One-sample optimal output smoothing method for wind farm with energy storage system

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Abstract
This paper proposes a novel optimization method for energy storage systems (ESSs) to smooth wind farm output to satisfy the technical requirements and reduce the rated power (rated energy capacity) and charge/discharge loss of the ESS. The state of charge of the ESS operated by the proposed method can be regulated, guaranteeing some constraints. The proposed method has a very simple structure, does not require the wind farm output forecast and numerical optimization, such as particle swarm optimization. Therefore, a high-grade functional computation device is not needed. The effectiveness of the proposed method is verified by comparative analysis with conventional approaches through simulations.

1 INTRODUCTION

Global environmental issues (such as global warming and the depletion of fossil fuel) are serious problems. Wind power generation has been highlighted worldwide as a solution for these problems [1]. However, wind power generator outputs fluctuate frequently and swiftly due to wind speed variations. The power quality such as the frequency and voltage, may be degraded in power systems with large-scale wind farms (WFs) [2–5]. To avoid this, technical requirements related to the power fluctuation of WF have been issued by power companies.

To mitigate power fluctuation, energy storage systems (ESSs) (such as batteries or flywheels [6–8]) have been used, as shown in Figure 1. One of the major issues with ESSs is how to design control systems that lead to lower costs. To this end, a control algorithm to reduce the rated power (rated energy capacity) of the ESS is required because the cost of an ESS, which absorbs the short-period component of the WF output, is dominated by the rated power. Although the cost of an ESS is also dependent on the rated energy capacity, it is constrained by the rated power of the ESS through the so-called C-rate [9]. In addition, although the charge/discharge loss of the ESS influences the cost, the issue has not been discussed in detail.

Some ESS control methods to reduce the rated power (rated energy capacity) have been reported. A first-order low-pass filter (FLF) is usually used in an ESS control system to mitigate the fluctuation of WF output by removing the short-period component of WF output [6, 7, 10, 11]. In refs. [10, 11], a time constant in the FLF which reduces the rated power (rated energy capacity) of an ESS is found through simulations. However, the FLF cannot reduce the rated power sufficiently because of the special structure of the FLF. In addition, the standard FLF cannot directly handle the technical requirement. In other words, a time constant of the FLF which satisfies the technical requirement has to be found through simulations. To overcome this drawback, an FLF with a continuously time-varying constant has been proposed in refs. [12, 13]. In ref. [12], an approach to find an optimal time constant of the FLF was proposed using power

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forecast and particle swarm optimization (PSO). This method can handle two constraints on the short-term and long-term fluctuation of WF output. However, the proposed method in ref. [12] requires predicting the WF output and may not find the optimal solution because it uses numerical optimization such as PSO. An optimal approach without WF output forecast is proposed in ref. [13]. This proposed method can reduce the rated power of an ESS sufficiently and can directly handle the single constraint in relation to the technical requirement. Nevertheless, the method may not regulate the state of charge (SOC) of an ESS within the proper range. Moreover, a conservative reduction in the rated power of an ESS due to the special structure of the FLF is inevitable.

Methods other than the FLF have also been reported. A short-term power dispatch control that can regulate the SOC and satisfy the constraints on the SOC and ESS output was proposed in ref. [14]. Nevertheless, this method requires WF output forecast and large amount of computation time because of the complicated process. A high-order filter was proposed in ref. [5]. Although this method may reduce the ESS energy capacity, it requires numerical optimization to design the filter and cannot handle the technical requirements directly. Fuzzy logic and optimization were applied to the ESS in ref. [15, 16]. The method proposed in ref. [16] can take into account various aspects of the ESS such as the capacity requirement, the state of health of devices, and the mitigation of wind variations. However, this method is complex because it requires not only the WF output forecast but also PSO. WF output ramp control based on the WF output forecast and fuzzy logic was proposed in ref. [17]. This method also requires the WF output forecast. Moreover, in these methods based on fuzzy logic, some membership functions have to be determined by trial and error. Some approaches based on machine learning were proposed in refs. [18, 19]. The mitigation of WF output fluctuation based on an adaptive linear neuron was proposed in ref. [18]. A recurrent fuzzy neural network and an online learning algorithm were proposed in ref. [19]. Although these approaches may reduce the rated power (rated energy capacity) of the ESS, a large amount of computation time is needed because of the complicated process. A Kalman filter was applied to the ESS in refs. [20–22]. These methods mitigate the short-term WF output. Although the methods in refs. [20, 21] require fuzzy logic, the Kalman filter approach in ref. [22] may reduce the rated power (rated energy capacity) of the ESS without fuzzy logic. However, the Kalman filter approach may not satisfy the technical requirements since it cannot handle them directly. A zero-phase low pass filter (LPF) was proposed in ref. [23]. This method can mitigate the short-term WF output by an ESS with the small rated power (energy capacity) since the zero-phase LPF does not have delays, unlike the standard FLF. Nevertheless, the zero-phase LPF requires accurate forecasted wind speed and cannot handle directly the constraints in relation to the technical requirements.

