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An Optimization Calculation Method of Wind Farm Energy Storage Capacity based on Economic Dispatch

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Abstract

At present, large-capacity storage systems can theoretically smooth fluctuations of wind power output, but its economy is a huge bottleneck in practical applications. From the perspective of optimal economic dispatching of wind-storage power system. Conversion cost of spinning reserve capacity of thermal power due to energy storage reduce wind power forecast error and smooth fluctuation of wind power output, published cost of curtailed wind energy storage reduced and discharged cost of thermal power unit's pollution and environmental management cost was mainly considered, a mathematical model was used to optimize economic dispatching, improved prediction accuracy and smoothed fluctuation of wind power output to satisfy the required standards of the State Grid was set up, a certain regional power grid with wind power in Xinjiang was taken as the example and simulated by employing genetic algorithm(GA). The result show that energy storage capacity is most economical when it accounts for 9.6% of the wind farm installed capacity, and corresponding capacity optimization method is practical, effective and promising in application.

Keywords*: wind power generation; economic dispatch; energy-storage capacity; genetic algorithm*

1. Introduction

Wind power as one of the most mature renewable energy generation technology, no pollution, short investment cycle, *etc*[1]-[4]. Howere, the characteristics of randomness, fluctuation and intermittence of wind power is more and more outstanding, which not only restrict the construction scale of wind farms, but also affect the stability and power quality of power system seriously after the integration of wind power[5]-[8]. Large-scale energy storage technology applied in wind power could smooth power and voltage fluctuations, reduce power sysytem oscillation and load shifting and peak smoothing, therefore, improving the stability and power quality of power system[9]-[11]. So constructing wind-energy power system was the most ideal scheme. But the price of energy storage was too expensive, the cost of cheaper compressed-air energy storage reached nearly 960～1250$/KW, cost is the main bottleneck to restrict the development of energy storage[12]-[13]. Reasonable and optimal configuration of energy storage in power system would save power system cost highly and improve the economy of power system.

The characteristics of the current energy storage such as battery storage, supercapacitor storage, flywheels storage, compressed-air storage, superconductive magnetic storage and pumped storage were described [14]. From the perspective of the wind speed change that affect the wind power output, the range of energy storage capacity was determined[15]. Based on spectrum analysis of renewable energy sources, proposed an calculation sheme of energy storage[16]. According to one year statistical data, a design scheme and a control method were proposed for the energy storage system in a large-scale wind farm in

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Zhejiang province[17]. The feasibility of the cogeneration system in current and future markets under two control modes are analyzed by ultilizing technical and economical estimation indices, the trend of optimal capacity allocation of energy storage in the cogeneration system is pointed out[18]. A simulation analysis has been carried out on a wind farm, the result show that the fuzzy control strategy of hybrid energy storage system can effectively improve the wind power shot-term forecast accuracy[19]. But based on the dispatching wind farm with energy storage, to improve prediction accuracy and smooth fluctuation of wind power output were set as constrain with considered economic operation hadn't been reported so far.

Improving wind power prediction accuracy and smoothing wind power fluctuations were both set as constrains in this paper, to minimize the cost of construction and operation of wind farm and energy storage, cost of spinning reserve capacity of thermal power, the punishment cost of curtailed wind energy, and cost of thermal power unit's pollution and environmental management were set as the final goal, and then the optimal energy storage capacity was calculated by using GA. A certain regional power grid with wind power in Xinjiang was taken as the example, the result show that energy storage capacity is most economical when it accounts for 9.6% of the wind farm installed capacity, and corresponding capacity optimization method is practical, effective and promising in application.

2. Construction of the Objective Function and Constraint Condition of Optimized Economic Dispatch in Wind-storage Power System

2.1. Objective Function

As show in equation(1), put the minimal total cost F_z of wind-storage power system as the final aim, calculate the optimal energy storage. Include fixed cost of wind-storage F_1 (F_{wind}+$F_{storage}$)、cost of spinning reserve capacity of thermal power due to energy storage reduce wind power forecast error F_{pe}, cost of spinning reserve capacity of thermal power due to energy storage smooth wind power fluctuations F_{pf}, the punishment cost of curtailed wind energy F_{aw}, cost of thermal power unit's pollution and environmental management F_P。

$$\min F_Z = F_{pe} + F_{pf} + F_{aw} + F_P + F_1 \tag{1}$$

2.1.1. Conversion Cost of Spinning Reserve Capacity of Thermal Power Due to Energy Storage Reduce Wind Power Forecast Error

