Control Strategy of Wind Turbine Generator with Storage in Short-term Dispatch Scheme

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Abstract— With growth in wind generation penetration it is imperative to investigate means of ensuring wind farm dispatchability so as to ensure reliability of power supply in future. Battery energy storage system (BESS) is widely considered as a potential solution. This paper presents an easily implementable online approach to adaptively establish best possible reference values for wind farm power dispatch. The approach takes into account the available wind speed forecasts and available state of charge in BESS in each dispatch interval. The proposed approach is validated using real wind farm data and evaluated using multiple simulation case studies to gauge the effects of practical factors such as forecasting errors and variations in BESS state of charge.

Keywords—Storage; dispatchability; wind generation

I. INTRODUCTION

Wind energy is one of the renewable energy sources that is completely free of greenhouse gas emission. The overall cost of wind generation shows an ongoing gradual reduction [1]. Nevertheless, despite growth in wind generation penetration, dispatchability continues to be a challenge and, if not addressed adequately, can pose a major obstacle in the reliable de-carbonization of electricity networks. That is, it may become necessary to treat wind farms as scheduled as opposed to semi-scheduled. Wind turbine generators (WTGs) equipped with Battery Energy Storage System (BESS) is one of the potential solution to the large-scale wind power integration problem so as to ensure that the actual power dispatch, $P_{\text{dis}}$, follows the pre-defined dispatch reference, $P_{\text{dis}}^{\text{ref}}$. In modern electricity markets, the scheduled generators usually need to submit the volume of electricity and price for the bidding process a day or so in advance. Generators are allowed to revise their bids at least $T$ hours before the dispatch time whereby $T$ commonly reflects the dispatch horizon [2-3]. The best possible use of BESS relies on the careful determination of $P_{\text{dis}}^{\text{ref}}$ every $T$ hours. The challenge here is to periodically determine best possible fixed values of $P_{\text{dis}}^{\text{ref}}$ while taking into account the wind forecasts and available BESS state of charge. It is essential to ensure the BESS is capable to compensate the excursion of WTG output power from $P_{\text{dis}}^{\text{ref}}$ during the dispatch time. The existing approaches include by averaging the forecasted wind power, $P_{\text{wind}}$ as in [4] but they tend to be detrimental for BESS lifetime when BESS is required to frequently change between charging and discharging mode. This will produce shallow-depth charge-discharge cycles called “micro-cycles” as the direction of BESS current rapidly change between positive and negative. Other approaches include min-max of the $P_{\text{wind}}$ such as suggested in [2], [5] and [6]. This approach is proposed to drive BESS to operate under full-depth charge-discharge cycles hence the switching between modes is reduced which could prolong BESS lifetime [7]. However, in this approach, $P_{\text{dis}}^{\text{ref}}$ determination is only addressed to $P_{\text{wind}}$ without considering the BESS capacity. During the dispatch time, WTG-BESS controller then will play its role to follow this $P_{\text{dis}}^{\text{ref}}$ so that the power is dispatched to the grid as desired.

The purpose of this paper is to present an approach to periodically establish $P_{\text{dis}}^{\text{ref}}$ by keeping in view the available BESS capacity, forecast $P_{\text{wind}}$ and simultaneously encouraging that BESS is either fully charged or discharged at the end of a given dispatch period. In addition, a controller is developed which coordinates the WTG and BESS to ensure the tracking of $P_{\text{dis}}^{\text{ref}}$ for every dispatch interval. The controller is specifically designed for the full operational range of a Doubly-Fed Induction Generator (DFIG)-based WTG with integration of BESS within the rotor-side PWM. The performance of the proposed control scheme is evaluated via several simulation studies.

This paper is organized as follows: In section II system description is presented. The dispatch scheme for WTG-BESS is discussed in Section III. In section IV control structure is developed. Simulation and discussion are given in section V. Finally, conclusion is presented in section VI.

