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Research and Application of Energy Storage Battery on Stabilizing Fluctuation Characteristics of Photovoltaic Power System

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Abstract

Photovoltaic power generation is clean, non-polluting, inexhaustible, but its characteristics of randomness, volatility and intermittent also produce its negative effects on power system economic, safe and reliable operation, which cannot be ignored. Storage battery in photovoltaic power generation system can not only absorb excess energy reserves, but also can stabilize the fluctuation, cut a peak to fill the valley and the stable voltage, it is very important and key part, At the same time, the energy storage capacity of the rational allocation of system not only for the photovoltaic power generation system of construction cost, also affects the performance and the service life of the system. This paper is based on the amount of solar radiation data of Liaoning area, proposed the hypothesis that PV fluctuation characteristics accord with normal distribution characteristics ,and fitted by normal distribution probability density function, verified the assumption of normal distribution, and proposed a selection strategy of energy storage power based on the normal distribution, Established mathematical model of battery energy storage capacity configuration, and regards the total power standard deviation, fluctuation of power capacity and power fluctuation rate as evaluation indicators to measure the effects of the long-term and short-term fluctuation of the storage battery on stabilizing fluctuation of photovoltaic power generation , through the examples and simulation proved that the model is correct and reasonable.

Keywords*: photovoltaic power generation; normal distribution; energy storage; stabilize fluctuation*

1. Introduction

In recent years, renewable energy has become the main supporting source in the world future energy structure, and as the representative of the renewable energy, photovoltaic power generation, may become a hotspot in the field of renewable energy power field. Photovoltaic power generation is clean, non-polluting, inexhaustible, but its characteristics of randomness, volatility and intermittent also produce its negative effects on power system economic, safe and reliable operation, which cannot be ignored. Literature [1] quantitatively analyses the volatility level PV output, the fluctuation characteristics of photovoltaic output on different -time scale. Literature [2-5] points out the adverse effects of photovoltaic output volatility to the safety and stable operation of the power grid. Energy system optimization technology of renewable energy power generation has made some achievements, mainly focus in the energy storage device and a storage capacity of two aspects. Literature [6] through FFT algorithm verifies that the low frequency dynamic characteristics of the photovoltaic fluctuation can stabilize by energy storaging, and puts forward the operation strategy about the using of energy storage battery

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stabilizing the short-term vibration of the photovoltaic output and the evaluation method of optimal capacity of battery. Literature [7] presents a method of energy optimization control system of battery capacity based on model prediction control to the real-time stabilization on power fluctuation of wind farm. Literature [8]uses the vanadium flow battery as energy storage component, regards wind power filtrated by low pass filter as the control target, combines with the AC/DC converter power decoupling control, establishes the control strategy balancing the fluctuating wind power based on VRFB energy storage system. Document [9] refers to decomposition of wind power fluctuation power, organically combination with the battery and super capacitor, composition of hybrid energy storage system by parallel connection, real-time stabilization on wind power fluctuation. Literature [10] by optimizing the storage capacity to improve the output power fluctuation, the proposed method is simple and easy, but do not consider to cope with the problem of the energy storage system and renewable energy.

Research shows that the storage battery can stabilize the PV fluctuation, but should be optimizing the allocation of in-depth study of its capacity in combination with storage batteries and photovoltaic power generation system on, Through the stability of using normal distribution function curve fitting curves of PV fluctuation, and the article presents the selection strategy of normal distribution storage capacity based on the standard deviation. It regards the total power, power fluctuation and the power fluctuation rate as the evaluation index, and uses the Matlab simulation, verifies the effect of selection method of storage battery.

2. Photovoltaic fluctuation characteristics

Taking Liaoning area as an example, the monthly change of total solar radiation show a single peak which is large in spring and summer, and small in autumn and winter. Total radiation maximum value appears in May, the lowest value appears in the December. Season total radiation accounts for the total annual amount of radiation 31.4%, 32.7%, 21.3% and 14.5% in spring, summer, autumn and winter. The feature of Sunshine hours is the most in spring, and the second one is in summer, the least is in winter, as shown in Figure 1. But the daily change of total solar radiation corresponds with the movement of sun sunrise and sunset. In Figure 2 shows diurnal variation of total solar radiation. As for the annual average situation, diurnal variation of the total radiation showed normal distribution between 11:00and 12:00 as the center. It had the tiny amount of radiation from 4:00 to 5:00 in the early morning and reached the maximum from 11:00 to 12:00, and then gradually began to reduce to disappear after 20 hours.

