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# Economic evaluation of wind-powered pumped storage system

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**Abstract**

Wind power, a green energy, has become another primary renewable resource of great value in economic utility and industrialization development, like hydraulic power at the time when comes with the pressure from energy crisis and environmental protection. This paper considers a wind-powered pumped storage system based on an 8 MW wind farm. The effect of pumped storage power station to wind power regulation is calculated, and an economic evaluation model was developed. This paper shows that a significant smoothing of the produced power is realized, dispatchable output power can be offered to the system, whereas extra economic benefit can also be achieved.



*Keywords: wind-powered pumped storage system, wind power regulation, energy gain, engineering economic evaluation*

## 1. Introduction

As a fully sustainable energy, wind energy is widely used, therefore, Bechrakis D A et al (2006) realized that wind power is regard as an important energy option in many countries[1]. It is well known that the wind is a highly volatile resource. Significant changes are found on time scales of less than a few hours, As a result, of the power grid capacity, the proportion of wind power directly supplied into the grid is relatively low, so an appropriate way to regulate the output of wind power is needed, which should be able to balance a surplus or deficit of wind power on a time scale of the order of several tens of minutes or longer. When the power system size increases beyond a few hundred kWs, battery storage, flywheels and other similar means become technically and economically unappealing, leaving pumped storage station as the only feasible solution. C.C.Warnick (1984) analyzed many aspects of Hydropower Engineering[2]. Castronuovo E D et al (2004) Proposed a optimal model for operation and sizing of a wind-hydro power plant[3]. Caralis G, Zervos A (2007) analyzed the combined use of wind and pumped storage systems in autonomous Greek islands[4]. Tan Zhizhong et al (2008), Denholm P et al (2006) and Elhadidy M A et al (1999) proposed three different operational strategies, established economic evaluation model, and optimized the best operational strategy of wind-powered pumped storage system based on comprehensive economic evaluation results[5-7]. Li Qiang et al (2009) and Horsley A et al (2002) analyzed wind power with water pumping energy storage based on a small power system simulation[8-9], Park H et al (2006) established the proposal's economic operation calculation analysis model under the condition of

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maximizing the use of wind power[10]. However, the literatures above only focus on the simulation of a certain day, and then extended it to one year, instead of simulating the operation of one year directly. In this paper, Logistic model is utilized to simulate the wind power output in one year based on the current research, quantitative analysis is made for wind power regulating effect of pumped storage power station, and economic evaluation model is established, a quantitative calculation is made for economic benefits of wind power- pumped storage system.

## 2. Modeling of the combined system

### *2.1 Wind-powered pumped storage system description*

The power system is illustrated in Figure 1, which includes a wind park with several identical wind turbines, a pumped storage station equipped with pumps and turbines. The pump can pump water up to the upper reservoir, and the electricity can be generated from the water turbine. The power output generated by the wind turbine and the water turbine are both connected to the grid.

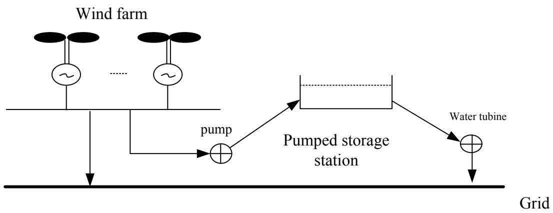


Fig. 1. Wind-powered pumped storage system structure

### *2.2 Wind park model*

A wind farm contains multiple wind turbines, assuming the number is $n_{WT}$ , and each wind turbine is identical.

The power output of individual wind turbine is represented by its power curve. The inputs are the power curve of the wind turbine and wind speed, which are transformed into the according power output of the wind turbine through the power curve of the wind turbine.

A single wind turbine power output $P(v)$ at $t$ can be calculated by the curve interpolation of wind turbine power output and wind speed. In this paper, we use Newton's interpolation to calculate the wind power output[11].

Assuming the three known point closest to the desire wind speed $v$ as $v_{j-1}$, $v_j$, $v_{j+1}$, the according power as $P(v_{j-1})$, $P(v_j)$, $P(v_{j+1})$, then we can calculate the wind power output when wind speed is $v$ by Newton's interpolation as equation (1):

$$P(v)= P(v_{j-1})+P[v_{j-1},v_j](v-v_{j-1})+P[v_{j-1},v_j,v_{j+1}](v-v_{j-1})(v-v_j) \tag{1}$$

Where， $P\left[v_{j-1},v_j\right]=\dfrac{P\left(v_j\right)-P\left(v_{j-1}\right)}{v_j-v_{j-1}}$ is second-order difference.

