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A New Method for Balancing the Fluctuation of Wind Power by a Hybrid Energy Storage System

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Abstract: Keeping the wind power constant is essential for the large-scale integration of wind power into electric power system. In this study, we classify the wind power fluctuation and propose a method of suppressing the fluctuant wind power by an Active-Parallel Hybrid Energy Storage System (APHESS). The APHESS consists of a battery, a supercapacitor and two charge-discharge controllers. By designing the configuration logically, the APHESS obtains the enhanced energy storage performance and the low investment cost. In order to realize the wind power suppression, the method of controlling the APHESS to exchange power precisely with the wind power system is developed in this study. For the purpose of making the battery and supercapacitor balance, respectively different kinds of fluctuation classified in this study, the power within APHESS is allocated reasonably between the battery and the supercapacitor. By the method proposed in this study, the fluctuant wind power can be balanced effectively and the service life of energy storage system can be prolonged.

Key words: Wind energy, wind power suppression, charging-discharging power, battery, supercapacitor, operation mode

INTRODUCTION

In recent years, wind power generation has been experiencing a big boom as it is a sustainable energy form and can serve as an important alternative for future energy supply (Vardar and Unal, 2006; Chen, 2011; Hosseinpour *et al.*, 2008). However, the wind power generation which is influenced by the weather and geographic conditions has the properties of intermittence and randomness. As a result, the wind power often fluctuates to a large extent. High penetration levels of fluctuant wind power will have adverse impacts on electric power system (Luo and Ooi, 2006; Abdelaziz *et al.*, 2011; Kabouris and Kanellos, 2010).

The general method for suppressing the fluctuation of wind power is to adjust the pitch angle and rotation speed of wind power generator according to the variation of wind speed (De Battista and Mantz, 2004; Kaneko *et al.*, 2011). However, the utilization efficiency of wind energy will be reduced by that method. In USA and Denmark, the method of suppressing the fluctuation of wind power by the hydropower has been widely put into practice (Brooks *et al.*, 2005). In China, the northwest and northeast regions have abundant wind and coal resources, where the wind power can be smoothed by local coal thermal power stations (Chuang-Ying *et al.*, 2010). The balanced wind power that can not be consumed by the local load can be delivered efficiently to the areas where the power demand is heavy.

Besides those methods above, the energy storage technique emerging in recent years can also be regarded as an effective way to regulate wind power. In Japan, a NaS energy storage system was set up with the support from NEDO Company to control the power fluctuation of the wind farm in Hachijojima Island (Zhaoyin, 2007). In USA, a 268 MW compressed air station was constructed to regulate the output power of a 100 MW wind farm (Daneshi *et al.*, 2010). In China, a 1200 MW pumped storage station has been under construction since 2006 to regulate the wind power (Yuntao and Jiang, 2010). In addition, there are many other energy storage technologies that can be applied for regulating the wind power, such as supercapacitor (Abbey and Joos, 2007), SEMS (Ali *et al.*, 2010) and flywheel energy storage (Wang *et al.*, 2005; Guo *et al.*, 2007). However, most of them are still at the experimental stage.

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In this study, the fluctuation of wind power is classified and a research on the performance requirement for energy storage system is conducted. Then, this study proposes a method of balancing the fluctuant wind power by an Active-parallel Hybrid Energy Storage System (APHESS). The analysis on the configuration and energy storage property of AEPHSS is conducted in this study. In order to achieve the wind power suppression and extend the service life of energy storage system, the operation mode of APHESS is devised elaborately. The simulation on the configuration and operation mode of APHESS is developed at the end of this study.

THE CLASSIFICATION ON THE FLUCTUATION OF WIND POWER

The classification on wind power fluctuation: At present, most of the wind power generators operate at the mode of maximum wind energy capture. Consequently, the wind power varies with the wind speed. The daily output power of a 850 kW wind turbine is shown in Fig. 1. The power ranges from 0 to 850 kW. The intense power fluctuation will have negative impacts on the operation stability of the grid-connected power system.

In China, a technical rule for integrating wind farm into the electric power system was established by the state grid corporation of China in 2006. It states that a 6 MW variation is permitted for the wind farm less than 30 MW. According to that principle, about 20% variation is allowable. In practice, we often set the wind power $P_{standard}$ obtained by the wind power prediction as the real-time dispatching plan. Therefore, $P_{standard}$ can be regarded as the target value for wind power suppression. In Fig. 1, we assume that $P_{standard}$ is equal to the average value of the wind power every fifteen minutes. P_{real} standards for the real-time wind power in Fig. 1. P_{error} denotes the difference between $P_{standard}$ and P_{real}. The power that P_{error} exceeds the boundary of ±20% $P_{standard}$ can be plotted in Fig. 2.