As show in Figure 1, inaccurate meteorological data resulted in greater prediction error of wind power output, after wind power integration, To ensure the safe and stable operation of the power grid, we need to prepare for a certain thermal power spinning reserve capacity all the time, ① area plus ②area in Figure 1 namely （$P_{M,t} - P_{F,t}$）. With energy storage device to compensate wind power prediction error charging and discharging, thus reducing the thermal power spinning reserve capacity, namely ① area（$P_{M,t} - P_{Y,t}$） in Figure 1. It's conversion cost is reduced cost of spinning capacity of thermal power which is used to compensate prediction error of wind power.

while $(P_{M,t} - P_{Y,t}) > 0$

$$F_{pe} = C_{src} \times h \times \int_{t1}^{t2} t(P_{M,t} - P_{Y,t})dt \tag{2}$$

Where

C_{src} the price of spinning reserve capacity per hour
$P_{F,t}$ prediction output of wind power at period t
$P_{M,t}$ actual output of wind power at period t
$P_{Y,t}$ absolute value of upper limit or lower limit of allowable error band at period t
h total compensation hours
t1-t2 Time domain compensation of wind power prediction error

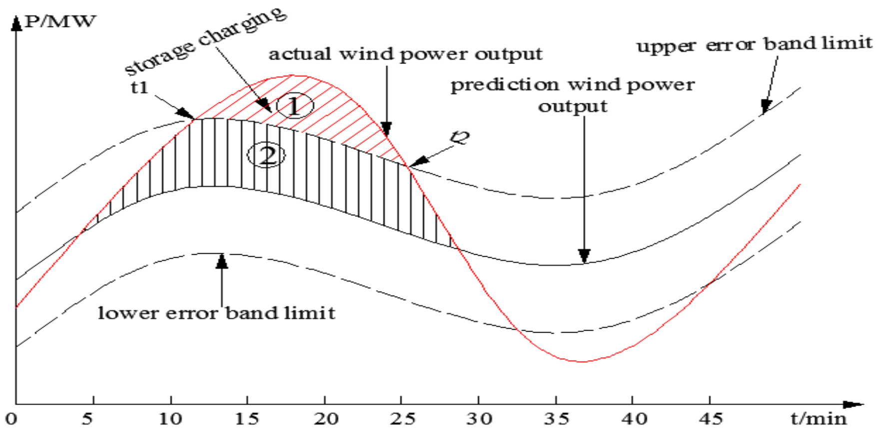

Figure 1. Prediction Error of Wind Power Output

2.1.2. Conversion Cost of Spinning Reserve Capacity of Thermal Power Due to Energy Storage Smooth Wind Power Fluctuations

Fluctuations of wind power output was showed in Figure 2, This feature will bring about a series of adverse effects on the operation and control of the power grid, a certain thermal power spinning reserve capacity should be prepared all the time, with energy storage device to smooth wind power fluctuations charging and discharging, thus reducing the thermal power spinning reserve capacity, namely in the shaded part in Figure 2 $(P_{M,t} - P_{B,t})$. It's conversion cost is reduced cost of spinning capacity of thermal power which is used to smooth wind power fluctuations, as show in equation(3):

while$(P_{M,t} - P_{B,t}) > 0$

$$F_{pf} = C_{src} \times h \times \int_{t1}^{t2} t(P_{M,t} - P_{B,t})dt \tag{3}$$

where

$P_{B,t}$ absolute value of upper limit or lower limit of fluctuations band at period t