$P\left[v_{j-1},v_j,v_{j+1}\right]=\dfrac{P\left[v_{j-1},v_{j+1}\right]-P\left[v_{j-1},v_j\right]}{v_{j+1}-v_{j-1}}$ is third-order difference, wind speed $v\in\left[v_{cut-in},v_{cut-out}\right]$, $v_{cut-in}$ is the cut-in speed of wind turbine.

According to the power output of single wind turbine determined by equation (1), incorporated into equation (2), the power output of wind farm $P_{WF}$ can be obtained as:

$$P_{WF}=k_{WP}\times n_{WT}\times P\left(v\right) \tag{2}$$

$k_{WP}$ in equation (2) is the same rate coefficient of wind turbine( $k_{WP}\leq 1$), which depends on the actual location of the wind farm, where, $k_{WP}=1$, to simplify the calculation.

*2.3 Pumped storage station model*

For a given power output, the water flow rate can be calculated by the following equations (4)-(7), for pump and turbines units:

$$P_p\left(t\right)=\rho\cdot g\cdot Q\left(t\right)\cdot\left(H+h_f\right)/\left(\eta_p\cdot\eta_{el}\right) \tag{3}$$
$$P_t\left(t\right)=\rho\cdot g\cdot Q\left(t\right)\cdot\left(H-h_f\right)\cdot\eta_t\cdot\eta_{el} \tag{4}$$

Where, $P_p\left(t\right)$——the pumping power of the pump at $t$; $P_t\left(t\right)$——the power generated by the turbine at $t$; $\rho$——fluid density; $g$——acceleration of gravity; $Q\left(t\right)$——water flow rate at $t$; $H$——head; $h_f=k\cdot Q^2$ ——head loss; $\eta_p$ ——pump efficiency; $\eta_t$ ——turbine efficiency； $\eta_{el}$ ——electrical efficiency of pumps or turbines.

For the estimation of the head loss, various methods are proposed in informed research. Gordon and Penman (1984) provide a simple equation to determine water pipe diameter of small hydropower installations:

$$D=0.72\cdot Q^{0.5} \tag{5}$$

Where, $D$——water pipe diameter; $Q$——water flow.

Then the head loss is given by the Darcy-Weisbach formula as:

$$h_f=\frac{LV^2}{2Dg}f \tag{6}$$

Where, $f$ ——friction factor; $L$ ——length of pipe; $V$ ——velocity of flow in pipe.

$f = 0.02$ can be set in the Darcy-Weisbach equation to get an initial estimate of head loss. Velocity of flow in the pipes can be calculated by the equation:

$$Q = V\pi\left(\frac{D}{2}\right)^2 \tag{7}$$

Equations (4), (5) provide an estimation of head loss, $h_f$ can be calculated as:

$$h_f = \frac{8fL}{g\pi^2 D^5}Q^2 \tag{8}$$

Equation (8) is incorporated in (3) and (4) for the calculation of power output of pumped storage station.

*2.4 Economic evaluation model of wind powered pumped storage system*

The investment cost per kWh in the conversion period of wind-powered pumped storage system is calculated as:

$$C_L = \frac{(C_{I0} - S_0)r\left[1-(1+r)^{-L}\right]^{-1} + C_{O\&M} + C_{EXT}}{\Delta P \cdot L} \tag{9}$$

Where, $C_{I0}$ ——static investment cost of pumped storage power station; $S_0$ ——state subsidies to wind power; $r$ ——discount rate; $L$ ——payback period; $C_{O\&M}$ ——the annual operating and maintenance expenses; $C_{EXT}$ ——other additional annual operating expenses; $\Delta P$ ——extra energy gain of the wind-powered pumped storage station.

Comprehensive economic indicator $\Delta S_L$ is calculated as:

$$\Delta S_L = \Delta P(P_L - C_L) \tag{10}$$

Where, $\Delta S_L$ ——the extra economic benefit of wind-powered pumped storage system compared with ordinary wind power system; $P_L$ ——the arithmetic mean of peak-valley price.

## 3. Constraints of the operation of wind-powered pumped storage system

The operation strategy of a wind-powered pumped storage station depends on the type of power system including the station. Wind-powered pumped storage system integrating into a large power system is not limited to their power output given by the system. Therefore, the operation strategy is merely aimed at on maximizing economic returns in the peak-valley price system, and meanwhile, the technical issues within the station should also be taken into consideration.

On the other hand, it is generally believed that the proportion of output of wind power integrating into grid can not exceed certain value due to instability and low utilization of wind power output. The operation of a wind-powered pumped storage station in autonomous power system is subject to restrictions imposed by the power absorption capability of the system, which changes over time and depends on the load variations, the scheduling algorithm of the conventional generating units, and the system reliability considerations. In this way, sudden loss of the output of the wind-powered pumped storage station can be avoided.

