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Optimal Control of Battery for Grid-Connected Wind-Storage System

Liang Liang, Student Member, IEEE, and Jin Zhong, Senior Member, IEEE

Abstract—The penetration level of large-scale wind farms is restricted by the output uncertainties of wind power generations. Energy storage systems with fast response time and high operation efficiencies, such as, flywheel and battery could be used as one of the solutions for large-scale wind power integration to power grid. To mitigate the power fluctuation of wind farm, an optimal control method of battery energy storage system is proposed for grid-connected wind system in this paper. Based on one-day ahead forecasted data of wind farm output, an optimization model is proposed to minimize the output power fluctuation as well as energy storage subject to battery capacity and power constraints. The solution algorithm is presented to solve the nonlinear optimization model. Finally, case studies with different output power curves of wind farm are presented to analyze the inter-relationship of energy storage capacity, energy storage output power and wind power fluctuation and typical configuration of battery energy storage system for wind-storage hybrid system is proposed.

Index Terms—Energy storage, optimal sizing, wind farm, renewable energy integration, power fluctuation.

I. INTRODUCTION

Within past two decades, the penetration level of wind power generation in power system has increased significantly due to the mature of wind power generation technologies and the requirement of energy and environment. Consequently, wind power could take greater effect to power grid than ever before [1]. It is a great challenge to integrate wind power generation to power systems due to the fluctuation of wind. Connection of large-scale wind power generations to the grid may cause frequency stability problem to the power system, as wind power fluctuations occur in the time scale of minutes and even in seconds [2-5]. The related research is mainly on two aspects, power system operation level and wind farm level. The first aspect concerns how to provide abundant reserves and manage them effectively [6]. The other aspect is to reduce the effect of power fluctuations of wind farms using various methods. Compared to the first aspect, reducing power fluctuations of wind farm could facilitate wind power integration to the grid and help maintain current operation modes of power system operations even with high wind penetration in the system.

Nowadays, battery energy storage system has been regarded as an effective solution to reduce power fluctuations of renewable energy [7-10]. Battery energy storage systems could compensate the output power fluctuation of renewable energy in seconds due to its ability of rapid change of power output. In this way, battery energy storage system could greatly mitigate the intermittent characteristics of renewable energy generations, hence, lower the output fluctuation to an operation-acceptable level. In this case, the compensated renewable energy generation could be integrated into power grid directly and easily.

Control methods have been proposed to reduce output power fluctuations of wind farm [11-14]. A real-time control method for the energy storage system is presented in [11]. The energy storage system works as a low-pass filter and the output power fluctuation of the whole system is greatly reduced in most cases. Some improved control methods are represented in [12-13]. The state of charging (SOC) has been introduced into the control loop. The control method could keep the battery system away from deep charging area so as to obtain a longer life for the system. The wind forecasting system has been introduced in [14]. Based on the forecasting, the system operator could obtain the hourly output of the wind farm in one day ahead. In this case, the battery system could select the daily average output of the wind farm as a set point, then compensate the difference between the actual output and the forecasted output of the wind farm. Furthermore, the development of wind forecast technology provides a possibility of predicating the wind farm output in a certain time [15-19].

In this paper, a new method is proposed for selecting suitable operating set points for various battery systems, such as Lithium-ion battery energy storage system, redox flow battery energy storage system and NaS battery energy storage system. The battery system could rapidly compensate the power fluctuation of wind farm based on these set points. It is assumed that the day-ahead wind farm output is available for the control system of the hybrid wind-battery system. The set points of the battery system could be calculated by carrying out the proposed optimization process. The topology structure of the studied wind-storage hybrid system is described in Section II. The objective function considering wind farm outputs and the power fluctuation of the wind-storage hybrid system is proposed in Section III. By minimizing the objective function, the battery set point of next day can be obtained. The solution algorithm is represented in Section IV. Case studies are presented in Section V, the relationship of the capacity of energy storage system, the output power of energy storage
system and the value of proposed objective function are studied and analyzed. Section VI concludes.

