

Day-ahead Coordinated Operation of a Wind-Storage System Considering Wind Forecast Uncertainty

Nhi Thi Ai Nguyen

Faculty of Electrical Engineering
The University of Danang - University of Science and
Technology
Danang, Vietnam
ntanhi@dut.udn.vn

Dinh Duong Le

Faculty of Electrical Engineering
The University of Danang - University of Science and
Technology
Danang, Vietnam
ldduong@dut.udn.vn

Abstract-This paper proposes an optimal operation for coordinated Battery Energy Storage (BES) and wind generation in a day-ahead market under wind uncertainty. A comprehensive AC Optimal Power Flow (AC OPF) model was established to incorporate wind and storage into a power system. To take into account wind forecast uncertainty, preprocessing technique, time series model, and fast forward selection method were applied for scenario generation and reduction processes. Tests were performed on a modified IEEE 14-bus system and the results show that the use of BESs is an alternative to guarantee a more efficient and flexible operation of wind power plants.

Keywords-AC OPF; Battery Energy Storage (BES); operation; wind; uncertainty

I. INTRODUCTION

Wind energy has gained considerable interest globally during the last decades due to the increased environment concern. The overall capacity of wind turbines installed worldwide by the end of 2019 reached 650.8GW, according to statistics by the World Wind Energy Association (WWEA). In 2019, 59,667MW were added, substantially more than the 50,252MW of 2018. The sum of the wind turbines installed by the end of 2019 can cover more than 6% of global electricity demand [1]. Unfortunately, wind power output is well documented for its variable and non-dispatchable nature. The output of a wind turbine depends on wind speed, which varies daily and seasonally. Thus, the high penetration level of wind generation brings new challenges to the power system. From the operational aspect, it is essential to find a solution regarding the provision of controllability to wind generation, improving power quality of grid-connected wind farms and hence, facilitating higher wind installation capacity. Energy storage systems (ESSs) can be an economically favorable option to mitigate the variability of renewable generation. ESSs can be used by system operators for reliability improvement, ancillary services, and transmission congestion relief [2-4]. For wind power producers, ESSs are utilized in capacity firming and energy time shifting [5]. In electricity markets, storage systems can take advantage of price difference and gain profits for wind power plant using energy arbitrage. Wind power output is usually high during night-time and low at daytime, whereas electricity demand and price are usually low at night and get

higher during daytime. If wind energy is stored during low-price periods and is discharged back to the supply load at high-price periods, higher profit can be obtained. Energy storage can benefit by providing other services to the grid, but energy arbitrage is by far the largest business opportunity. The co-operation strategy of a wind-storage system is substantially important in achieving optimal tradeoff between operation cost and profit. This operation problem is challenging due to the stochastic behavior of wind power output.

The issue of coupling operation of wind and storage has been extensively studied with regard to operation and planning aspects [6-13]. Authors in [9] presented a dynamic programming algorithm employed to determine optimal energy exchange with the market for a specified scheduling period, taking into account transmission constraints. In [10], research was conducted to analyze the possibility of coupling wind and storage systems for time-shifting application, reducing grid congestions and making renewables more controllable on grid operator side. Authors in [11] investigate the problem of planning and operation of a combined wind-storage system. Specifically, a procedure is proposed, aiming to determine an hourly operation schedule of the combined system. In [12], a joint planning problem is established for transmission congestion and wind curtailment, including wind power installed capacity and location, transmission network expansion, and ESS locating and sizing. The problem was formulated into a linearized MILP model. An optimized output strategy of wind storage system is formulated in [13]. The storage is shown to effectively improve the efficiency of the wind farm while reducing wind power output fluctuations. There are many publications discussing the incorporation of an energy storage system in day-ahead market. In [14], a deterministic centralized unit commitment problem is proposed to optimally schedule storage operation in power systems with high wind penetration. Authors in [15] formulate an optimal joint bidding problem of wind hydro system under deterministic scenarios of wind generation, and illustrate its solution with a simple three-reservoir cascade. In addition to those deterministic formulations, wind uncertainty has also been dealt with, applying scenario-based stochastic programming [16-20]. Authors in [16] present a stochastic unit commitment model with energy storage and obtained a reduced

