Battery–supercapacitor hybrid energy storage system for wind power suppression based on the turbulence model of wind speed

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Abstract: Based on the turbulence model, the volatility of real-time wind speed is discussed, which is composed of an average component and a fluctuant component. By deriving the probability density function of fluctuant wind speed and investigating the probability density curve, the authors decompose the fluctuant wind power into the steady fluctuation and peak fluctuation. According to the properties of steady fluctuation and peak fluctuation, the authors determine that the energy storage system applied into the real-time wind power fluctuation should be of the performance of high power density, high energy density and long cycle life. Through the comparative analysis on the energy storage performance, the battery and supercapacitor are proved to be suitable for regulating the steady and peak fluctuation, respectively. According to that task assignment, the energy storage performance of a battery–supercapacitor hybrid system is investigated. Based on the wind power decomposition, this study develops a new capacity configuration method for the hybrid system and gives an example analysis. By that method, the battery and supercapacitor in the hybrid system can be allocated proper energy and power capacity to balance the steady and peak fluctuation, respectively. Consequently, their energy storage merits can be fully utilised.

1 Introduction

With the development in wind turbine technologies, the wind power generation has become competitive with other conventional power generation patterns [1–3]. The fluctuant wind power will bring many negative impacts to the stable operation of power grid. In order to achieve the large-scale integration of wind power into electric power system, the technique for the real-time wind power regulation becomes essential [4, 5].

The volatility of wind speed has a direct influence on the output power of wind turbines. The research on the characteristics of wind speed has been widely carried out to lay theoretical foundation for the real-time wind power suppression. Some researchers have proposed that the wind speed obeys the Gaussian, chi-square, Weibull or Rayleigh distribution [6–8]. The linear regression method, maximum likelihood method and Bayesian method were utilised to obtain the distribution function of wind speed. Furthermore, the clustering method was adopted to discuss the fluctuation of wind speed [9]. However, those above-mentioned modelling methods emphasised the statistical description on the average wind speed within 10 min or longer. With regard to the dynamic model of real-time wind speed, a model composed of a basic component, a gusty component, a ramp component and a random component was commonly adopted, especially in the simulation system [10]. However, the parameters in that model were hard to determine. The analysis on the operation data of wind farm was considered as another feasible approach to reveal the fluctuation characteristic of real-time wind power. In that field, the Poisson process and the time sequence method were utilised by many researchers [11]. During the course of balancing fluctuant wind power in real time, the calculation results obtained by that method often lag behind the variation of real-time wind power. As the main motion morphology of the atmosphere is turbulence, the turbulence model is considered as another effective way to describe the real-time wind speed [12, 13]. With the presence of supersonic-flow anemometer, the real-time measurement and statistical analysis became the main method to study the property of atmospheric turbulence [14]. In USA and Norway, the database of local atmospheric turbulence has been established, which can precisely describe the fluctuation properties of real-time wind speed [15].

The battery and supercapacitor are considered as good solutions to wind power regulation. For the purpose of reducing the investment and maintenance cost, the capacity configuration method for the battery or supercapacitor energy storage system has drawn plenty of interests. In [16], an objective function that measured the economic benefit obtainable from the dispatched power from the wind farm against the cost of the battery energy storage system (BESS) was discussed. Based on the statistical long-term wind speed data captured at a wind farm, Li et al. [17] proposed a dispatch strategy for the battery capacity so as to maximise a defined service lifetime/unit cost index of the energy storage system. Jiang and Wang [18] developed a flexible first-order low-pass filter to limit the power fluctuation under restriction with smaller BESS capacity. The authors in [19, 20] proposed new algorithms to properly size the battery–supercapacitor hybrid system, in which the technical merits of the two energy storage media have been taken into consideration. However, those methods did not focus on analysing the fluctuating characteristics of real-time wind power.

In this paper, we handle a research on the volatility of real-time wind speed based on the turbulence model. According to the turbulence model, the probability density function of fluctuant wind speed is deduced and the fluctuant wind power $P_{\text{wave}}$ is decomposed into steady fluctuation $P_{\text{steady}}$ and peak fluctuation $P_{\text{peak}}$. Also, the properties of $P_{\text{steady}}$ and $P_{\text{peak}}$ are investigated. By a comparative analysis of the performance of battery and supercapacitor, the suppression task for battery and supercapacitor is assigned. Accordingly, the performance of the battery–supercapacitor hybrid system is discussed by a mathematical derivation. Then, we develop a new method for the capacity configuration of battery–supercapacitor hybrid system based on the decomposition of wind power fluctuation. Finally, we carry out an example analysis to illustrate the proposed capacity configuration method.
2 Decomposition of wind power fluctuation based on the turbulence model of real-time wind speed

2.1 Turbulence model of real-time wind speed

In the wind farm, the wind driving the wind turbines belongs to the atmospheric boundary layer, where the material and energy exchange between the atmosphere and the earth surface takes place. In the atmospheric boundary layer, the Reynolds number is large, and therefore, the main motion morphology of the atmosphere is turbulence [12, 13].