In spite of these aforementioned studies, there is no simple method to operate an ESS optimally, regulate the SOC, and satisfy the technical requirements. To address this problem, this paper proposes a novel optimization approach to smooth the WF output so as to satisfy the technical requirements and reduce the rated power (rated energy capacity) and the charge/discharge loss of the ESS. The SOC of the ESS operated by the proposed method can be regulated, guaranteeing the technical requirements. The proposed method has a very simple structure and does not require the WF output forecast, numerical optimization, fuzzy logic, or machine learning.

The contributions of the paper are summarized as follows.

1) An optimal ESS output control law taking the technical requirements into consideration is presented; that is, the ESS can be optimally operated by the proposed method reducing the ESS power and guaranteeing the technical requirements without the WF output forecast. In addition, the SOC is regulated to its reference. As a result, the rated power (rated energy capacity) and the charge/discharge loss of the ESS controlled by the proposed method are approximately 26% and 81% less than those of the conventional FLF controller.

2) A high-grade functional computation device is not required in the proposed approach because the optimal ESS output reference can be found without numerical optimization. In addition, software (CPLEX and Gurobi etc.) is not needed to find the optimal ESS output reference. Consequently, the proposed approach can be easily implemented.

3) The proposed approach does not depend on the FLF structure. Therefore, the conservativeness of the FLF in reducing the rated power of the ESS can be mitigated.

The rest of this paper is organized as follows. In Section 2, the system configuration and the technical requirement are described. Section 3 proposes an optimization approach to smooth the WF output to directly satisfy the technical requirement and reduce the rated power of the ESS. It is illustrated that the effectiveness of the proposed method based on simulations and comparisons with the standard FLF; the optimal FLF [13], the Kalman filter approach [22] and the zero-phase LPF [23] in Section 4. Section 5 concludes the study.

## 2 PRELIMINARIES

This section describes the system configuration of the proposed ESS control system and explains the WF output fluctuation and its technical requirement.

### 2.1 System configuration

Figure 2 shows the system configuration (the block diagram of Figure 1). In Figure 2, \(P_{WF}(t)\) is the WF output, \(P_b(t)\) is the ESS output, \(P_{ext}(t)\) is its reference and \(P_b(t) = P_{WF}(t) - P_b(t)\) is the power supplied to the power system called the combined output. \(P_{loss}(t)\) is the charge/discharge loss of the ESS given by:

\[
P_{loss}(t) = \begin{cases} (1 - \eta) \cdot R_b(t) & (P_b(t) > 0) \\ (1 - \frac{1}{\eta}) \cdot R_b(t) & (P_b(t) < 0) \end{cases},
\]
where \( \eta \) is the charge/discharge efficiency of the ESS. \( E(t) \) denotes the remaining energy (RE) of the ESS which is calculated by integrating \( P_b(t) - P_{\text{loss}}(t) \). In the optimization block, \( P_b^{\text{ref}}(t) \) is generated, which operates the ESS optimally. The dynamics of the ESS can be ignored because it is known that the dynamics of the ESS is fast enough and does not affect its control performance \([5, 24]\). Moreover, the positive sign of \( P_b(t) \) implies the power charge of the ESS.

In this paper, subscript ‘pu’ denotes the per-unit value.