Corresponding author: Dinh Duong Le

system constraint violation in the N-1 analysis. Authors in [17] adopt a scenario-based stochastic unit commitment model to address uncertainties of renewables and demands in evaluating the reserves provided by ESSs and generators. The problem is solved using the progressive hedging algorithm with heuristic approaches. In [18], a stochastic unit commitment model with ESS and wind for system scheduling at day-ahead and real-time stages is proposed. A stochastic unit commitment model is presented in [19] for optimal energy and reserve bids in systems with high wind penetration. In [20], a stochastic battery arbitrage model for day-ahead and real-time prices is proposed. Authors in [21] formulated a robust unit commitment model with pumped hydro storage units. This approach models the randomness using an uncertainty set to protect the system against worst- case scenarios.

Most previous studies explored the value of storage systems with wind generation in day-ahead market, either using deterministic models [11, 14, 15, 22-23] or focusing on price uncertainties [24-26]. However, with the increasing level of wind energy integration, the variable nature of wind should be examined in any optimization model. Therefore, in this paper, we establish a day-ahead optimal dispatch model of wind-storage system while taking into account wind power uncertainties. This is implemented by formulating an AC OPF model with BES and wind integration and applying wind uncertainty modeling techniques, including preprocessing technique, time series model, and fast forward selection method. The model focuses on the use of BES to time-shift wind energy to higher price periods, i.e. arbitrage, which is a particularly important service that energy storage systems can provide in day-ahead energy markets. This model is an effective tool for wind farm operators to determine the optimal day-ahead operating strategies of wind-storage systems under wind uncertainties. Extensive tests were performed on a modified IEEE 14-bus system.

II. WIND UNCERTAINTY MODELING

In this section an approach to capture wind uncertainty is presented. Combined preprocessing technique and time series analysis are used to build a model representing the uncertainty associated with wind speed. Taken as an example, three-year measured hourly wind speed values of a real wind farm (rated at 85MW) in Italy, are used. Wind speed is usually not stationary with distinct diurnal and seasonal patterns [27] while a time series model such as Auto-Regressive Moving Average (ARMA) requires stationary data. To handle this issue, we adopt preprocessing techniques [27]. After that we make use of the process described in detail in [28] to build the ARMA model for the obtained stationary data. By sampling from the resulting time series model, the set of 10,000 hourly wind speed scenarios for day-ahead operation is generated as in Figure 1. Equal probability is assigned to each scenario of the set. To capture the uncertainty, a large number of scenarios should be generated, leading to increased complexity and computational burden. In this research, the fast forward selection approach [29] was used to select a limited number of representative scenarios for the set. Figure 2 depicts 10 selected wind speed scenarios. For determining an optimal operation for coordinated BES and wind generation in a day-ahead market,

wind power data are necessary. For this purpose, an aggregate power curve for the entire wind farm is needed to map wind speed scenarios into wind power scenarios. In this paper, we make use of the method of bins [27, 30, 31] using wind power-wind speed pairs at the wind farm to obtain the aggregate power curve as in Figure 3. Using the power curve, 10 representative wind power scenarios are obtained from 10 representative wind speed scenarios as shown in Figure 4.

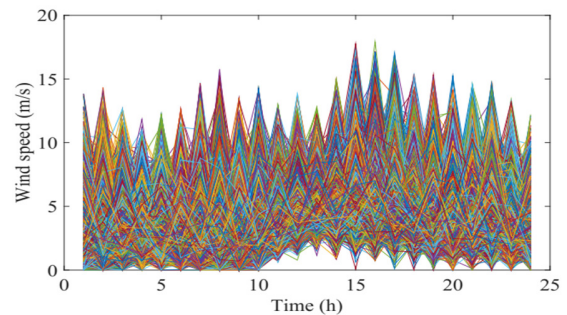


Fig. 1. Wind speed scenarios.

