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Article

An Energy Storage System Sizing Method for Wind Power Integration

Wei Wang *, Chengxiong Mao, Jiming Lu and Dan Wang

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Hua Zhong University of Science and Technology, Wuhan 430074, China; E-Mails: cxmao@mail.hust.edu.cn (C.M.); lujiming@mail.hust.edu.cn (J.L.); wangdan@mail.hust.edu.cn (D.W.)

* Author to whom correspondence should be addressed; E-Mail: wangwei8418@mail.hust.edu.cn; Tel./Fax: +86-27-8754-2669.

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Abstract: Combining an energy storage system (ESS) with a wind farm is an effective way to increase the penetration rate of wind power. ESS sizing is an important part in wind farm planning nowadays. In this paper, a basic method for determining the optimal capacity of an ESS integrated with a wind power generator to meet the requirements of grid integration is presented. With the proposed method, the necessary ESS capacity which can provide the best benefits between the regulation effects and energy storage size was calculated. The segmentation method and automatic segmentation method are proposed to improve the performance of the basic method. Further work on expanding the method to determine the necessary capacity of ESS for real-time control is studied. The time window method is used to enable the proposed method available under all working conditions. The simulation results verify the effectiveness of the proposed method.

Keywords: energy storage system; wind power; grid integration; necessary capacity

1. Introduction

Sustainable energy availability is increasing these years, mainly with the use of wind power. The rapid growth of wind power presents many new challenges for the existing power grid. One of the challenges is the conflict between the high penetration rate and stochastic availability of wind power.

The World needs more wind power integrated into the power grid to meet the increasing need of renewable generation, however, if the penetration of wind power were to exceed 20% [1] of the total generation, the electrical energy consumption difficulty will increase due to wind power stochasticity. Increasing the penetration of wind power has become the biggest challenge for further development of wind power. Connecting energy storage systems to wind farms is a feasible way to decrease the stochasticity of wind power which makes energy storage systems an important part when wind power is integrated into the power grid. Significant work has been reported by many researchers on ESS sizing in the past years. Some papers have already studied the topic of operation scheduling for renewable energy generation utility grids with battery storage [2–6]. There are also papers focused on determination of the optimal size of ESS in parallel with optimal operation scheduling of generation units [7,8]. Some papers have proposed methods to optimize the size of ESS for different ESS working conditions [9–17]. In these papers, the optimal size of ESS was determined by using a per unit plant cost of a particular time frame, taking the economic benefits as the basic consideration. Chakraborty [18] proposed a determination methodology for optimizing the size of an ESS integrated with a thermal power system. The formulations presented in this study, to find the optimal ESS size, are derived through the economic cost benefit analysis of the installed ESS for its entire life cycle. Brekken *et al*. [19] describe optimal energy storage system sizing and control to increase the predictability of wind plant outputs and decrease the cost of integration associated with reserve requirements. Bludszuweit [20] proposed a method for ESS sizing based on wind power forecast uncertainty using real wind farm data. Li [21] proposed a simple optimization algorithm to determine the optimum component size for a standalone micro grid power system employing an iterative scheme.

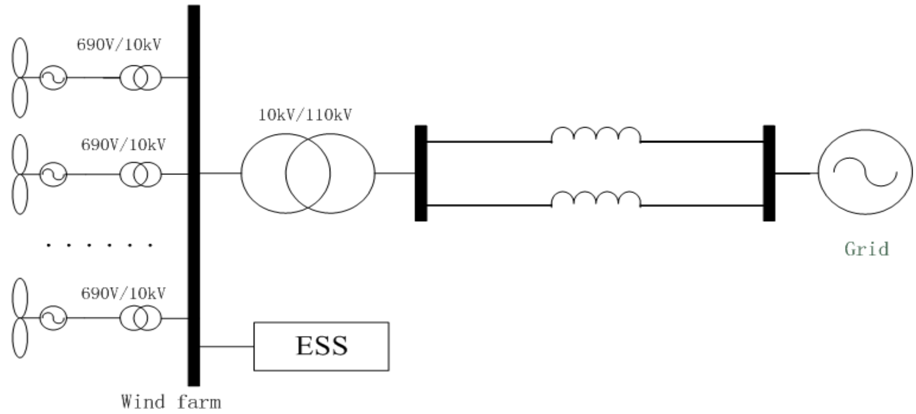
These papers are focused on the economic benefits which the ESS will bring into the system, and sizing the ESS based on these economic considerations, however there is lack of ESS sizing studies based on grid integration requirements.

This work is in focused on the requirement of grid integration while ensuring the ESS has continuous regulation ability. The necessary ESS capacity is determined from the requirements of grid integration. The actual type of ESS is not considered in this study. The main objective of the research is determine the necessary capacity of ESS for use in conjunction with a wind power generator that allows the output of combined wind power generator and energy storage system to meet the connected grid requirements. This research uses actual wind farm data from a large modern wind farm. The rest of this paper is organized as follows: in Part 2, the basic minimal mathematical expectation methodology is presented. In Part 3 the average segmentation method is presented to improve the performance. In Part 4, the automatic segmentation method is studied. In Part 5, the time window method for real-time control is studied. Part 6 presents our final remarks and conclusions.