### 2.2 Fluctuation of WF output and its technical requirement

The fluctuation ratio of combined output in an \( h \)-second window is defined by

\[
\Delta F_{g}(t, h) = \frac{\max_{t-h \leq \tau \leq t} P_{g}(\tau) - \min_{t-h \leq \tau \leq t} P_{g}(\tau)}{P_{\text{WF}}^\text{pu}},
\]

where \( P_{\text{WF}}^\text{pu} \) is the rated power of the WF \([13]\). The technical requirements related to the regulation of this fluctuation are issued by the power companies. Figure 3 illustrates an example where the technical requirement is given by

\[
\Delta F_{g}(t, h) \leq \gamma_h,
\]

where \( \gamma_h \geq 0 \) denotes the allowable fluctuation level in the \( h \)-second window. For example, if \( \gamma_h = 0.1 \) and \( h = 600 \text{ s} \), the error between the maximum and minimum WF output in a period of 600 s must be suppressed within 0.1 p.u. by the ESS. Note that \( \gamma_h \) and \( b \) are given by the technical requirement \([13]\). In addition, there may exist some technical requirements such as \( \Delta F_{g}(t, b_1) \leq \gamma_{b_1} \) and \( \Delta F_{g}(t, b_2) \leq \gamma_{b_2} \).

### 3 OPTIMAL ESS OUTPUT CONTROL

This section derives an optimal ESS output to reduce the rated power of the ESS and to regulate the SOC to its reference subject to the technical requirements.

#### 3.1 Constraint

Equations (2) and (3) are rewritten in discrete time as \([13]\)

\[
\Delta F_{g}[n, \hat{b}] = \frac{1}{P_{\text{WF}}^\text{pu}} \left( \max(P_g[n], P_g[n-1], ..., P_g[n-\hat{b}]) - \min(P_g[n], P_g[n-1], ..., P_g[n-\hat{b}]) \right),
\]

\[
\Delta F_{g}[n, \hat{b}] \leq \gamma_{b},
\]

respectively, where \( \hat{b} = \left\lfloor h/T_s \right\rfloor \) is the total number of samples in the interval \( b \), and \( T_s (T_s \leq h) \) is the sampling period\(^1\).

To rewrite Equation (5) as a constraint on \( P_b[n], \overline{\zeta}[n, \hat{b}] \) and \( \overline{\chi}[n, \hat{b}] \) are defined as follows:

\[
\overline{\zeta}[n, \hat{b}] = \max \left( P_g[n-1], ..., P_g[n-\hat{b}] \right),
\]

\[
\overline{\chi}[n, \hat{b}] = \min \left( P_g[n-1], ..., P_g[n-\hat{b}] \right).
\]

As illustrated in Figure 4(a), when \( P_b[n] \geq \overline{\zeta}[n, \hat{b}] \), it is obtained from Equation (4) and (5), \( P_b[n] = \max(P_g[n], \overline{\zeta}[n, \hat{b}]) \) and \( \overline{\chi}[n, \hat{b}] = \min(P_g[n], \overline{\chi}[n, \hat{b}]) \) that

\[
P_b[n] \leq \gamma_h \cdot P_{\text{WF}}^\text{pu} + \overline{\chi}[n, \hat{b}].
\]

Moreover, as illustrated in Figure 4(b), when \( P_b[n] \leq \overline{\chi}[n, \hat{b}] \), it is obtained from Equation (4) and (5), \( \overline{\zeta}[n, \hat{b}] = \max(P_g[n], \overline{\chi}[n, \hat{b}]) \) and \( P_b[n] = \min(P_g[n], \overline{\zeta}[n, \hat{b}]) \) that

\[
P_b[n] \geq -\gamma_h \cdot P_{\text{WF}}^\text{pu} + \overline{\chi}[n, \hat{b}].
\]

From Equation (8) and (9) and \( P_b[n] = P_{\text{WF}}[n] - R_b[n] \), the constraint is given by\(^2\)

\[
R_b[n, \gamma_h, \gamma_s] \leq R_b[n] \leq \overline{R}[n, b, \gamma_s],
\]

\(^1\) For simplicity, it is used that \( f[s] = f(sT_s) \) where \( s \) is the sample number.

\(^2\) The authors would like to acknowledge an anonymous reviewer for suggesting this constraint.
where

\[ \bar{P}_b[n] = P_{WF}[n] + \gamma_b \cdot P_{WF}^p[n] - \bar{\alpha}[n, \hat{h}] \]  
(11)

\[ \Gamma[n, h, \gamma_b] = P_{WF}[n] - \gamma_b \cdot P_{WF}^p[n] - \bar{\alpha}[n, \hat{h}] \]  
(12)

Therefore, \( P_b[n] \) has to be bounded by the constraint (10). Note that in the case where there are multiple technical requirements, the constraints are given by

\[
\max(\Gamma[n, h, \gamma_b], \Gamma[n, h, \gamma_{b_2}], \ldots) \leq P_b[n] \\
\leq \min(\bar{P}_b[n], \Gamma[n, h, \gamma_b], \bar{\Gamma}[n, h, \gamma_{b_2}], \ldots) .
\]  
(13)