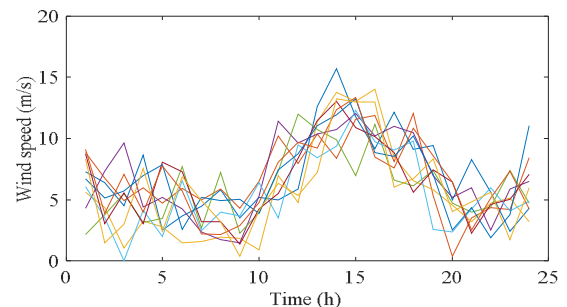


Fig. 2. Representative wind speed scenarios.

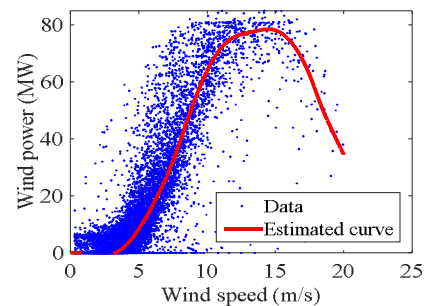


Fig. 3. Estimated power curve.

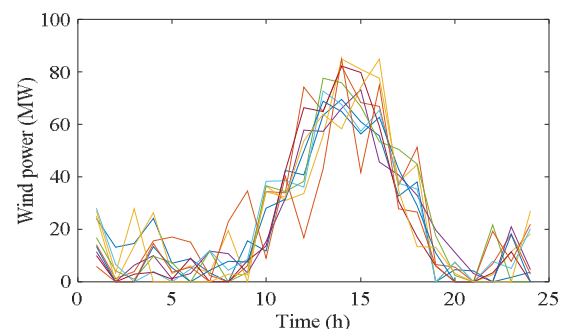


Fig. 4. Representative wind power scenarios.

III. THE AC OPF MODEL

A. Objective Function

The problem is formulated into an AC OPF model with an optimization goal of minimizing total system operating cost, which includes generating cost of all generating units and BES operation cost.

$$\text{Min } \sum_{t=1}^T \sum_{i=1}^{NG} (c_{0,i} + c_{1,i}P_{G,i}(t) + c_{2,i}[P_{G,i}(t)]^2) + \sum_{t=1}^T \sum_{j=1}^{NS} (c_{d,j}P_{d,j}(t) - c_{ch,j}P_{ch,j}(t)) \quad (1)$$

where $P_{G,i}(t)$ is real power generating at bus i and period t , $P_{ch,j}(t)$ is the charging power of BES at bus i and period t , $P_{d,j}(t)$ is the discharging power of BES at bus i and period t , $c_{0,i}$; $c_{1,i}$; $c_{2,i}$ are the cost coefficients of generating unit at bus i , $c_{ch,j}$; $c_{d,j}$ are the cost coefficients for charging and discharging power of BES at bus j , NG is the number of generating units, NS the number of BESSs, and T is the optimization time horizon.

B. System Constraints

The objective function must fulfill the following network constraints:

- Power balance:

$$P_{G,i}(t) - P_{L,i}(t) + P_{d,i}(t) - P_{ch,i}(t) = V_i(t) \sum_{k=1}^{NB} V_k(t) \{G_{ik} \cos[\theta_i(t) - \theta_k(t)] + B_{ik} \sin[\theta_i(t) - \theta_k(t)]\} \quad (2)$$

$$Q_{G,i}(t) - Q_{L,i}(t) + Q_{d,i}(t) - Q_{ch,i}(t) = V_i(t) \sum_{k=1}^{NB} V_k(t) \{G_{ik} \sin[\theta_i(t) - \theta_k(t)] + B_{ik} \cos[\theta_i(t) - \theta_k(t)]\} \quad (3)$$

where $Q_{G,i}(t)$ is the reactive power generating at bus i and period t , $P_{L,i}(t)$ is the real load power at bus i and period t , $Q_{L,i}(t)$ is the reactive load power at bus i and period t , $Q_{d,i}(t)$ is the reactive discharging power of BES bus i and period t , $Q_{ch,i}(t)$ is the reactive charging power of BES at bus i and period t , $V_i(t)$ is the magnitude of voltage at bus i and period t , $V_k(t)$ the magnitude of voltage at bus k and period t , $\theta_i(t)$ the angle of voltage at bus i and period t , $\theta_k(t)$ the angle of voltage at bus k , period t , G_{ik} the line conductance of branch ik , B_{ik} the line susceptance of branch ik , and NB the total system bus number.