Figure 2 describes the fluctuant power that needs to be smoothed. According to the character of fluctuation, we can divide the power fluctuation into three categories:

- P_{peak} : The fluctuant power exceeding the two dotted lines in Fig. 2. P_{peak} is induced by the acute increase or decrease of wind speed. Consequently, P_{peak} is of high power value. Nevertheless, the energy variation induced by P_{peak} is small because of the short duration
- P_{steady} : The fluctuation staying within the two dotted lines in Fig. 2. P_{steady} results from the continuously positive or negative deviation of wind speed. Although the value of P_{steady} is moderate, the energy varies considerably due to the long duration of P_{steady}
- P_{recy} : The fluctuation varying along the zero axis back and forth in a short time in Fig. 2. P_{recy} is caused by the reciprocating variation of wind speed. Because the duration of P_{recy} is short, P_{recy} leads to small energy variation. At the same time, the frequency of P_{recy} is high

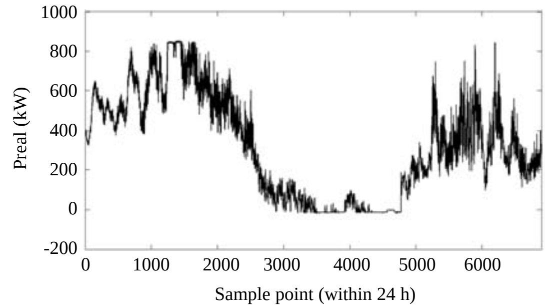

Fig. 1: Daily output power of a single wind turbine generator in certain wind farm

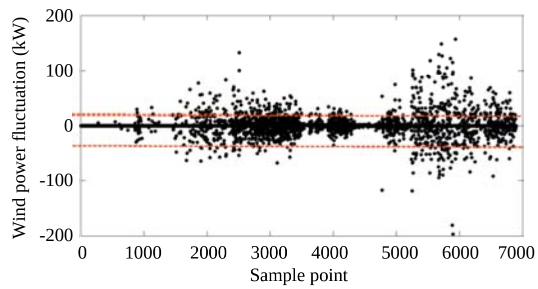

Fig. 2: The fluctuation of wind power

The research on the performance requirement for energy storage system: By regulating precisely the charging-discharging power of the energy storage system, the difference between P_{real} and $P_{standard}$ can be compensated. Thus, the fluctuation of wind power can be suppressed. For the all the three kinds of fluctuation, the energy storage system should have the following abilities:

- The ability to be charged or discharge frequently (for balancing P_{recy})
- The ability to endure high power charge-discharge (for balancing P_{peak})
- The ability to store abundant energy (for balancing P_{steady})

In general, the investment cost for the energy storage system which possesses all the three abilities above is high. For the sake of reducing the investment cost, the energy storage system should be of the performance of long cycle life, high power density and high energy density.

A NEW PATTERN HYBRID ENERGY STORAGE SYSTEM

The configuration of hybrid energy storage system: This paper develops an Active-Parallel Hybrid Energy Storage System (APHESS) to balance the fluctuation of wind power. The configuration of APHESS is illustrated in Fig. 3.

The APHESS consists of a battery, a supercapacitor and two charge-discharge controllers. By a PWM voltage source inverter, the APHESS is connected to the output bus of wind farm in parallel. When the wind power generation is higher than the dispatching plan, the APHESS absorbs the surplus energy. When the wind power generation is relatively small, the APHESS discharges to make up for the shortage of wind power. By the real-time power exchange between the APHESS and the wind power system, the fluctuant wind power can be balanced.

In APHESS, the DC/DC (A) and DC/DC (B) serve as the charge-discharge controllers. They adopt the structure of bidirectional dc/dc converter, as shown in Fig. 4. The battery and supercapacitor are located at the low voltage side of DC/DC (B) and DC/DC (A), respectively. In APHESS, the supercapacitor acts as the power/energy buffer between DC/DC (A) and DC/DC (B). As a result, the DC/DC(A) and DC/DC(B) can operate independently.