### 3.2 Optimal ESS output

The aim is to reduce the rated power, the charge/discharge loss of the ESS and to regulate the SOC of the ESS to its reference. The ESS has a small rated power and low charge/discharge loss if the ESS can mitigate the WF output fluctuation with a small output. To derive an optimal ESS output \( P_b[n] \), consider the following objective function:

\[
J(P_b[n], E^{\text{ref}}, E[n - 1]) = P_b^2[n] + q \cdot (E^{\text{ref}} - E[n - 1])^2 \\
= P_b^2[n] + q \cdot (E^{\text{ref}} - E[n - 1] - \frac{T_e}{3600} \cdot P_b[n])^2,
\]  
(14)

where \( E^{\text{ref}} \) is the reference of the ESS and \( q(>0) \) is a weight. Omitting \( P_{loss}(t), E[n] \) is given by

\[
E[n] = E[n - 1] + \frac{T_e}{3600} \cdot P_b[n] \quad \text{[MWh]}.
\]  
(15)

Note that \( E_{\text{ref}}[n] = E[n]/E^n \) where \( E^n \) is the rated energy capacity of the ESS. In Equation (14), the role of the first term is to minimize the rated power and the charge/discharge loss of the ESS, and the other term regulates the SOC of the ESS to its reference. \( P_b^\text{opt}[n] \) given by

\[
P_b^\text{opt}[n] = \frac{q \cdot (E^{\text{ref}} - E[n - 1]) \cdot \bar{\Gamma}}{1 + q \cdot (\frac{T_e}{3600})^2},
\]  
(16)

which minimizes Equation (14) as long as there is no constraint.

Actually, Equation (14) should be minimized under the constraint (13). The optimal ESS output reference \( P_b^\text{opt}[n] \) is then obtained as the solution for the following optimization:

\[
P_b^\text{opt}[n] = \arg\min_{P_b[n]} J(P_b[n], E^{\text{ref}}, E[n - 1])
\]  
subject to (13).

As shown in Figure 5, since the objective function \( J \) is convex for \( P_b[n] \), the optimal ESS output reference \( P_b^\text{opt}[n] \) can be determined as follows:

\[
P_b^\text{opt}[n] = \begin{cases} 
\bar{P}_b[n] & \bar{\Gamma} \leq \bar{P}_b[n] \\
p_{b,\text{opt}}[n] & \bar{\Gamma} \leq p_{b,\text{opt}}[n] \leq \bar{P}_b[n] \\
\Gamma_b & \bar{\Gamma} \leq \Gamma_b \end{cases},
\]  
(18)

where

\[
\bar{\Gamma} = \min(\Gamma[n, h, \gamma_b], \bar{\Gamma}[n, h, \gamma_{b_2}], \ldots),
\]  
(19)

\[
\Gamma_b = \max(\Gamma[n, h, \gamma_b], \Gamma[n, h, \gamma_{b_2}], \ldots).
\]  
(20)

The proposed method can find the ESS output reference which minimizes \( P_b[n] \) and satisfies the technical requirements.
directly. The calculation time of Equation (18) is short because Equation (18) is a purely algebraic calculation. As a result, the ESS controlled by the proposed method can smooth the WF output while keeping a lower charge/discharge loss with relatively less rated power (rated energy capacity).

3.3 Weight design procedure

This subsection describes the design procedure for the weight \( q \) in Equation (16). Although a large weight \( q \) can regulate the SOC of the ESS to its reference, excessively large \( q \) requires a high power on the ESS. In other words, there is a trade-off between the SOC regulation and the rated power. In addition, a small \( q \) leads to low charge/discharge loss. Therefore, the weight \( q \) has to be properly determined.