- Voltage magnitude limits:

$$V_{i,min} \leq V_i(t) \leq V_{i,max} \quad (4)$$

where $V_{i,min}$ is the lower limit and $V_{i,max}$ is the upper limit for voltage bus i .

- Generator power limits:

$$P_{G,i-min} \leq P_{G,i}(t) \leq P_{G,i-max} \quad (5)$$

$$Q_{G,i-min} \leq Q_{G,i}(t) \leq Q_{G,i-max} \quad (6)$$

where $P_{G,i-min}$, $P_{G,i-max}$ are the active and $Q_{G,i-min}$, $Q_{G,i-max}$ the reactive generating power limits.

- Branch current limits:

$$I_{ij}(t) \leq I_{ij,max} \quad (7)$$

$$I_{ji}(t) \leq I_{ji,max} \quad (8)$$

where $I_{ij}(t)$ is the magnitude of current flowing from i to j , in period t , $I_{ji}(t)$ the magnitude of current flowing from bus j to bus i , in period t , and $I_{ij,max}$, $I_{ji,max}$ the current limits.

C. BES Constraints

- Energy balance:

$$B_i(t) = B_{i-1}(t) + (\eta_{ch}P_{ch,i}(t) - P_{d,i}(t)/\eta_d)\Delta t \quad (9)$$

where $B_i(t)$ is the energy level of BES at bus i in period t , $B_{i-1}(t)$ the energy level of BES at bus i in period $t - 1$, η_{ch} the charging efficiency, η_d the discharging efficiency, and Δt the time interval between two consecutive periods.

- Charging/discharging power limits:

$$P_{d,i-min} \leq P_{d,i}(t) \leq R_{i,max} \quad (10)$$

$$P_{ch,i-min} \leq P_{ch,i}(t) \leq R_{i,max} \quad (11)$$

where $R_{i,max}$ is the power rating of BES at bus i and $P_{ch,i-min}$, $P_{d,i-min}$ the minimum charging/discharging power of BES at bus i .

- ESS energy limits:

$$B_{i,min} \leq B_i(t) \leq B_{i,max} \quad (12)$$

where $B_{i,min}$ is the minimum energy limit of BES at bus i and $B_{i,max}$ the energy rating of BES at bus i .

IV. THE PROPOSED APPROACH

The overall procedure for the proposed approach is described in Figure 5, where N_s is the number of representative wind power scenarios. According to this procedure, wind data are first preprocessed to create wind power scenarios. These wind scenarios and load data will be the input of the AC OPF model which optimizes the operation of wind-storage systems. The model is run for all wind scenarios and the obtained results will be the optimal dispatching schedules for the systems.

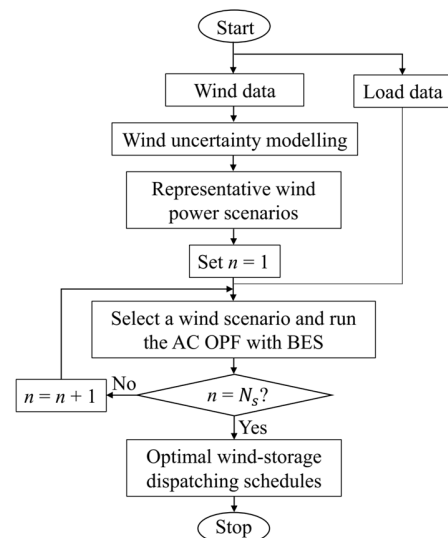


Fig. 5. Overall procedure of the proposed approach.

