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Unit Commitment with Battery Energy Storage Considering Wind Forecast Error

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Abstract

The integration of wind resource into the electric grid brings significant challenges due to the variable nature and anti-peak-regulation characteristic of wind power. Based on least square method, an improved normal distribution model is proposed to fit the actual wind power forcast error. Furthermore, considering wind power forecast error and the great potential of battery energy storage system (BESS) technology to mitigate the impact of volatile wind power, a unit commitment (UC) model with large capacity BESS has been estanbished in this study. Case studies with modified IEEE 39-bus system are employed to validate the proposed method. The role of BESS on economics, peak load shifting and accommodating wind power is discussed.

***Keywords**: unit commitment, wind power, forecast error, battery energy storage system (BESS)*

1. Introduction

Wind power has grown significantly in China in recent years for environmental and sustainable purpose. Mainland China has added wind energy capacity 12960MW in 2012, up 20.8%, and the total wind energy capacity has reached 75324.2MW. In contrast to the rapid development of wind energy capacity, the accommodation of wind power is relatively limited. Due to the uncertainty characteristic of wind power, the power grid faces great challenges if large-scale wind generations are integrated. Besides, wind power has anti-peak-regulation characteristic, especially in winter, wind power has to be curtailed when conventional thermal power increases for heating system.

Energy storage system (ESS) is considered to be a good option to undertake the tasks of peak load shifting and support the wind power penetration. Considering that energy storage technologies can help the power system to accommodate more wind power, they have come to the attention of all the world [1]. Energy storage technology includes pumped hydro storage system, battery energy storage system (BESS), compressed air storage, flywheel, supercapacitor and so on. Among all feasible energy storage technologies, battery systems are the most widely used energy storage device [2, 3]. BESS technologies aim to transform electricity into chemical form of energy, which is stored and afterwards converted back to electricity, such as conventional batteries (Li-ion, Pb-Acid), high-temperature batteries (NaS, ZEBRA) and flow batteries (VRB, PSB, ZnBr). Comparing with pump hydro storage, BESS is more expensive. However, in some places where don't have water condition to build pump hydro system, large-scale BESS is a unnegligible alternative choice. There are already some successful applications of BESS in different countries such as Castle Valley America, King Island Australia and Shanghai China.

Some researches on power system techonologies with wind power and ESS have been carried out. A SCUC formation emphasizing on wind power and CAES is presented in [4]. Garcia-Gonzalez et al. [5] investigate the impact of pumped-storage on system with high wind penetration. Rodica Loisel [6] proposes a technical-economic assessment of a large-scale storage facility. In current power grid, BESS is usually utilized in small scale and combined with wind generations. In this case, this small-scale energy storage is considered dependent on wind unit and not modeled in unit commitment. This paper focuses on independent large capacity BESS which is suitable for places where are not possible to build pump hydro storage systems.

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This paper presents a unit commitment model considering large capacity BESS as it might become a development trend in the future.

The remainder of this paper is organized as follows: An improved wind forecast error model is proposed in Section 2. In Section 3, characteristics of BESS are analyzed and the establishment of unit commitment model considering wind power forecast error is introduced. Cases with 10 units and 100 units are studied and analyzed in Section 4. Section 5 draws the conclusions.

2. Improved Wind Forecast Error Model

In wind forecast error modeling research field, the normal distribution function is most commonly applied [7, 8]. The probability density function can be expressed as:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

Where μ is the expected value of wind forecast error x, σ is the standard deviation, it shows the degree of deviation from the expected value.

Figure 1 is a diagram of EIRGRID 2010.2~2010.11 wind power forecast error fitted by normal distribution. The values of errors are expressed as percentages of wind capacity. The model generally suits the actual values, however, within 0%~5% actual values are higher than normal density function value, while actual density values are lower within -10%~0% and 5%~20%. To a certain extent, this normal function exaggerates the wind power prediction error.