II. HYBRID WIND-BATTERY SYSTEM TOPOLOGY

Fig.1 The topology diagram of the hybrid wind-storage system

Fig.1 shows the topology diagram of the wind-storage hybrid system. The wind-storage hybrid system includes several wind turbines, which are controlled by power converters and connected with power grid through individual transformers. The total output power of the wind farm is the sum of output from all wind turbines. The battery bank is consisted of a large number of serial and parallel connected batteries. The battery bank is connected to the system through the power converter system (PCS) and a transformer. As a result, the capacity of the battery energy storage is decided by the total capacity of all batteries, and the rated output power is equal to the rated power of PCS. The wind-storage hybrid system connects to the power grid through a 35kV/110kV transformer.

The battery energy storage system is a controllable source in the wind-storage hybrid system. The information of actual output of the total wind turbines could be transferred to the battery system. This feature makes it possible to reduce the output fluctuation of the wind-storage hybrid system by selecting a series of suitable operation set points for the controllable battery energy storage system.

III. MATHEMATICAL MODEL

The purpose of the proposed model is to pre-determine set points of battery systems according to day-ahead forecasted wind power, in order to minimize the output fluctuation of wind farm. The objective function is optimized subject to the battery capacity and power constraints.

A. Objective Function

The objective function is to minimize the power fluctuation and the energy charged and discharged in the wind-storage hybrid system.

\[
C = \sum_{i=1}^{n} \left( P_{r,i} - P_{t,i} \right)^2 + F_{\text{battery}} \times \left( \sum_{i=1}^{n} P_{b,i} - \frac{E_{\text{ herein}}}{T_{\text{wp}}} \right)^2
\]

where, \( P_{t,i} \) indicates the output power of the wind-storage hybrid system at time \( i \), and \( P_{r,i} = P_{b,i} + P_{w,i} \). \( P_{b,i} \) and \( P_{w,i} \) indicate the output power of the battery energy storage system and wind turbines at time \( i \), respectively. \( E_{\text{ herein}} \) indicates the desired exchanging energy of battery energy storage system in one day. \( T_{\text{wp}} \) indicates the time interval between two data points. \( F_{\text{ battery }} \) indicates the factor of energy exchanging of the battery energy storage system.

In the objective function, \( P_{w,i} \) could be obtained from the day-ahead wind forecasting results. \( T_{\text{wp}} \) is decided by the wind forecasting system. Normally a smaller time interval leads to a better compensation result. Different \( F_{\text{ battery }} \) and \( E_{\text{ herein}} \) can be used to represent different operation status of the wind-storage hybrid system. The operation set points of battery system, \( P_{b,i} \), are obtained by solving the proposed optimization model.

The first item of the objective function represents the power fluctuation of the wind-storage hybrid system, and the second item represents the total energy of wind system exchanged with the battery system. The first item minimizes the fluctuation of hybrid wind-storage system.

The second item minimizes the difference between the actual energy and the desired energy exchanged between the battery system and the power grid.

The control method is proposed to calculate the optimal operation set points for the next day, as a result, the SOC of the battery is expected to be kept around 50% at the end of each day. In other word, the energy exchanged between the battery system and the power grid is supposed to be the difference between the 50% SOC and the initial energy of the battery system. When the second item is minimized, the difference between the actual exchanged energy and the expected exchange energy is minimized. For example, as shown in Fig.2, the curve represents the wind farm output of one day. When the capacity is large enough, says \( E_{\text{ max }} \), the output of the wind-storage hybrid system could be controlled as the average output of the wind farm. If the capacity of the battery energy storage system is larger than \( E_{\text{ max }} \), the output power could even be controlled as a constant value within a region between the upper and lower boundary as shown in Fig.2. In this case, by minimizing the second item in the objective function, the set points of the battery energy storage system will be set to help to control the SOC of the battery system close to 50%.
Based on the initial value of the SOC, the value of $E_{\text{max}}$ can be obtained to make sure that the final SOC at the end of the day is close to 50%.

The two items are optimized simultaneously, and in certain cases, both items could be minimized to zero at the same time.