V. TESTS AND RESULTS

In this section, a case study is carried out on a modified IEEE 14-bus network (Figure 6), with a wind-storage system located at bus 6. The BES is used for energy arbitrage. It is charged from both wind and conventional sources during low price periods and discharged at peak price hours. The wind farm has an installed capacity of 85MW, accounting for 40% wind penetration level. There are 4 conventional generators, at buses 1, 2, 3, and 8, with total capacity of 292.4MW. The typical load per day, with peak value of 212MW, is calculated through statistical average data. Wind scenarios are generated as described in Section II. The optimization horizon is 24h. Simulations are performed for both deterministic and scenario-based cases, using Matlab 2016a, on a PC with Intel Core i7 – 3.4GHz CPU and 8.0GB of memory. First, a base case is run with BES parameters as shown in Table I and wind penetration level of 40% to obtain optimal day-ahead operating schedules of the wind-storage system. Then, in order to show the effect of wind uncertainties on optimization results, sensitivity analysis is performed on BES capacities with different wind penetration levels in both deterministic and scenario-based cases. The energy arbitrage profits of the system are also calculated for all wind penetration levels.

TABLE I. BES PARAMETERS

R_{max} [MW]	B_{max} [MWh]	η_{ch}	η_d
80	200	0.85	0.85

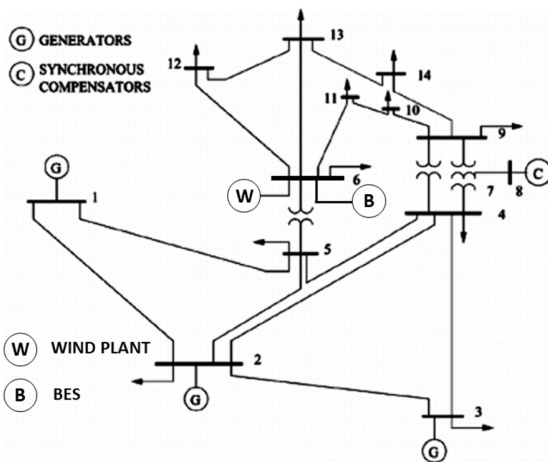


Fig. 6. The modified IEEE 14-bus system.

As a result, the optimal output of wind - storage system in a typical day can be observed in Figure 7. As can be seen in this Figure, the available wind generation in a single day is negatively correlated to the market price. However, with the use of BES, the actual wind-storage system output is made to positively follow market prices. Accordingly, less power is generated during low-price hours (from 12 to 16), instead, more power is generated at peak-price periods (hours 7, 8 and 18 to 21). Figure 8 presents the storage system operation. As can be seen, the BES has a large possibility of charging during valley hours to store more power and transfer that to peak hours for energy arbitrage. This operation effectively follows system market prices.

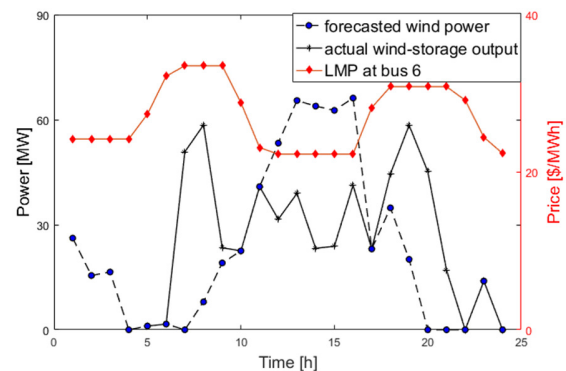


Fig. 7. The output of wind-storage system in a typical day.

The optimal day-ahead power dispatches of BES in deterministic and scenario-based cases are shown in Figure 9. This figure shows that BES operation follows the market price trend in all wind scenarios, thus effectively supports wind generation.