2. Basic Method

Figure 1 shows the topology of a wind farm with ESS. The ESS is used to compensate the power fluctuations from the wind farm. The energy storage system is commanded to supply or absorb power equal to the fluctuations between the original output of the wind power generator and the desired output of the ESS conjunction with the wind power generator in a particular regulation period.

Figure 1. Wind power system with ESS.



The basic capacity of an energy storage system could be described by Equation (1):

$$E_{ESS} = \sum_{i=1}^{i=N} (\left|P_{WIIND}(t_i) - P_{ref}(t_i)\right|)\Delta t \tag{1}$$

where $P_{WIND}(t_i)$ is the original wind power generator output at ith point; $P_{ref}(t_i)$ is the desired output that the ESS conjunction with the wind power generator that meets the requirements of grid integration at ith point; Δt is the length of one sample period. Once the desired output P_{ref} is determined, the capacity of the ESS can be calculated.

Getting the optimal size of an ESS with Equation (1) will be difficult. In this study, this problem is transformed to minimize the square differences between the original output of wind power generator $P_{WIND}(t_i)$ and the desired output $P_{ref}(t_i)$, which can be described as follows:

$$E'_{ESS} = \sum_{i=1}^{i=N} (P_{WIND}(t_i) - P_{ref}(t_i))^2 \tag{2}$$

This hypothesis can avoid the difficulty of absolute value. There will be deviation between the two results, but this hypothesis is available and can satisfy the need of solving the problem above.

The detailed method is presented below:

$$P_{ref}(t_i) = P_{WIND}(t_i) + P_{ESS}(t_i) \tag{3}$$

$$P_{ref}(t_i) = at_i + b \tag{4}$$

Assuming $P_{ref}(t_i)$ is the expected output of the combined wind power generator and energy storage system. When the energy storage system absorbs energy, $P_{ref}(t_i)$ is negative, and when the energy storage system releases energy $P_{ref}(t_i)$ is positive. The term a is the change rate, which depends on the grid connection requirements and the wind power generator parameters:

$$\sum_{i=1}^{i=N} P_{ESS}(t_i) = \sum_{i=1}^{i=N} (P_{WIND}(t_i) - P_{ref}(t_i)) = 0 \tag{5}$$

The ESS should have continuous regulation ability, which means the ESS should satisfy the need of the next regulated period at the end of one regulation period. For this consideration, the absorbed energy of the ESS should be equal to the released energy of the ESS during one regulated period. This means the SOC (state of charge) of ESS should be initialized at a proper value:

$$E_{ESS} = \sum_{i=1}^{i=N} (P_{WIND}(t_i) - P_{ref}(t_i))^2 \tag{6}$$

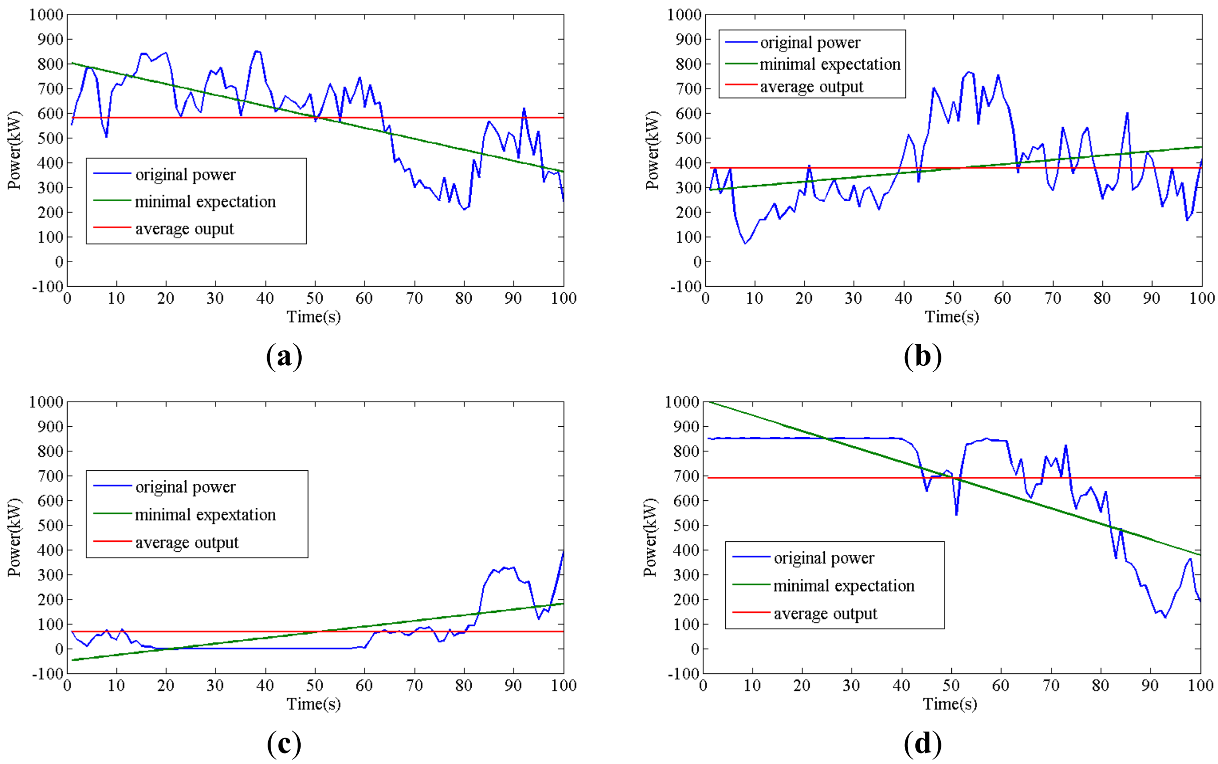
This is the objective function, to determine the minimal capacity of the energy storage system. According to the standards of the wind power grid integration [22], the two basic requirements of integration are as follows: the maximum power fluctuation of one minute is one fifth of the power rating of the wind turbine generator. The maximum power fluctuation of ten minutes is two-thirds of the power rating of the wind turbine generator output power. The other conditions of this study are as follows: power rating of the wind power generator is 850 kW. The length of one regulation period is ten minutes. The sample time is eight seconds and every data point stands for the average value of one sample period.