B. Constrains

Battery energy storage system is a new type of power component in the power system. Battery energy storage system could change the real-time balancing characteristic of power generation and demand. Different from conventional generation components in the power system, the battery system has capacity and power constrains need to be considered:

\[
-\frac{E_{\text{max}}}{T_{\text{step}}} \leq \sum_{i=1}^{n} (P_{B_i}) \leq \frac{E_{\text{max}}}{T_{\text{step}}} \quad (\forall n \in \mathbb{N})
\]

(2)

\[
E_{\text{Battery}} = E_{\text{max}} + E_{\text{max}}
\]

(3)

\[
-P_{\text{min}} \leq P_{B_i} \leq P_{\text{max}}
\]

(4)

where, $E_{\text{max}}$ indicates the maximum amount of energy that can be absorbed from the power grid. $E_{\text{max}}$ indicates the maximum energy of the battery system could be injected to the power grid. $E_{\text{Battery}}$ indicates the capacity of battery energy storage system. $N$ indicates the total data points in the forecast results of wind farm. $P_{\text{max}}$ indicates the maximum output power of battery energy storage system.

Equation (2) shows that the energy exchanged with battery system should not exceed the capacity limit of the battery system. Normally, it is assumed that the initial SOC of the battery is 50%, and $E_{\text{max}} = E_{\text{max}} = \frac{E_{\text{Battery}}}{2}$.

Equation (4) shows that the output power constraint of the battery system. The maxim output power is decided by the PCS system of the battery system.

IV. SOLUTION ALGORITHM

The main idea of this control method of hybrid wind-storage system is to minimize the objective function:

\[
\min C = \sum_{i=1}^{n} \left( P_{B_i} - P_{W_i} \right)^2 + F_{\text{Battery}} \times \frac{E_{\text{Ricardo}}}{T_{\text{step}}}^2
\]

(5)

\[
P_{B_i} = P_{W_i} + P_{H_i}
\]

(6)

As $P_{W_i}$ could be obtained from one-day ahead wind farm forecast system, the $P_{H_i}$ will decide the value of the objective function. The battery energy storage system needs to select suitable value to minimize the value of objective function. Consequently, the control system of battery system is required to complete the quadratic optimization problem effectively. The problem could be described as below:

\[
\min \frac{1}{2} x^T H x + f^T x
\]

(7)

\[
s.t. \left\{ \begin{array}{l}
Ax \leq b \\
lb \leq x \leq ub
\end{array} \right.
\]

(8)

where $H,f,A,lb$ and $ub$ are defined as below:

\[
H = C + 2 \times F_{\text{Battery}} \times D
\]

(9)

\[
D = \begin{bmatrix}
2 & -2 \\
-2 & 4 & -2 \\
-2 & 4 & -2 \\
-2 & 2 & -2
\end{bmatrix}
\]

(10)

\[
f_i = 2 \times \left( P_{W_i} - P_{B_i} \right) - 2 \times F_{\text{Battery}} \times \frac{E_{\text{Ricardo}}}{T_{\text{step}}}
\]

(12)

\[
f_i = 2 \times \left( P_{W_i} - P_{B_i} \right) - 2 \times \left( P_{B_{i+1}} - P_{W_i} \right)
\]

(13)

\[
f_i = 2 \times \left( P_{W_i} - P_{B_{i+1}} \right) - 2 \times F_{\text{Battery}} \times \frac{E_{\text{Ricardo}}}{T_{\text{step}}}
\]