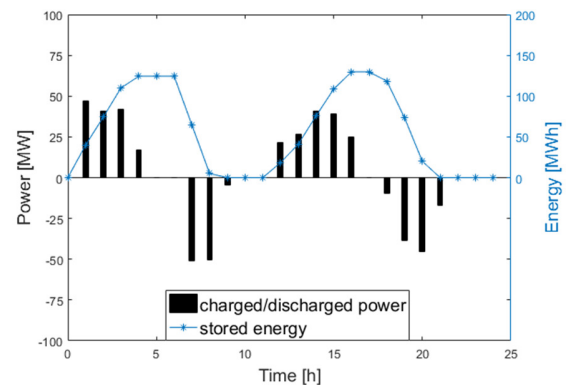


Fig. 8. BES operation.

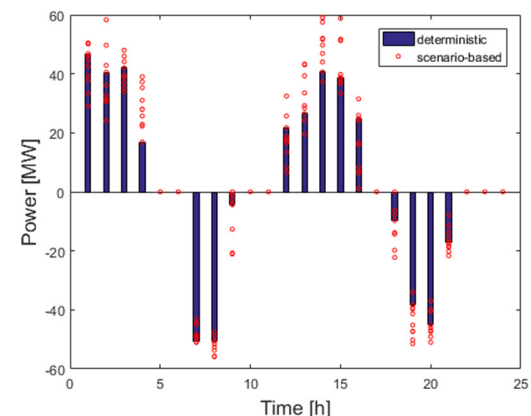


Fig. 9. BES optimal day-ahead power dispatch.

In order to see the impact of wind uncertainty on storage capacities, sensitivity analysis was performed. Wind penetration level varied from 20% to 50% and the rest was kept to the same level as in the base case. Deterministic and scenario-based models were run. The simulation results are shown in Figure 10. It is seen that wind uncertainty has a high impact on BES capacities. For example, at 40% wind

penetration level, a BES capacity of approximately 45MW and 130MWh is required for the deterministic case while a BES capacity of about 59MW and 150MWh is found in the scenario-based case. Besides, wind penetration level leads to increasing BES capacities. Table II shows the energy arbitrage profit of wind-storage system at different wind penetration levels, with and without BES. This Table shows the obvious benefit of using energy storage systems along with a wind farm for energy arbitrage. In addition, considerably higher profits are gained for the wind-storage system with higher wind penetration levels.

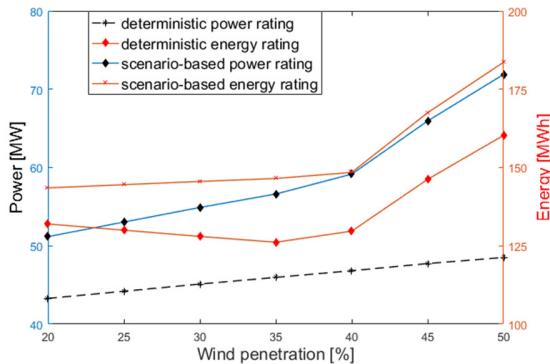


Fig. 10. BES capacities.

TABLE II. WIND-STORAGE SYSTEM ENERGY ARBITRAGE PROFIT [\$]

Wind penetration [%]	20	25	30	35	40	45	50
no BES	7.14 x 10 ³	8.75 x 10 ³	1.028 x 10 ⁴	1.056 x 10 ⁴	1.058 x 10 ⁴	1.028 x 10 ⁴	7.68 x 10 ³
with BES	7.24 x 10 ³	8.95 x 10 ³	1.064 x 10 ⁴	1.215 x 10 ⁴	1.362 x 10 ⁴	1.517 x 10 ⁴	1.644 x 10 ⁴

VI. CONCLUSIONS

In this paper, a model was developed to simulate the BES operation for energy arbitrage in power systems with high wind integration. The problem was formulated into an AC OPF model. Wind uncertainty was taken into account by applying generation and reduction techniques. Tests were carried out on a modified IEEE 14-bus system and day-ahead optimal operation schedule for wind-storage system was obtained. The simulation results show that the use of BES with wind generation can significantly improve profit for wind farm operators, especially at high wind penetration level. Furthermore, when considering wind uncertainty, higher capacities of BES are noted for the system as compared with deterministic cases, which means wind uncertainty should be examined in any optimization model with wind penetration.

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