Using C-rate \( [9] \) defined by

\[
C_{\text{rate}} = \frac{\text{Rated power of ESS} \, P_b^{\text{n}} \, [\text{MW}]}{\text{Rated energy capacity of ESS} \, E_n^{\text{n}} \, [\text{MWh}]},
\]

Equation (16) can be rewrite as follows:

\[
P_b^{\#} = \frac{q \cdot \Delta E \cdot \frac{E}{3600}}{P_b^{\text{n}} \cdot (1 + q \cdot \left(\frac{E}{3600}\right)^2)}
\]

\[
= \frac{q \cdot \Delta E_{\text{pu}} \cdot \frac{E_{\text{pu}}}{3600}}{C_{\text{rate}} \cdot (1 + q \cdot \left(\frac{E}{3600}\right)^2)}, \quad [\text{p.u.}]
\]

(22)

where \( P_b^{\text{n}} \) is the rated power of the ESS and the error \( \Delta E \) denotes \( E_{\text{ref}} - E[n - 1] \) (\( \Delta E = \Delta E / E_n^{\text{n}} \)). Note that \( E_{\text{pu}}^{\text{ref}} = E_{\text{pu}}^{\text{ref}} / E_n^{\text{n}} \) \( (0 \leq E_{\text{pu}}^{\text{ref}} \leq 1) \) corresponds to the SOC reference of the ESS. Here, the worst-case error \( \Delta E_{\text{pu}}^{\text{worst}} \) (Figure 7) defined by

\[
\Delta E_{\text{pu}}^{\text{worst}} = \begin{cases} 
E_{\text{pu}}^{\text{ref}} & (E_{\text{pu}}^{\text{ref}} \geq \frac{1}{2}) \\
E_{\text{pu}}^{\text{n}} - E_{\text{pu}}^{\text{ref}} & (E_{\text{pu}}^{\text{ref}} < \frac{1}{2})
\end{cases}
\]

(23)

is considered, where \( E_{\text{pu}}^{\text{n}} \) (\( = 1 \) p.u.) is the per-unit value of rated energy capacity. \( \Delta E_{\text{pu}}^{\text{worst}} \) can be calculated by \( E_{\text{pu}}^{\text{ref}} \) (see Appendix A.1 for the computation of \( E_{\text{pu}}^{\text{ref}} \)). From (22) and (23), a sufficient condition to prevent the overpower on the ESS is given by

\[
P_b^{\#} = \Delta E_{\text{pu}}^{\text{worst}} \cdot \frac{q \cdot \frac{E_{\text{pu}}}{3600}}{C_{\text{rate}} \cdot (1 + q \cdot \left(\frac{E}{3600}\right)^2)} \leq 1 \text{ p.u.},
\]

(24)

where \( P_b^{\#} \) denotes the maximum ESS output. Equation (24) is functions of \( q \) and \( E_{\text{pu}}^{\text{ref}} \). The overpower on the ESS is prevented by choosing \( q \) satisfying Equation (24) (see Appendix A.1 for the computation of \( E_{\text{pu}}^{\text{ref}} \)). Note that the stability of the ESS control system is not always guaranteed just because Equation (24) is satisfied. According to Equation (18), the large \( q \) may cause hunting in the system and high charge/discharge loss of the ESS. Nevertheless, \( q \) can be determined based on Equation (24) since Equation (24) reveals the upper bound of \( q \). As an illustration, it is shown that the region of \( q \) preventing the overpower of the ESS. Figure 6 shows the 2D plot of Equation (24). As shown in Figure 6, the overpower on the ESS is prevented when \( q \leq 1825 \). The search region of \( q \) can be narrowed by using Figure 6.

4 SIMULATION RESULTS

To validate the effectiveness of the proposed method, a comparative analysis is performed among the ESS controlled by the proposed method, the standard FLF shown in Figure 8 [5, 6], the optimal FLF [13], the Kalman filter approach [22] and the zero-phase LPF [23]. The WF output data shown in Figure 9 are used [25]. This data is the benchmark WF output, published by the Institute of Electrical Engineers of Japan (IEEJ). The rated power of a WF \( P_{\text{WF}}^{\text{n}} \) is 280 MW. The evaluation is conducted...
based on 1) one technical requirement: \( \gamma_h = 0.1 \) in a 10-min time window \((h = 600 \text{ s})\) (Case 1) and (Case 2) two technical requirements: \( \gamma_{h1} = 0.1 \) in a 10-min time window \((h_1 = 600 \text{ s})\) and \( \gamma_{h2} = 0.01 \) in a 1-min time window \((h_2 = 60 \text{ s})\) (Case 2). The sampling period is \( T_s = 10 \text{ s} \). The weight \( q \) is determined through simulations and set to 1000. It is assumed in the simulations that the ESS efficiency \( \eta \) is 85\% (in both charge and discharge) and the initial SOC and the SOC reference are 60\%. The \( C \)-rate of the ESS is 3 \[^9\]. For a fair comparison, the time constant of FLF is best tuned by scenario simulation to ensure the technical requirements in Case 1 and Case 2. The time constant is 821 rad/s in Case 1 and 3350 rad/s in Case 2. In addition, the time constant of the zero-phase LPF is also set to 821 rad/s in Case 1. As shown in Figure 8, the FLF controller has an SOC feedback to regulate the SOC to its reference. In Figure 8, \( A \) is the SOC feedback gain and \( A = 0.01 \) is tuned by scenario simulation. The prediction interval of WF output in the Kalman filter approach and the zero-phase LPF is 1 min because it is known that the prediction error is small before 1 min \[^26\]. The simulations are performed in MATLAB/Simulink, and the simulation period is 6 h.