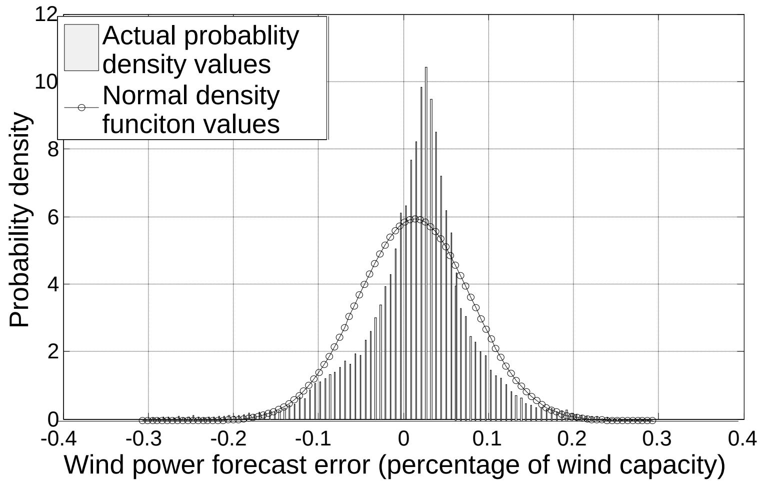

Figure 1. Diagram of Forecast Error Fitted by Normal Distribution (EIRGRID)

In order to improve the accuracy of normal distribution model, an improved density function is proposed:

$$g(x) = \frac{1}{\sqrt{2\pi}(\sigma / a)} e^{-\frac{(x-\mu)^2}{2(\sigma/a)^2}} (a > 0) \tag{2}$$

We can obtain the value of variable a to get a more suitable standard deviation by following next steps:

Step 1: Wind power forecast error standard deviation σ and expectation μ are calculated based on historic datas.

Step 2: The amount of actual errors beyond a certain boundary (such as $\pm 30\%$ in this case) is significantly small, so we can set boundary in this model. Assuming that maximum error is Ub and lower minimum error is Lb, and symmetrically $Ub = -Lb$, then we can divide the erros into $Tzone$ intervals:

$$[Lb, Lb + \frac{Ub - Lb}{Tzone}], (Lb + \frac{Ub - Lb}{Tzone}, Lb + 2 \times \frac{Ub - Lb}{Tzone}], \cdots, (Ub - \frac{Ub - Lb}{Tzone}, Ub]$$

Each error belongs to one of the intervals obtain a new value. The values in the $Tzone$ internals are:

$$Lb + \frac{1}{2} \times \frac{Ub - Lb}{Tzone}, Lb + \frac{3}{2} \times \frac{(Ub - Lb)}{Tzone}, \cdots, Ub - \frac{1}{2} \times \frac{Ub - Lb}{Tzone}$$

Step 3: The logarithmic form of the Equation (2):

$$\ln g(x) = \ln(\frac{a}{\sqrt{2\pi}\sigma}) - \frac{a^2}{2\sigma^2}(x - \mu)^2 \tag{3}$$

Assuming $Y = \ln g(x)$, $X = (x - \mu)^2$, $\tilde{B} = \ln(\frac{a}{\sqrt{2\pi}\sigma})$, $\tilde{A} = -\frac{a^2}{2\sigma^2}$, then $Y = \tilde{B} + \tilde{A}X$. Least square method can be used to obtain the value of $\tilde{A}$ and $\tilde{B}$. We use $\tilde{A}$ to identify the value of a as $\tilde{A}$ has higher reliability than $\tilde{B}$.

Step 4: Each $Tzone$ has a corresponding $g(x)$, we can select the best $Tzone$ by calculating the expression as follows:

$$Error_{g(x)}(Tzone) = \sum_{i=1}^{Tzone} \left| \frac{Tzone \times P_i}{Ub - Lb} - g(Lb + \frac{2i - 1}{2} \times \frac{Ub - Lb}{Tzone}) \right| \tag{4}$$

$$Error_{f(x)} = \sum_{i=1}^{Tzone} \left| \frac{Tzone \times P_i}{Ub - Lb} - f(Lb + \frac{2i - 1}{2} \times \frac{Ub - Lb}{Tzone}) \right| \tag{5}$$

$$ERR(Tzone) = \frac{Error_{f(x)} - Error_{g(x)}}{Error_{f(x)}} \times 100\% \tag{6}$$

Where P_i indicates the probability in interval $(Lb + (i-1) \times \frac{Ub - Lb}{Tzone}, Lb + i \times \frac{Ub - Lb}{Tzone}]$. The maximum $ERR(Tzone)$ indicates the best $Tzone$.

In EIRGRID case, $\mu = 0.0203$, $\sigma = 0.0667$. Following the above steps, we obtain $Tzone = 80$, $a = 1.265$, $Error_{g(x)}(Tzone) = 20.17\%$. The actual values, impoved and original curves are shown in Figure 2. The improved wind power forecast error curve is closer to the actual probability distribution than original model, which verifies the validity of proposed method.