II. SYSTEM DESCRIPTION

A. Wind Turbine Model

The WTG considered in this paper is the DFIG type. The full specifications are given in Table 1. The mathematical model used for the control system development is based on [8], and comprises of mechanical and electrical models.
(a) **Mechanical dynamics:** The mechanical rotational dynamics of a WTG are governed by the following equation:

\[ J \frac{d\omega_r}{dt} = \frac{1}{2} (T_{\text{mech}} - D\omega_r - T_{\text{elec}}) \]  

where \( J \) defines the inertia, \( D \) is the viscous damping, \( \omega_r \) is the rotor speed, \( T_{\text{mech}} = P_{\text{mech}}/\omega_r \) is the mechanical torque and \( T_{\text{elec}} \) is the generator electromagnetic torque. \( P_{\text{mech}} \) refers to the mechanical power given by [9]

\[ P_{\text{mech}} = \frac{1}{2} \rho R^2 \omega^3 \eta_p(\theta, \lambda) \]  

Here \( \rho \) denotes the air density, \( R \) is the rotor radius, \( V_m \) is the wind speed, \( \eta_p \) is the turbine power coefficient (refer [8] for the details of \( \eta_p \) function). \( P_{\text{wind}} \) can be forecasted using (2) where it is controlled through rotor speed to achieve the maximum \( C_p \) [10].

(b) **Electrical dynamics:** The electrical dynamics are modeled as follows:

\[ \frac{d}{dt} \begin{bmatrix} V_{qs} \\ V_{qs} \\ \phi \\ \phi \\ I_{\phi} \\ I_{\phi} \end{bmatrix} = \begin{bmatrix} (MV_{ds} - L_s V_{dr}) + (M \omega \phi_{qs} - L_s (\omega - \omega_r) \phi_{qr}) \\ + (L_s R_s i_{dr} - M R_s i_{qs}) \\ (MV_{dq} - L_s V_{dq}) - (L_r \omega \phi_{ds} - M (\omega - \omega_r) \phi_{dr}) \\ + (L_r R_s i_{rq} - M R_s i_{qs}) \\ (MV_{qr} - L_s V_{qr}) + (L_r \omega \phi_{ds} - M L_s (\omega - \omega_r) \phi_{dr}) \\ + (L_r R_s i_{rq} - M R_s i_{qs}) \end{bmatrix} \]  

where \( i = [i_{dr}, i_{ds}, i_{qr}, i_{qs}]^T \), \( \omega = (M^2 - L_s L_q)/2\pi \), \( \phi_{ds} = L_s i_{qs} + M i_{dr} \), \( \phi_{dq} = L_s i_{qs} + M i_{dr} \), \( \phi_{dr} = L_s i_{qs} + M i_{dr} \), \( \phi_{qr} = L_s i_{qs} + M i_{dr} \), \( V \) is the voltage, \( i \) is the current, \( \omega \) is the synchronous, \( \phi \) is the flux, \( R \) is the resistance, \( L \) is the inductance and \( M \) is the mutual inductance while all the components with subscript \( s \) and \( r \) refer to the stator and rotor components respectively. \( T_{\text{elec}} = \phi_{qr} i_{dr} - \phi_{dr} i_{qr} = \phi_{ds} i_{qs} - \phi_{qs} i_{ds} \) is given to (1).

(c) **Dispatch power:** The total output power delivered to grid can be expressed as

\[ P_{\text{dis}} = T_{\text{elec}} \omega_r + P_{\text{batt}} \]  

where \( P_{\text{batt}} \) is the power supplied by BESS.