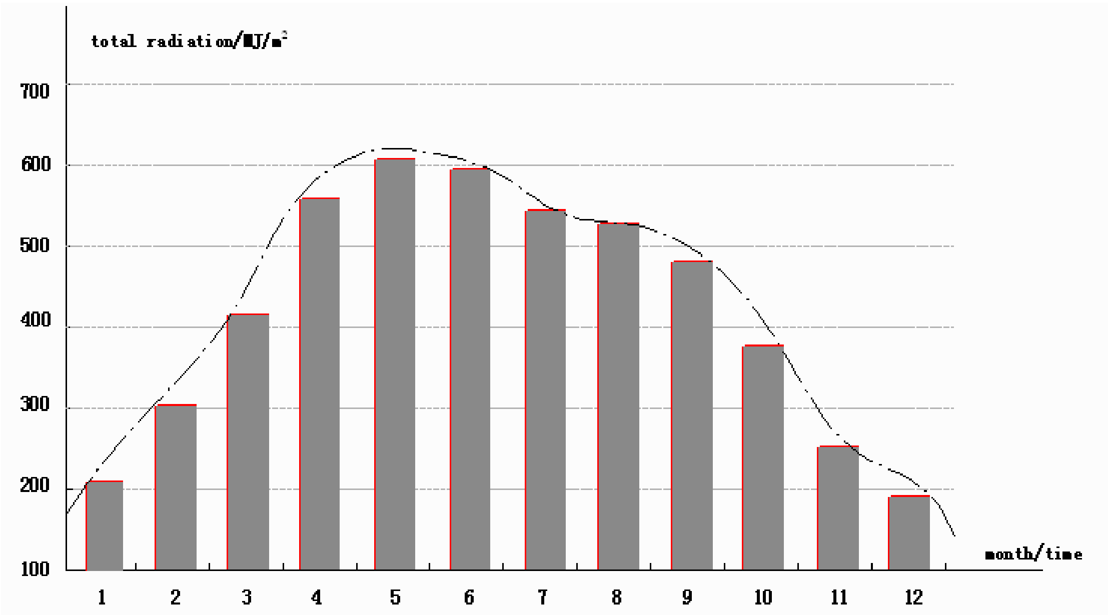


Figure 1. Seasonal Changes Curve of Total Solar Radiation Intensity

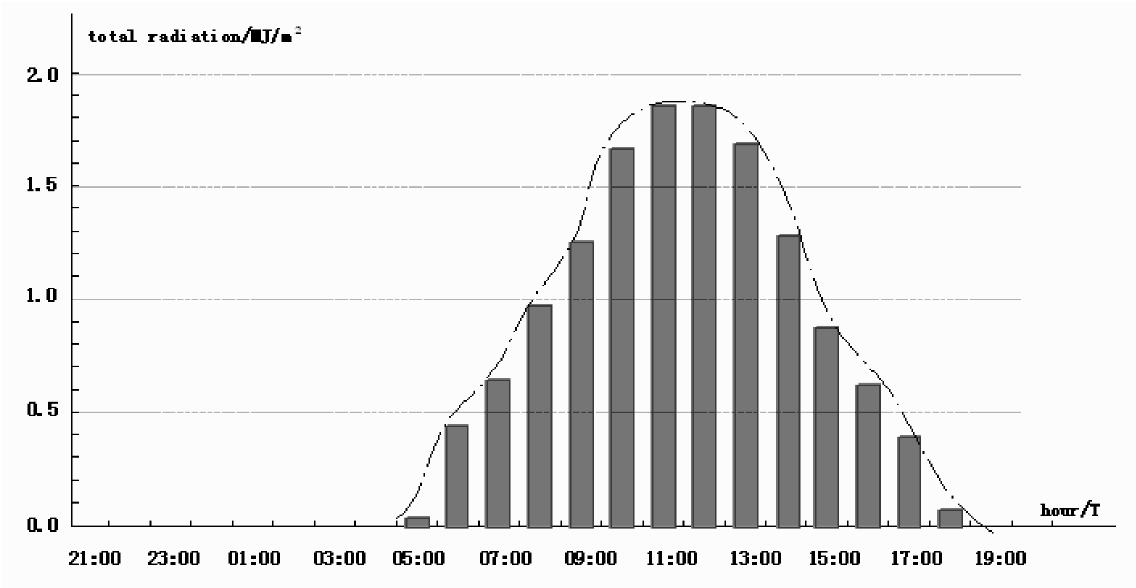


Figure 2. Diurnal Variation of the Total Solar Radiation

The basic principle of photovoltaic power generation is based on the photovoltaic effect, use of photovoltaic panels convert solar energy into electrical energy component. The actual output of photovoltaic panels within t moment (P_t) can use formula (1) calculated [11] ：

$$P_t = P_{stc}\frac{I_{r\cdot t}}{I_{stc}}[1+\alpha_T(T_t - T_{stc})] \qquad (1)$$

In the formula, P_{stc} is output of photovoltaic panels in standard conditions (corresponding to the solar radiation intensity I_{sc}=1000W/m^2, the temperature of T_{stc}=25℃); α_T as the temperature coefficient of power photovoltaic panel; $I_{r\cdot t}$ is the actual intensity of solar radiation at time t; Tt is temperature of photovoltaic plate at time t.

From equation (1) can be seen, the output of main parameters related to the photovoltaic panel is the intensity of solar radiation Ir*t and temperature T, a rough calculation which not considering the latitude and longitude, shadows, occlusions and other uncertain factors, can be considered that a linear relationship between the output power of photovoltaic cells and solar radiation.

Assuming that P_t obeys normal distribution of X ~ N (μ, σ^2) , then the probability density function:

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

In the formula, μ is the mean, σ is variance.

Based on the different time scales of the PV output data of normal distribution function fitting, observe the photovoltaic output whether accord with normal distribution. In order to measure the fitting results, the evaluation index was defined, the expression for the:

$$I = \mathrm{d}^2 \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{y_i} - \mathrm{m_i})^2 \tag{3}$$

Of which, d for frequency distribution histogram group distance; i=1, 2... n; n is the number of packets histogram; y_i is a value of fitting the probability density at the i bin center position; m_i is the i histogram column height of data frequency distribution, index of i is more smaller, the fitting effect is better. Table 1 is from one minute to 150 minute of PV output fluctuation data fitting.

