Optimal Short-term Power Dispatch Scheduling for a Wind Farm with Battery Energy Storage System

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Abstract: The penetration of renewable energy is increasing rapidly in recent years due to the environmental concerns. The intermittent nature of renewable energy makes the dispatch of the grid a major challenge. Hence, there are many restrictions stipulated for the integration of the renewable energy. The development of battery energy storage systems (BESS) enables the renewable generation with flexible operation and to meet the requirements of the grid. In this paper, an optimal power dispatch scheduling method based on model predictive control (MPC) scheme is proposed for a wind farm with battery energy storage system. The objective of the proposed method is to minimize the energy loss of the wind farm and the battery usage while meeting the grid constraints. During the operation process, the information of wind farm output and battery state is updated continuously and short-term power dispatch is scheduled by wind speed forecast within the optimal horizon. The proposed optimization problem is solved by a differential evolution (DE) algorithm at each time interval. Finally, the novel short-term wind power dispatch scheme is demonstrated in a 30MW wind farm test case with historic wind speed data.

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Keywords: Battery energy storage system (BESS), Wind farm, Dispatch scheduling, Differential evolution (DE)

1. INTRODUCTION

Economic and environmental concerns are encouraging the application of renewable energy technologies. The growing demand speeds up the development of renewable energy, especially wind power and solar energy. In recent years, the technology for wind power has become more mature and the penetration is increasing around the world. However, the intermittent nature of wind power will affect the operation of the grid as more connected wind farms are integrated in the system (Ortega-Vazquez et al., 2010), (Karki et al., 2012), (Parvania et al., 2013), (Xie et al., 2011), (Liu et al., 2012). In this situation, supplementary measures and operation strategies should be studied and apply to enhance the dispatch ability of the wind farms in order to meet the grid requirements.

Energy storage is a fast developing field and makes high renewable integration possible. The energy can be stored in an energy storage system to offset the fluctuation of the wind farm output to some extent. There are various energy storage technologies, such as supercapacitors, superconducting magnetic energy storage, flywheels, batteries and hydro-pumped storage (Teleke et al., 2009). Battery energy storage system (BESS) is the most cost-effective one for the wind farm operation. The value of BESS in wind power integration is described and verified by projects – see Tewari et al.(2013). Many researchers have also proposed methods for the BESS application in wind power dispatch problem. In (Ghofrani et al., 2013) and (Li et al., 2011) the placement or capacity of energy storage in the system is optimized to minimize the social cost. A dual-battery scheme is proposed in (Yao et al., 2012) for short-term wind power dispatch. Khatamianfar et al., (2013) proposed an improved dispatch scheme for a wind farm with BESS to make more profit in the Australian electricity market. A hybrid energy storage coordination method is proposed for smoothing wind output in (Jiang et al., 2013a). A two-time-scale control strategy is proposed in (Jiang et al., 2013b) to mitigate wind power fluctuations.

These above mentioned research proposed a strategy for coordinating wind farm and BESS to dispatch wind power. The targets are various in different scenarios. In China, the integration of wind farms should follow the specific grid code including power change limit as Table 1. To meet this requirement and make the integration of wind power more
feasible and economic, a BESS based wind farm dispatch scheme is proposed in this paper. The operation schedule of a wind farm is affected by the accuracy of the forecast. In this paper, leading forecasting software OptiWind is used (OptiSeries Manual, 2009). The short-term operation schedule is made according to updated information by using a model predictive control (MPC) strategy (Khatamianfar et al., 2013), (Xu et al., 2012). In this way, the online optimization is implemented in a receding horizon and the future actions can be optimized. During each time horizon, the optimal wind farm dispatch is acquired with respect to the updated system state and the forecast information. The proposed objective function for each power scheduling is a continuous nonlinear and non-convex programming problem, which is difficult to be solved by conventional mathematical programming methods. In recent years, heuristic optimization techniques have shown satisfactory performance in solving such problems (Meng et al., 2010a) (Meng et al., 2010b) (Su et al., 2011). In this paper, a differential evolution (DE) algorithm is used for solving the proposed optimization problem. DE is fast, simple, and appropriate to solve the dispatch model.

Table 1. Power change limit of wind farm

| Capacity of wind farm | Maximum power change within 10 min (MW) | Maximum power change within 1 min (MW) |
|-----------------------|----------------------------------------|---------------------------------------|
| <30                   | 10                                     | 3                                     |
| 30–150               | Capacity/3                             | Capacity/10                           |
| >150                  | 50                                     | 15                                    |

This paper is organized as follows. After the introduction section, a BESS based wind farm operation model is presented, followed by the detailed overview of prediction methodologies. And then, the explicit model of BESS and corresponding MPC-based dispatch strategy is proposed to meet the grid requirements and minimize the operation cost. After that, the proposed short-term wind farm dispatch scheduling scheme is verified on a test system, and the minimum operation cost of wind farm is quantified. Conclusions and further developments are discussed in the last section.