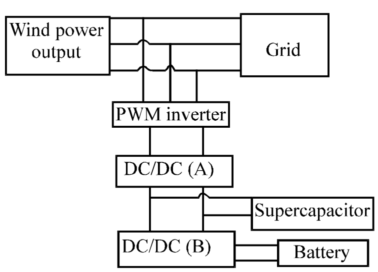

Fig. 3: The configuration of APHESS

The DC/DC(A) is responsible for controlling accurately the charging-discharging power of APHESS P_{whole}. By regulating DC/DC(A), the APHESS could release or absorb energy as the desired power value to compensate for the difference between P_{real} and $P_{standard}$. Thus, the wind power can be smoothed. The DC/DC(B) manages precisely the charging-discharging power of the battery P_{bat}. It is obvious by the configuration of APHESS that the charging-discharging power of supercapacitor P_{cap} is equal to the difference between P_{whole} and P_{bat}. By managing P_{bat} and P_{whole} precisely, the relationship among P_{whole}, P_{bat} and P_{bat} can be adjusted flexibly.

The mathematical model of the charge-discharge controller: We assume that U_{bat} represents the terminal voltage of battery and that U_{cap} stands for the terminal voltage of supercapacitor. At the same time, we assume the current flowing through the inductor of DC/DC(B) and DC/DC(A) to be I_{LB} and L_{LA}, respectively. According to the configuration of APHESS, the charging-discharging power of battery and APHESS can be described as $P_{bat} = U_{bat}\times I_{LB}$ and $P_{whole} = U_{cap}\times I_{LB}$, respectively. As U_{bat} and U_{cap} can be measured in real-time, the regulation on P_{bat} and P_{whole} can be realized by controlling the current flowing through the inductor of DC/DC(A) and DC/DC(B). In Fig. 4, V_1 and V_2 are the terminal voltage of the voltage source on both sides. R_{s1} and R_{s2} are the equivalent series resistances. The current flowing through the inductor is I_L. We assume the duty cycle of G_1 and G_2 to be D and 1-D, respectively. Based on the large-signal model of bidirectional dc/dc converter, we deduce the transfer function of I_L as follows.

When the charge-discharge controller operates at the Boost mode, the input vector is $V_s = V_1$. At the same time, we assume that V_2, C_1 and R_{s1} are equal to zero and that R_{s2} is equal to R. Then, the transfer function of I_L can be expressed by:

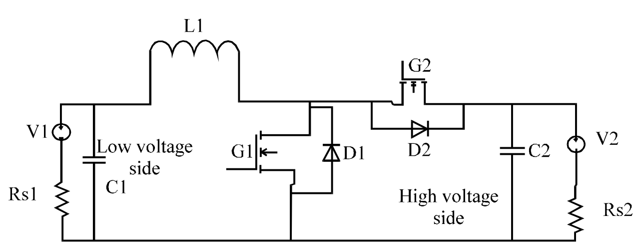

Fig. 4: The structure of charge-discharge controller

$$\left.\frac{\hat{i}_L(s)}{\hat{d}(s)}\right|_{\hat{v}_1(s)} = \frac{sRC_2V_{c20} + RI_{L0}(1-D) + V_{c20}}{LRC_2s^2 + Ls + (1-D)^2R} \quad (1)$$

Where:

$$\begin{pmatrix} I_{L0} \\ V_{C20} \end{pmatrix} = \begin{pmatrix} \dfrac{V_1}{(1-D)^2R} \\ \dfrac{V_1}{1-D} \end{pmatrix}$$

When the charge-discharge controller operates at the Buck mode, the input vector is $V_s = V_2$. We assume that V_2, C_2 and R_{s2} are equal to zero and that R_{s1} is equal to R. The transfer function of I_L can be given by:

$$\left.\frac{\hat{i}_L(s)}{\hat{d}(s)}\right|_{\hat{v}_2(s)} = \frac{(1+sRC_1)V_{c10}}{LRC_1s^2 + Ls + R} \quad (2)$$

Where:

$$\begin{pmatrix} I_{L0} \\ V_{C20} \end{pmatrix} = \begin{pmatrix} -\dfrac{V_2(1-D)}{R} \\ (1-D)V_2 \end{pmatrix}$$

Based on Eq. 1 and 2, we conclude that the open-loop zero and pole of the transfer function of I_L are both located in the left-half plane of S-Domain no matter the charge-discharge controller operates at the Boost mode or at the Buck mode. Consequently, I_L is open-loop stable. We adopt the closed-loop control which incorporates a PI controller to manage I_L accurately. Therefore, the precise regulation on P_{bat} and P_{whole} can be realized.