The turbulence is of complex nature, unordered and universal [21, 22]. Meanwhile, the time and space scale of turbulence are broad. In 1973, Taylor and Kármán defined turbulence as an unordered and random fluid motion in time and space domain [23]. The similarity theory of atmospheric boundary layer proposed by Monin and Obukhov laid theoretical foundation for the establishment of turbulence theory of the atmospheric boundary layer [24]. Some researchers suggest that the atmospheric turbulence has the following characteristics [25]:

- In time and space domain, the atmospheric turbulence follows an unordered and random fluid motion.
- The whirlpool is the main movement pattern, accompanied by the interaction between vorticity and strain.
- Its behaviour is unrepeatable. However, its statistic property is predictable.
- The atmospheric turbulence is intermittent.

Reynolds proposed that the turbulence could be decomposed into average and fluctuation components [26]. Consequently, the real-time wind speed $V$ can be decomposed into the average wind speed $\bar{V}$ and the fluctuant wind speed $\Delta V$ [13, 27]. $\bar{V}$, which varies slightly, represents the average of the air velocity within 10 min. In a certain time length, $\bar{V}$ can be considered as a constant. However, $\Delta V$ induced by the irregular motion in atmospheric turbulence often varies frequently and rapidly and can be considered to be non-linear and fluctuant in time and space domain. As a result of the existence of $\Delta V$, the real-time wind speed $\bar{V}$ in the wind farm fluctuates irregularly and intermittently along the average value determined by $V$. In general, the fluctuant wind speed $\Delta V$ regarded as the stable ergodic random process follows the Gauss distribution [13, 27]. Therefore, the probability density function of $\Delta V$ is expressed as

$$ f_{\Delta V}(x) = \frac{1}{\sqrt{2\pi} \sigma} e^{-x^2/(2\sigma^2)} \tag{1} $$

Based on (1), we can carry out researches on the stochastic volatility of real-time wind speed.

2.2 Volatility of real-time wind power

In order to fully exploit the wind energy, the variable speed pitch regulated wind turbine is widely constructed in the wind farm. The variable speed pitch regulated wind turbine often operates at the maximum wind energy capture mode. At that mode, the wind power varies with the wind speed.

According to the turbulence model of the real-time wind power, $\bar{V}$ represents the average speed of air flow in the wind farm. Thus, $\bar{V}$ determines the average power of wind farm. According to $\bar{V}$, we can establish the reference power value $P_{ref}$ for the wind farm. At the same time, the real-time wind speed $\bar{V}$ in wind farm contains the mass fluctuation component $\Delta V$ that often accounts for 50% of the real-time wind speed. As a result, the wind power fluctuates irregularly and rapidly to a large extent along with the reference value $P_{ref}$ determined by $\bar{V}$.

2.3 Decomposition of wind power fluctuation based on the turbulence model

As a kind of power source in power grid, the wind farm should be able to offer a constant and controllable power supply to the power grid. Consequently, we carry out research on the decomposition of wind power fluctuation to lay a theoretical foundation for the real-time wind power regulation.

The real-time power generated by the wind turbine operating at the maximum wind energy capture mode contains the average and fluctuant component, as shown in the following equation:

$$ P_{\text{real}} = P_{\text{wave}} + P_{\text{ref}}. \tag{2} $$

where $P_{\text{ref}}$ and $P_{\text{wave}}$ are caused by $\bar{V}$ and $\Delta V$, respectively. Generally, $\bar{V}$ can be obtained by the wind speed forecasting. Therefore, $P_{\text{ref}}$ can be considered as the reference value for wind power generation. Under the maximum wind energy capture mode, $\Delta V$ makes the real-time wind power $P_{\text{real}}$ deviate from $P_{\text{ref}}$. $P_{\text{wave}}$ induced by $\Delta V$ is the fluctuant wind power needing to be regulated in real time. The value and probability distribution of $\Delta V$ will have a direct influence on $P_{\text{wave}}$

As discussed above, $\Delta V$ follows the Gauss distribution. Then, we can derive the distribution function of the amplitude of $\Delta V$ ($\Delta V\|\bar{V}$). Assuming that the distribution function of $|\Delta V|$ is $F_{\Delta V}(y)$, $y = \Delta V$. $F_{\Delta V}(y)$ can be derived as follows:

$$ F_{\Delta V}(y) = P(|y| \leq \sigma) = P(|\Delta V| \leq \sigma) = P(-\sigma \leq \Delta V \leq \sigma) = P(\Delta V \leq \sigma) - P(\Delta V \leq -\sigma) \tag{3} $$