Table 1. Different Time Scale Photovoltaic Output Fluctuation Fit Index

time scale/(min)	fit index/(i)	time scale/(min)	fit index/(i)
1min	0.1601	50min	0.0037
2min	0.1030	60min	0.0034
5min	0.0796	90min	0.0039
10min	0.0246	100min	0.0035
20min	0.0149	120min	0.0032
30min	0.0104	130min	0.0027
40min	0.0046	150min	0.0018

From the data in Table 1 can be seen, with the continuous increase of time scale, the fitting index of i gradually stabilized, indicating the probability distribution of the PV output fluctuation is approaching normal distribution.

3. Stabilizing Strategy of Energy Storage System

For photovoltaic spectrum analysis [6] showed by FFT algorithm, the low frequency area of more than 95.5% PV fluctuation, can be stabilize through the storage battery. According to the law of conservation of energy and low pass filtering principle, the actual output of photovoltaic battery power, storage throughput and the light output power stabilized by the storage battery satisfy the following relationship:

$$P_{o(\mathrm{s})} = \frac{1}{1+\tau s} P_{V(S)} \tag{4}$$

$$P_{B(s)} = P_{V(s)} - P_{o(s)} = \frac{\tau s}{1+\tau s} P_{V(S)} \quad (5)$$

$$\tau = \frac{1}{2\pi f_c} \quad (6)$$

$P_{v\,(s)}$ for photovoltaic power, $P_{B(s)}$ for storage battery power, $P_{o(s)}$ is for the PV output power stabilized by the energy storage battery, τ as the time constant, f_c as the cut-off frequency. In the formula, such as $P_{B(s)}>0$ for the battery power output, in a discharging state, $P_{B(s)}<0$, for the battery power absorption, in a charging state. On the type of discretization, with t as the control period, in the tk=kt (k=1, 2, 3....n) moment:

$$P_{V(k)} = \tau \frac{P_{o(k)} - P_{o(k-1)}}{t} + P_{o(k)} \quad (7)$$

Solution:

$$\begin{aligned} P_{o(k)} &= \frac{\tau}{\tau + t} P_{o(k-1)} + \frac{t}{\tau + t} P_{V(k)} \\ &= (1-\lambda) P_{o(k-1)} + \lambda P_{V(k)} \end{aligned} \quad (8)$$