The analysis on the energy storage property of APHESS: The supercapacitor has the properties of high power density, long cycle life and low energy density (Conway, 1994; Fathi *et al*., 2011; Kiamahalleh *et al*., 2011). According to the properties of P_{recy} and P_{peak}, it can be found that the supercapacitor is fit for undertaking the task of balancing P_{peak} and P_{recy}. In the APHESS, we assume the energy storage capacity of supercapacitor to be $Energy_{cap}$. Since the battery has the characteristic of high energy density and short life cycle (Shakir and Wang, 2008; Nallusamy and Duraiswamy, 2011), it can be used to suppress P_{stady}. We assume that the energy storage capacity of battery is $Energy_{bat}$. As the life cycle of the battery is far lower than that of the supercapacitor, the service life of APHESS is mainly dependent on the charging-discharging frequency of the battery.

The energy storage capacity of APHESS can be described as:

$$Energy_{whole} = Energy_{cap} + Energy_{bat} \quad (3)$$

Then, the energy density of APHESS can be given as:

$$Per\_E_{hyb} = \frac{Energy_{whole}}{\dfrac{Energy_{bat}}{Per\_E_{bat}} + \dfrac{Energy_{cap}}{Per\_E_{cap}}} \quad (4)$$

where, Per_E_{bat} and Per_E_{cap} represent the energy density of battery and supercapacitor, respectively. At the same time, the power density of APHESS can be defined as:

$$Per\_P_{hyb} = \frac{P_{peak}}{\dfrac{P_{peak}}{Per\_P_{cap}} + \dfrac{P_{steady}}{Per\_P_{bat}}} \quad (5)$$

where, Per_P_{cap} and Per_P_{bat} stand for the power density of supercapacitor and battery separately.

It can be identified from the property of the battery and supercapacitor that:

$$Per\_E_{bat} >> Per\_E_{cap} \quad (6)$$

$$Per\_P_{cap} >> Per\_P_{bat} \quad (7)$$

From the classification of the wind power fluctuation, we can recognize that:

$$P_{peak} >> P_{steady} \quad (8)$$

$$Energy_{bat} >> Energy_{cap} \quad (9)$$

According to Eq. 6, 7, 8 and 9, we can simplify Eq. 4 and 5 into:

$$Per\_E_{cap} << Per\_E_{hyb} < Per\_E_{bat} \quad (10)$$

$$Per\_P_{bat} << Per\_P_{hyb} < Per\_P_{cap} \quad (11)$$

By Eq. 10 and 11, it can be seen that the energy density of APHESS is slightly lower than that of the battery and much higher than that of the supercapacitor and that the APHESS' power density is slightly lower than the supercapacitor's and much higher than the battery's. As P_{recy} and P_{peak} are suppressed by the supercapacitor, the charging-discharging frequency of battery can be reduced. Thus, the service life of APHESS can be prolonged. On the whole, the APHESS possesses the properties of high power density, high energy density and long life cycle. As a result, the APHESS meets the performance requirement for energy storage system in the process of balancing fluctuant wind power.

Furthermore, we can deduce Eq. 10 and 11 as:

$$\frac{Energy_{whole}}{Per\_E_{hyb}} << \frac{Energy_{whole}}{Per\_E_{cap}} \tag{12}$$

$$\frac{P_{peak}}{Per\_P_{hyb}} << \frac{P_{peak}}{Per\_P_{bat}} \tag{13}$$

It can be concluded from Eq. 12 and 13 that the investment cost of APHESS will be far lower than that of the battery-only or supercapacitor-only energy storage system as the APHESS obtains the enhanced energy storage performance.

THE DESIGN ON THE OPERATION MODE OF APHESS

In order to realize the wind power balance and also prolong the service life of APHESS, we carry out a research on the operation mode of APHESS.

The realization of the control on P_{whole}: According to the deviation of P_{real} from $P_{standard}$, the desired charging-discharging power for APHESS P_{whole} can be determined. When $P_{real}<P_{standard}$, the APHESS needs to release energy as the power $P_{whole} = P_{standard}-P_{real}$. When $P_{real}<P_{standard}$, the APHESS should absorb energy as the power $P_{whole} = P_{real}-P_{standard}$.

In APHESS, the control on P_{whole} is up to DC/DC(A). First, the real-time terminal voltage of supercapacitor U_{cap} should be obtained. Then, the control target of I_L in DC/DC(A) can be given as:

$$I_L = {P_{whole}}/{U_{cap}}$$

By implementing the closed-loop control onto I_L of DC/DC(A), we are able to control accurately the magnitude and direction of P_{whole}.