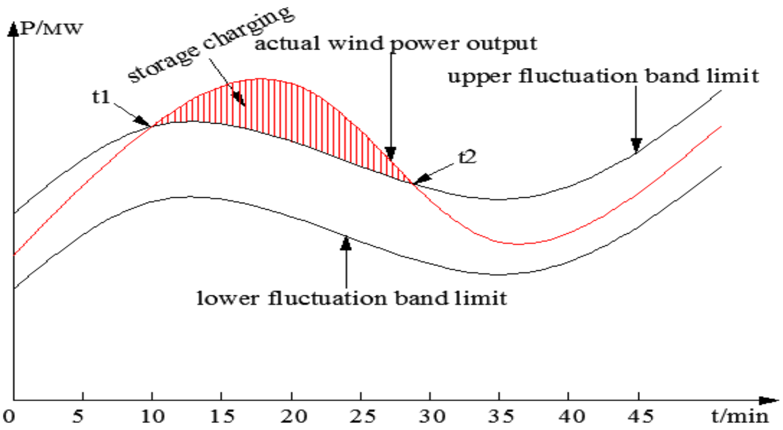

Figure 2. Fluctuations of Wind Power Output

2.1.3. Wind Abandonment Cost of Energy Storage Compensation

Due to the lack of grid penetration ability, sometimes wind abandonment measures must be taken. After installing energy storage, the abandoned wind capacity ΔQ_A will be reduced, it's conversion cost was F_{AW}, as show in equation(4)-(6):

$$\Delta Q_{A1} = \sum_{i=1}^{n_1}\left[\int_{t_1}^{t_2} f\left(P_M,\ E_{up},\ t_1,\ t_2\right)_i dt\right] \quad (4)$$

$$\Delta Q_{A2} = \sum_{i=1}^{n_2}\left[\int_{t_1}^{t_2} f\left(P_{MS},\ E_{up},\ t_1,\ t_2\right)_i dt\right] \quad (5)$$

$$\Delta Q_A = \Delta Q_{A1} - \Delta Q_{A2},\ F_{aw} = \rho \Delta Q_A \quad (6)$$

Where

ΔQ_{A1} abandoned wind capacity with no energy storage

ΔQ_{A2} abandoned wind capacity with energy storage

ΔQ_A variable quantity of abandoned wind capacity before and after the installation of energy storage

ρ the price of abandoned wind capacity per MW

n_1, n_2 times of abandoned wind before and after the installation of energy storage

P_M actual wind power output

P_{MS} wind-storage power output

E_{up} variable quantity of loads

2.1.4. Thermal Power Pollution Discharge and Environmental Management Cost of Energy Storage Compensation

When coal-fired thermal power unit oprerated and generated normally, Emissions of a certain amount of environmental pollutants would come. The thermal power unit's pollution discharge characteristics is quantified by its generated nitrogen oxide during a period, pollution discharge characteristics were showed in equation(7):

$$W_i(P_j) = \alpha_i + \beta_i \times P_{i,j} + \gamma_i \times P_{i,j}^{\ 2} \quad (7)$$

Where

α_i, β_i, γ_i emmision coefficients of the *i*th thermal power unit per MW

$P_{i,j}$ power output of the *i*th thermal power unit at period *j*

$W_i(P_j)$ discharge capacity of the *i*th thermal power unit at period *j* per MW

Emmision cost of thermal power units per MW was showed in equation(8):

$$F_{ep} = C_{ep} \times \sum_{i=1}^{n} \sum_{j=1}^{m} W_i(P_j) P_{i,j} \quad (8)$$

Where

n total numbers of thermal power units in system

m The number of thermal power units that participate in generation

C_{ep} Conversion unit price of emmision cost of thermal power units

Thermal plants is responsible to take measures against emission thermal power units product, so its corresponding cost is defined as pollution abatement cost, showed in equation(9):

$$F_{pl} = C_{pl} \times \sum_{i=1}^{n} \sum_{j=1}^{m} W_i(P_j) P_{i,j} \quad (9)$$

Where

C_{pl} pollution abatement cost per ton

Therefore, thermal power pollution discharge and environmental management cost of energy storage compensation was given by

$$F_P = F_{ep} + F_{pl} \quad (10)$$

2.2. Constraint Conditions

Control strategy of energy storage in wind farm was: when the actual wind power output exceeded the allowable limit reference value, the storage battery wouldn't be charged until its electric quantity reached the maximum rated capacity E_{Smax}; while the actual wind power output was lower than the allowable limit reference value, the storage battery wouldn't discharge untilt its electric quantity reached the minimum rated capacity E_{Smin}. Charge/discharge capacity of energy storage was based on the actual operation of wind farm, therefore, the allowable upper limit and lower limit of target bandwidth should be determined, which could make the active power output of wind farm within the specified range. To improve prediction accuracy and smooth fluctuation of wind power output were set as constrain with considered economic operation, so the capacity of energy storage was sized in this paper.

