–max dispatching method [17], and the ramp-rate limit method [23]. In the low-pass filter and the ramp-rate limit methods, the maximum allowable variation level of the dispatched power is defined by the grid code of the electric power systems. In this evaluation, the maximum allowable variation level of the dispatched power is 10% of the WT power rating per minute, which is usually adopted by the grid code [24]. Compared with the min–max method, the proposed dispatching method based on the averaged wind power is able to significantly reduce the battery capacity. The low-pass filter method and the ramp-rate limit method also result in small battery capacities, but the power dispatch in these methods are not constant; they do not enable the WFs to cooperate with the TSO. In the min–max method, although the power is dispatched constantly, a larger battery capacity is required. Therefore, the proposed power dispatching method is a promising candidate to apply to the modern electric power systems.

5.2 Determination of the power dispatch capability

To demonstrate the proposed determination method of the power dispatch capability, the wind power profile from March 15th, 2013 on Jeju Island is used. The real wind power is obtained by adding an error that is a pseudorandom value drawn from a standard uniform distribution to the wind power data. Fig. 6 shows the wind power profile as well as the upper and lower wind power ranges in the first 12 h of the day. The estimated wind power values and the real values are quite different, but are bounded by the specified range.

On the basis of wind power profile and the power forecast range, the power dispatch capability is determined. Table 3 shows the data obtained from the proposed power dispatch capability decision method, in which the *SOC* value represents the initial SOC of the battery in each dispatching interval. The power dispatch capability in 12 dispatching intervals is determined by keeping two constraints. In the first constraint, $P_d^{\min 1}$ and $P_d^{\max 1}$ ensure that the battery power is lower than its power rating. In addition, $P_d^{\min 2}$ and $P_d^{\max 2}$ involve the SOC control, which ensures that the SOC is in the safe range: 20 to 100%. Finally, the maximum and minimum levels of power dispatch are defined based on (30) and (31). For example, at the first dispatching interval, the battery SOC is initially set at 50%, and the maximum and minimum levels of the power dispatch to satisfy the first constraint are $P_d^{\max 1} = 2.309$ MW and $P_d^{\min 1} = -0.37$ MW. To meet the second constraint, $P_d^{\max 2} = 0.882$ MW and $P_d^{\min 2} = 0.654$ MW. Therefore, from (30) and (31), the power dispatch capability is $P_d^{\max} = 0.882$ MW and $P_d^{\min} = 0.654$ MW.

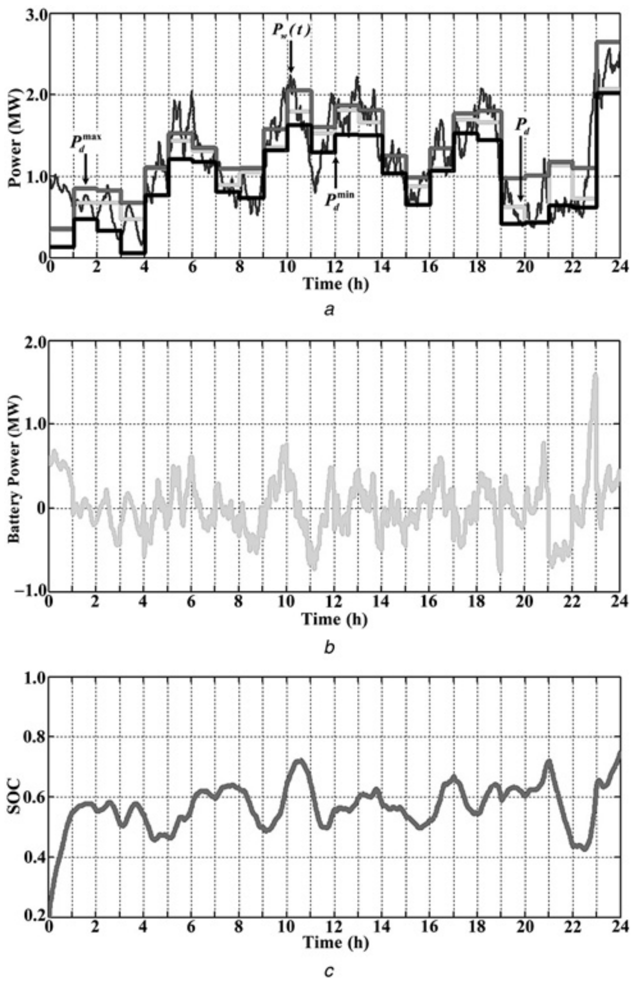

Fig. 8 *System performance when the battery is initially empty*

a Wind power, maximum and minimum power dispatch levels, and power dispatch
b Battery power response
c SOC of the battery