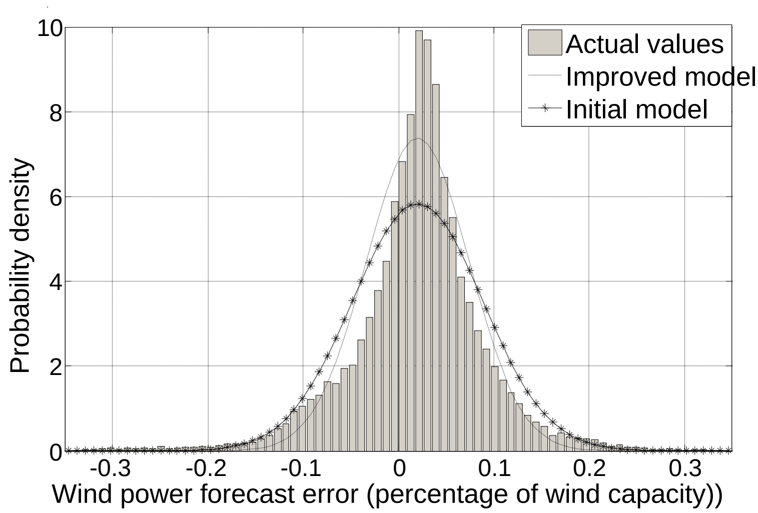

Figure 2. Forecast Error Fitted with Initial Normal Distribution and Improved Normal Distribution

3. UC Formation

The main UC model is formulated as an optimization problem that minimizes the objective function constrained by system requirement considering wind power forecast error.

(1) Objective Function

The objective function is expressed as follows:

$$\min\sum_{i=1}^{NG}\sum_{h=1}^{H}[F_{ci}(P_{i,h})I_{i,h}+SU_{i,h}]-M\sum_{m=1}^{W}\sum_{h=1}^{H}\left|q_{m,h}\right|+N\sum_{m=1}^{W}\sum_{h=1}^{H}(P_{f,m,h}^{forecast}-P_{f,m,h}) \tag{7}$$

Where $F_{ci}(P_{i,h})$ indicates thermal unit i operating cost at time h; $I_{i,h}$ indicates the status thermal unit i; $P_{i,h}$ indicates the active power of thermal unit i at time h; $SU_{i,h}$ indicates startup cost of thermal unit i at time h; $P_{f,m,h}^{forecast}$ indicates the forecast value of wind unit m at time h; $P_{f,m,h}$ indicates the schedule value of wind unit m at time h; M indicates the weight of wind power forecast deviation penalty function; N indicates the weight of wind curtailment penalty function; $q_{m,h}$ is wind power deviation indicator expressed as follows:

$$q_{m,h}=\frac{P_{f,m,h}^{forecast}-P_{f,m,h}^{actual}-\mu_{wind,m,h}\times P_{m,Cap}}{\sigma_{wind,m,h}} \tag{8}$$

Where $P_{f,m,h}^{actual}$ indicates the actual power of wind unit m at time h; $\mu_{wind,m,h}$ and $\sigma_{wind,m,h}(=\sigma/a)$ indicate expectation and improved standard deviation of wind unit m forecast relative error at time h, respectively; $P_{m,Cap}$ indicates the capacity of wind unit m.

If actual power of wind unit is greater than forecast value, $q_{m,h}$ is written as $q_{m,h}^{up,actual}$. If actual power of wind unit is smaller than forecast value, $q_{m,h}$ is written as $q_{m,h}^{down,actual}$.

(2) System Constraints

Thermal unit capacity constraints:

$$P_{i,\min}\times I_{i,h}\le PL_{i,h}\le P_{i,h}\le PU_{i,h}\le P_{i,\max}\times I_{i,h}(i=1...NG;h=1...H) \tag{9}$$