2. OPERATION MODEL OF WIND FARM WITH BESS

2.1 Operation framework of wind farm with BESS

The basic investigated system is a grid-connected wind farm with a BESS. The schematic of this system is shown as Fig.1. The power output of the wind generator and battery are injected into the grid through converters at the common coupling point. The total wind farm output is expressed as equation (1). The BESS is applied to smooth the fluctuation of wind farm output. To achieve this target, the control system generates the reference charging power signal for the battery and pitch angle signal for the wind machine, respectively. The reference signals are calculated according to the forecast information and the status of the system. This algorithm will be introduced in the paper.

$$P_{\text{total}}^t = P_{\text{Wind}}^t + P_{\text{BESS}}^t$$  \hspace{1cm} (1)

Where, $P_{\text{total}}^t$, $P_{\text{Wind}}^t$, and $P_{\text{BESS}}^t$ are the power output of wind farm, wind machine and the BESS, respectively.

Fig.1 Schematic of the grid-connected wind farm with BESS

2.2 Forecast toolbox

Wind speed forecasting plays a key role in the operation of a wind farm power dispatching. It is a basic task to facilitate renewable penetrations (Sideratos et al., 2007) (Bhaskar et al., 2012). The forecasting software, OptiWind, is used for wind speed forecasting in this paper. Several important factors considered in the forecasting model include temperature, seasonal weather, public holidays, and historical load data. OptiWind incorporates highly customized numerical weather prediction models and the latest statistical methods. The mean absolute percentage error (MAPE) is used to assess the forecast accuracy:

$$MAPE = \frac{1}{N_A} \sum_{p=1}^{N_A} \left| \frac{P_p - \overline{P}_p}{P_p} \right| \times 100\%$$  \hspace{1cm} (2)

where, $N_A$ is the sampling quantity; $P_p$ is the actual wind speed; and $\overline{P}_p$ is the forecasted wind speed. The curves of forecast wind speed and the actual speed within the time horizon are compared in Fig.2.

Fig.2 Wind speed forecasting curve

Wind power output strongly depends on the wind speed. The
real wind power is controlled through rotor speed by the maximum power point tracking (MPPT) method. Meanwhile, the pitch angle of the blade can be controlled to adjust the output of wind machine. The wind turbine output will start when the wind speed reaches the lower threshold and will be cut off under high wind speed.

2.3 Battery charging issues

Suitable capacity storage of energy and charging at the appropriate time can help to smooth the output of the wind farm and to maintain system balancing. In the following study, battery operation issues are addressed for better utilization of BESS in the wind farm. Table 2 compares the parameters of Lithium-Ion battery and Lead-Acid battery (Khaligh et al., 2010). These two types of batteries are considered in this paper.

| Item          | Li-Ion Battery | Lead-Acid Battery |
|---------------|----------------|-------------------|
| Energy Density| 250 Wh/kg      | 30 Wh/kg          |
| Power Density | 500 W/kg       | 30 W/kg           |
| Life Cycle    | 1500 times     | 1000 times        |
| Self-discharge| 2% per month   | 3% per month      |
| Reliability   | Medium         | High              |
| Investment cost CI ($) | 300000E_r   | 80000E_r         |

The energy charging of BESS, the key issue for a battery operation strategy, can be described as,

\[ E_{\text{BEFF}}^{t+1} = E_{\text{BEFF}}^t + \Delta t \cdot P_{\text{BEFF}}^{t} - \Delta t \cdot E_{\text{BEFF}}^t \cdot \eta_c - \Delta t \cdot E_{\text{BEFF}}^t \cdot \eta_l \cdot \Delta t \]  
\[ (3) \]

The state-of-charge (SOC) is expressed as follows,

\[ SOC^t = E_{\text{BEFF}}^t / E_{\text{BEFF}}^t \]  
\[ (4) \]

And the operation of BESS is constrained as follows,

Power limits:  
\[ P_{\text{BEFF}}^{\text{Dis,Max}} \leq P_{\text{BEFF}}^t \leq P_{\text{BEFF}}^{\text{Chg,Max}} \]  
\[ (5) \]

SOC limits:  
\[ SOC_{\text{Min}}^{t} \leq SOC^t \leq SOC_{\text{Max}}^{t} \]  
\[ (6) \]

where, \( E_{\text{BEFF}}^t \) and \( E_{\text{BEFF}}^t \) are the energy stored in the BESS at time t and the rated energy capacity of the BESS. \( SOC^t, SOC_{\text{Max}}^{t}, SOC_{\text{Min}}^{t} \), \( \eta_c \) and \( \eta_l \) are the charging loss and leakage loss factors of BESS.