In this paper, attention is only paid to the case of autonomous power system. The maximum allowable penetration of the wind-powered pumped storage station is subject to the following two constraints:

Minimum technical limit of conventional generating units:

$$P_{HS} \le D_L - \sum_{i=1}^{N_{op}} P_{D_{\min},i} \tag{11}$$

Maximum penetration limit:

$$P_{HS} \le p_{\max} \cdot \sum_{i=1}^{N_{op}} P_{D_n,i} \tag{12}$$

Where, $P_{HS}$ ——power output of wind-powered pumped storage system; $D_L$ ——total demand; $P_{D_n,i}$ ——nominal power of conventional generating unit $i$ ; $P_{D_{\min},i}$ ——minimum technical limit of generating unit $i$ ; $N_{op}$ ——numbers of conventional generating units; $p_{\max}$ ——maximum allowable penetration for the wind-powered pumped storage system.

The first constraint ensures that the load of every conventional generating unit in operation is always more than its technical minimum. The second constraint limits the penetration level to a pre-set maximum value, which is usually related to transient stability of the power system. It is also assumed that the conventional generating units run 100% spinning reserve, which means that the capacity of the conventional generating units cover all load, even if all power of wind-powered pumped storage station is lost.

## 4. Application results

A wind park consisting of 10 wind turbines is utilized here, and the nominal power of each wind turbine is 800 kW. The output of the park is estimated using the power curve shown in Figure 2, for each wind turbine.

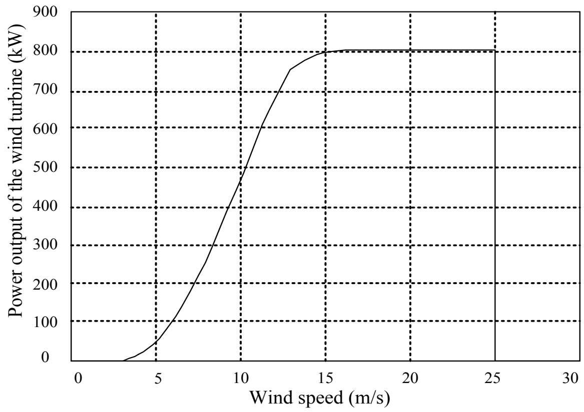


Fig. 2. Power curve of the wind turbines

The relevant annual wind speed time series is presented in Figure 3.

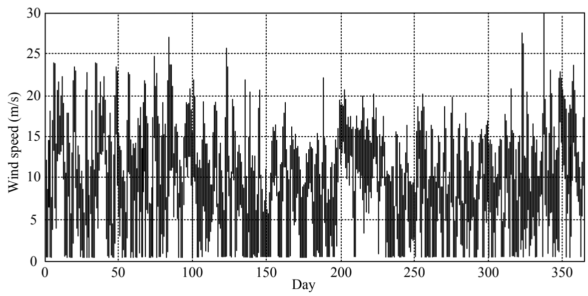


Fig. 3. Wind speed time series in one year

The pumped storage station consists of 10 pumps and 8 turbines, and nominal electrical power all rate 500 kW. It is assumed that head is 100 $m$, whereas the pipe length is taken 500 $m$. Head losses caused by friction in the pipes are calculated by the equations (6)—(7). Electrical loss is assumed to be fixed at 90%.

Because an operating minimum state is equivalent to 40% of the reservoir capacity and the technical minimum state is equivalent to 10% of the reservoir capacity, reservoir capacity (720,000 $m^3$) can guarantee that the turbines run continuously at rated power in 12 hours. In order to simulate the operation of the station in an autonomous power system, a power system is selected with a maximum load of 17 MW and the annual load aviations are shown in Figure 5. There are 7 conventional generating units in total and their capacity range from 1.2 to 6.3MW and the total installed capacity of the conventional generating units is 28.4 MW. The technical minimum value of capacity factor is 50%.

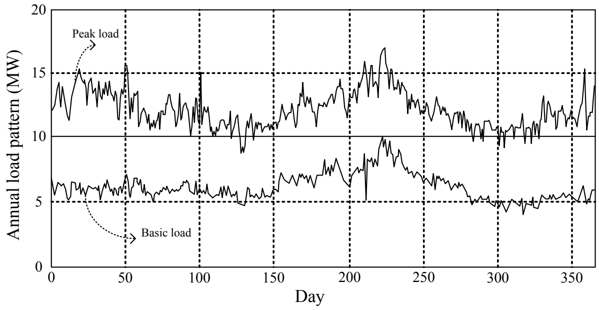


Fig. 4. Autonomous system annual load time series

Based on the wind speed time series of Figure 3, the logistic model is applied to simulate the wind park operation by MATLAB. The simulation results for the first 20 days are illustrated in Figure 6 (without any restriction to its output power).