2.2.1. Determination of Allowable Upper Limit or Lower Limit of Target Bandwidth of Wind Power Output

(1) Determination of target bandwidth of improving wind power predictiion accuracy which satisfied the standard upper and lower limit regulated by state grid. According to the relevant regulations of enterprise edition: Q/GDW432-2010《Specification of dispatching and oprerating management for wind power》formulated by state grid [20], under the premise of meeting dispatching requirements, the prediction output of wind power should be within prescriptive range, specific recommended values are shown in Table 1.

Table 1. Recommended Values of Wind Power Prediction Accuracy

Dispatching plan values /MW	Percentage of upper allowable deviation limit	Percentage of lower allowable deviation limit
50	+25	-30
50~100	+20	-25
≥100	15	-20

According to Table 1, the allowable prediction error bandwidth of wind power was showed in Figure 1.

(2)Determination of target bandwidth of smoothing wind power fluctuations which satisfied the standard upper and lower limit regulated by state grid

There are definited standard regulations formulated by state grid in Q/GDW392-2009《Technical rule for for connecting wind farm to power network》[21], the upper and lower limit value of active output rate of wind farm should refer to frequency regulation performance of the local power grid. The maximum variable quantity of wind power in 10 minutes generally not exceed 33% of installed capacity, not exceed 10% of installed capacity in 1 minutes, specific recommended values are shown in Table 2.

Table 2. Recommended Values of the Maximum Amount of Wind Farm Power Fluctuations

Installed capacity of wind farms/MW	Maximum variable quantity in 10 min/MW	Maximum variable quantity in 1 min/MW
＜ 30	20	3
30~150	Installed capacity/3	Installed capacity/10
>150	50	15

According to Table 2, the allowable fluctuations error bandwidth of wind power was showed in Figure 2

(3)Determination of the upper and lower limit of final target bandwidth

As shown in Figure 3, the final upper and lower limit of target bandwidth that satisfied both improving wind powe prediction accuracy and smoothing wind powe fluctuations was determined by the minimum value of upper limt and maximum value of lower limit.

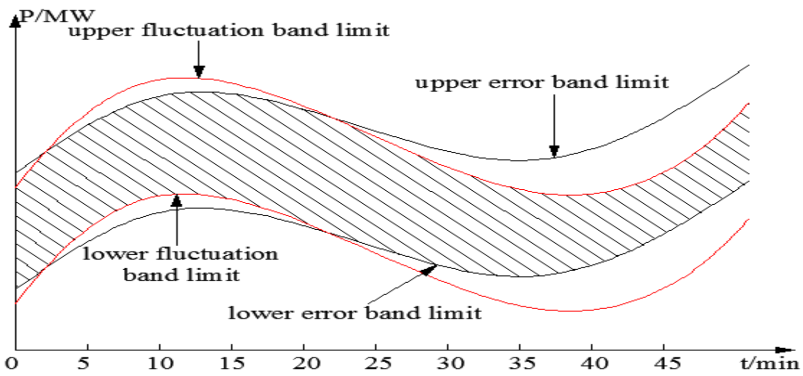

Figure 3. Allowed Bandwidth Range

2.2.2. Equality Constraint

In the condition of excluding the system power loss, power balance constraint was given by

$$\sum_{i=1}^{m} P_i + \sum_{j=1}^{n} P_j + \sum_{k=1}^{u} P_k = P_{load} \tag{11}$$

Where

P_i the ith thermal power output

P_j the jth wind turbines power output

P_k the kth energy storage system power output

P_{load} load value in this period

2.2.3. Inequality Constraints

(1) Constraint conditions of wind-energy power output

Wind-energy power output must satisfy the allowable bandwidth range given by Figure 3, the power output was showed in equation(12):

$$-\Delta P_{max} + (P_{f(i-1)} + P_{c(i-1)}) \leq P_{fi} + P_{ci} \leq \Delta P_{max} + (P_{f(i-1)} + P_{c(i-1)}) \tag{12}$$

$$\min\{P_1, P_3\} \leq \Delta P_{max} \leq \min\{P_2, P_4\} \tag{13}$$

Where

$P_{f(i-1)}, P_{fi}$ active power output of wind farm at period i-1, i

$P_{c(i-1)}, P_{ci}$ active power output of wind farm at period i-1, i

P_2, P_1 upper and lower limit value of wind power fluctuations

P_2, P_1 maximum and minimum value of wind power prediction output

$P_{f(i-1)}, P_{fi}$ active power output of wind farm at period i-1, i

$P_{c(i-1)}, P_{ci}$ active power output of energy storage at period i-1, i

(2) Constraint conditions of wind farm and thermal power units

① Constraints of wind power output

$$P_{i,min} \leq P_i \leq P_{i,max} \tag{14}$$

Where $P_{i,min}$ and $P_{i,max}$ are the minimum and maximum output value of the ith wind turbine unit.