2.4 MPC-based dispatch scheme

With the framework of a wind farm and the forecasted wind speed, the MPC strategy is proposed to pursue the optimal wind power dispatch. Within the MPC-based dispatch scheme, a finite time horizon and time interval is decided first. Before a dispatch step, the optimization process is performed to generate a series power dispatch plan in this time horizon. After the first action of the optimal plan, we update the system information with actual data and repeat the optimization for next step with the fixed time horizon. In this paper, detailed steps of the MPC-based dispatch scheduling are implemented as shown in Fig.3.

![Fig.3 Schematic of MPC-based dispatch scheduling step](image)

3. OPTIMIZATION PROBLEM

Based on the framework of MPC-based wind farm power dispatch scheduling, the reference signal is send to BESS and wind turbines to adjust total output of the wind farm. During each step, the optimal series of reference signals are generated for the whole time horizon. After each time interval, this optimization problem is resolved with updated information for next time horizon.

In this part, this optimization problem is introduced. Given the forecasted wind speed and the configuration of the battery, the optimal dispatch schedule aims to control the charging/discharging currents of the battery and pitch angle of wind machine over the dispatch horizon. The whole objective of the wind farm dispatch is to minimize the sum of the following three aspects of the operation cost:

- The profit loss incurred by cutting off the wind power;
- The operation cost of the battery due to charging or discharging process;
- Penalty cost incurred by violating the ramp rate constraint.

3.1 Objective function

The objective function of the wind farm dispatch model is expressed as follows:

\[ f = \min \left( \sum_{t=1}^{T} (C_{\text{bw}}^t + C_{\text{ESS}}^t + C_{\text{penalty}}^t) \right) \]  
\[ (7) \]
where $C'_{tot}$ is the cost of wind power curtailed at time $t$; $C'_{pen}$ is the cost of decrease of battery lifetime at time $t$; $C'_{pen}$ is the penalty cost by violating the ramp rate constraint at time $t$. Detailed cost function of $C'_{tot}$, $C'_{pen}$, and $C'_{pen}$ are expressed as Eqs. (8) - (10):

$$C'_{tot} = \begin{cases} 0, & \text{if } |P'_{total} - P'_{total}| \leq P_{ramp} \\ P_{violate} \cdot (P'_{total} - P'_{total}) \cdot \Delta t, & \text{else} \end{cases}$$ (8)

$$C'_{pen} = \beta \cdot P_{pen} \cdot \Delta t + \beta \cdot E_{BESS} \cdot \eta \cdot \Delta t$$ (9)

$$C'_{pen} = \begin{cases} 0, & \text{if } P'_{wind} = P'_{wind_{max}} \\ \delta \cdot (P'_{wind_{max} - P'_{wind}}) \cdot \Delta t, & \text{else} \end{cases}$$ (10)

where $P'_{BESS} > 0$ indicates the battery is discharging, and $P'_{BESS} < 0$ indicates the battery is charging. $P_{ramp}$ is the ramping Power limit of wind farm. $\beta$ is the cost coefficient of the battery lifetime decrease. $\delta$ is the penalty coefficient of violating the ramp power constraint. It should be noted that the battery cost is calculated by the total energy usage. According to the impact of discharge rate on battery life in (Fortune CP, 2010), the total energy usage of the battery remains stable with the determined depth of discharge (DOD), e.g. 70%. Base on this conclusion, the $\beta$ can be calculated as,

$$\beta = \frac{CI}{E_{r} \cdot \text{(Life Cycle)}}$$ (11)

where, CI is the investment cost of BESS.

3.2 Constraints

The dispatch model is constrained by following constraints.

1. Battery constraint

The battery constraints are show as equations (5) (6); Battery rated power capacity constraint,

2. Wind turbine constraint

The wind turbine is operated under appropriate wind speed.

3. Power Limit

Reverse power flow is not allowed in this paper.

$$P'_{total} \geq 0$$ (14)

4. SOLUTION TO THE DISPATCH MODEL

The proposed dispatch scheduling model above is a continuous, nonlinear, constrained programming problem which cannot be solved by classical deterministic integer programming techniques. In this paper, a differential evolution algorithm is adopted to solve the problem.