Four sections of typical wind power generator output data which come from a real wind power farm were tested with the proposed method. Every part corresponds to ten minutes. The simple average output method is tested for comparison. The results are shown in Figure 2 and Table 1.

Table 1. The capacity comparison of the two methods.

kWh	Period 1	Period 2	Period 3	Period 4
Minimal expectation	8.1361	10.5500	4.9286	8.6030
Average output	12.1824	11.2370	5.9544	14.7424

Figure 2. The regulation effect with average output method and the proposed method.



In Figure 2, the blue line indicates the original output of wind power generator; the red line and green line indicate the regulated power which will be supplied to the grid. The red line indicates the simple method which keeps the regulated power at a constant value while the green line indicates the proposed method. Figure 2a shows the typical wind power generator output; Figure 2b shows the wind power generator output under gust conditions, Figure 2c shows wind power generator output increasing from zero and the Figure 2d shows wind power generator output decreasing from the ratio value.

From Table 1 it can be seen that the ESS capacity is reduced with the proposed method. However, from Figure 2, there are some unexpected performances at the beginning of Figure 2c and Figure 2d. In Figure 2c, the original output of wind power generator is very low from 0 s to 450 s, especially zero from 100 s to 350 s, and then shows a very fast rise until the end of the regulation period. In Figure 2d the original wind power output keeps the ratio power of the wind power generator from 0 s to 220 s, and then decreases from the ratio power to 30 kW during 220 s to 540 s. Apparently, with the simple basic method, the regulation effects were not suitable for real system application. Especially in Figure 2d, when the wind power generator is at maximal output it does not need to be regulated, but with the proposed method the output is higher than the maximal value which is not expected for the real system. This phenomenon is caused by the regulation principle Equations (3–6) due to the rapid increase and decrease of original wind power output.

3. Average Segmentation Method

The main problem of the former proposed simple method is that it is not satisfactory when the original wind power generator output shows rapid fluctuations. To improve the performance of the regulated output P_{ref}, an improved method, called segmentation method, is proposed.

We divide the regulation period into several parts, and every part has the same length; in each part the original wind power output has a smoother change. We regulate every part with the method proposed in Section 2 and keep the regulation continuous. The segmentation method can be mathematically presented as follows:

$$\begin{aligned} &P_{ref1} = a_1 t_i + b_1 \\ &P_{ref2} = a_2(t_i - N_1) + a_1 N_1 + b_1 \\ &. \\ &. \\ &. \\ &P_{ref\,m} = a_m(t_i - N_{m-1}) + a_{m-1}(N_{m-1} - N_{m-2}) + \cdots \\ &+ a_2(N_2 - N_1) + a_1 N_1 + b_1 \end{aligned} \tag{7}$$

P_{refm} is the expected output of combined wind power generator and energy storage system of part *m*. These oblique lines are continuous:

$$f = \sum_{i=1}^{i=N_1}(P_{ref1} - P(t_i)) + \sum_{i=N_1}^{i=N_2}(P_{ref2} - P(t_i)) + \cdots + \sum_{i=N_{m-2}}^{i=N_{m-1}}(P_{ref(m-1)} - P(t_i)) + \sum_{i=N_{m-1}}^{i=N}(P_{ref\,m} - P(t_i)) = 0 \tag{8}$$

Keeping the SOC the same at the beginning and ending point of one regulation period, which means the absorbed energy of ESS should be equal to the released energy of ESS during one regulated period:

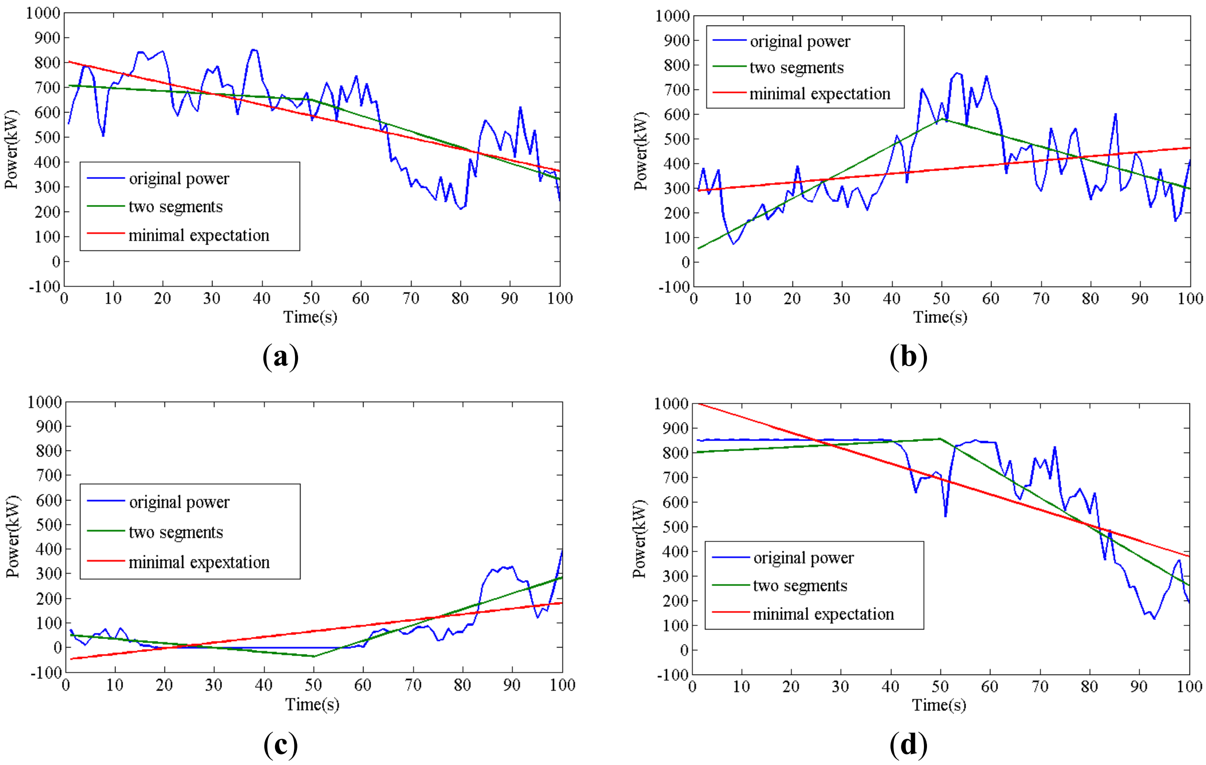
$$J = \sum_{i=1}^{i=N_1}(P_{ref1} - P(t_i))^2 + \sum_{i=N_1}^{i=N_2}(P_{ref2} - P(t_i))^2 + \cdots + \sum_{i=N_{m-2}}^{i=N_{m-1}}(P_{ref(m-1)} - P(t_i))^2 + \sum_{i=N_{m-1}}^{i=N}(P_{ref\,m} - P(t_i))^2 \tag{9}$$

This is the objective function, to determine the minimal capacity of energy storage system. The same four parts of the original wind power generator output data used in Section 2 are tested under our two segments situation. The results are shown in Table 2 and Figure 3.

Table 2. Capacity of ESS comparison of the two methods.

kWh	Period 1	Period 2	Period 3	Period 4
Minimal expectation	8.1361	10.5500	4.9286	8.6030
Two segments	7.9150	7.4038	2.8383	6.0186

Figure 3. Regulation effect comparison of the two methods.