② Constraints of thermal power units

$$P_{j,min} \leq P_j \leq P_{j,max} \tag{15}$$

Where $P_{j,min}$ and $P_{j,max}$ are the minimum and maximum output value of the jth thermal power units.

③ Ramp rate constraints of thermal power unit

$$-\delta_{idown} \leq P_i(t) - P_i(t-1) \leq \delta_{iup} \tag{16}$$

Where δ_{idown} is the minimum ramp falling rate, δ_{iup} is maximum rising rate.

④ Limit penetration power Constraints of wind farm

$$P_f \leq P_{jmax} \tag{17}$$

Where P_f and P_{jmax} are the toatal active capacity and limit penetration power of wind power intergration.

3. Energy storage Optimization Sizing Method and Optimization Computing of Wind-Storage Economic Dispatch Based on GA

3.1. Solving Method for Wind-Storage Economic Optimization Dispatch Based on GA

Many research literature have shown that GA can conduct random search and adaptive optimization[22], is highly parallel and therefore applied in this paper. F_z is a objective function which was defined as the total cost of power system with wind-storage and satisfied all of constraint condition, so optimal capacity of energy storage could be computed through simulation. The steps was listed as follow:

*Step*1:input initial related data of power system with wind-storage and thermal generators, formulate corresponding equality constraint conditions and inequality constraint conditions.

*Step*2:Translate the variables into codes, product the initial area of chromosome.The equation: $E_i = \mathrm{INT}\left\{\mathrm{RAND}\cdot(E_i^{\max} - E_i^{\min} + 1)\right\} + E_i^{\min}$ can be applied in the first stage of chromosome, where INT is limited to integer and Rand is sole random number.

*Step*3:compute moderate function value of each chromosome.

*Step*4:product the new stage of chromosome on the basis of the former stage by reproduction, overlapping, variation and compute new adaptive value after decoding the stage of chromosome.

*Step*5:terminate the circulation if genetic time is over presetting time, return if the corresponding equality constraint conditions and inequality constraint conditions is not satisfied and variables fall outside scope of constraint area.

*Step*6:If the adaptive degree of chromosome is the best, the chromosome is optimal solution, namely optimal capacity of energy storage in this study.

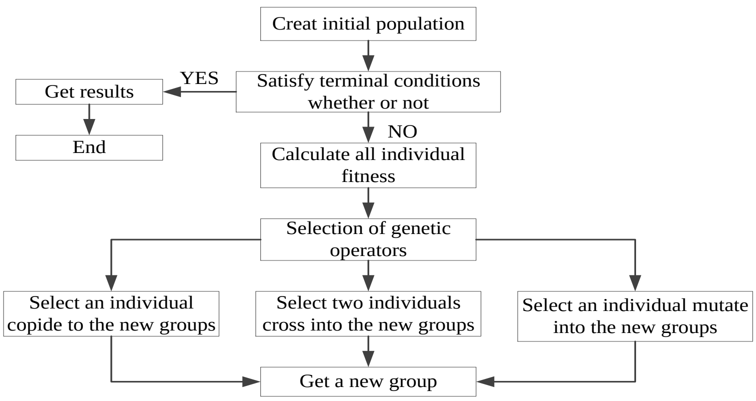

Figure 4. The Basic Flow Chart of Genetic Algorithm

3.2. Compute Optimal Capacity of Energy Storage

The prediction of output of the wind farm during the period t was assume as P_i, installed capacity and dispatching plan output of the wind farm 30-150MW and P_j respectively. where:($50 < P_{j.min} < P_{j.max} < 100$)

The change of fluctuation ΔP and the upper and lower limit of fluctuation($P_{l.x1}$,$P_{l.x2}$) was respectively shown in the Figure 2 and equation(18), (19).