Among $P_{o(k)}, P_{o(k-1)}$ were the output power of k, k-1 moment, $\lambda = \frac{t}{\tau + t}$. By iterativering:

$$\begin{aligned} P_{o(k)} &= \lambda P_{V(k)} + (1-\lambda)(\lambda P_{V(k-1)} + (1-\lambda) P_{o(k-2)}) \\ &= \lambda P_{V(k)} + \lambda (1-\lambda) P_{V(k-1)} + (1-\lambda)^2 P_{o(k-2)} \\ &= \lambda \sum_{j=0}^{k-1} (1-\lambda)^{i} P_{V(k-j)} + (1-\lambda)^k P_{o(1)} \end{aligned} \quad (9)$$

By formula (9), when $\lambda \to 0$, instant $\tau \to \infty$, output power after stabilization is approximate Po(1)'s line, so the time constant determines the stabilizing effect and the cost of investment, but also the selection of key storage capacity.

4. Capacity Selection Based on the Normal Distribution of Energy Storage

The normal distribution 3 principles: P ($\mu-\sigma$<X≤$\mu+\sigma$) =68.3%, P (μ-2σ<X ≤μ+2σ) =95.4%, P (μ-3σ<X≤μ+3σ) =99.7%. σ describe the discrete degreet of **the** normal distribution of data distribution, σ is larger, data distribution is more dispersed, σ is smaller, data distribution is more concentrated, It is also known as the shape parameter of the normal distribution, σ is bigger, the curve is flatter, conversely, σ smaller, the curve is sharp. As shown in Figure 3.

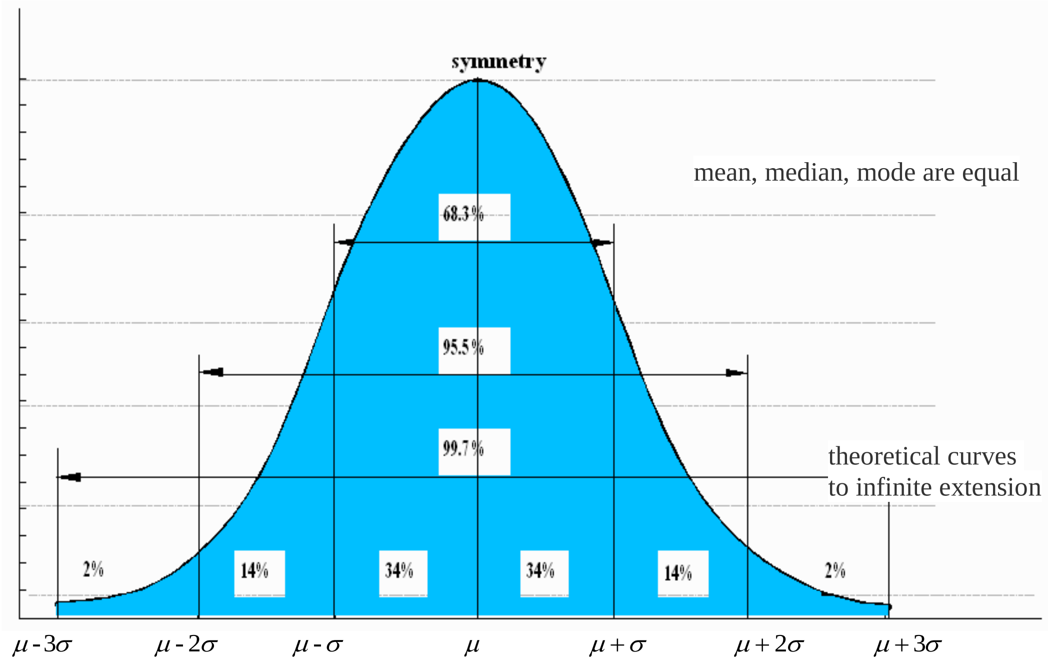


Figure 3. Normal Distribution 3σ

Based on the normal distribution function properties, energy storage change range of system output power:

$$\left|P_{B(k)}\right| \leq \Delta P_{V\max(t)} - \Delta P_{o\max(t)} \tag{10}$$