4.1 | Case 1

This subsection tests the proposed method based on one technical requirement \( \gamma_h = 0.1 \) in a 10-min time window). Figure 10 shows the combined output of the WF and the ESS. Figure 11 shows their fluctuation level. As shown in Figure 11, the proposed method and the standard FLF can satisfy the technical requirement by smoothing the WF output. However, the optimal FLF, the Kalman filter approach and the zero-phase LPF cannot satisfy the technical requirement. Note that some time responses obtained with the optimal FLF are omitted because the SOC reaches 0\% at 2.6 h, as shown in Figure 15(a). Since the time constant of the FLF must be large to satisfy the technical requirement, the response delay occurs in the FLF. As a result, the output (rated power) of the ESS with FLF is larger than that of the ESS with the proposed method, as shown in Figure 12. The proposed method can decrease the ESS output (rated power) directly. Therefore, it is possible to mitigate the WF output while keeping a lower charge/discharge loss (Figures 13 and 14) by using the proposed ESS with a small rated power. Figure 15 shows the SOC and its references indicated by dashed lines. The SOC of the ESS with the proposed controller is regulated to its reference \( (E_{\text{ref pu}} = 0.6 \text{ p.u.}) \). The SOC of the ESS with the proposed controller approaches to zero. If the SOC is zero, the rated capacity of the ESS should be...
FIGURE 12  ESS output

(a) Optimal FLF vs. proposed method

(b) Kalman filter vs. proposed method

(c) Zero-phase filter vs. proposed method

(d) Standard FLF vs. proposed method

FIGURE 13  Charge/discharge loss on the ESS

(a) Kalman filter vs. proposed method

(b) Zero-phase filter vs. proposed method

(c) Standard FLF vs. proposed method

(d) Standard FLF vs. proposed method

FIGURE 14  Integrated charge/discharge loss on the ESS

(a) Optimal FLF vs. proposed method

(b) Kalman filter vs. proposed method

(c) Zero-phase filter vs. proposed method

(d) Standard FLF vs. proposed method

FIGURE 15  SOC
redesigned. In that case, the cost of the ESS is dominated by the rated capacity. However, the rated capacity of the ESS with the proposed controller can be smaller than that of the FLF controller because the objective function (14) involves the error between the SOC and its reference. In other words, the proposed method optimizes not only the rated power of the ESS but also the rated capacity.

Table 1 summarizes the simulation results. In addition, Table 1 lists the number of charge/discharge operations of the ESS and \( \int |E_{\text{pu}}(t) - E_{\text{ref}}(t)| \, dt \), which is the integral of the charge/discharge energy of the ESS. These factors influence the lifetime of the ESS. Table 2 summarizes the performance indices of the ESS determined through Table 1. In Table 2, the cost of the ESS is calculated based on the unit price of a lithium ion battery (1000 $/kWh) [9]. The rated power and the charge/discharge loss of the ESS controlled by the proposed method are approximately 26% and 81% less than those of the standard FLF controller. The cost of the ESS with the proposed method is less than that with the standard FLF. Moreover, the lifetime of the ESS with the proposed method is expected to be longer than the lifetime of the ESS with other methods since the factor related to the lifetime is small. The optimal FLF, the Kalman filter approach and the zero-phase LPF cannot satisfy the technical requirement and cannot regulate the SOC to its reference, depending on the scenario.

### 4.2 Case 2

This subsection tests the proposed method based on two technical requirements \( \Delta F_{\text{pu}}[n, b_1] \leq \gamma_{b1} \) and \( \Delta F_{\text{pu}}[n, b_2] \leq \gamma_{b2} \) \( (\gamma_{b1} = 0.1, b_1 = 600 \, \text{s}, \gamma_{b2} = 0.01 \) and \( b_2 = 60 \, \text{s} \). The time responses obtained by the optimized FLF, the Kalman filter approach and the zero-phase filter are omitted because these methods did not satisfy the technical requirement in Case 1.