Demand balance constraints:

$$\begin{aligned}
&\sum_{i=1}^{NG} P_{i,h} \times I_{i,h} + \sum_{m=1}^{W} P_{f,m,h} + \sum_{s=1}^{S} P_{stor,s,h} = P_{D,h} \\
&\sum_{i=1}^{NG} PU_{i,h} \times I_{i,h} + \sum_{m=1}^{W} (P_{f,m,h} + q_{m,h}^{down,actual} \sigma_{wind,m,h}) + \sum_{s=1}^{S} P_{stor,s,h} = P_{D,h} \\
&\sum_{i=1}^{NG} PL_{i,h} \times I_{i,h} + \sum_{m=1}^{W} (P_{f,m,h} + q_{m,h}^{up,actual} \sigma_{wind,m,h}) + \sum_{s=1}^{S} P_{stor,s,h} = P_{D,h} \\
&(h = 1, 2...H)
\end{aligned} \tag{10}$$

Ramping constraints:

$$\begin{aligned}
&PU_{i,h} - PL_{i,h-1} \le [1 - I_{i,h}(1 - I_{i,h-1})]UR_i + I_{i,h}(1 - I_{i,h-1})P_{i,\min} \\
&PU_{i,h-1} - PL_{i,h} \le [1 - I_{i,h-1}(1 - I_{i,h})]DR_i + I_{i,h-1}(1 - I_{i,h})P_{i,\min} \\
&(i = 1...NG; h = 1...H)
\end{aligned} \tag{11}$$

Regulation capacity constraints:

$$\begin{aligned}
&\sum_{i=1}^{NG} (P_{i,\max} - PU_{i,h}) \times I_{i,h} + \sum_{s=1}^{S} R_{stor,up,s,h} \ge R_{up,h} (h = 1, 2...H) \\
&\sum_{i=1}^{NG} (PL_{i,h} - P_{i,\min}) \times I_{i,h} + \sum_{s=1}^{S} R_{stor,down,s,h} \ge R_{down,h} (h = 1, 2...H)
\end{aligned} \tag{12}$$

Line flow constraints:

$$P_{Line,l,\min} \le P_{Line,l,h} \le P_{Line,l,\max} (l = 1...L; h = 1...H) \tag{13}$$

Wind power constraints:

$$\begin{aligned}
&0 \le P_{f,m,h} \le P_{f,m,h}^{forecast} \\
&P_{f,m,h} + q_{m,h}^{down,actual} \sigma_{wind,m,h} \ge 0 \\
&P_{f,m,h} + q_{m,h}^{up,actual} \sigma_{wind,m,h} \le P_{m,cap} \\
&(m = 1...W; h = 1...H)
\end{aligned} \tag{14}$$

Wind power deviation constraints:

$$\begin{aligned}
&0 \le q_{m,h}^{up,actual} \le q_{given} \\
&0 \le -q_{m,h}^{down,actual} \le q_{given} \\
&(m = 1...W; h = 1...H)
\end{aligned} \tag{15}$$

Where $P_{i,\min}$ and $P_{i,\max}$ represent the minimum/maximum active power of unit i; $PU_{i,h}$ and $PL_{i,h}$ represent the active power of unit i when wind power is greater or smaller than forecast value, respectively; $P_{D,h}$ indicates the system load at time h; $P_{stor,s,h}$ indicates active power of energy storage unit s at time h; UR_i and DR_i indicate the ramping up/down limit of unit i; $R_{up,h}$ and $R_{down,h}$ indicate the regulation up/down capacity at time h; $R_{stor,up,s,h}$ and $R_{stor,down,s,h}$

indicate the regulation up/down reserve capacity of storage unit s at time h; $P_{Line,l,h}$ indicates the active power flow of line l at time h; $P_{Line,l,\min}$ and $P_{Line,l,\max}$ indicate the maximum and minimum active power flow of line l; q_{given} is a given limit according to the reliabity of power grid.

(3) BESS Formation

The following modes for BESS are considered:

a. BESS can be used as either generator or load.

b. Maximum charge and discharge power are not constants and change in accordance with the state of charge (SOC) which is the percentage of stored electric energy. Their relationship can be represented by a piecewise linear function.

c. In order to extend the service life, the degree of stored energy should be kept in a certain ranger.

d. Power ramping speed is much faster than thermal so that the responce time can be neglected.

e. After the schedule, BESS should have more than a given amount of electric energy.