According to (1), $P(\Delta V \leq y)$ and $P(\Delta V \leq -y)$ can be obtained separately

$$ P(\Delta V \leq y) = \int_{-\sigma}^{\sigma} \frac{1}{\sqrt{2\pi} \sigma} e^{-x^2/(2\sigma^2)} dx \tag{4} $$

$$ P(\Delta V \leq -y) = \int_{-\infty}^{-\sigma} \frac{1}{\sqrt{2\pi} \sigma} e^{-x^2/(2\sigma^2)} dx \tag{5} $$

Substituting (4) and (5) into (3) and performing derivation calculus, the following equation is deduced:

$$ F_{\Delta V}(y) = \frac{\sigma}{\sqrt{2\pi}} e^{-y^2/(2\sigma^2)} \tag{6} $$

As $F_{\Delta V}(y) = f_{\Delta V}(y)$, the probability density function of $|\Delta V|$ can be given as

$$ f_{\Delta V}(y) = \frac{\sigma}{\sqrt{2\pi}} e^{-y^2/(2\sigma^2)} \tag{7} $$

By (7), the probability density curve of $|\Delta V|$ can be obtained as shown in Fig. 1, where $\sigma_i > \sigma_j > \sigma_k$. According to Fig. 1, it can be seen that the probability decreases with increase in $|\Delta V|$, tending towards zero gradually.

When the wind turbines operate at the mode of maximum wind energy capture, the real-time wind power is proportional to the cube of wind speed. Therefore, the wind power fluctuation will be slight when $|\Delta V|$ is small. On the contrary, the wind power will fluctuate heavily when $|\Delta V|$ is large. According to the distribution
3 Research on the performance of the battery–supercapacitor hybrid system based on the decomposition of fluctuant wind power

3.1 Performance requirement for the energy storage system in real-time wind power regulation

By the integration of a power electronic converter, the energy storage system can be made to exchange power/energy precisely with the wind farm to balance the fluctuant wind power in real time. In general, we set the energy storage system to the low voltage side of transformer substation of the wind farm, as shown in Fig. 2.

In order to make the wind farm dispatchable, the fluctuant power $P_{\text{wave}}$ of the wind farm should be suppressed. By balancing the fluctuant wind power, the power of wind farm can be regulated to track the reference value. When the real-time wind power $P_{\text{ref}}$ is greater than the reference value $P_{\text{ref}}$ the energy storage system should be controlled to absorb the excessive energy as the power $P_{\text{energy}} = P_{\text{wave}} - P_{\text{ref}}$.

On the contrary, the energy storage system should be designed to release energy as the power $P_{\text{energy}} = P_{\text{wave}} - P_{\text{ref}}$ to compensate for the shortage of wind power when $P_{\text{ref}} > P_{\text{real}}$. By that means, the wind power can be dispatched actively. Then, the wind farm will be able to participate in the frequency regulation of power grid.

In the course of regulating fluctuant wind power in real time, the charging–discharging behaviour of the energy storage system depends on the fluctuation characteristics of $P_{\text{wave}}$. The amplitude of $P_{\text{wave}}$ determines the charging–discharging power of the energy storage system. Simultaneously, the duration of $P_{\text{wave}}$ influences the charging–discharging time of the energy storage system. According to the decomposition of $P_{\text{wave}}$, the charging–discharging behaviour of the energy storage system is discussed as follows:

- As $P_{\text{steady}}$ often leads to great energy variation, the energy storage system must be able to store abundant energy to balance $P_{\text{steady}}$.
- As the amplitude of $P_{\text{peak}}$ is large, the energy storage system must be able to endure high-power charging–discharging process for balancing $P_{\text{peak}}$. In the course of suppressing $P_{\text{peak}}$, the energy storage system needs not to store or release plenty of energy as the energy variation induced by $P_{\text{peak}}$ is small.

Furthermore, the wind power always fluctuates in a reciprocate manner because of the reciprocating variation of wind speed. For the wind power regulation, the operation mode of the energy storage system has to be switched frequently between the charging and discharging modes. As a result, a long cycle life for the energy storage system is required.

In conclusion, in the course of suppressing $P_{\text{wave}}$, large power and energy configuration as well as long cycle life are required for the energy storage system. In order to reduce the investment and maintenance cost, the energy storage system should have the properties of high power density, high energy density and long cycle life.

3.2 Comparative analysis on the properties of battery and supercapacitor

3.2.1 Comparison on cycle life: As for the battery, some irreversible chemical reaction will occur when the battery is absorbing or releasing energy. Gradually, the amount of active material in the electrode will decrease. As a result, the internal resistance will increase after frequent charging–discharging cycle. In general, the cycle life of different batteries is as follows: lead-acid battery is about 500–700 charging–discharging cycles, Ni–MH battery is about 800–1000 cycles, Ni–Cd battery about 1000–1200 cycles and sodium-sulphur cell is about 2000 cycles.