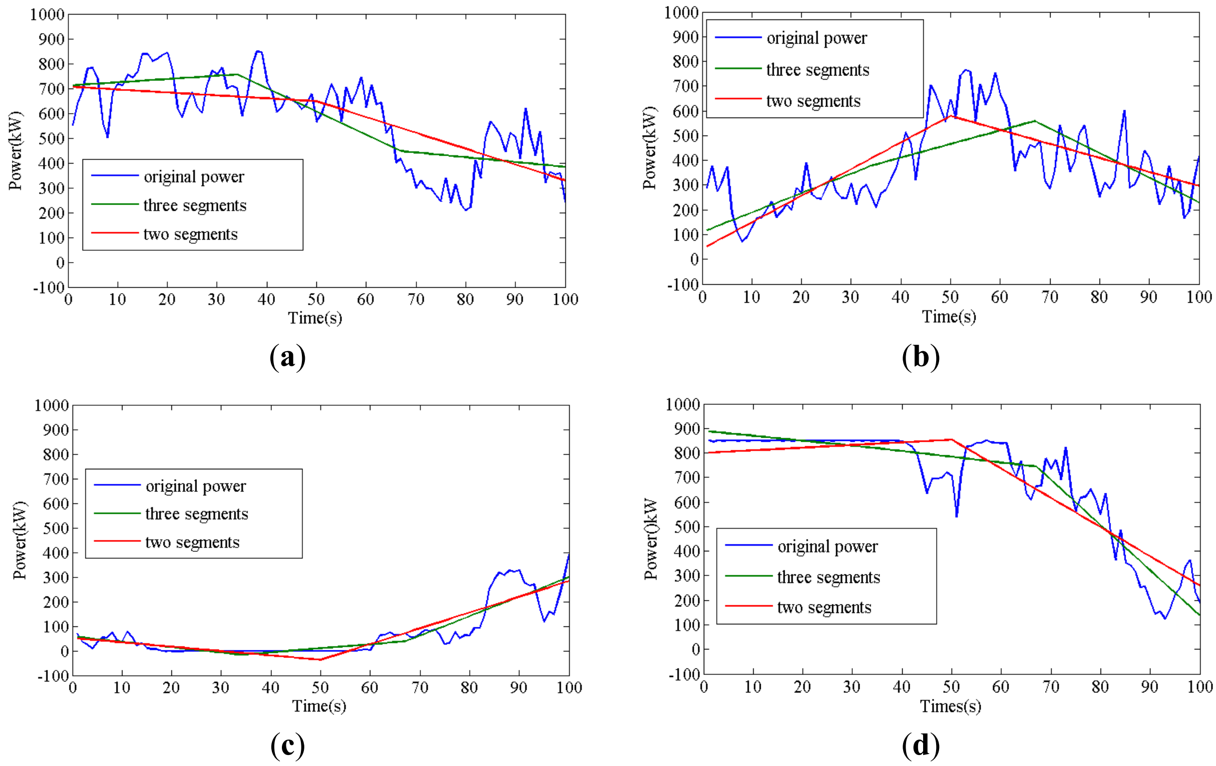


From Figure 3 and Table 2, it can be seen that a significant improvement is obtained with the two-part segmentation method. The necessary capacity of the ESS is reduced and the performance of P_{ref} is much more reasonable at the beginning of period 3 and period 4. Expanding the segmentation method, a three segments situation is studied. The results are presented in Table 3 and Figure 4.

Table 3. Capacity comparison of all methods.

kWh	Period 1	Period 2	Period 3	Period 4
Average output	12.1824	11.2370	5.9544	14.7424
Minimal expectation	8.1361	10.5500	4.9286	8.6030
Two segments	7.9150	7.4038	2.8383	6.0186
Three segments	7.3991	8.4944	2.5864	4.7499

Figure 4. Regulation effect with two segments method and three segments method.



From Figure 4 and Table 3, it can be seen that the simple increase of the number of segments from two to three will cause unsure performance. From Figure 4c, the regulated outputs are more suitable for real application, while Figure 4d shows unexpected performance from 0 s to 120 s. The necessary capacity is reduced in all four periods except period 2 with three segments which is shown in Table 3. Meanwhile, from the analysis of the regulation principle, the more parts to divide the more risk of up/down rate over the limits.

The proposed basic method can reduce the necessary capacity of the ESS, but in some cases, such as those involving continuous low output or maximum output, the basic method does not perform very well. To improve the performance, a segmentation method is proposed. The segmentation method can reduce the necessary capacity of the ESS further than the simple basic method, and can satisfy more working situations. From Table 3, it can be seen that the necessary capacity of the ESS may increase when the segments increase with the simple average segmentation (period two). Meanwhile, the performance may degenerate (Figure 4d). An automatic segmentation method is the next research topic, where we will analyze the data and automatically divide the regulation period into proper parts and proper lengths.

4. Automatic Segmentation Method

The simple segmentation method has some basic issues to address such as how the time period of each segment should be defined and how many segments are sufficient. The proposed automatic segmentation now can solve the predicted two issues. Here are some of the basic notions used:

- L the length of one regulation period;
- L*min* the minimum length of one segment;

- M segments of one regulation period;
- L(m) the length of the mth segment;
- K(m) the change rate of the mth segment;
- Cap [L (1), L (2)…L (m)] the energy capacity of energy storage system.