Figure 16(a) shows the combined output of the WF and the ESS. In Case 2, the time constant of the FLF must be large enough to satisfy the technical requirement \( \Delta F_{\text{pu}}[n, b_2] \leq \gamma_{b2} \) since the ESS removes the short-period components of the WF output. It is evident that the response delay is significantly large in the standard FLF. Figure 16(b,c) shows the fluctuation levels in a 10-min and in a 1-min windows, respectively. Both the proposed method and the standard FLF satisfy the technical requirements, but the standard FLF over-suppresses the output fluctuation. Consequently, as shown in Figure 16(d) the ESS output of the proposed method is smaller than that of the standard FLF. As a result, the charge/discharge loss (Figure 16(e,f) of the ESS with the proposed method is also small. Figure 16(g,h) show the RE of the ESS and the SOC. The SOC is regulated to its reference indicated by dashed lines in both methods. However, it is clear that the standard FLF with a large time constant requires a large-capacity ESS.

Table 3 summarizes the simulation results. The rated power and the charge/discharge loss of the ESS controlled by the proposed method are approximately 25% and 62% less than those of the standard FLF controller. The cost of the ESS with the proposed method is less than that of the ESS with the standard FLF since the proposed method can smooth the WF output by an ESS with a lower rated power (rated energy capacity). The number of charge/discharge operations of the ESS with the proposed method is about 2.18 times more than that of the ESS with the standard FLF. However, \( \int |E_{\text{pu}}(t) - E_{\text{ref}}(t)| \, dt \) of the standard FLF is about three times larger than that of the proposed method. Therefore, the lifetime of the ESS with the

### TABLE 1 Simulation results (Case 1)

|                      | w/o ESS | Proposed | optimal FLF | Kalman filter | Zero-phase LPF | FLF |
|----------------------|---------|----------|-------------|---------------|----------------|-----|
| Maximum fluctuation level [%] | 18.1    | 10.0     | –           | 16.6          | 15.7           | 10.0 |
| Technical requirement | –       | ✓        | Unsatisfied | Unsatisfied   | Unsatisfied    | ✓   |
| Prediction of WF output | –       | –        | Needed      | Needed        | –              | –   |
| SOC management       | –       | ✓        | Unsatisfied | ✓             | ✓              | ✓   |
| Maximum power of the ESS [MW] | – 22.7  | – 22.7   | – 9.09      | 6.88          | 30.5           |     |
| Power ratio*         | – 0.74  | – 0.74   | – 0.30      | 0.23          | 1              |     |
| Loss of the ESS [MWh] | – 1.28  | – 1.28   | – 1.49      | 1.64          | 6.71           |     |
| Loss ratio†          | – 0.19  | – 0.19   | – 0.22      | 0.24          | 1              |     |
| Number of charge/discharge operations | – 6     | – 6      | 836         | 658           | 160            |     |
| \( \int |E_{\text{pu}}(t) - E_{\text{ref}}(t)| \, dt \) | – 954.1 | – 954.1   | – 201.1      | 186.7         | 2948.5         |     |

|                      | Proposed | FLF |
|----------------------|----------|-----|
| Rated power [MW]     | 22.7     | 30.5 |
| Power ratio          | 0.74     | –   |
| Energy capacity [MWh]| 7.57     | 10.2|
| Capacity ratio‡      | 0.74     | –   |
| Cost [$]             | 7,570,000| 10,200,000|

|                      | Proposed | FLF |
|----------------------|----------|-----|
| Rated power [MW]     | 22.7     | 30.5 |
| Power ratio          | 0.74     | –   |
| Energy capacity [MWh]| 7.57     | 10.2|
| Capacity ratio‡      | 0.74     | –   |
| Cost [$]             | 7,570,000| 10,200,000|

*Power ratio is \( \frac{\text{Maximum power of the ESS with the proposed controller [MW]}}{\text{Maximum power of the ESS with the FLF controller [MW]}} \).
†Loss ratio is \( \frac{\text{Loss of the ESS with the proposed controller [MWh]}}{\text{Loss of the ESS with the FLF controller [MWh]}} \).
‡Capacity ratio is \( \frac{\text{Energy capacity of the ESS with the proposed controller [MWh]}}{\text{Energy capacity of the ESS with the FLF controller [MWh]}} \).
4.3 Analysis of the impact of SOC reference and initial SOC