The supercapacitor is a kind of energy storage element that lies between batteries and conventional capacitors. It absorbs or releases energy by the charge transfer of surface ion of active material. The charging–discharging process in the supercapacitor is just a physical process without any phase transition and composition change. As a result, the supercapacitor can endure the repeated charging–discharging process, with its cycle life up to $10^{6}$. The supercapacitor is suitable for undertaking the task of absorbing or releasing energy frequently.

3.2.2 Comparison on power density: The power density of the energy storage element reflects the maximum power per weight, volume or price. The power density is considered as an important index to evaluate the charging or discharging ability of the energy storage element.

The discharging power of a battery can be described as follows:

$$P = \sum \eta_{\text{bln}} b_{\text{ln}} + \sum \eta_{\text{bln}},$$

where $b$ represents the Tafel slope, $\eta_{\text{bln}}$ shows the ideal power factor, $i$ is the current density, $\eta_{\text{bln}}$ is the exchange current density, $\eta_{\text{bln}}$ reflects the power loss caused by the ohmic resistance and $\eta_{\text{bln}}$ represents the power loss caused by the polarisation resistance. When the polarisation resistance is relatively small, the discharging power $P$ increases along with the increase in discharging current. If the current keeps on increasing, $\eta_{\text{bln}}$ will increase heavily. The discharging power of the battery will reach the maximum when $dP/dl = 0$. The significant increase in $\sum \eta_{\text{bln}}$ will heat the battery. Eventually, the battery will suffer from a permanent injury. In addition, the charging process of the battery will be limited by the diffusion velocity of ion. If the battery is charged by excessively high current, there will not be enough time for the electrochemical reaction between the active material in the electrode and the electrolyte. Gradually, the capacity of battery will degrade, leading to the fact that the high rate charging–discharging current is not permitted for the battery. In general, the power density of battery is within the scope of 100–500 W/kg.

The supercapacitor is a kind of physical energy storage element. In essence, its charging–discharging process is like the adsorption–desorption process of conducting ions. As a result of the enormous surface area of supercapacitor, a few obstacles will be encountered during that process. Also, the equivalent series resistance of supercapacitor is extremely small. In theory, the charging–discharging process of supercapacitor has no limit. As a result, the
power density of supercapacitor is high, with its value up to several kW/kg.

3.2.3 Comparison on energy density: The energy density of the energy storage element depends on the product of the induced charge \(Q\) in active material and the terminal voltage \(V\). In total, 10% of the effective area in every atom in the supercapacitor is utilised. At the same time, the utilisation ration of the effective area for batteries is 20%. For the same volume or quality, the active material that can be utilised in the battery is more than that in the supercapacitor. Consequently, the energy density of the battery is higher than that of the supercapacitor. In general, the energy density of a supercapacitor is 3–15 Wh/kg. The energy density of various batteries is about 30–120 Wh/kg. For the purpose of reducing the investment cost, the battery is more suitable for the long-term energy storage.

As discussed above, the battery and supercapacitor have their own advantages and deficiencies. Neither the battery nor the supercapacitor can completely meet the performance demand for the energy storage system in the course of wind power suppression. If the single battery is made to balance the fluctuant wind power, excessive power allocation is required for suppressing \(P_{\text{peak}}\). Moreover, the energy storage capacity of battery will not be fully utilised as \(P_{\text{peak}}\) seldom occurs. If the single supercapacitor is employed, the massive energy storage capacity will be essential for balancing \(P_{\text{steady}}\). Due to the low energy density of supercapacitor, the investment will be high.

3.3 Analysis on the performance of the battery–supercapacitor hybrid energy storage system

According to the power density, energy density and cycle life described above, the battery and supercapacitor can be well complementary. Therefore, the battery and supercapacitor are suitable for constituting the hybrid system to enhance the performance of the energy storage system. In order to fully develop the advantages of battery and supercapacitor, the suppression tasks for battery and supercapacitor are assigned as follows:

- The battery undertakes the task of suppressing \(P_{\text{steady}}\) due to its high energy density.
- Due to the advantages of high power density and long cycle life, the supercapacitor is designed to regulate \(P_{\text{peak}}\).

When \(P_{\text{wave}}\) is decomposed into \(P_{\text{steady}}\) and \(P_{\text{peak}}\), the mean value and the maximum value of \(P_{\text{steady}}\) are supposed to be \(P_{\text{steady,ave}}\) and \(P_{\text{steady,peak}}\) respectively. \(T_{\text{steady}}\) represents the duration of \(P_{\text{steady}}\). The energy storage capacity of battery in the battery-supercapacitor hybrid energy storage system can be expressed as follows:

\[
E_{\text{bat}} = P_{\text{steady,ave}}T_{\text{steady}}
\]  

(9)

At the same time, the power configuration of battery is described as

\[
P_{\text{bat}} = P_{\text{steady,peak}}
\]  

(10)