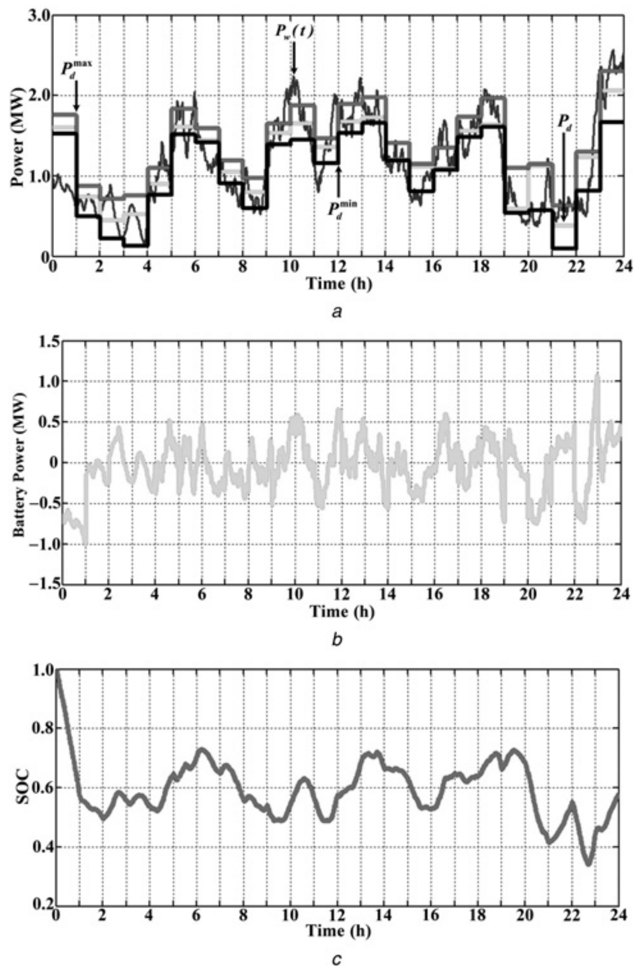

Fig. 9 *System performance when the battery is initially full*

a Wind power, maximum and minimum power dispatch levels, and power dispatch
b Battery power response
c SOC of the battery

Based on the power dispatch capability, the TSO can command the power dispatch to the PMS in a suitable manner and $P_d = 0.696$ MW.

Fig. 7 shows the system performance including the maximum and minimum power dispatch levels, the power dispatch to grid, the battery power response, and the SOC of the battery in one day. We can see that the battery power is always kept below the 2.1 MW battery power rating. In addition, the SOC is controlled successfully within the expected range.

Because the power dispatch capability depends on the initial conditions of the battery in each dispatching interval, we investigate the system with the critical SOC limits. In Fig. 8, the system is started when the battery is empty. We also evaluate the system when the battery is full, as shown in Fig. 9. In both cases, the battery power is always smaller than its rating, and the SOC is regulated between 20 and 100%, as expected. This demonstrates that under any condition the proposed power dispatch capability decision method always satisfies the system requirements.

6 Conclusions

This paper presented a method to effectively determine the power dispatch capability of a WBHPS based on the availability of wind power that is evaluated by using the forecasted upper and lower wind power ranges. With the obtained power dispatch capability, the TSO is able to give a suitable power command to the PMS so that the WBHPS can operate reliably. The proposed method ensures the following crucial requirements: the battery should operate below its power rating and within the safe SOC range. In addition, based on the averaged power dispatch method, we also determined the optimal battery capacity to guarantee a constant power dispatch. Compared with conventional dispatching methods, the proposed method requires a smaller battery capacity; the system cost is reduced.

To evaluate the effectiveness of the proposed method, we performed a numerical study using a 3-MW WT generator with real wind speed data measured on Jeju Island. From the case study, it is proved that the power dispatch in each dispatching interval was constant and that the SOC was always kept in a safe range by using the proposed power dispatch capability decision method.

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