The impact of SOC reference and initial SOC on an ESS was analysed through simulations in which the SOC reference and the initial SOC deviated ±10% from the nominal value 60%. Two typical cases, (the SOC reference and the initial SOC are (a) 70% and 50% and (b) 50% and 70%) are shown. The evaluation was conducted for the case when both 10-min and 1-min constraints are required. Figure 17 shows the SOC. The SOC is regulated to its reference indicated by dashed lines in both cases regardless of initial SOC. However, the SOC approaches zero at about 2.8 h when the reference of SOC is 50%. Therefore, the reference of SOC should be set to more than 60% as analysed in appendix A.1.

5 CONCLUSION

This paper has studied an optimal ESS output control method in order to reduce the rated power (rated energy capacity) and
charge/discharge loss of the ESS in the output smoothing of WFs. An optimal reference to reduce ESS output can be found by using the proposed method without any numerical optimization. As a result, the proposed method can reduce the loss without increasing the rated power (rated energy capacity) of the ESS.

A comparative simulation analysis between the proposed method and the conventional methods shows that the proposed controller can mitigate the WF output fluctuation with a small rated power (energy capacity) of the ESS, yielding a low charge/discharge loss compared to the conventional methods. It is concluded that the proposed controller is very effective in mitigating WF output fluctuation.

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NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| \( P_{WF} \) | WF output |
| \( P_{WF}^{n} \) | Rated power of WF |
| \( P_{b} \) | ESS output |
| \( P_{b}^{r} \) | Rated power of the ESS |
| \( P_{b}^{ref} \) | Reference ESS output |
| \( P_{g}^{b} \) | Combined output |
| \( P_{loss} \) | Charge/discharge loss of the ESS |
| \( E \) | Remaining energy of the ESS |
| \( E^{n} \) | Rated energy capacity of the ESS |
| \( E^{ref} \) | Reference remaining energy |
| \( \Delta \gamma_{g} \) | Fluctuation ratio of combined output |
| \( \gamma_{h} \) | Allowable fluctuation level |
| \( C_{rate} \) | C-rate |

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APPENDIX A

A.1 | Determination of $E_{\text{ref}}^{\text{pu}}$

The impact of the charge/discharge loss on the SOC of an ESS is analysed to determine $E_{\text{ref}}^{\text{pu}}$. It is assumed that the ESS charges or discharges the rated power ($P_b(t) = P_n$ or $P_b(t) = -P_n$) to mitigate the WF output. Then, from Equation (1), the integrated value of the charge/discharge loss $E_{\text{loss,pu}}$ is given by

$$E_{\text{loss,pu}} = \frac{1}{E_n} \int_0^b P_{\text{loss}}(t) \, dt$$

where $E_n$ is the energy of the ESS.

$$E_{\text{loss,pu}} = \left[ -\eta \cdot \frac{P_n}{E_n} \cdot \frac{b_c}{3600} \right] + \left[ (1 - \eta) \cdot \frac{P_n}{E_n} \cdot \frac{b_d}{3600} \right]$$

$$= \left[ (1 - \eta) \cdot C_{\text{rate}} \cdot \frac{P_n}{E_n} \cdot \frac{b_c}{3600} \right] + \left[ (1 - \eta) \cdot C_{\text{rate}} \cdot \frac{P_n}{E_n} \cdot \frac{b_d}{3600} \right]$$

(A.1)

where $b_c$ and $b_d$ are the charge time and the discharge time, respectively, $b = b_c + b_d$. The impact of the charge/discharge loss on the SOC of an ESS can be analysed using Equation (A.1). Although the reference of the SOC is set as 0.5 p.u., in general the reference should be set as 0.5 + $E_{\text{loss,pu}}$ p.u. if it is determined by considering the impact of the loss. This paper investigates the fluctuation of WF output in a 10-min window ($b = 600$ s), $b_c = 300$ s, $b_d = 300$ s, $\eta = 0.85\%$, $P_{b,\text{pu}} = 1$ p.u. and $C_{\text{rate}} = 3$. From Equation (A.1), the integrated value of the charge/discharge loss is $E_{\text{loss,pu}} = 0.0816$ p.u. Therefore, $E_{\text{ref}}^{\text{pu}} = 0.6$ p.u. is set for simplicity.