The mean value and the maximum value of \(P_{\text{peak}}\) are supposed to be \(P_{\text{peak,ave}}\) and \(P_{\text{peak,peak}}\) respectively. The duration of \(P_{\text{peak}}\) is assumed to be \(T_{\text{peak}}\). Therefore, in the hybrid system, the energy and power configuration of supercapacitor can be given as

\[
E_{\text{cap}} = P_{\text{peak,ave}}T_{\text{peak}}
\]  

(11)

\[
P_{\text{cap}} = P_{\text{peak,peak}}
\]  

(12)

According to (9)–(12), the energy and power configuration of the battery-supercapacitor hybrid energy storage system can be given by

\[
E_{\text{whole}} = E_{\text{bat}} + E_{\text{cap}}
\]  

(13)

\[
P_{\text{whole}} = P_{\text{peak,peak}}
\]  

(14)

Thus, the power and energy density of the battery–supercapacitor hybrid system can be described as

\[
\text{Per}_{E_{\text{hyb}}} = \left(\frac{E_{\text{whole}}}{P_{\text{peak,peak}}/\text{Per}_{E_{\text{cap}}}}\right) + \left(\frac{E_{\text{cap}}}{P_{\text{cap}}/\text{Per}_{E_{\text{cap}}}}\right)
\]  

(15)

\[
\text{Per}_{P_{\text{hyb}}} = \left(\frac{P_{\text{peak,peak}}}{P_{\text{peak,peak}}/\text{Per}_{P_{\text{cap}}}}\right) + \left(\frac{P_{\text{steady,peak}}}{P_{\text{steady,peak}}/\text{Per}_{P_{\text{bat}}}}\right)
\]  

(16)

where \(E_{\text{bat}}, P_{\text{bat}}, E_{\text{cap}}\) and \(P_{\text{cap}}\) represent the energy and power density of battery and supercapacitor, respectively.

According to the energy storage properties of battery and supercapacitor, it can be derived that

\[
\text{Per}_{E_{\text{bat}}} \gg \text{Per}_{E_{\text{cap}}}
\]  

(17)

\[
\text{Per}_{P_{\text{cap}}} \gg \text{Per}_{P_{\text{bat}}}
\]  

(18)

At the same time, by the task assignment for the battery and supercapacitor, we can obtain that

\[
P_{\text{peak,peak}} \gg P_{\text{steady,peak}}
\]  

(19)

\[
E_{\text{bat}} \gg E_{\text{cap}}
\]  

(20)

According to (17)–(20), (15) and (16) can be simplified into

\[
\text{Per}_{E_{\text{cap}}} \ll \text{Per}_{E_{\text{hyb}}} < \text{Per}_{E_{\text{bat}}}
\]  

(21)

\[
\text{Per}_{P_{\text{bat}}} \ll \text{Per}_{P_{\text{hyb}}} < \text{Per}_{P_{\text{cap}}}
\]  

(22)

It can be concluded by (21) and (22) that the energy density of the battery–supercapacitor hybrid system is slightly lower than that of the battery and far higher than that of the supercapacitor. At the same time, the power density of the battery–supercapacitor is slightly lower than that of the supercapacitor and far higher than that of the battery.

As for the battery–supercapacitor hybrid system, the charge-discharge frequency of battery can be reduced due to the integration of supercapacitor. When the battery–supercapacitor hybrid system is employed to balance the fluctuant wind power, the battery is responsible for balancing \(P_{\text{steady}}\) to avoid being charged or discharging over rated. As a result, the service life of battery in hybrid system can be extended. As a conclusion, the battery-supercapacitor hybrid system possesses the properties of high power density, high energy density and long cycle life. Therefore, the battery-supercapacitor hybrid system can meet the performance demand for the energy storage system in the course of real-time wind power regulation.

4 New capacity configuration method for the battery-supercapacitor hybrid system based on wind power decomposition

In order that the battery and supercapacitor in the hybrid system can be allocated with appropriate capacity to realise the proposed suppression task assignment, we develop a new capacity configuration method based on the decomposition of wind power fluctuation. As for a certain wind farm, the geographical and climatic conditions are relatively stable. Therefore, the fluctuating characteristics of wind power are relatively stable. The capacity configuration can be determined by analysing the historical power data of wind farm with the statistical method.
1922

4.1 Determining $P_{\text{wave}}$

The power deviating from the reference value $P_{\text{ref}}$ of wind power is represented as $P_{\text{error}}$, given as follows:

$$P_{\text{error}} = P_{\text{real}} - P_{\text{ref}}.$$  \hfill (23)

where $P_{\text{real}}$ describes the real-time wind power. According to the technique rule of integrating wind farm into power grid established by the State Grid, we obtain the power data $P_{\text{wave}}$ from $P_{\text{error}}$.