The detailed automatic segmentation method is described by the following:

Step 1, Set M as 2;

Step 2, Set L(1) to L(m − 2) constant as the minimum length of one segment, then change the length of L(m − 1) from 80 s to (528 – 72 × m) s, using the method proposed in Section 2 to get a series of K(m), cap [L(1), L(2), …, L(m)] , P_{reg} (max) and P_{reg} (min) correspond to every L(m − 1);

Step 3, Abandon all L(m − 1) correspond to [P_{reg} (max) − P_{reg} (min)] > 0.67 × P_{WIND} which do not satisfy the requirements of maximum power change in one regulation period;

Step 4, Abandon all L(m − 1) correspond to either of the K(m) beyond [−2.83, 2.83] which do not satisfy the requirements of change rate;

Step 5, Choose the L(m − 1) correspond to the minimal cap [L(1), L(2), …, L(m − 1), L(m)];

Step 6, Change L(m − 2) from its minimal value to its maximum value and repeat the process step 2 to step 5 to get the [L(1), L(2), …, L(m)] corresponds to the minimal cap [L(1), L(2), …, L(m − 2), L(m − 1), L(m)];

Step 7, Change the left L(m) in sequence, and repeat the process above to get [L(1), L(2), …, L(m)] which corresponds to the minimal cap [L(1), L(2), …, L(m − 2), L(m − 1), L(m)];

Step 8, Change m from 3 to M and repeat step 2 to step 7 to get {m, [L(1), L(2), …, L(m − 1), L (m)]} which correspond to the minimal cap [L(1), L(2), …, L(m − 1), L(m)].

By doing this, it can define how many segments and the length of each segment which can satisfy the requirements of integration with the smallest ESS energy capacity.

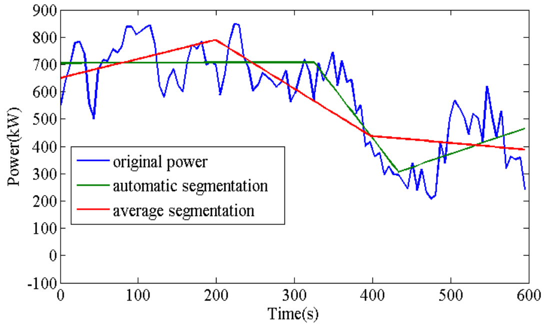
The same four scenarios used in Section 2 were tested here using the automatic segmentation method. The results obtained in Section 2 are used for comparisons. The results are shown in Figure 5 and Table 4.

Figure 5 shows the comparison of the regulation effect with the average segmentation method and the automatic segmentation method. Table 4 shows the necessary energy capacity of the ESS and the necessary power capacity of the ESS with the average segmentation method and automatic segmentation method.

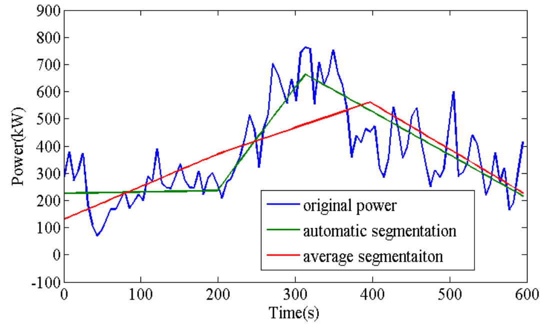
Table 4. Capacity of ESS with average segmentation method and automatic segmentation method.

kWh	Period1	Period2	Peried3	Period4
Average segmentation	7.3991	7.3991	7.3991	7.3991
Automatic segmentation	5.9447	5.9447	5.9447	5.9447

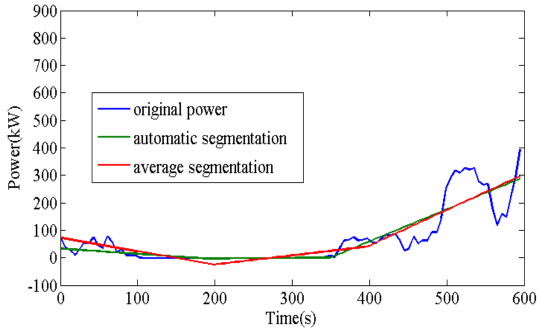
Figure 5. Regulation effect with average segmentation and automatic segmentation method.



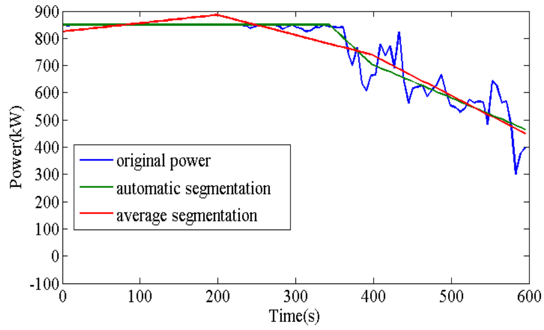
(a)



(b)



(c)



(d)

Table 4 shows that the necessary ESS energy capacity is reduced with the automatic segmentation method. Figure 5 shows that the regulated outputs are more reasonable in all four scenarios with the automatic segmentation method. Especially in Figure 5c and Figure 5d, the regulated output has better performance with the automatic segmentation method. Figure 5 part c and Figure 5 part d show that the regulated output is negative with the average segmentation method while the regulated output is kept at zero with the automatic segmentation method from 140 s to 270 s in Figure 5c. The regulated output is over 850 kW the power rating of the wind power generator with the average segmentation method while the regulated output keep the power rating with the automatic segmentation method from 100 s to 220 s in Figure 5d. Figure 5 and Table 4 show that the automatic segmentation method is effective for sizing an ESS in wind power generator grid integration applications.