(14)
\[ A = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 \\ 1 & 1 & \cdots & 0 & 0 \\ 1 & 1 & \cdots & 1 & 0 \\ 1 & 1 & \cdots & 1 & 1 \\ -1 & 0 & \cdots & 0 & 0 \\ -1 & -1 & \cdots & 0 & 0 \\ -1 & -1 & \cdots & -1 & 0 \\ -1 & -1 & \cdots & -1 & -1 \end{bmatrix} \]

\[ b = \frac{E_{\text{ref}}}{T_{\text{ref}}} \]

\[ \begin{bmatrix} \frac{E_{\text{ref}}}{T_{\text{ref}}} \\ \vdots \\ \frac{E_{\text{ref}}}{T_{\text{ref}}} \\ \vdots \\ \frac{E_{\text{ref}}}{T_{\text{ref}}} \end{bmatrix} \]

\[ lb = \begin{bmatrix} -P_{\text{ref}} \\ \vdots \\ -P_{\text{ref}} \end{bmatrix}, \quad ub = \begin{bmatrix} P_{\text{ref}} \\ \vdots \\ P_{\text{ref}} \end{bmatrix} \]

\[ x_i = P_{\text{ref}} \]

V. CASE STUDY

The daily output power curve of wind farm includes 1440 points, the time interval is one minute. The maximum output power of battery system is set to 60\% rated power of the wind farm. The maximum capacity is set to 4 hours according to the rated power of battery system. There are 4 typical daily curves of wind farm in this case study. The value of \( F_{\text{battery}} \) is set to \( 1 \times 10^{-4} \). The value of \( E_{\text{ref,wind}} \) is set to zero. Based on the proposed optimal control method, Fig.3 to Fig.6 shows the compensation result for the wind-storage hybrid system.

Fig.3 The output of wind farm with small fluctuation

Fig.3 shows one typical power curve of wind farm compensated with battery system which has different rated output power. The average output power of the wind farm is more than 0.6 p.u. of the wind farm, while the power fluctuation is not large. The output power fluctuation of wind farm could be greatly reduced with a 10\% rated battery energy storage system. The output power of the wind-storage hybrid system could be kept at a constant value when the rated power of battery system increasing to 60\% in this case.

Fig.4 The output of wind farm with strong wind

Fig.4 is the second typical output power curve of wind farm compensated with battery system. The total wind output power in Fig.4 is larger than in Fig.3. The average output power is more than 0.7 p.u. of the wind farm. The output power of wind farm has reduced more than 0.6 p.u. in one hour. Even in this case, a battery system with 60\% rated output power could totally compensate the output power fluctuation of wind farm.
Fig. 5 shows the situation of output power curve of wind farm with large fluctuation. In this case, even if the battery with a 60% rated output power, the large power fluctuation could not be eliminated totally. And more, in order to store more output power from wind farm, the battery with a 10% rated power need to send power into grid at initial state to obtain a larger energy storage capacity.

In all four output power curves of wind farm studied above, a battery system with 10% rated power could compensate the small transient power fluctuation part in the output power of wind farm. While a battery with 30% rated power could compensate the output power of wind farm into a general flat output. At most time, a battery system with 60% rated power could totally compensate the output of the wind-storage hybrid system into a constant value or flat output with small slope. The capacity of battery system in the 4 case studies is assumed to 4 hours.

VI. CONCLUSION

An optimal control of battery system for grid-connected wind-storage system is presented in this paper. Based on the results of wind forecasting, an optimization model is proposed to plan the set points of the battery system for the next day to reduce the power fluctuation of the wind-storage hybrid system. The model could be described as a quadratic optimization problem. Such problem could be solved in less than one minute with modern computer.

Four typical output power curves of wind farm are tested in section V. The results show that battery energy storage system with a 10% rated power and 0.8 hours capacity could greatly reduce the output power fluctuation and facilitate the wind power system integrate into power grid. If the rated power of battery system is larger than 60% rated power, it is possible to eliminate the power fluctuation in the output power of wind farm in one day.

Although the precision of wind forecast system may take great effect to the result, some researchers are focusing on this area and better forecast methods with higher accuracy could be expected.

VII. REFERENCES


Liang Liang was born in Beijing, China, in 1983. He received his B.Sc. degree from Tsinghua University, Beijing, China, in 2005, and the M. Sc. degree from Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 2008. He is currently working toward the Ph.D. Degree in Electrical Engineering at the University of Hong Kong, Hong Kong. His current research interests include areas of energy storage applications in power system, wind energy and renewable energy.

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