$P_{B(k)}$ for energy storage system t power output for the moment, $\Delta P_{V\max(t)}$for the maximum T power fluctuation photovoltaic output before stabilization, $\Delta P_{o\max(t)}$for the maximum T power ramp rate allowed value.

Based on the principle of normal distribution 3σ, in the interval $(\mu-3\sigma, \mu+3\sigma)$ to calculate the output power value of the energy storage by stabilizing fluctuations photovoltaic.

$$\mu_1 = \overline{P_B} = \frac{1}{i} \times \sum_{0}^{i} \left|P_{B(k)}\right| \tag{11}$$

$$\sigma_1 = \sqrt{\frac{1}{i}\left[(P_{B(1)} - \overline{P_B})^2 + (P_{B(2)} - \overline{P_B})^2 + \ldots + (P_{B(k)} - \overline{P_B})^2\right]} \tag{12}$$

$\overline{P_B}$ shows sample in t_i time average power of the storage power, i is the number of samples, μ_1, $\sigma_1$respectively is the mean and standard deviation in the sample. Then the energy storage power can be selected as:

$$P_B = MAX\left\{\left|\mu - 3\sigma\right|, \left|\mu + 3\sigma\right|\right\} \tag{13}$$

By formula (7) have to:

$$\left|\frac{tP_{B(k)}}{\tau}\right| = \left|P_{o(k)} - P_{o(k-1)}\right| \leq \Delta P_{\max(t)} \tag{14}$$

$$\tau \geq \left|\frac{tP_{B(k)}}{\Delta P_{\max(t)}}\right| = \left|\frac{tP_B}{\Delta P_{\max(t)}}\right| \tag{15}$$

So we can select the time constant of the minimum value:

$$\tau = \left| \frac{tP_B}{\Delta P_{\max(t)}} \right| \tag{16}$$

This can stabilized photovoltaic power fluctuation frequency above f_c.

Energy storage capacity is a integral of storage system power ($P_{B)}$ in the time domain, given to the type (5) the Laplace inverse transform and integration in sampling time between t and t_0 available:

$$E(t) = \int_{t_0}^{t} L^{-1}(P_{B(s)})dt = \int_{t_0}^{t} e^{-\frac{t}{\tau}}(P_{B(t)})dt \tag{17}$$

E $_{(t)}$ as the energy storage capacity of the battery of the real-time throughput, values is change as different time of T. But meet the following formula:

$$0 \leqslant E(t) \leqslant Emax(t) \tag{18}$$

5. Evaluation Index

The domestic and foreign literature presents many guiding storage capacity ratio index on wind-solar-storage power supply system, The introduction presents the two evaluation indexes η_{LPSP} and η_{EXC} of evaluating the storage capacity, which are used to cited in wind-solar-storage power supply system by current international more references , respectively is the system reliability and economic indicators, can be indirect evaluation system and mentioned in the current domestic and foreign literature.

η_{LPSP} is the ratio of system unsatisfied load demand and total load demand of the evaluation period[12],It is a widely used standard application engineering optimization capacity configuration of wind-solar-storage power supply combined system. When the battery discharge to the minimum value of C_{batmin}, control system disconnect the connection of the battery and load, this moment load demand cannot be satisfied.

Value of the loss of power supply at t time:

$$E_{LPS}(t) = P_{load}\Delta t - [P_{pv}(t)\Delta t + P_{WG}(t)\Delta t + C_{bat}(t) - C_{bat\min}]\eta_{inv} \tag{19}$$

Within the evaluation period T, power supply loss rate is expressed as:

$$\eta_{LPSP}(T) = \sum_{t=1}^{T} E_{LPS}(t) / \sum_{t=1}^{T} P_{out}(t)\Delta t \tag{20}$$

In the formula, $E_{LPS}(t)$ is the value of the loss of power supply at t time; T as the evaluation period, Δt for calculating the step.