$$\Delta P = \frac{\text{installed capacity}}{3} \tag{18}$$

$$\begin{cases} P_{l,x1} = P_{i(t-1)} + \Delta P & \text{upper limit} \\ P_{l,x2} = P_{i(t-2)} + \Delta P & \text{lower limit} \end{cases} \tag{19}$$

The value of upper limit and lower limit was indicated in Table 1 and equation(20)

$$\begin{cases} P_{l,x3} = P_{j(t-1)} + P_{j(t-1)} \cdot 20\% & \text{upper limit} \\ P_{l,x4} = P_{j(t-2)} + P_{j(t-2)} \cdot 20\% & \text{lower limit} \end{cases} \tag{20}$$

The method shown in Figure 3 to determine the final upper and lower limit of fluctuation was combined with actual power output curve ,so computing method of energy storage could be seen in Figure 5.

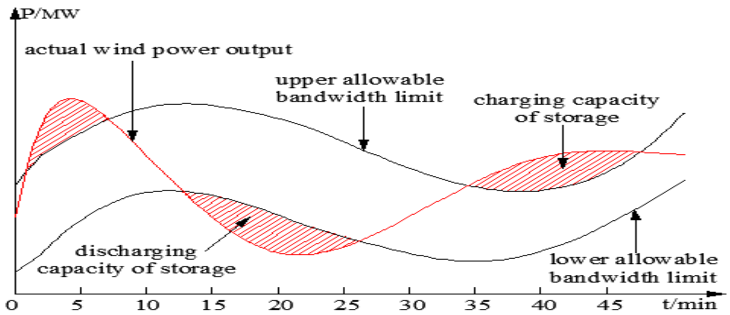

Figure 5. Caculation of Optimal Storage Capacity

If the actual active output of the wind farm is over upper limit, the excess part of the electrical energy will charge energy storage, while it will discharge if that is below the lower limit. The capacity of energy storage's charging or discharging was translated into enclosed area by actual output of the wind farm over allowable bandwidth and upper and lower limit of fluctuation, which could be shown in equation(21).

$$E_{ss} = \max \int_{t1}^{t2} f(P_f, \pm P_c, t)dt \tag{21}$$

where: P_f is actual active output of the wind farm, P_c is absolute value of final upper limit or lower limit. The biggest enclosed area by P_f and P_c is represented by capcacity of energy storage that should be size.GA toolbox in Matlab could be used to get optimal capacity of energy storage according to solving method based on GA in chapter 2.1.

4. Analysis and Verification of Examples Based on a Certain Regional Wind Power System with Energy Storage in Xinjiang

Wind power output of short-term forecast and the actual from a 148MW wind farm in Xinjiang during 00:00:00 on 1st July, 2011 to 23:50:00 on 1st October, 2011 was sampled with 10min interval and its former 8000 points was used to investigate, which was illustrated in Figure 6 and Figure 7 respectively. The GA toolbox inside Matlab was applied to successfully caculate the optimal value of energy storage optimization sizing.