According to the specific characteristics, the BESS model is established as follows:

Charge and discharge power limit constraints:

$$-P_{stor,s,h}^{cha,\max} \le P_{stor,s,h} \le P_{stor,s,h}^{discha,\max} (s=1...S; h=1...H) \quad (16)$$

Stored enery limit constraints:

$$\gamma_{stor,s,\min} \times C_{stor,s,\max} \le C_{stor,s,h} \le \gamma_{stor,s,\max} \times C_{stor,s,\max} (s=1...S; h=1...H) \quad (17)$$

Energy constraints:

$$C_{stor,s,h-1} - \begin{cases} \eta_s^{discha} \times P_{stor,s,h} \times 1_H (P_{stor,s,h} > 0) \\ \eta_s^{cha} \times P_{stor,s,h} \times 1_H (P_{stor,s,h} \le 0) \end{cases} = C_{stor,s,h} (s=1...S; h=1...H) \quad (18)$$

Regulation reserve capacity constraints:

$$\begin{aligned} R_{stor,up,s,h} &= \min\{P_{stor,s,h}^{discha,\max} - P_{stor,s,h}, \frac{C_{stor,s,h} - \gamma_{stor,s,\min} \times C_{stor,s,\max}}{1_H}\} \\ R_{stor,down,s,h} &= \min\{P_{stor,s,h} + P_{stor,s,h}^{cha,\max}, \frac{\gamma_{stor,s,\max} \times C_{stor,s,\max} - C_{stor,s,h}}{1_H}\} \\ &(s=1...S; h=1...H) \end{aligned} \quad (19)$$

Amount of stored energy in the end of schedule:

$$C_{stor,s,h} \ge C_{stor,s,\max} \times \gamma_{stor,s,\min}^{cap} (s=1...S; h=H) \quad (20)$$

Where $P_{stor,s,h}^{discha,\max}$ and $P_{stor,s,h}^{cha,\max}$ indicates maximum discharge and charge power of storage unit s at time h; $\gamma_{stor,s,\min}$ and $\gamma_{stor,s,\max}$ indicate the maximum/minimum proportions of electric energy; $C_{stor,s,h}$ indicates the stored energy of unit s at time h; $C_{stor,s,\max}$ indicates the energy capacity of storage unit s; η_s^{discha} and η_s^{cha} indicate the charge and discharge efficiencies of unit s; 1_H is one hour; $\gamma_{stor,s,\min}^{cap}$ indicates the required minimum proportion of energy in the end of schedule.

4. Results and Analysis

In order to testify the feasibility of proposed method, a modified 10-unit IEEE 39-bus system is employed as shown in Figure 3. A wind generator is located at Bus 5 whose capacity is set 400MW. An BESS is located at Bus 6 whose capacity is set 100MW.

As shown in Figure 4, Case 1 represents the number of operating thermal units with BESS and Case 2 represents result without BESS. During time 2~5, system has a high proportion of wind power owing to low load. Time 11~14 is on-peak load hours. During time 15~21, the wind power increases. In these periods, more operation thermal units are required due to the uncertainty of wind power and peak load. But with the charge and discharge power provided by BESS, the number of operating thermal units can be reduced significantly. Peak-load shifting attribute of energy storage system is evidently represented through this result. In Figure 5, results of total thermal regulation reserve capacity with/without BESS are shown. In most time periods, thermal regulation up reserve capacity decreases with the capacity brought by BESS, but thermal regulation down reserve capacity doesn't change much. The average of Thermal regulation up reserve capacities is 431.7MW which can be reduced to 324.3MW with the help of BESS. In Figure 6, we can observe the acceptable boundaries of wind power error are slightly broadened with the help of BESS. This term mostly related to weight M . If M becomes larger, more thermal units will be turned on to tolerate more wind power forecast deviation. For instance, if M is tripled in this case, the acceptable boundaries of wind power error will rise up 7.2%.

