A Comparative Analysis among Power Dispatching Control Strategies for Hybrid Wind and Energy Storage System

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Abstract – In this paper, a numerical comparison among power dispatching control strategies for hybrid wind and energy storage system is presented. Utilizing energy storage systems (ESSs) has been emphasized as a possible solution to mitigate the wind power fluctuation. In order to integrate ESSs into wind energy conversion system, the combined power dispatch to grid has to be taken into account. We investigate several power dispatching methods that are classified into three control groups including the smoothing-based control, the constant power dispatching method, and the power ramp-rate limit. The innovation of this paper relies on the fact that each power dispatching control method owns one or some advantageous features such as the competitive ESS capacity, no requirement of the wind power forecast, the communication ability with the transmission system operator (TSO), and the full ESS charge-discharge outcome. This paper provides the theoretical background how to select an effective power dispatching control method for its own wind farm to satisfy the technical system requirements. The numerical comparison presented in this paper is based on a 3-MW wind turbine with using a real wind speed data measured in a wind farm in Jeju Island.

Keywords: Wind energy conversion system (WECS), Energy storage system (ESS), Power dispatching control method.

1. Introduction

Although the wind is considered as a clean and immense resource to solve the current global problem of the exhausted fossil fuels, one main challenge preventing a high penetration wind power into electric market is the intermittency of the harnessed wind energy [1], [2]. A large wind power variation injected into the grid could bring a negative impact on power quality and network reliability and lead to that the wind power is nondispatchable [3]. Therefore, wind energy system developers need to overcome the wind intermittent problem before intending to dispatch high wind power level to the grid.

In order to mitigate the wind power fluctuation, the use of energy storage systems (ESSs) has been emphasized as one of the possible solutions [4]. Combination of ESS with wind energy conversion system results in a hybrid system in which the ESS plays a role of energy buffer to compensate the wind power intermittent components. In literatures [5] and [6], for example, the authors proposed the use of battery energy storage systems (BESSs) incorporated into the wind farm (WF) to dispatch a firm power for each dispatching interval. These papers considered optimal BESS capacity and optimal control of the power dispatch so as to economize the wind system operation. In practical systems, typical examples including the 254-MWh NAS battery installed for stabilizing a 51-MW WF presented in [7], a 2-MWh Li-ion battery build in a 4.5-MW WF described in [8], and the use of 1-kWh superconducting magnetic energy storage (SMES) to handle the fluctuation of 1-MW wind turbine (WT) discussed in [9] demonstrate that the use of ESSs is a feasible solution.

Even though the ESS provides WFs with ability to supply a firm power to grid, it makes the wind system expensive. In [10], cost per kWh of storage was meticulously analyzed to show that the pumped hydro added around one-third of the whole scale peak electricity price, and the BESS increased the retail electricity price in three times. The significant additional cost of storages requires economizing the capacity of ESSs, so that researchers have concentrated on optimizing the operation of the hybrid wind-storage system. In the optimal system, the way of dispatching power to grid decides the storage power flow; hence, the power dispatch strategy takes a key role and needs to be defined primarily. In [11] and [12], by using a low-pass filter, the power dispatch is defined and the wind-battery system is optimally controlled. The authors in [13]-[16] optimized the hybrid wind-storage system based on a power dispatching strategy that assigned an optimal constant power dispatch in each dispatching time interval. Another common power dispatching method is the power ramp-rate.
control, which aims to limit the ramp rate of power dispatch in a certain range [17].

It is expected that the penetration level of wind power into electric power systems is dramatically increased so as to reduce the massive market share of the conventional power stations such as thermal electric, hydroelectric, and nuclear power plants. When this scenario occurs, the transmission system operator (TSO) hopes that WFs can supply a committed power in a manner like the conventional power plants did [6]. In other words, the power dispatch strategy must be able to communicate with TSO to submit the WF power dispatch schedule in several hours ahead, and then in next every dispatching interval, the WF has to supply a power to commit this plan. Therefore, depending on the grid codes, WF owners should choose a suitable power dispatch strategy to minimize the system cost and meet the grid code requirement.