η_{EXC} is the ratio of power wasting of wind&PV generation and the total output power at evaluation period[13], when $P_{V(T)}$ +$P_{W(T)}$ +$P_{B(T)}$ =$P_{out(T)}$ >$P_{ref(T)}$, then the power wasting of wind&PV generation is:

$$E_{waste}(t) = P_v(t)\Delta t - \frac{P_{ref}(t)\Delta t}{\eta_{inv}} + \frac{C_{b\max} - C_b(t-1)}{\eta_{cha}} \tag{21}$$

$$\eta_{EXC}(T) = \frac{E_{waste}(t)}{2\sum_{t=1}^{T} P_{out}(t)\Delta t} \tag{22}$$

E_{waste} is the energy waste of wind and solar power on the basis of system power requirements and energy storage element charging requirements.

The above evaluation indexes are mainly the reliability evaluation of power source for the wind and solar, But still not has a comprehensive evaluation on the different capacity storage a in stabilize power fluctuation capability indices, On the basis of this, the paper put forward two indexes by measuring the power characteristics of photovoltaic system which are the general power deviation rate and power fluctuation rate. The output fluctuation of photovoltaic power generation is divided into the second level of the ultra-short term fluctuations, minute level short-term fluctuations and hours or days level mid volatility, defined statistics in months or years for long-term fluctuations, the total power deviation rate was used as the index to evaluate the energy storage battery to stabilize the photovoltaic effect of long-term fluctuations, the evaluation index to power fluctuation rate as to stabilize short-term fluctuation effect, and then choose the optimal storage capacity configuration.

4.1 Total Power Deviation Rate

Power is a random variable to describe relative to the reference value of the degree of deviation from P_{ref}, α value is small, that stabilize the output power and the relative stability and smooth.

$$\alpha = \frac{1}{n}\sqrt{\frac{\sum_{\mathrm{i=1}}^{\mathrm{n}}(P_{i(t)} - P_{\mathrm{ref(t)}})}{P_{\mathrm{ref(t)}}}} \tag{23}$$

4.2 Power Fluctuation Rate

The ratio of the power fluctuation $\Delta P_{n(i)}$ and installed capacity.

$$\Delta P_{n(i)} = \sum_{i=1}^{n}\left|P_{i(t)}\right| - \sum_{i=1}^{n}\left|P_{(i-1)t}\right| \tag{24}$$

$$\beta = \frac{\Delta P_{\mathrm{n}}}{P_{\mathrm{Q}}} \times 100\% \tag{25}$$

In the formula, $P_{i(t)}$, $P_{(i-1)\ t}$ were the output power of PV at the first i sampling and i-1 sampling time, P_{ref} as a reference value, is equal to the power average value generally, P_Q is installed PV capacity, t is the sampling time.

5. The Example Results and Analysis

The analysis program is written with Matlab in this paper, calculating the total output power of photovoltaic system, the initial capacity of storage battery and charge and discharge power energy, thereinto, the photovoltaic installed capacity is 2800KW, to simplify calculation, the example in one min steps, PV input 20min power discrete power sequence, and assume that at each simulation step, the storage battery terminal the voltage remains constant, calculation of indicators, T=20, Δt =1, efficiency ζ =0.8, power expectation function reference value $P_{ref\ (t)}$ =2000 KW, $0 \le P_B \le 800$KW.min(the storage battery configuration capacity range).

Figure 5 is a group of contrast curves of photovoltaic power generation output by stabilizing storage battery before and after, Figure6 is a change curve of battery energy storage throughput power, active power is positive, indicates storage battery power absorption, it is in a state of charge, the active power is negative, indicates storage battery power, it is in a discharge state. Through the shape of T curve in 30min ~ 120min period analysis, storage battery throughput power and abscissa axis intersection of 38 times, which is the battery charge and discharge 38 times, every time charge and discharge in a few minutes, but the battery minimum response time for a few seconds, visible, in the allowable operating range, energy storage the battery system to the level fluctuation amount of hours can play a better stabilize effect for photovoltaic power minutes.