According to the technique rule of integrating wind farm into power grid established by the State Grid, the permitted fluctuation is $\pm 20\% P_{\text{ref}}$. The power beyond that scope is exactly the power needed to be suppressed. Therefore, the fluctuant wind power $P_{\text{wave}}$ can be expressed as

$$P_{\text{wave}} = \begin{cases} 0 & |P_{\text{error}}| < 20\% P_{\text{ref}} \\ \pm (|P_{\text{error}}| - 20\% P_{\text{ref}}) & |P_{\text{error}}| > 20\% P_{\text{ref}} \end{cases}$$  \hfill (24)

When $|P_{\text{error}}| < 20\% P_{\text{ref}}$, the direction of $P_{\text{wave}}$ is the same as that of $P_{\text{ref}}$.

4.2 Calculating the duration of $P_{\text{wave}}$

The ratio of the data amount of $P_{\text{wave}}$ in all the observed power data is assumed to be $\alpha$. Correspondingly, the duration of $P_{\text{wave}}$ can be given as follows:

$$T_{\text{wave}} = \alpha T_{\text{data}}.$$  \hfill (25)

where $T_{\text{data}}$ represents the duration of all the observed power data.

4.3 Calculating the duration of $P_{\text{steady}}$ and $P_{\text{peak}}$

The data in $P_{\text{wave}}$ are processed by the statistical method. Then, the range of the amplitude of $P_{\text{steady}}$ and $P_{\text{peak}}$ is determined according to the properties of $P_{\text{steady}}$ and $P_{\text{peak}}$ discussed above. As a result, the fluctuant wind power is decomposed into $P_{\text{steady}}$ and $P_{\text{peak}}$. The ratio of the date amount of $P_{\text{steady}}$ in $P_{\text{wave}}$ is calculated as $\beta$. The ratio of $P_{\text{peak}}$ in $P_{\text{wave}}$ is $1 - \beta$. Then, the duration of $P_{\text{steady}}$ and $P_{\text{peak}}$ can be given as

$$T_{\text{peak}} = (1 - \beta) T_{\text{data}} = (1 - \beta) T_{\text{data}}$$  \hfill (26)

$$T_{\text{steady}} = \beta T_{\text{wave}} = \beta \alpha T_{\text{data}}$$  \hfill (27)

4.4 Calculating the mean values of $|P_{\text{steady}}|$ and $|P_{\text{peak}}|$

Consider the amplitude of $P_{\text{steady}}$ ($P_{\text{steady}}$) as a sample $X_{\text{steady}}$. At the same time, another sample $X_{\text{peak}}$ is composed of the amplitude of $P_{\text{peak}}$ ($P_{\text{peak}}$). We process $X_{\text{steady}}$ and $X_{\text{peak}}$ by the statistical method to derive the probability density function of $|P_{\text{steady}}|$ and $|P_{\text{peak}}|$ expressed as $f_{P_{\text{steady}}}(x)$ and $f_{P_{\text{peak}}}(x)$, respectively. Then, the mean value of $P_{\text{steady}}$ and $P_{\text{peak}}$ can be obtained as follows:

$$P_{\text{steady ave}} = \int f_{P_{\text{steady}}}(x) dx$$  \hfill (28)

$$P_{\text{peak ave}} = \int f_{P_{\text{peak}}}(x) dx$$  \hfill (29)

4.5 Calculating the capacity configuration of battery and supercapacitor

According to (9)–(12), the capacity configuration of battery and supercapacitor can be determined.

As for the method discussed above, the selected amplitude range of $P_{\text{steady}}$ and $P_{\text{peak}}$ has a great influence on the capacity configuration of battery and supercapacitor. The higher the upper limit of $|P_{\text{steady}}|$ is chosen to be, the more capacity of the battery will be required. In that condition, the battery will undertake the major regulation task. Correspondingly, the service life of battery will be short, leading to a high maintenance cost. On the contrary, the capacity of battery will be required less if the upper limit of $|P_{\text{steady}}|$ is set to be low. Therefore, the battery will undertake less suppression task, with the extended service life. However, the supercapacitor will be allocated great capacity to take on the majority balance task, resulting in the high investment cost. When the fluctuation of wind power is decomposed to determine the capacity of the battery-supercapacitor hybrid system, the investment and maintenance cost must be considered at the same time.

5 Example analysis on the capacity configuration method

An example analysis is carried out to illustrate the proposed capacity configuration method for the battery–supercapacitor hybrid system. In this example, the statistical method employed is the Byrne method.

5.1 Determining $P_{\text{wave}}$

In Fig. 3, the operation power data of a wind farm within 24 h is displayed. The sampling interval is 12 s. Therefore, the data size in Fig. 3 is 7200. In this example, we set the real-time reference value $P_{\text{ref}}$ of wind power to be the mean value of the data every 15 min. According to (23) and (24), the scatter diagram of $P_{\text{wave}}$ is shown in Fig. 4.