The solution to the model is represented as a vector, called coding. The output power of BESS and blade angle of wind turbine can be coded in a vector. In this paper, each vector is a matrix with fixed-size $2A$ where $A$ is the number of operation steps within the time horizon. The coding rules are shown in Fig.4.

Fig. 4. Coding rules of the DE solution method

During the process of calculating the fitness, the benefits part of the objective function is affected by the charging power of BESS and blade angle of wind machine. The flow chart is showed as Fig.5.

Fig. 5. Flow chart of solution program

5. SIMULATION RESULTS

The proposed methodology has been tested on a 30 MW wind farm simulation. The benefit of optimal BESS control scheme is calculated. After the simulation, we compare the operation cost of the proposed optimal dispatch strategy with the wind farm without BESS.

Table 3. General Parameters of test system

| Item                      | Value     |
|---------------------------|-----------|
| Wind energy price $p$     | 0.05$/\text{MWh}$ |
| $v_{\text{start}}$ / $v_{\text{cut}}$ | $4\text{m/s} / 25\text{m/s}$ |
| $\Delta t$               | 10 mins   |
In the study, a 30MW wind farm is constructed with BESS. The detail parameters are shown below. The ramp limit is adjusted to make the output of the wind farm smoother.

Fig.6. shows the expected wind farm output and penalty cost caused by the ramp rate violation without dispatch scheduling in a sample day.

![Fig. 6. Wind power and penalty cost of wind farm for one day.](image)

Fig. 6. Wind power and penalty cost of wind farm for one day.

Based on a reference scenario, we perform the proposed wind farm dispatch scheduling method. During the first step, the optimal dispatch plan is set for the time horizon. The charging power and wind output percentage are optimized for minimum total operation cost. During this horizon, the total forecast penalty cost is minimized and the optimal dispatch scheme is acquired. After the time interval, the new optimization problem is implemented with updated information. Based on this time horizon receding method, we calculate the scheduling for a whole day and draw the dispatch curve as Fig. 7.

![Fig. 7. Wind farm output comparison through a day.](image)

Fig. 7. Wind farm output comparison through a day.

From the output curve, the proposed dispatch scheme, the output of the wind farm is smoother and better integrated into the grid. The operation cost of the wind farm is shown in the following table.

| Item (a sample day) | Without BESS | With Proposed Dispatch Scheme |
|---------------------|--------------|-------------------------------|
| Penalty Cost($)     | 5737         | 0                             |
| BESS Operation Cost | 0            | 1863.6                        |
| Wind Cutting Loss   | 0            | 466.43                        |
| Total Cost          | 5737         | 2330.03                       |

A full dispatch plan is performed using a wind forecast. We use historic wind speed data for simulation. The forecast is done 4 hours in advance. The continuous operation plan and system state of a week is shown in the following figures. Fig. 9 is the SOC curve of BESS through a week. The wind farm output with proposed dispatch scheme is compared with the original wind power in Fig. 10. The detail operation cost of the wind farm per day is shown in Fig.11. Total cost of the wind farm through a week is listed and compared in Table 5. From the table, the total saving through a week is $21263 which is 38.35% of original cost. The results show that the proposed method can increase the benefits from the wind farm and mitigate the risk of grid connected wind energy.

![Fig. 8. Charging power and state of BESS](image)

Fig. 8. Charging power and state of BESS

![Fig. 9. Wind farm output comparison through a week.](image)

Fig. 9. Wind farm output comparison through a week.

| Item (a week) | Without BESS | With Proposed Dispatch Scheme |
|--------------|--------------|-------------------------------|
| Penalty Cost($) | 55446 | 4388                      |
| BESS Operation Cost | 0 | 19094                    |
| Wind Cutting Loss | 0 | 10791                    |
| Total Cost   | 55446        | 34183                       |
This paper proposes an optimal short-term wind farm dispatch model and efficient method with BESS for better integration of wind energy. The effectiveness of the proposed method has been tested with wind farm case studies, which demonstrate that the optimal plan of charging and discharging processes and wind energy shedding can help reduce the fast intermittency and high fluctuation of wind power to meet the grid requirements. From the case study results, the wind farm operator can make benefits through optimal dispatch planning. The ramping rate violation is decreased significantly. With the widespread use of the BESS in the wind farm, the system reserve generation can also be reduced. Along with the battery technology development and the introduction of more stimulus policies, the costs of battery and related ancillary facilities will decrease, which makes the proposal of BESS and corresponding dispatch methods more feasible and beneficial.

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