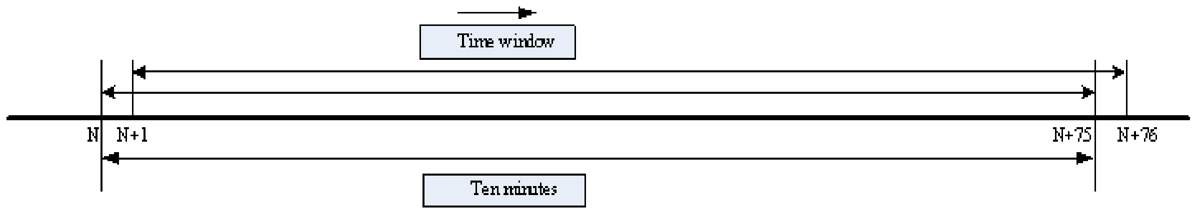
5. Time Window Method for Real-Time Control

The method mentioned above just provides the necessary capacity of an ESS in a particular regulation period. If the method is expanded for real-time control, there are some additional problems to solve. The basic problem is how to get continuous regulation results while time passes. The time window method is applied to achieve this goal. The detailed method is presented below:

Step 1, initial the work condition;
Step 2, picking up the first ten minutes' original wind power data and put it in time window;
Step 3, processing the data with the method proposed in Section 2;
Step 4, determine the desired wind power output and the necessary capacity of ESS;
Step 5, update the data in time window as shown in Figure 6;
Step 6, repeat step 3 to step 5;

Step 7, get the finial output of desired wind power output curve and capacity curve.

Figure 6. Time window method.



In this way, we can get a curve of the necessary ESS capacity which can satisfy the need of integration for real-time control. The ESS curve can be satisfied every ten minutes, which is the setting regulation period, while choosing the ESS capacity as the maximal value of the curve.

The automatic segmentation method with time window is tested with four sets of real wind farm data. The average output method with time window and average segmentation method are tested for comparison. Results are shown in Figure 7, Figure 8 and Table 5.

Table 5. Maximal energy needed with the three methods.

kWh	Period 1	Period 2	Period 3	Period 4
Average segmentation	4.37	4.73	5.25	6.25
Minimal expectation	5.72	7.87	5.73	8.31
Automatic segmentation	3.72	4.52	4.92	5.47

Figure 7. Regulation effect comparisons.

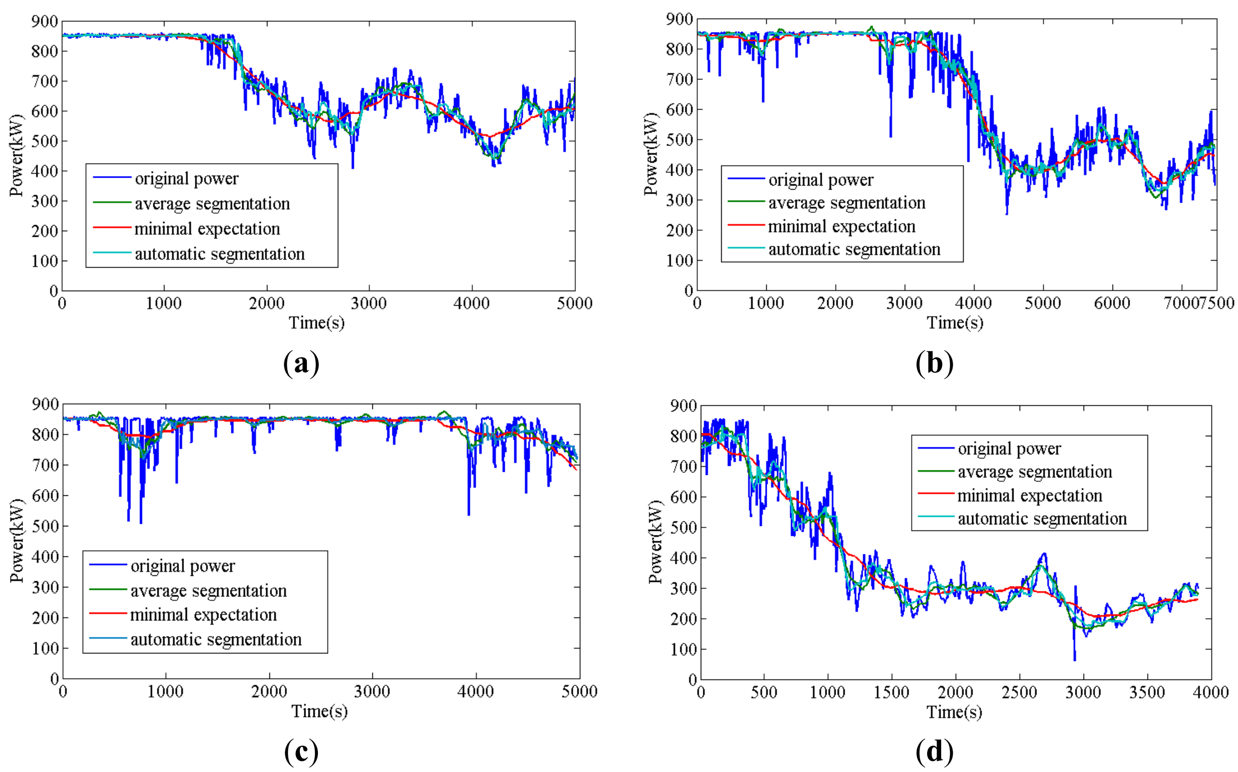


Figure 8. Capacity curves of ESS.

