Mitigation of Wind Output Curtailment by Coordinating with Pumped Storage and Increasing Transmission Capacity

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***Abstract*—Integrating additional wind energy into the existing power system may cause wind curtailment due to the system operational constraints and reliability requirements. Effective ways to mitigate this problem are to use energy storage or increase transmission capacity. In this paper, the impacts of coordinating with pumped storage and increasing transmission capacity on wind output curtailment mitigation are analyzed by formulating a mixed integer linear programming problem. A detailed operational model of a pumped storage plant along with other system operational constraints are developed to study the wind curtailment problem. Simulation results in the modified IEEE 30 bus system show that wind curtailment can be significantly decreased by adding pumped storage into the power system or by increasing transmission capacity.**

***Index Terms*—Wind energy, wind curtailment, pumped storage, power system, optimization.**

I. INTRODUCTION

As wind power capacity is increasing rapidly around the world, it has been expected to make up a large part of renewable generation in recent years. However, due to the stochastic and unpredictable nature of wind energy as well as the system stability and reliability requirements, large part of wind generation need to be curtailed [1], [2]. Wind curtailment has already become the principal issue toward higher penetration of renewable energy, which will not only affect the existing wind projects but also impede the future development of wind energy. Therefore, a detailed consideration of wind curtailment problem is needed.

Many factors could induce wind curtailment according to the previous studies. The lack of transmission capacity has been the principal factor in areas where wind penetration level is high, as wind power cannot be exported to other balancing areas [3], [4]. Also, for system reliability and stability reasons, reserve requirements increase significantly comparing to the conventional power systems [5]. This will become a major problem when off-peak hours coincide with high wind generation, which would lead to high curtailment of wind energy. Other factors such as financial and regulatory mechanisms may also affect the overall wind curtailment [6], [7].

A variety of approaches have been developed to deal with the wind curtailment issues, among which transmission enforcement is a direct method to be considered [8], though it will be expensive and time-consuming to expand the existing transmission network [9]. In addition to this method, using energy storage resources is an alternative option. Energy storage can reduce wind curtailment by storing otherwise curtailed wind energy and releasing them when the system can absorb [10]. Among all forms of energy storage which have been developed, pumped storage has been one of the most promising options to reduce wind curtailment, due to the relatively low cost and large capacity [11].

Previous researches on using energy storage for reducing wind curtailment have mainly focused on the cost benefit perspective, usually with general energy storage model [12], [13]. However, each kind of energy storage technology has significant differences on operational characteristics from others, more targeted investigations should be carried out. As for pumped storage, which is the most widely utilized form of energy storage, there are some particular operational requirements such as discrete pumping power [14]. This paper presents an optimization problem on wind curtailment emphasizing on the detailed pumped storage plant model, and investigates the optimal scheduling of pumped storage units when they are coordinated with wind farms in the power system networks. The transmission capacity limits are also considered in the optimization model in order to reflect the contribution of increasing the transmission capacity to wind curtailment mitigation.

The necessary of considering operational characteristics of pumped storage in wind curtailment studies is that pumped storage can deal with different situations, in which wind curtailment may occur, with different operation status. Also, some operational constraints, which are typical on pumped storage, may restrict it from reducing wind curtailment further. By implementing more feasible pumped storage models, investigations on wind curtailment will be more practical.

The operational characteristics and details of pumped storage model as well as related system constraints which

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form the common basis for this study are outlined in Section II. In Section III, a case study with the modified IEEE 30 bus system is conducted to analyze the existing wind curtailment and verify the effects of coordinating with pumped storage as well as increasing the transmission capacity on mitigating wind curtailment. Conclusions and future work are addressed Section IV.

II. Problem Formulation

Most of the existing wind curtailment studies use energy storage as the energy shifting tool and concern few about the operational characteristics. In this section, typical constraints on pumped storage operation are described first, and then simplified network and thermal generators model are proposed. Based on these, wind curtailment problem is formulated. Finally, these models are adopted into the power system scheduling simulation.

This problem is formulated as a mixed integer linear programing problem. The objective function (1) is set to minimize the overall wind curtailment. Operation costs of each kind of generation units are not considered in the objective function, therefore the system will always absorb as much wind power when there is wind available.

$$Minimize \sum_{t \in T} \sum_{w \in W} WC_{w,t} \tag{1}$$

where $WC_{w,t}$ is the wind curtailment of wind farm w at time t.