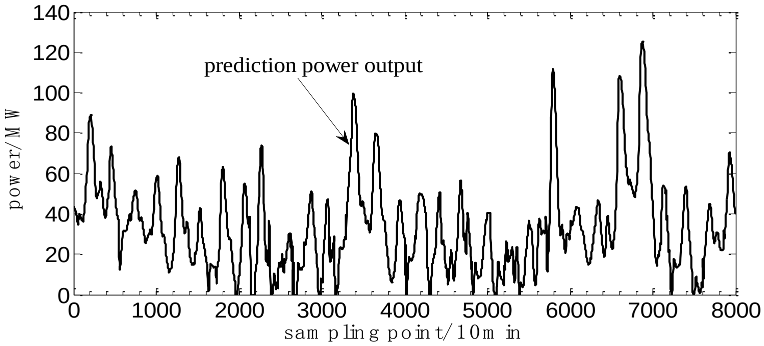

Figure 6. Wind Farm Prediction Output

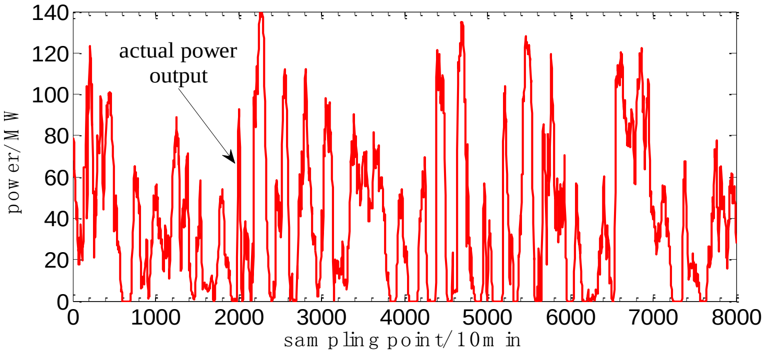

Figure 7. Wind Farm Actual Output

4.1. Analysis and Verification with No Energy Storage

Figure 8 shows the correlation between the actual power output and allowed bandwidth with no storage capacity. if there were no other control measures during the operation of wind farm, the active power output of wind farm was difficult to keep in the allowable bandwidth range. In Figure 8, between the sampling range [3730,3740] and [3788,3800], part of the sampling points corresponding to the power had exceeded the limit and the output status is unstable, which can not satisfy the allowable power fluctuation and accuracy requirements specified by the State Grid.

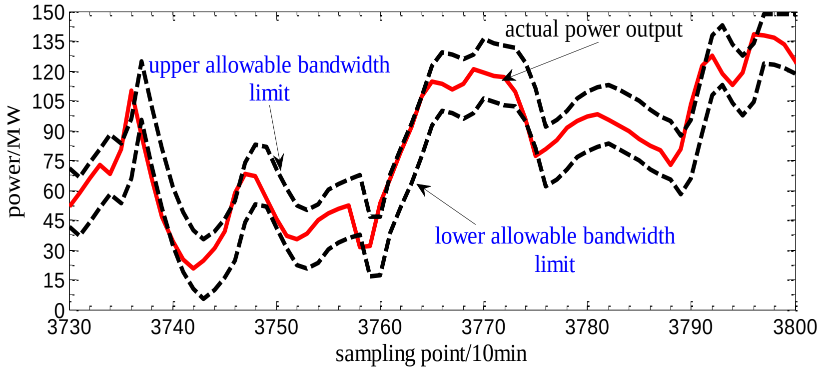

Figure 8. The Correlation between the Actual Power Output and Allowed Bandwidth with No Storage Capacity

4.2. Analysis and Verification with Energy Storage

Figure 9 show the correlation between wind-storage power output and allowed bandwidth with storge capacity. By charging and discharging of the energy storage, the exceeded power points in Figure 8 were pulled back within the allowable bandwidth.

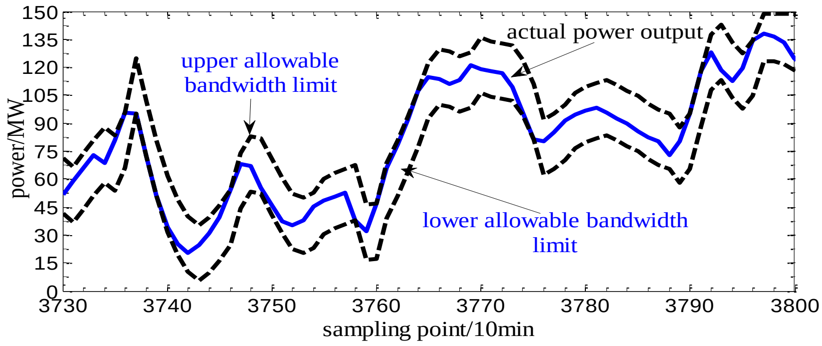

Figure 9. The Correlation between Wind-Storage Power Output and Allowed Bandwidth with Storage Capacity

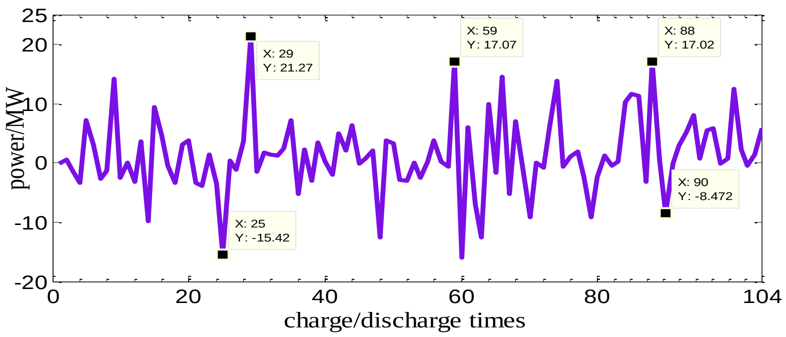

Figure 10. Charge and Discharge Power Curve of Storage System

Figure 10 was corresponding charge and discharge curve of each operation of installing ESS. It is seen that the energy storage has been charged and discharged for total 104 times in the sampling interval.