5.2 Calculating the duration of $P_{\text{wave}}$

The data size of $P_{\text{wave}}$ is 3042. Therefore, the ratio of $P_{\text{wave}}$ in all the observed data is given by $\alpha = 3042/7200 = 42.25\%$. According to (25), the duration of $P_{\text{wave}}$ is $T_{\text{wave}} = 10.14$ h.

5.3 Calculating the duration of $P_{\text{steady}}$ and $P_{\text{peak}}$

Consider the aggregation of the absolute value of as a sample $X$. The sample size of $X$ is $n = 3042$. $X$ is processed by the Byrne method as follows. First, the maximum data $x_{\text{max}}$ and minimum data $x_{\text{min}}$ in $X$ are obtained. Second, the data space $[x_{\text{min}}, x_{\text{max}}]$ is divided into $M$ sections. Third, the number $N$ of the data located in
Table 1  Frequency distribution of |P\textsubscript{wave}|

| Power range, MW | N   | N/n |
|-----------------|-----|-----|
| 0.002–2.054     | 1639| 0.5388 |
| 2.054–4.108     | 724 | 0.2380 |
| 4.108–6.162     | 332 | 0.1091 |
| 6.162–8.216     | 154 | 0.0506 |
| 8.216–10.270    | 81  | 0.0266 |
| 10.270–12.324   | 36  | 0.0118 |
| 12.324–14.377   | 31  | 0.0102 |
| 14.377–16.431   | 16  | 0.0053 |
| 16.431–18.485   | 9   | 0.0030 |
| 18.485–20.539   | 9   | 0.0030 |
| 20.539–22.593   | 5   | 0.0016 |

According to (30), \(M = 1 + 3.332 \lg (n)\)

\[ M = 1 + 3.332 \lg (n) \]

By the Byrne method, the frequency distribution table and frequency histogram of |P\textsubscript{wave}| are given in Table 1 and Fig. 5, respectively.

As shown in Table 1 and Fig. 5, the majority of the data in |P\textsubscript{wave}| is within the range of 0.002–12.324 MW. The amount of data within that scope accounts for 97.5% of the data size of |X|. Other data with the larger value accounts for 2.5% of the data size of |X|. According to the properties of P\textsubscript{steady} and P\textsubscript{peak}, the data within the range of 0.002–12.324 MW belongs to the steady fluctuation P\textsubscript{steady}. At the same time, the data within the range of 12.324–24.647 MW belongs to the peak fluctuation P\textsubscript{peak}. As a result, the proportion of P\textsubscript{steady} and P\textsubscript{peak} can be obtained by Table 1, \(\beta = 97.5\%\), \(1 – \beta = 2.5\%\).

From (26) and (27), the duration of P\textsubscript{steady} and P\textsubscript{peak} can be determined as \(T\textsubscript{steady} = 10.14 \times 97.5\% = 9.89\) h and \(T\textsubscript{peak} = 10.14 \times 2.5\% = 0.25\) h, respectively.

5.4 Calculating the mean values of |P\textsubscript{steady}| and |P\textsubscript{peak}|

5.4.1 Calculating the mean value of |P\textsubscript{steady}|: Consider the data belonging to P\textsubscript{steady} in X as a new sample \(X\textsubscript{steady}\). The sample size is 2966. \(X\textsubscript{steady}\) is processed by the Byrne method. According to (30), the data in \(X\textsubscript{steady}\) are divided into 12 sections, \(M = 12\). Then, the frequency histogram of |P\textsubscript{steady}| is acquired as shown in Fig. 6.

Correspondingly, the frequency density histogram of |P\textsubscript{steady}| can be obtained, as shown in Fig. 7.

In that frequency density histogram, the middle of the abscissa in each rectangular area is supposed to be \(x_i\). The corresponding ordinate is supposed to be \(y_i\). By connecting the \((x_i, y_i)\) in Fig. 7, the polyline of frequency density histogram of |P\textsubscript{steady}| is displayed in Fig. 8.

If the sample size and the grouping number are supposed to be infinite, the curve in Fig. 8 will be infinitely close to the probability density curve of |P\textsubscript{steady}|. By the least square method, the curve in Fig. 8 can be fitted and the probability density function of |P\textsubscript{steady}| is derived as

\[ f_{P\textsubscript{steady}}(x) = \sum_{i=0}^{8} a_i x^i, \]

where \(a_i\) is listed in Table 2.