There are a number of equality and inequality constraints which should be taken into account by the model while minimizing the overall wind curtailment. These constraints are described separately as follows:

A. Pumped Storge Model

The pumped storage plant model is represented by a reservoir, along with inefficiencies associated reversible pumped storage units. The units can be either in generating or pumping mode, with both very short start-up time and modes transformation time. The following mathematical expressions of pumped storage units can be employed to perform the optimization.

$$P_{k,j}^{HGmin} x_{k,j,t} \le P_{k,j,t}^{g} \le P_{k,j}^{HGmax} x_{k,j,t} \tag{2}$$

$$P_{k,j}^{HPmin} y_{k,j,t} \le P_{k,j,t}^{p} \le P_{k,j}^{HPmax} y_{k,j,t} \tag{3}$$

$$x_{k,j,t} + y_{k,j,t} \le 1 \tag{4}$$

$$\sum_{j \in N_k} x_{k,j,t} \le N_k \delta_{k,t}^{g} \tag{5}$$

$$\sum_{j \in N_k} y_{k,j,t} \le N_k \delta_{k,t}^{p} \tag{6}$$

$$\delta_{k,t}^{g} + \delta_{k,t}^{p} \le 1 \tag{7}$$

$$E_k^{min} \le E_{k,t} \le E_k^{max} \tag{8}$$

$$E_{k,0} - E_{k,24} = 0 \tag{9}$$

$$E_{k,t+1} = E_{k,t} + \Delta T \cdot \eta_p \cdot \sum_{k \in K} \sum_{j \in N_k} P_{k,j,t}^{g} - \Delta T \cdot \sum_{k \in K} \sum_{j \in N_k} P_{k,j,t}^{p} \Big/ \eta_g \tag{10}$$

where $P_{k,j,t}^{g}$ and $P_{k,j,t}^{p}$ represent the generation and pumping power of pumped storage unit j in the k^{th} plant; $P_{k,j}^{HGmin}$ and $P_{k,j}^{HGmax}$ are the lower and upper bounds of generating power, while $P_{k,j}^{HPmin}$ and $P_{k,j}^{HPmax}$ are the pumping power bounds of the unit; $x_{k,j,t}$ and $y_{k,j,t}$ are binary variables indicating the on/off status of generating and pumping mode; N_k is the number of unit in the k^{th} plant; $\delta_{k,t}^{g}$ and $\delta_{k,t}^{p}$ are binary variables indicating the operation mode of the k^{th} plant; $E_{k,t}$ represents the amount of energy stored in the reservoir of k^{th} plant at time t; E_k^{min} and E_k^{max} are minimum and maximum energy to be stored in the reservoir; η_g and η_p are the efficiency in generating and pumping mode of pumped storage units; ΔT is the length of time interval.

Constraints (2)-(3) represent the generating and pumping power limits of each pumped storage unit, and constraints (4) means that the two operation modes of each pumped storage unit are exclusive at the same time. By setting the minimum and maximum pumping power to the same value, pumped storage units will operate in discrete pumping power. With constraints (5)-(7), the total number of units that can function as turbines or pumps in each plant is decided. These three constraints will also ensure the coincidence of operation mode of each unit in the same plant [15]. The storing energy limit and balance in the reservoir are described in constraints (8)-(10). Time interval in this model is one hour and cycling period of pumped storage is one day as shown in constraint (9). As pumped storage units usually have very high ramping rates, this constraint is not considered in the model.

Operation of pumped storage is optimized as part of the unit commitment and dispatch process to ensure it is used to reduce the total wind curtailment. Other energy storage forms may be modelled similarly, but specific characteristics of these energy storage types are needed to be taken into account.

B. Network and Thermal Generators Model

Apply the detailed and precision model of whole power system to investigate wind curtailment is a very computational task. Simplified models are, therefore used to make the wind curtailment studies tractable so that specific factors such as transmission capacity limits, generation and ramping rate limits of thermal generators can be highlighted. The network and thermal generators model are described as follows:

$$P_i^{Gmin} u_{i,t} \le P_{i,t} \le P_i^{Gmax} u_{i,t} \tag{11}$$

$$P_{i,t} - P_{i,t-1} \le R_i^{max} \cdot u_{i,t-1} + P_i^{Gmin} \cdot (u_{i,t} - u_{i,t-1}) \tag{12}$$