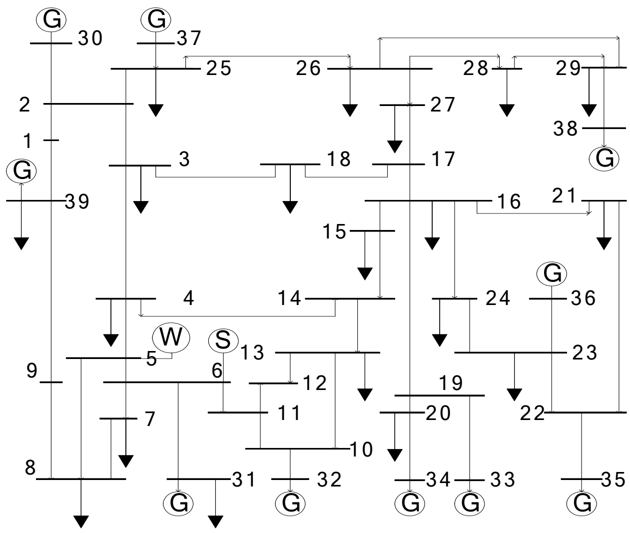

Figure 3. Structure of Power System with 10 Thermal Units and 1 Wind Unit

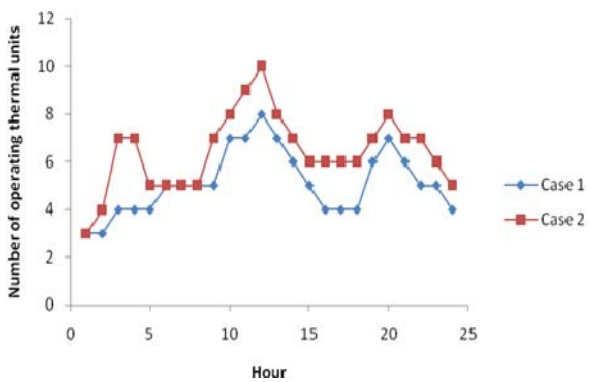

Figure 4. Operating Thermal Units' Number of UC Results with/without BESS

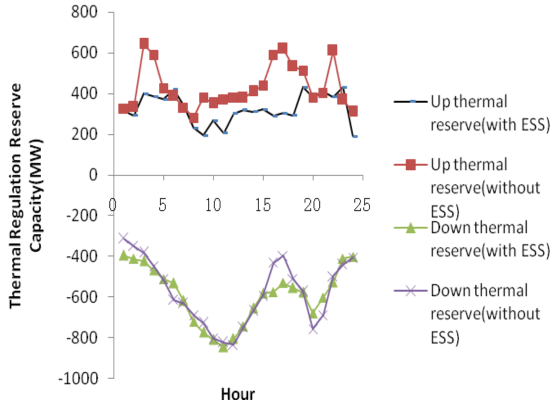

Figure 5. Thermal Units Regulation Reserve Capacity of UC Results with/without BESS

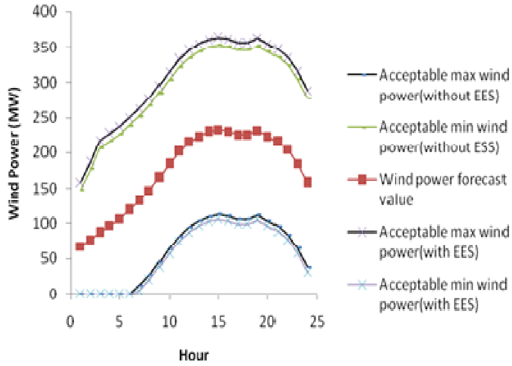

Figure 6. Acceptable Boundaries of Wind Power Error with/without BESS

Table 1 is the results of UC and wind power stochastic simulation check. Obeying the normal distribution, wind power stochastic simulation check datas are generated from MATLAB which have mean μ and standard deviation σ / a. As shown in Table 1, the proposed model passes all simulation checks. Calculation time has an increase with BESS, while the system's total cost becomes $ 869,661, down 2.35%, comparing to the case without BESS.

Table 1. Results of UC and Wind Power Stochastic Simulation Check

	Stochastic Simulation Check					Total cost($)
	1	2	3	4	5	
Without BESS	Pass	Pass	Pass	Pass	Pass	890604
With BESS	Pass	Pass	Pass	Pass	Pass	869661

A 100-unit system which consists of ten above 10-unit systems is employed excluding line flow constraints. The numbers of operating thermal units in every time slice more or less decrease with the help of BESS. The costs of unit commitment are $7172815 and $7213122 with/without BESS, respectively. In this case, we observe the economic impact of BESS on larger scale power grid.

5. Conclusion

In response to the insecurity brought by wind energy uncertainty, large capacity BESS is proposed to solve this problem. An improved wind forecast error model is proposed to suit the actual datas. Based on this, a unit commitment model with wind power and large capacity BESS is analyzed and established. Cases study with 10 units and 100 units are employed to validate the model. The effect of the BESS on power system can be summarized as follows: (1) help peak load shifting; (2) decrease the number of operating thermal units; (3) reduce the system operating costs; (4) help power system accommodate wind power. In further research, the energy loss in charging and discharging processes should be analyzed.

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