In this paper, we evaluate several power dispatching strategies in order to support the WF developers having an overview of advantageous features of each method and selecting a suitable power dispatching control method for their own wind farm. We classify power dispatching control methods into three control groups, including the smoothing-based control, the constant power dispatching method, and the power ramp-rate limit. The innovation of this paper relies on the fact that each power dispatching control method owns one or some advantageous features such as the competitive ESS capacity, no requirement of the wind power forecast, the communication ability with the transmission system operator (TSO), and the full ESS charge-discharge outcome. The numerical comparison shown in this paper is based on a 3-MW WT with using a real wind speed data measured in a WF in Jeju Island.

2. Hybrid Wind and Storage System

Fig. 1 illustrates a common configuration of the hybrid wind and storage system in which both WT generator and ESS are connected to grid at the point of common coupling (PCC) through their power conversion systems, PCS1 and PCS2. While the output of the generator $P_w$ and the power dispatch $P_d$ are always positive, the ESS output power $P_e$ is capable of delivering positive or negative powers so as to correspondingly charge or discharge the storage. If we neglect the power losses in the system, then the ESS power $P_e$ can be calculated as

$$P_e = P_w - P_d. \quad (1)$$

2.1 Power and Energy Ratings of ESS

The minimum requirement of ESS capacity, which is normally specified in term of energy rating $E_{\text{ess}}^{\text{min}}$ and power rating $P_{\text{ess}}^{\text{min}}$, is determined based on the power dispatch and the WT output power profiles [13]. Considering that the system is operating in a time period $T$, the ESS power rating is defined as

$$P_{\text{ess}}^{\text{min}} = \text{MAX}_0^T |P_e(t)| = \text{MAX}_0^T |P_w(t) - P_d(t)|. \quad (2)$$

Integrating the ESS power with respect to time yields the net energy injected into or drawn from the storage up to time $t$,

$$E_{\text{ess}}^{\text{min}} = \int_0^t [P_w(\tau) - P_d(\tau)] d\tau. \quad (3)$$

Along with the power rating, the energy rating is the maximum energy range that can be stored or released by the ESS while system operating for $T$, and is defined as follows:

$$E_{\text{ess}}^{\text{min}} = \text{MAX}_0^T |E_{\text{ess}}(t)| = \text{MIN}_0^T |E_{\text{ess}}(t)|. \quad (4)$$

2.2 ESS Technical Aspects Consideration

Fig. 2 shows the control principle of power dispatch of the hybrid wind-storage system, in which the power dispatching strategy (PDS) takes a key role. In Fig. 2, the power dispatch command $P_d^\ast$ is determined from the PDS based on the wind power, the power dispatch, and the state of charge (SOC) of ESS, and the ESS power is regulated by means of PCS as shown in Fig. 1. During the system operation, the ESS technical information needs to be strictly considered, which includes the SOC and deep of discharge.
(DOD). In order to prevent the storage overcharged, the system controller should keep the SOC within a proper limit (usually, 20% to 90%). Moreover, a high DOD causes a significant degradation of the storage lifetime, so that DOD needs to be limited during discharging; and the maximum DOD is usually lower than 80%.

3. Power Dispatching Strategies

So far, several PDSs have been introduced; however, we can classify them into three control groups that include the low-pass-filter-based smoothing method, the constant power dispatch control, and the power ramp-rate limit.