$$P_{i,t} - P_{i,t-1} \geq R_i^{min} \cdot u_{i,t} - P_i^{Gmin} \cdot (u_{i,t-1} - u_{i,t}) \tag{13}$$

$$\sum_{t' \in [t, t+UT_i - 1]} u_{i,t'} \geq UT_i \cdot \upsilon_{i,t} \tag{14}$$

$$\sum_{t' \in [t, t+DT_i - 1]} (1 - u_{i,t'}) \geq DT_i \cdot w_{i,t} \tag{15}$$

$$u_{i,t} - u_{i,t-1} = \upsilon_{i,t} - \omega_{i,t} \tag{16}$$

$$u_{i,t} + w_{i,t} \leq 1 \tag{17}$$

$$0 \leq WC_{w,t} \leq WP_{w,t} \tag{18}$$

$$-PL_l^{max} \leq PL_{l,t} \leq PL_l^{max} \tag{19}$$

$$PL_{l,t} = (\theta_{m,t} - \theta_{n,t}) / X_{mn} \tag{20}$$

$$\sum_{i \in B_b} P_{i,t} + \sum_{k \in B_b} \sum_{j \in N_k} P_{k,j,t}^g + \sum_{k \in B_b} \sum_{j \in N_k} P_{k,j,t}^p + \sum_{w \in B_b} WP_{w,t} - \sum_{w \in B_b} WC_{w,t} = \sum_{d \in B_b} D_{d,t} \tag{21}$$

$$P_i^{Gmax} u_{i,t} + P_{k,j}^{HGmax} x_{k,j,t} - P_{k,j}^{HPmax} y_{k,j,t} + \sum_w WP_{w,t} - \sum_w WC_{w,t} \geq \sum_d D_{d,t} + SR_t \tag{22}$$

where $P_{i,t}$ is the generating power of the thermal generator i; P_i^{Gmin} and P_i^{Gmax} are the lower and upper bounds of generating power; $u_{i,t}$ is a binary variable indicating the on/off status of thermal generators; R_i^{min} and R_i^{max} are the ramp down and ramp up limits of generator i; UT_i and DT_i are the minimum up and down time of generator i; $\upsilon_{i,t}$ and $w_{i,t}$ are the start-up and shut-down indicators of generator i; $WP_{w,t}$ is the wind generation power of wind farm w; $PL_{l,t}$ is the power flow on transmission line l; PL_l^{max} is the capacity limit of transmission line l; $\theta_{m,t}$ and $\theta_{n,t}$ are the bus voltage angle on buses m and n; X_{mn} is the inductance of transmission line between buses m and n; $D_{d,t}$ represents the d^{th} load and B_b is the set of units which are connected to bus b; SR_t represents the spinning reserve requirements of the system at time t.

The operational constraints of thermal generating units include: (i) minimum and maximum output constraints (11); (ii) ramping rate constraints (12)-(13); (iii) minimum up (14) and down time (15) constraints; (iv) constraints between binary variables (16)-(17). Constraint (18) defines the range of wind curtailment that can be applied. In constraints (19)-(21), a lossless linear dc power flow is applied due to the simplified representation of transmission network used in this work. Power flows are calculated in (20), while power balance is described in constraint (21), which ensures the whole supply and demand, taking into account pumped storage and wind curtailment, are balanced at all time. Constraint (22) represents the spinning reserve requirements of the system.

With the model formulated above, the optimal operation of pumped storage units which would make wind curtailment to be the minimum amount is determined. With reasonable constraints considered in the pumped storage model, results that reflect the impact of pumped storage on wind curtailment are more valuable. With the power flow considered at the same time, investigations on how pumped storage can deal with the transmission congestion induced wind curtailment problem are also possible.

It should be noted that models implemented are used to examine the impact of pumped storage on wind curtailment, so more details are focus on pumped storage and factors which could possibly induce wind curtailment. These models can be modified for the application of different energy storage technologies and other perspective of studies in the future.

III. Case Study

In this section, a case study is conducted in order to apply the model developed in Section II. Amounts of wind curtailment with and without integrating pumped storage into the system are calculated and compared to evaluate the coordination of wind and pumped storage. Also, transmission congestion induced wind curtailment is verified by increasing the transmission capacity. All the results are obtained in MATLAB and Cplex using the MATLAB/Cplex interface.