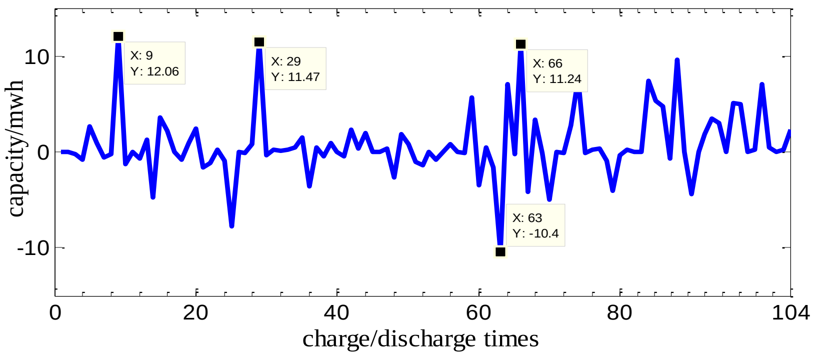

Figure 11. Charge and Discharge Capacity Curve of Storage System

As shown in Figure 11, the energy storage capacity reached the maximum value at the 9th charge and discharge, namely $\max E_{SS} = 12.06$mwh.

4.3. Analysis and Verification Based on GA

The minimum value of objective function Fz is the minimum cost of wind-storage. The GA toolbox inside matlab was applied to compute the equation(21) to get the optimal value of energy storage which is the capacity that the wind farm need to be sized. It would be seen as followed:

$$E_{YS} = 11.76\text{mwh} < E_{SS}$$

energy storage power: $P_{YS} = 14.26\text{MW}$

power accounted for: $\theta = \frac{P_{YS}}{148.5} = 9.60\%$

Application effect is confirmed in Figure 12 after the installing of E_{YS}.

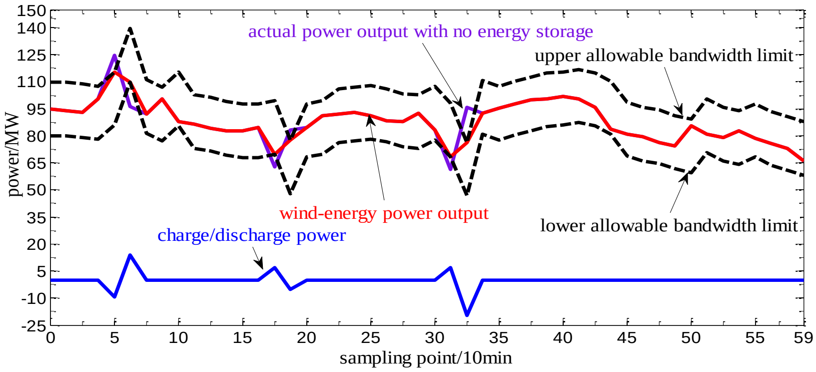

Figure 12. Wind-Storage Power Output and Charging Curves with Optimal Storage Capacity

While E_{YS} was accessed to the model, according to stastics that there were 7989 sampling points satisfied in the allowable bandwidth and the qualified rate was 99.86%. The maximum wind-energy power fluctuation value was just 0.037MW beyond the allowable bandwidth range, which could make no impact on the grid thus the configuration of the energy storage was most economical and reasonable.

5. Conclusion

From the perspective of optimal economic dispatching of wind-storage power system, a calculation method to get the capacity of storage system by minimizing the cost of wind-energy system was proposed, it could improve prediction accuracy and smooth fluctuation of wind power output to satisfy the required standards of the State Grid. Analysis of examples based on a certain regional wind power system with energy storage in Xinjiang were conducted, the optimal economical energy storage capacity was calculated by GA and accessed to wind-storage model system for simulation verification. The method is completely promising because it can be used to smooth output of wind power, combine wind power dispatching and press-day grid dispatching efficiently and improve accommodated capacity to grid of wind power and the economy of power system with wind-storage.

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