3.1 Low-Pass-Filter-Based Smoothing Method

In this method, the power dispatch is determined by a low-pass filter (LPF) that extracts the low fluctuation power components delivered to grid, whereas the high fluctuation components is compensated by the ESS [11], [12]. The LPF is usually a first-order one written as

\[ G(s) = \frac{1}{1 + Ts} , \]  

where \( T_s \) is the filter smoothing time constant (FSTC) determining the wind power attenuation level. As a result, the power dispatch and the ESS power are defined by

\[ P_d(s) = \frac{1}{1 + Ts} P_s(s) , \] 
\[ P_s(s) = \frac{T_s}{1 + Ts} P_d(s) . \]  

In this dispatching method, the FSTC is defined based on the fluctuation mitigation requirement (FMR) in \( \kappa \)-min time window. At current time \( t_0 \), the maximum fluctuation of the power dispatch \( P_d \) in \( \kappa \)-min time window can be defined as follows:

\[ \Delta P_d^\kappa (t_0) = MAX \{ P_d(t) \} - MIN \{ P_d(t) \} . \]  

Thus, the FSTC must guarantee that at any time \( t \), the system delivers a power \( P_d \) with a maximum fluctuation:

\[ \Delta P_d^\kappa (t) \leq \gamma_{\kappa-min} \times P_{WT} , \]  

where \( P_{WT} \) is the WT power rating, and \( \gamma_{\kappa-min} \) denotes the FMR imposed by a grid code that is usually set at 10% fluctuation level in 10-min time window.

3.2 Constant Power Dispatch Control

The constant power dispatch control method aims to deliver a constant power to grid in each dispatching interval \( T_s \) (usually \( T_s = 1h \)). There are two concepts to determine the constant power dispatch; the first one is to average the available wind power in \( T_s \), and the second is based on minimum and maximum level of wind power.

In the averaged approach [13], the power dispatch within a dispatching interval \( t_0 \leq t \leq t_0 + T_s \) is defined as

\[ P_d(t) = \frac{1}{T_s} \int_{t_0}^{t} P_e(t)dt . \]  

Like the low-pass-filter-based smoothing method, the ESS power is alternated from charge to discharge states in a short time period, which results in a significant reduction of ESS operational lifetime [14]. To tackle this problem, one enhanced approach named the min-max method was introduced in [15] and [16] that defined the power dispatch based on the SOC of ESS. While the ESS is being charged, the power dispatch is at the minimum wind power; meanwhile the power dispatch is defined at the maximum level of wind power when the ESS is being discharged. At the current \( i^{th} \) dispatching interval, the power dispatch is

\[ P_d(i) = \begin{cases} 
\text{MIN} & \text{when ESS is charged} \\
\text{MAX} & \text{when ESS is discharged.} 
\end{cases} \]  

3.3 Power Ramp Rate Limit

According to the grid code, the ramp rate which is defined as the derivative of the power dispatch must be kept within a certain limits. The ESS provides a necessary power to obtain the required ramp rate by the following method: When the ramp rate of wind power exceeds the upper limit, the ESS is charged to absorb the surplus energy; and the ESS is discharged to compensate the desired energy when the ramp rate is smaller than the lower limit. The power ramp limit method can be summarized as follows:

\[ P_d(t) = \begin{cases} 
P_e(t) & \text{if } \lambda_L \leq \frac{dP_e(t)}{dt} \leq \lambda_U \\
P_d(t - \Delta t) + \lambda_L \Delta t & \text{if } \frac{dP_e(t)}{dt} > \lambda_U \\
P_d(t - \Delta t) + \lambda_U \Delta t & \text{if } \frac{dP_e(t)}{dt} < \lambda_L 
\end{cases} \]  

where, \( \lambda_L \) and \( \lambda_U \) are the upper and lower limits, respectively, which are usually same magnitude but opposite sign; and \( \Delta t \) denotes the sampling time, then \( P_d(t - \Delta t) \) is the previous value of power dispatch.