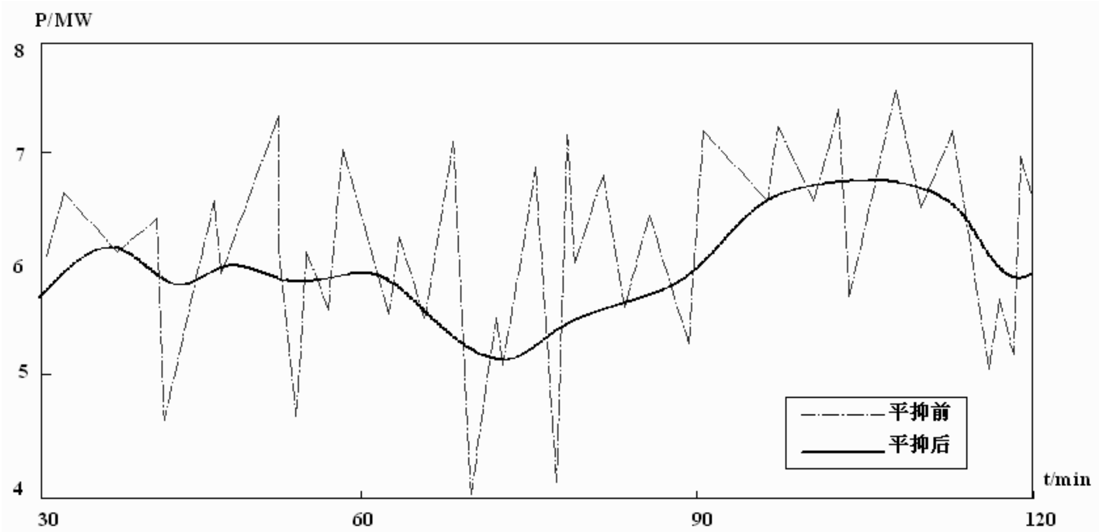


Figure 5. PV Power Output Curve of Stabilizing By Storage Battery before and After

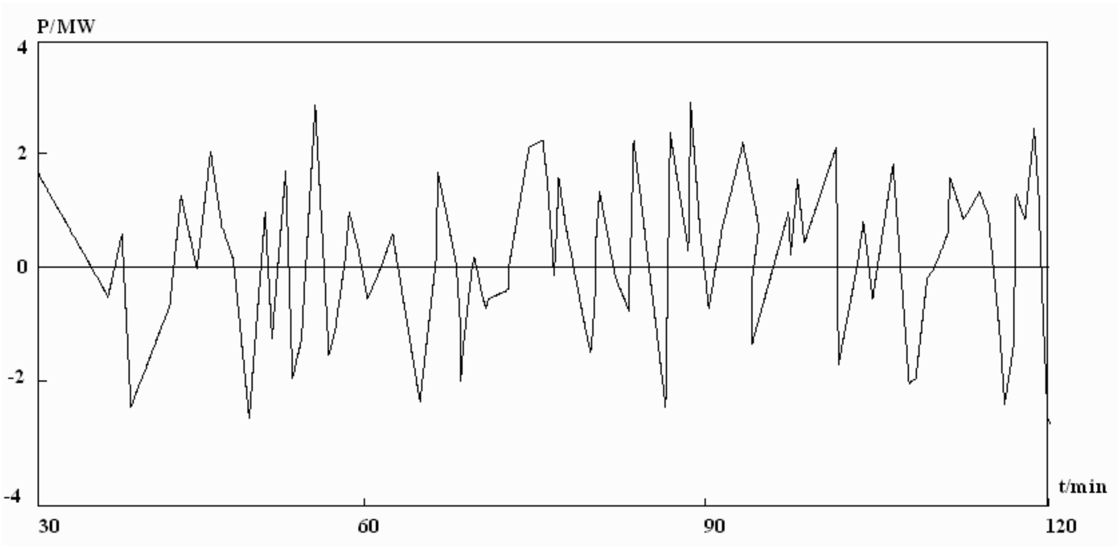
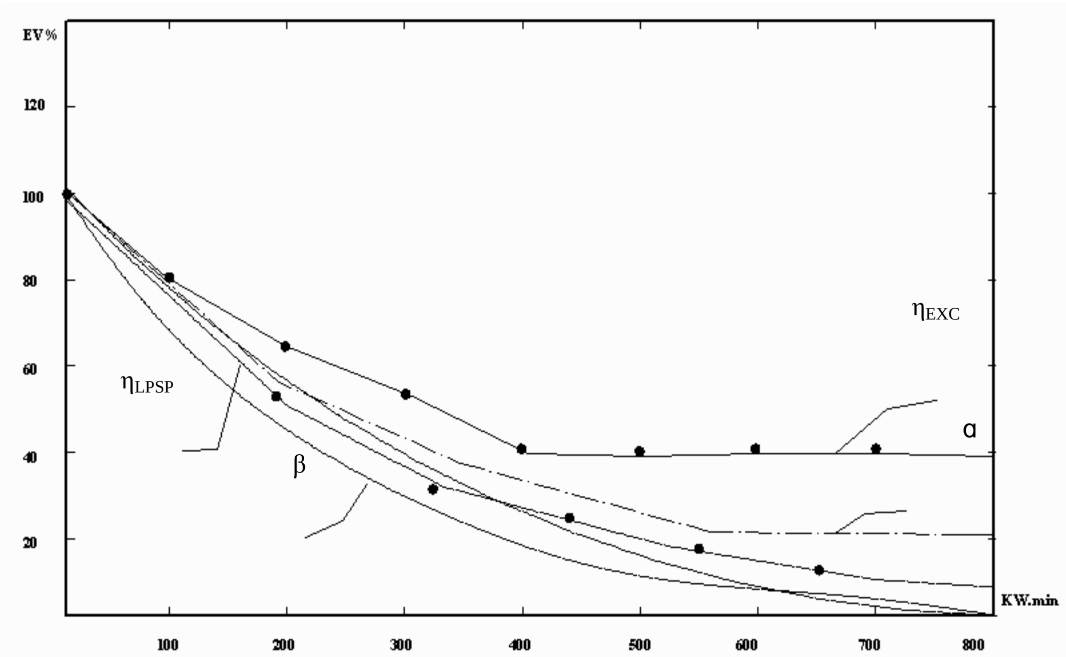