Table 2  Coefficient of probability density function of |P\textsubscript{steady}|

| Coefficients | Value       |
|--------------|-------------|
| \(a_8\)      | \(-1.7826 \times 10^{-60}\) |
| \(a_7\)      | \(8.8979 \times 10^{-53}\)  |
| \(a_6\)      | \(-1.8332 \times 10^{-45}\) |
| \(a_5\)      | \(2.0111 \times 10^{-38}\)  |
| \(a_4\)      | \(-1.2627 \times 10^{-31}\) |
| \(a_3\)      | \(4.5205 \times 10^{-25}\)  |
| \(a_2\)      | \(-8.535 \times 10^{-19}\)  |
| \(a_1\)      | \(6.3654 \times 10^{-13}\)  |
| \(a_0\)      | \(1.699 \times 10^{-7}\)    |

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Byrne method, as shown in Figs. 10 and 11, respectively. According to (28), the mathematical expectation of $|P_{\text{peak}}|$ can be determined by the following equation, which is the mean value of $|P_{\text{steady}}|$:

$$P_{\text{steady, ave}} = \int_{12.324\ MW}^{24.647\ MW} xf_{P_{\text{steady}}}(x) \, dx \simeq 2.55\ MW \tag{32}$$

5.4.2 Calculating the mean value of $|P_{\text{peak}}|$: As discussed above, the range of $|P_{\text{peak}}|$ in the sample $X$ is $12.324$–$24.647$ MW. The data within that scope constitutes another sample $X_{\text{peak}}$ with the sample size being 76. The frequency histogram and polyline of the frequency density histogram of $|P_{\text{peak}}|$ are obtained by the Byrne method, as shown in Figs. 10 and 11, respectively.

In that process, the grouping number is $M = 7$. Then, the polyline of the frequency density histogram of $|P_{\text{peak}}|$ is fitted. The probability density function of $|P_{\text{peak}}|$ is obtained as

$$f_{P_{\text{peak}}}(x) = \sum_{i=0}^{b} b_i x^i, \tag{33}$$

where the value of $b_i$ is given in Table 3.

The fitted probability density curve and polyline of the frequency density histogram of $|P_{\text{peak}}|$ are displayed in Fig. 12.

At the same time, the mean value of $|P_{\text{peak}}|$ can be derived as

$$P_{\text{peak, ave}} = \int_{12.324\ MW}^{24.647\ MW} xf_{P_{\text{peak}}}(x) \, dx \simeq 13.36\ MW \tag{34}$$

5.5 Calculating the capacity configuration of battery and supercapacitor

According to (9), the capacity of the battery employed to suppress $P_{\text{steady}}$ is allocated to be $E_{\text{bat}} = 2.55\ MW \times 9.89\ h = 25.22\ MWh$. Furthermore, the maximum power configuration of battery pack should be set as $P_{\text{steady, peak}} = 12.324\ MW$ to meet the requirement of regulating the peak value of $P_{\text{steady}}$.

According to (11), the energy capacity of supercapacitor is set to be $E_{\text{cap}} = 16.36\ MW \times 0.25\ h \times 3600 = 14724\ MJ$. Meanwhile, the maximum power configuration of supercapacitor should be allocated as the peak value of $P_{\text{peak}}$, $P_{\text{peak, peak}} \simeq 24.647\ MW$. By the above method, the battery and supercapacitor are allocated proper power and energy capacity according to the suppression task assignment. As a result, the battery and supercapacitor are able to undertake the task of balancing the steady fluctuation and peak fluctuation, respectively. Furthermore, the investment and maintenance cost for the battery–supercapacitor hybrid system can be reduced.

6 Conclusion

Based on the turbulence model of wind speed, this paper decomposes fluctuant wind power into the steady fluctuation $P_{\text{steady}}$ and peak fluctuation $P_{\text{peak}}$ to reveal the characteristics of the real-time fluctuant wind power. By analysing the energy storage performance of battery and supercapacitor, it can be found that the battery is fit for smoothing $P_{\text{steady}}$ and that supercapacitor is suitable for balancing $P_{\text{peak}}$. Through studying the performance of the battery–supercapacitor hybrid system according to that task allocation, it can be concluded that the hybrid system obtains the properties of high power density, high energy density and long cycle. Therefore, the hybrid system meets the performance requirement for the energy storage system in the course of wind power regulation. On the basis of the decomposition of wind power fluctuation, a new capacity configuration method for the battery–supercapacitor hybrid system is developed. By that method, the battery and supercapacitor can be allocated proper capacity in the wind power fluctuation to reveal the characteristics of the real-time fluctuant wind power. By analysing the energy storage performance of battery and supercapacitor, it can be found that the battery is fit for smoothing $P_{\text{steady}}$ and that supercapacitor is suitable for balancing $P_{\text{peak}}$. Through studying the performance of the battery–supercapacitor hybrid system according to that task allocation, it can be concluded that the hybrid system obtains the properties of high power density, high energy density and long cycle. Therefore, the hybrid system meets the performance requirement for the energy storage system in the course of wind power regulation. On the basis of the decomposition of wind power fluctuation, a new capacity configuration method for the battery–supercapacitor hybrid system is developed. By that method, the battery and supercapacitor can be allocated proper capacity
according to their energy storage merits to undertake the task of suppressing $P_{\text{steady}}$ and $P_{\text{peak}}$, respectively. As a result, the investment can be reduced and the service life of energy storage element can be extended.

7 References

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