**B. Battery Energy Storage System Model**

BESS State-of-charge, \( (SOC) \) at time \( t \) can be estimated using coulomb counting method such as follows:

\[ SOC_t = SOC_0 + \eta_{\text{eff}} \int_{t_0}^{t} \frac{I_{\text{batt}}}{Q_{\text{batt}}} \]  

where \( SOC_0, \eta_{\text{eff}} \) and \( I_{\text{batt}} \) refer to the \( SOC \) initial value, coulombic efficiency and battery current respectively. Considering a BESS with specific rated power, \( P_{\text{batt(rated)}} \) that could supply for \( T_{\text{batt}} \) hour of duration has been installed. In view of that, its capacity, \( Q_{\text{batt}} \) can be represented as

\[ Q_{\text{batt}} = I_{\text{batt(rated)}} \times T_{\text{batt}} \]  

where the rated battery current, \( I_{\text{batt(rated)}} \) is obtained from \( P_{\text{batt(rated)}} / V_{\text{dc(rated)}} \) in which \( V_{\text{dc(rated)}} \) denotes the rated DC bus voltage and assumed to be 1 p.u.

**III. Dispatch scheme for wind turbine generator with BESS**

The proposed dispatch scheme is illustrated in Fig. 1. The overall control structure comprises of Time-Frame 1 and Time-Frame 2 to separately take into account the pre-dispatch reference calculations and the real-time tracking of the committed dispatch. In Time-Frame 1, an optimization algorithm is run to determine the \( I_{\text{dis(ref)}} \). \( P_{\text{dis(ref)}} \) is calculated periodically every \( T \) time intervals (set by the corresponding electricity market design and rules) and depends on multiple factors including the accuracy of available forecast \( P_{\text{wind}} \), which is at the heart of the optimization algorithm (as demonstrated in the next section). In the present study, it is assumed the WTG does enjoy priority in power selling where the whole power is sold.

In Time-Frame 2, \( P_{\text{dis(ref)}} \) is passed on to the WTG’s local controller as the desired set-point. Although a single WTG is considered in this paper, the concept is applicable to a wind farm (comprising of multiple WTGs) whereby the BESS management is organized through a centralized controller. In the wind farm, each WTG will experience a difference wind speed due to surrounding geography or wake effects from the other turbines. Therefore, different dispatch power, \( P_{\text{dis}} \) is expected from different WTG.

**IV. Control Structure**

**A. Time-Frame 1: Determination of Dispatch Reference**

An algorithm is developed to choose an optimum \( P_{\text{dis(ref)}} \) at each dispatch horizon, \( T \), while taking into account the BESS capacity constraints and the available forecasted wind power. In order to formulate the optimization problem, the following objective function is defined:

![Diagram of WTG-BESS dispatch scheme](image_url)
\[ F(P_{\text{wind},j}, P_{\text{ref},j}, T) = \sum_{j=1}^{n}(P_{\text{wind},j} - P_{\text{ref},j}) \]  \hspace{1cm} (7)

where \( P_{\text{wind},j} - P_{\text{ref},j} = P_{\text{batt},j} \). The objective function \( F(.) \) is to be optimized (maximized or minimized) subject to the following technical constraints:

\[ p_{\text{ref}}^{\text{(min)}} \leq p_{\text{ref}}^{\text{dis}} \leq p_{\text{ref}}^{\text{(max)}} \]  \hspace{1cm} (8)
\[ F(P_{\text{wind},j}, P_{\text{ref},j}, T) \geq 0 \hspace{0.5cm} \text{for max} \]  \hspace{1cm} (9)
\[ F(P_{\text{wind},j}, P_{\text{ref},j}, T) \leq 0 \hspace{0.5cm} \text{for min} \]  \hspace{1cm} (10)
\[ \Delta t_{\text{batt}}^{(\text{min})} \leq \Delta t_{\text{batt}}^{j} \leq \Delta t_{\text{batt}}^{(\text{max})} \]  \hspace{1cm} (11)
\[ \partial \text{SOC}^{(\text{min})} + \text{SOC}^{(\text{min})} \leq \text{SOC} \leq \text{SOC}^{(\text{max})} \]  \hspace{1cm} (12)

where superscript of \text{min} and \text{max} represent the minimum and maximum constraints. While \( \partial \text{SOC}^{(\cdot)} \) describes the uncertainty in the required \text{SOC} levels and is governed by the wind speed forecast errors. \( p_{\text{ref}}^{\text{dis}} \) boundaries are set at full range of power that could be generated by the WTG from cut-in to cut-out wind speeds.