A. Test System Description

For the case study, a modified IEEE 30 bus system is used to carry out the operation simulation. Configuration of the system is shown in Fig.1. The system includes two thermal generators, three wind farms and one pumped storage plant which contains two pumped storage units. The parameters of the two thermal generators are listed in Table I. Also, capacity limits are set to transmission lines connecting different areas, which is shown in Table II.

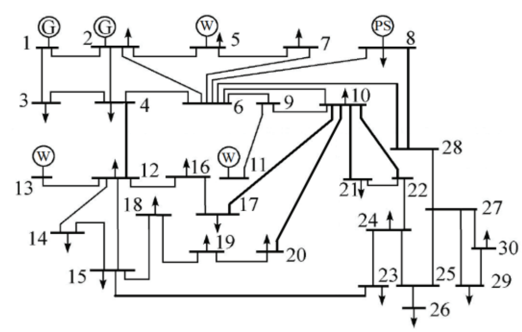

Figure 1. Modified IEEE 30-bus system

TABLE I
Parameters of Thermal Units

Bus No.	PGmax (MW)	PGmin (MW)	Ramp Rate (MW/h)
1	360	160	60
2	140	60	25

TABLE II

CAPACITY LIMIT OF TRANSMISSION LINES

From Bus	To Bus	Capacity Limit (MW)	Enlarged Capacity (MW)
4	12	60	75
10	20	20	25
10	17	20	25
10	21	30	37.5
10	22	20	25
6	28	40	50
15	23	20	25

The three wind farms added into the test system, named wind farm A (on node 5), B (on node 11), C (on node 13), have the same capacity of 50MW, while the two pumped storage units (on node 8) have the same capacity of 15MW. Pumping power of each unit is fixed to its rated capacity, which is 15MW, to guarantee the pumped storage units working in a discrete operation mode.

Time series data of wind and load based on real existing power system are used in the case study. Further information are detailed as follow:

1) *Wind Data:* Recorded historical wind data for a whole year with 5-min time resolution are collected from the BPA power system [16]. The average values of wind power for each hour are calculated and rescaled according to different capacity levels of wind farms positioned at various locations in the test system for the hourly simulation.

2) *Load Data:* Load data are also collected from the BPA power system and rescaled by peak load according to the portion of loads at different bus nodes in the test system in order to get the cycle properties of the system load.

Total amounts of rescaled wind power and load data for a whole year are shown in Fig.2.

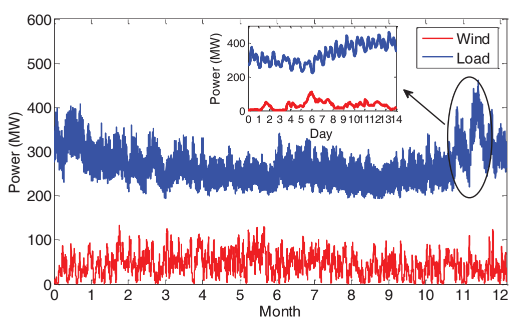

Figure 2. Wind and load profiles for the whole year

B. Coordinating With Pumped Storage

To fully study the impact of pumped storage on the level of wind curtailment, simulations of the test system are carried out with the model developed in Section II. Two weeks in December are selected for analysis as shown in the subfigure in Fig.2. During these two weeks, the load increases from a very low point to the highest point while wind power output drops from a high level (when the load is low) to a low level (when the load is high). This causes the most wind curtailment. Cycling period of the pumped storage plant is 24 hours, and simulation results are discussed as follows:

1) *Wind Curtailment:* During the two weeks, there is no wind curtailment except on the 6th day when a low load occurs during high wind periods. Fig.3 shows wind curtailment of the three wind farms on the 6th day of selected two weeks before and after integrating pumped storage on node 8 in the test system.Wind curtailment reduces by a significant level when wind farms operate in the presence of pumped storage. Specially, for wind farm C, wind curtailment reduces to zero during the whole day.