Figure 6. Throughput Power of Storage Battery

Whether the storage capacity selection being the best depends on the evaluation index, as shown in Figure 7 the change of evaluation index of output under the condition of different energy storage capacity. Visibly, evaluation index trend also changes along with the change of the energy storage capacity. When the storage capacity increases in 0-400KW.min interval, index curve steepens, when the storage capacity in the range of 500-800KW.min increases, the basic indicators tend to smooth. The change trend of α and β, when the energy storage capacity changes in the 400-800KW.min the α basically keeps unchanged, the β decreased obviously. And this shows that in the system with big energy storage capacity, α cannot measure the changes under different storage capacity, while β can obviously distinguish the difference. The main reason is, in the principle of not wasting energy, when P_Q is greater than P_{ref} (photovoltaic and adequate margin and in the case of the battery being full), the total output power of the system is greater than the load demand, therefore cannot stabilize fluctuations by increasing the storage capacity. So α basically keep unchanged, while β changes obviously after ruling out of this situation. When the energy storage capacity has gradually increased to more than 400KW.min, the energy waste is great. This shows that reduce of the reliability of power supply and power fluctuation is based on energy waste.

Figure 7. Change of Evaluation Index of Output under Different Storage



5. Conclusion

Through the analysis of illumination variation curve of solar radiation, the paper puts forward the photovoltaic output fluctuation characteristic is accord with normal distribution function, and has carried on the normal distribution function curve fitting in different time scales, by fitting the index results show that, with increasing time scale, the normal distribution fitting effect tend to be more stable, verify the hypothesis above mentioned that the characteristics of photovoltaic output fluctuation accord with normal distribution.

In this paper, set up a mathematical model of battery energy storage capacity configuration normal based on normal distribution with 3 principle, and combined with the evaluation index of common engineering standard η_{EXC} and η_{LPSP} , considering the photovoltaic long term and short term fluctuation characteristic, put forward to join the general power deviation rate of and power fluctuation rate to stabilize the fluctuation of evaluation index, Through the example to the power fluctuation minimum, energy waste less premise as the goal, to select the best storage battery capacity.

In this paper, the storage battery capacity when the selected has yet to consider the economic costs of index, the need in future studies to further in-depth discussion.

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