For each dispatch horizon, our objective is to find a fixed value of \( p_{\text{ref}}^{\text{dis}} \) for the whole dispatch horizon, \( T \) while ensuring the BESS technical constraints are satisfied. Accordingly, depending upon the current \text{SOC} value, the objective function \( F(.) \) may be subject to minimization or maximization. The details of the algorithm are summarized in the flowchart presented in Fig. 2.

From the implementation point of view, the algorithm may be initialized as either a minimization or a maximization problem. Then, the current Status is maintained as long as the constraints are satisfied. Any potential violation in constraints switches the status from min to max and vice versa.

\[ u(t) = K_{p}e(t) + K_{i}\int e(t)dt \]  \hspace{1cm} (13)

where \( e = \omega_{d} - \omega_{m} \), \( u = [V_{dr}, V_{qr}, \theta]^{T} \) and \( K_{p} \) and \( K_{i} \) denote the coefficients for the proportional and integral terms respectively. The magnitudes of \( K_{p} \) and \( K_{i} \) are determined by using system model (1)-(3) and frequency domain analysis for appropriate stability, robustness and performance guarantees. It may be noted that any errors in wind speed forecasts eventually translate to errors in actual and forecast power outputs. Such mismatches are accounted for through \( \partial \text{SOC}^{(\cdot)} \) term included in the \text{SOC} constraints as per (12).

V. CASE-STUDIES AND SIMULATION RESULTS

The approach presented in the preceding sections is implemented on the 2 MW wind turbine with specifications as per Table 1. Consistent with Australian Energy Market Operator (AEMO) market clearing interval for simulations the dispatch horizon is chosen as \( T = \frac{1}{2} \) hour. The BESS

![Figure 2. Computational procedure to update reference dispatch power in Time-Frame 1](image)
simulation parameters are summarized in Table 2. Simulations are based on a real wind speed dataset obtained from an existing Australian wind farm. Wind speed forecast error is chosen as ±10% to account for the worst case error for ½ hour forecasts which is considered as short horizon [7].

**TABLE I. WIND TURBINE PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J$</td>
<td>4.5207 s</td>
</tr>
<tr>
<td>Gear ratio, $n_g$</td>
<td>84.15</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.0049 pu</td>
</tr>
<tr>
<td>$R_r$</td>
<td>0.0055 pu</td>
</tr>
<tr>
<td>$L_m$</td>
<td>3.9530 pu</td>
</tr>
<tr>
<td>$L_s$</td>
<td>4.0454 pu</td>
</tr>
<tr>
<td>$L_{rr}$</td>
<td>4.0525 pu</td>
</tr>
<tr>
<td>Rotor radius, $R$</td>
<td>37.5 m</td>
</tr>
</tbody>
</table>

**TABLE II. BATTERY PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Soc_0$</td>
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</tr>
<tr>
<td>$\eta_{ef}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$[Soc_{(min)}, Soc_{(max)}]$</td>
<td>[0.2, 1] pu</td>
</tr>
<tr>
<td>$[\Delta J_{batt}^{(min)}, \Delta J_{batt}^{(max)}]$</td>
<td>[−0.5, 0.5] pu</td>
</tr>
<tr>
<td>$[\delta Soc_{(min)}, \delta Soc_{(max)}]$</td>
<td>[−0.1, 0.1] pu</td>
</tr>
</tbody>
</table>

Figure 3. Actual wind speed versus forecasted wind speed

A. Determination of Dispatch Reference

Using the approach presented in section IV-A, $P_{dis}^{ref}$ is calculated for wind speed data given in Fig. 3. The $P_{dis}^{ref}$ response thus obtained is given in Fig. 4. For comparison $P_{dis}^{ref}$ is also determined using an existing approach of average wind power method [4] (Fig. 5). Three different $T_{batt,1,2,3} = 0.25, 0.5, 1$ hour are tested to observe the effect of BESS sizes in deciding $P_{dis}^{ref}$.