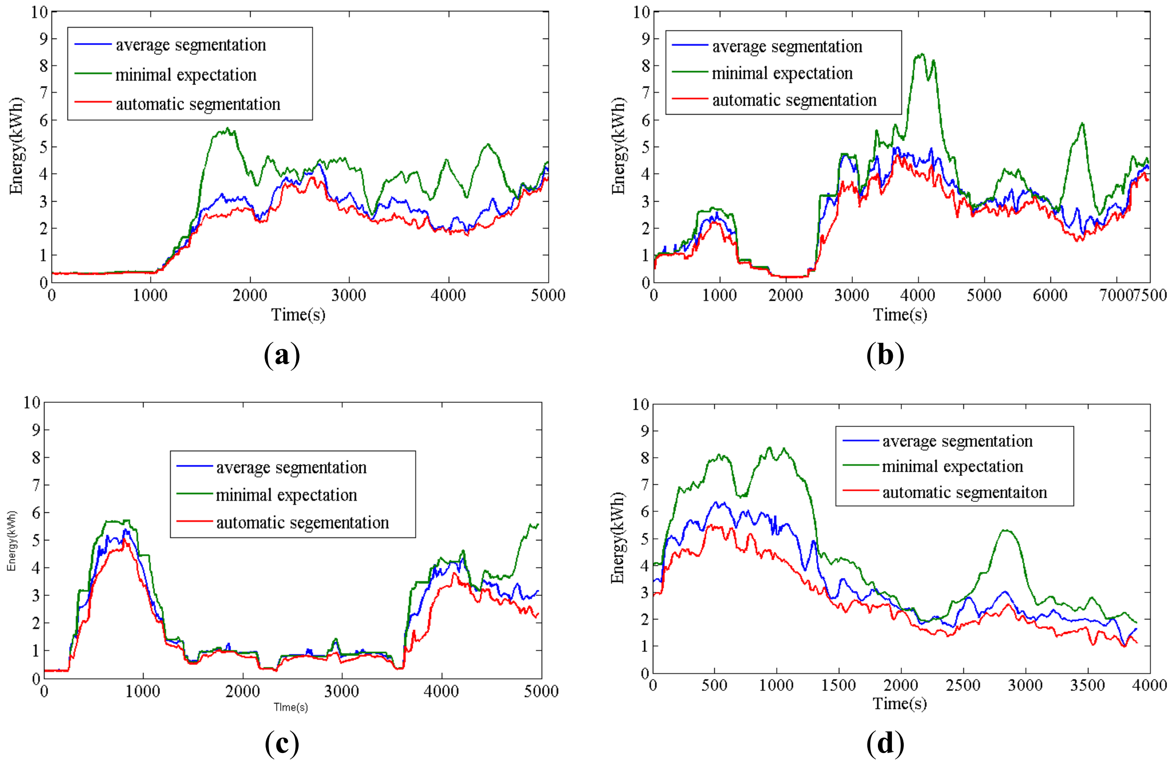


Figure 7 shows the regulation effects with the basic method, average segmentation method and automatic segmentation method. In Figure 8, every point in the capacity curves stands for the necessary capacity which can satisfy one regulation period. From Figure 7 and Figure 8, it can be seen that the necessary energy is reduced with the proposed automatic segmentation method and verify the effectiveness of the proposed method. With sufficient historical data, the proposed method can give a capacity curve which satisfies all ESS working conditions and this capacity curve can used for ESS sizing in real wind farm planning.

6. Conclusions

This paper proposes a determination methodology for optimizing the capacity of an ESS which enables the wind power generator to meet the requirements of grid integration. By minimizing the square of the differences between the original wind power generator output and the combined wind power generator and ESS output which meet the requirement of grid integration, we can get the minimal necessary ESS capacity. To improve the regulation effects, an advanced method, called segmentation method, is proposed. The automatic segmentation method which can process the data in intelligent method to decide the number of parts to divide and the length of every part is proposed to get even better performance. Expanding the proposed method for real-time control, the time window method is applied. Using the proposed method with time window, one can get a curve of necessary ESS capacity. Using this curve, it can get the minimal ESS capacities which can satisfy different levels of regulation availability, and this kind of ESS capacity curve can be used as a guideline for real wind farm planning.

Acknowledgments

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Conflict of Interest

The authors declare no conflict of interest.

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