4. Numerical Comparison among PDSs.
In order to evaluate characteristics of the PDSs, several simulations are made using MATLAB software. For the assessment, a 3-MW WT is selected [18] and the real wind speed in Jeju Island in 2012 is measured with 1-min sampling (i.e., $\Delta t = 1$ min and $P_{WTR} = 3$ MW). In the low-pass-filter-based method, the FMR in 10-min and 1-min time windows are assigned by the grid code, and they are set at $\gamma_{10-min} = 10\%$ and $\gamma_{1-min} = 0.5\%$ [19]. In the constant power dispatch control, the dispatching time interval is set at one hour, i.e., $T_d = 1$ h. And, in the power ramp rate limit approach, the upper and lower ramp rate limits are defined according to $\gamma_{1-min}$, and they are $\lambda_U = 15$ kW/min and $\lambda_L = -15$ kW/min.
The performances of four PDSs classified into three control groups are shown in Figs. 3-6; in each figure, the upper plot is the wind power profile and the power dispatch outcome, and the lower one is the ESS power response in a day. We can see that the power dispatch is stabilized successfully in accordance with respective PDS; for example, in Fig. 3(a), the low-pass-filter-based method filters the highly-fluctuated wind power and provides a stable power that can be dispatchable. Considering the ESS power response, it is noted that only min-max method in Fig. 5 leads to the ESS power being one direction for long period; this advantageous feature can prolong the operational lifetime of storage.

The most competitive aspect to be evaluated is the required ESS capacity in each PDS, and it is are plotted with four different seasons wind data in Fig. 7 for ESS power rating and Fig. 8 for ESS energy rating. From the required ESS capacity, we can conclude that the min-max dispatching method requires the largest capacity whereas the averaged method needs the smallest ESS volume.

In Table 1, we summarize numerical results for ESS capacity and typical characteristics of each PDS. It is noted that 1 p.u. in the ESS power rating means the WT rated power or 3 MW, and 1 p.u. in ESS energy rating denotes the storage volume reaching 3 MWh. The dispatching methods with simple implementation are the low-pass-filter-based smoothing and the power ramp rate limit approaches because no wind power forecast is required. Among the PDSs, only min-max dispatching method leads to the ESS performing the deep charge-discharge cycle, which may prolong the ESS operational lifetime. Therefore, for enhancement of ESS lifetime, we should utilize the min-max dispatching method. One prospective trend in smart-grid concept is the communication between TSO and WF owner to dispatch a scheduled power; therefore, the min-max and constant power dispatching methods can satisfy this cooperative schedule.

5. Conclusion

In this paper, we evaluated several power dispatching strategies for hybrid wind and energy storage system in order to figure out the advantageous features of each strategy. The power dispatching strategies are classified into three control groups including the smoothing-based control, the constant power dispatching method, and the power ramp-rate limit. Based on comparative analysis, the wind farm planners could select a suitable power dispatching control method for their own system to satisfy the technical requirements. For example, the low-pass-filter-based smoothing control or the ramp-rate limit method can be selected in case that it is hard to forecast the wind power and needs a quite low ESS capacity. And, if the system requires the communication with the TSO and prolonging ESS operational lifetime, the min-max method can be selected. It is noted that the averaged method has two competitive features such as the ability to communicate with TSO and the lowest ESS capacity; therefore, this method is recommended to apply widely in real wind energy conversion system.

Fig. 7. Comparison of power rating with four PDSs in accordance with four seasons.

Fig. 8. Comparison of energy rating with four PDSs in accordance with four seasons.

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Table 1. The summary of comparative analysis with different power dispatching strategies

<table>
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<tr>
<th>Method</th>
<th>ESS Power Rating (p.u.)</th>
<th>ESS Energy Rating (p.u.)</th>
<th>Require Wind Power Forecast</th>
<th>Cooperation with TSO</th>
<th>Deep Charge-Discharge Cycles of ESS</th>
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<tr>
<td>LPF-Based Method</td>
<td>0.62</td>
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<td>Averaged Method</td>
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<tr>
<td>Min-max Method</td>
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<tr>
<td>Ramp-Rate Method</td>
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References