It is clear from Fig. 4 and Fig. 5, that the existing method determines $P_{dis}^{ref}$ independent of the available $SOC$ capacity and, therefore, delivers conservative $P_{dis}^{ref}$ commands. The main idea of this method is to minimize the usage of BESS energy. On the other hand, the $P_{dis}^{ref}$ determined using the proposed method is capable of adaptively adjusting its value based on the variations in $SOC$ magnitudes. This is evident from Fig. 4 whereby the commanded $P_{dis}^{ref}$ frequently changes the values to actively take the $SOC$ magnitude into account and, therefore, better utilizes the available BESS resource. It is indicated in the figure that BESS attains a smooth and nearly full charge-discharge cycle. As a result the number of rapid charging-discharging micro-cycles are successfully reduced to approximately 43 – 58.3 % as compared to the average method. As can be seen, there are three possible scenarios those can be experienced by the BESS during each interval. It is either charged, discharged or both. For example as shown in Fig. 4 during 510 – 570 minutes of simulation time where BESS with $T_{batt}$ is charged and discharged according to the commanded $P_{dis}^{ref}$. Note that it is happening in the charging cycle. Instead of choosing the minimum $P_{wind}$ as proposed in [2], [5], [6], the volume of $P_{dis}^{ref}$ is reduced to satisfy the $SOC$ upper limit. It proves that this method is more tolerable.

B. WTG-BESS Short-term Dispatch

To evaluate the effect of forecast error and tracking of the commanded $P_{dis}^{ref}$ two case studies are considered, namely, Case 1 and Case 2 for without and wind forecasting error respectively. BESS with $P_{batt(rated)} = 0.5$ p.u. and $T_{batt} = 1$ hour is used. The simulation results corresponding to Case 1
are given in Fig. 6-8. It is clear demonstrated that by the combined action of WTG and active BESS management accurate tracking of $P_{\text{dis}}^{\text{ref}}$ is achieved.

On the other hand, in Case 2 in presence of forecast error (randomly generated within $\pm 10\%$ from the real wind speed time-series data shown in Fig. 3), although accurate tracking is obtained, however, there is greater deviation between the actual and forecast SOC profile. The simulation results for Case 2 are presented in Fig. 9-11. Clearly, with increasing forecasting error it is critical to have greater margin for adjustment in the SOC response.
This paper proposes a control strategy of WTG with BESS to improve the dispatchability of short-term dispatch scheme. This study is demonstrated to a single WTG to represent a wind farm. A new algorithm is suggested to optimally determine the reference dispatch power. In this algorithm the reference power is scheduled suitably subjects to BESS constraints and encourages a full charge-discharge cycles. The outcomes show that this algorithm could extend the BESS lifetime and also more tolerable than the existing approaches. The performance of WTG-BESS controller is evaluated to follow the reference power in two cases; with and without error of wind speed forecast. In the simulation, WTG PI-based controller shows an effective regulation of the turbine to follow the desired rotor speed. The excursion of WTG output power to the reference power due to wind intermittency has been successfully compensated by BESS while the constraints are satisfied. As a conclusion, the proposed strategy has performed well and achieved the objectives.

VI. CONCLUSION

This paper proposes a control strategy of WTG with BESS to improve the dispatchability of short-term dispatch scheme. This study is demonstrated to a single WTG to represent a wind farm. A new algorithm is suggested to optimally determine the reference dispatch power. In this algorithm the reference power is scheduled suitably subjects to BESS constraints and encourages a full charge-discharge cycles. The outcomes show that this algorithm could extend the BESS lifetime and also more tolerable than the existing approaches. The performance of WTG-BESS controller is evaluated to follow the reference power in two cases; with and without error of wind speed forecast. In the simulation, WTG PI-based controller shows an effective regulation of the turbine to follow the desired rotor speed. The excursion of WTG output power to the reference power due to wind intermittency has been successfully compensated by BESS while the constraints are satisfied. As a conclusion, the proposed strategy has performed well and achieved the objectives.

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