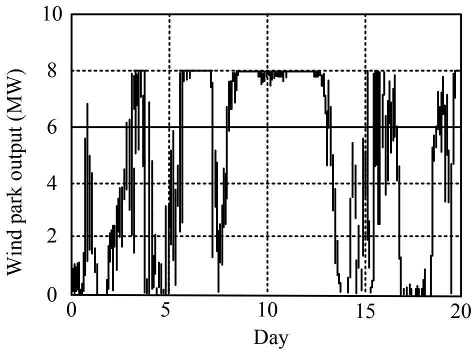


Fig. 5. Wind park output for the first 20 days of operation, without any restriction to its output power

In order to compare the operation of the system with and without the pumped storage power station, the time period is set to be one year. Main results of this case study are summarized in Table 1.

When there is plenty of wind with low load, a large amount of available wind energy will be abandoned due to the penetration limit of wind power. This wasted wind power is equivalent to about 30% of the baseline value of available wind energy in a year (Table 1). When there is insufficient wind water in the upper reservoir can be used to generate power.

Table 1. Contrast of operation in an autonomous power system

| | without pumped storage station | with pumped storage station |
|---|---|---|
| Mean available wind power (MW) | 4.10 | |
| Standard deviation of available wind power (MW) | 3.08 | |
| Available wind energy (MWh) | 35702.3 | |
| Mean wind-powered pumped storage system output power (MW) | 2.78 | 3.36 |
| Standard deviation of hybrid station output power (MW) | 1.96 | 1.84 |
| Wind energy generated (MWh) | 24256.5 | 24256.5 |
| Wind energy used for pumping (MWh) | - | 7323.0 |
| Wind energy spilt (MWh) | 11445.8 | 4122.8 |
| Energy generated by the pumped storage station (MWh) | - | 4975.3 |
| Energy generated by the wind-powered pumped storage system (MWh) | 24256.5 | 29231.8 |

Comparing the simulation results of operation in the two cases, it is apparent that when wind farm operate independently, a large amount of wind energy which may be abandoned, but now it is utilized to provide power for pump to pump water, so the wind-powered pumped storage station improves the utilization of the available wind energy effectively. Besides, the volatility of the power output (standard deviation by its rough estimated) decreases slightly by about 6%.

The data used in this paper were sourced from the literature [12-13]: the static investment cost of wind farm is 8,000 yuan/kW, a variety of state subsidies to wind power is 0.5yuan/kWh; static investment cost of pumped storage power station is 3700 yuan/kW; the annual operating rate of wind-powered pumped storage system is 0.025; other additional annual operating expenses is 15% of the annual operating expenses, and payback period $L = 20$; discount rate $r = 0.07\%$; generally, assuming that peak-valley price: 22:00~8:00: 0.25 yuan/kWh; 8:00 ~ 22:00 0.6 yuan/kWh. The peak price is assumed to be fixed at 0.45 yuan/kWh which is the arithmetic mean value.

The data obtained above is employed to calculate the formula (9)-(10) where $\Delta P$ is set to be 4975.3MWh. Results indicate that compared to ordinary wind power systems, the added economic benefit of the new wind-powered pumped storage system is about 5479.49 yuan/d.

## 5. Conclusion

The comprehensive analysis of this numerical example shows that wind-powered pumped storage system provides huge operating advantages for the power system. The advantages are as follows:

(1) When there is plenty wind with low load, wind energy would be abandoned due to output restrictions on wind power generation. Simulation results show that the spilt wind energy can be stored by pumping water to the upper reservoir. This energy is subsequently reused when the constraints of the conventional generating units are eliminated (such as peak load periods). In addition, if a peak-valley price system is applied, with a higher energy price during the peak load period, there will be much more economic benefits for the operators of the wind-powered pumped storage system.

(2) The objective of smoothing of the wind power output can be realized by setting a target for the output of wind-powered pumped storage system, and using the pumps and turbines to balance the excess or deficit wind power. In this paper, the results of standard deviation of power output show that the wind-powered pumped storage system can offer a smoothing wind turbine power output in a short term.

However, peak-valley price system is not taken into consideration directly in this paper and the power output is roughly estimated by the standard deviation results. Therefore, further study is required to obtain more accurate conclusions.

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