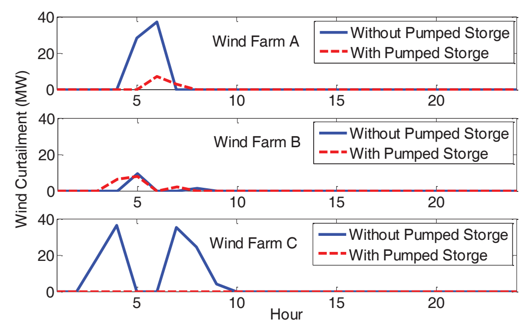

Figure 3. Wind curtailment in three wind farms for the 6th day in selected two weeks

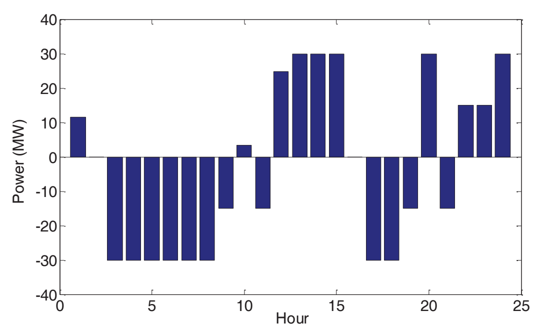

Figure 4. Pumped storage plant output for the 6th day in selected two weeks

2) *Pumped Storage Operation:* Generating and pumping power of the pumped storage plant are shown in Fig.4. Operation with discrete pumping power is obviously reflected as the pumping power either to be 15MW or 30MW, which means one or two units are operating in pumping mode. This operational charteristic of pumped storage unit limits its ability to match fast variations in wind power outputs.

Correlations between the operation patterns of pumped storage and wind curtailment are shown when comparing wind curtailment and pumped storage output. Energy storing, by means of pumping in this case, mostly occurs when wind curtailment arises. Other pumping time may happen as the pumped storage plant must keep the energy balance in the reservoir during each cycling period.

3) Whole Year Benefits: To further evaluate improvement made by pumped storage on wind curtailment mitigation, a whole year simulation with pumped storage is carried out. Simulation results in Fig.5 show that a significant reduction in wind curtailment after coordinating with pumped storage - from 8197MWh to 1053MWh.

On the other hand, for some specific time when wind curtailment is very high, pumped storage cannot mitigate it very well. During these time periods, other measures, like transmission capacity enhancement, may be considered to reduce the wind curtailment.

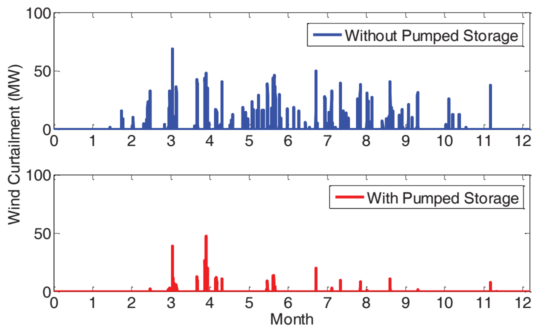

Figure 5. Wind curtailment for whole year simulation

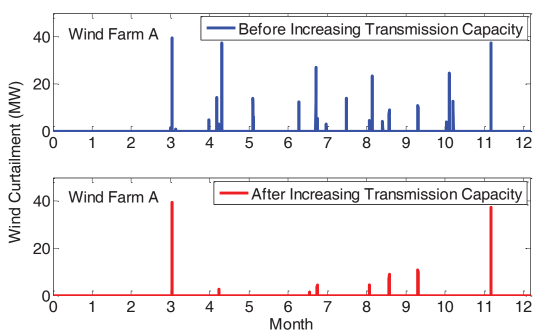

Figure 6. Wind curtailment in wind farm A before and after increasing the transmission capacity

C. Increasing Transmission Capcity

To verify that transmission capacity increase could reduce wind curtailment, simulations are carried out with increasing the transmission capacity by 25%. Increased transmission line capacities are shown in Table II, and Fig.6 shows the wind curtailment reduction in wind farm A after increasing the transmission capacity, which is from 580MWh to 236MWh. This result shows that increasing the transmission capacity can help to mitigate wind curtailment problem.

IV. Conclusion And Future Work

In this paper, the effects of pumped storage on wind curtailment mitigation have been illustrated by developing a wind and pumped storage coordinated operation model. Different operational characteristics of pumped storage units from other generic energy forms have been discussed in order to build a more practical pumped storage model. By taking the specific operational constraints of pumped storage units and other system constraints including the operational limits of thermal generators and transmission capacity limits into consideration, the wind curtailment optimization problem is formulated. A case study is carried out using the modified IEEE 30 bus test system to verify the proposed approach. Results show that wind curtailment would significantly decrease by coordinating with pumped storage in the power system or by increasing the transmission capacity.

There are many other factors including financial and regulatory mechanisms, frequency and voltage stability, which may also affect the overall wind curtailment level. Additional work is needed to take these factors into consideration to improve the model presented in this paper.

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