The high voltage side of DC/DC(A) is the interface of APHESS to ac system. When the APHESS participates in the wind power regulation, the PWM voltage source inverter holds the interface voltage constant.

By the method above, the APHESS could exchange power precisely and efficiently with the wind power system. Therefore, the fluctuation of wind power can be suppressed.

The power allocation of APHESS and its realization: In order to prolong the service life of APHESS, we should make the battery and supercapacitor balance P_{stady}, P_{peak} and P_{recy}, respectively. As a result, we need to allocate P_{whole} between the battery and the supercapacitor according to the energy storage properties of the battery and supercapacitor.

The power allocation of APHESS in the course of balancing P_{recy} and P_{peak}: As we have discussed above, the supercapacitor has the properties of high power density and long life cycle. In order to utilize fully its properties, the supercapacitor should balance P_{recy} and P_{peak} alone. During that process, the battery stops operating. As a result, the power within the APHESS is allocated as:

$$P_{whole} = P_{cap} \tag{14}$$

$$P_{bat} = 0 \tag{15}$$

For achieving that power allocation, the supercapacitor is given the priority in absorbing or releasing energy. We assume the optimum working scope of supercapacitor to be (U_{optim_down} U_{optim_up}). When the terminal voltage of supercapacitor U_{cap} is within the optimum working scope, the battery stops working and the supercapacitor is made to interchange power alone with the wind power system. Because the energy variation induced by P_{recy} and P_{peak} is relatively small, the supercapacitor could supply the desired energy. In the course of balancing P_{recy} and P_{peak}, U_{cap} will stay within the optimum working scope all the time.

As P_{recy} and P_{oeak} are balanced by the supercapacitor, the charging-discharging frequency of the battery is reduced. The reduction of the charging-discharging frequency of the battery contributes to prolonging the service life of APHESS.

The power allocation of APHESS in the process of balancing P_{steady}: In the course of suppressing P_{steady}, the principle that the supercapacitor has priority in absorbing or releasing energy is maintained. Because the energy variation induced by P_{steady} is considerable and the energy density of supercapacitor is low, U_{cap} will be driven beyond the optimum working scope when P_{steady} occurs.

When U_{cap} is driven beyond the optimum working scope, we regulate the battery to adjust the SOC of supercapacitor. Thus, the energy required for balancing P_{steady} is supplied ultimately by the battery. As a result, the property of high energy density of battery can be fully utilized. By regulating the SOC of supercapacitor in real-time, the supercapacitor can cope with P_{recy} and P_{peak} at all times.

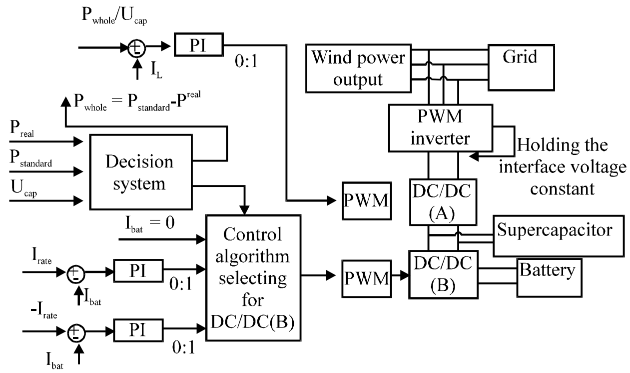

Fig. 5: The control block for the operation of APHESS

Then we elaborate the realization of the above operation mode. We assume that the adjustment point of SOC of supercapacitor is U_{optim}. When U_{cap} drops to U_{cap}<= U_{optim_down}, DC/DC(B) manages the battery to discharge as the rated current to supply energy for the supercapacitor until $U_{cap} = U_{optim}$. When U_{cap} rises to U_{cap}>= U_{optim_up}, DC/DC(B) manages the battery to be charged with the rated current to absorb the surplus energy from the supercapacitor until $U_{cap} = U_{optim}$.

When the battery participates in regulating the SOC of supercapacitor, the power within APHESS is allocated as follows: When both the APHESS and the battery work at energy storage or release state:

$$P_{bat} = P_{whole} + P_{cap} \tag{16}$$

When they work at different states:

$$P_{cap} = P_{whole} + P_{bat} \tag{17}$$

The control block for the operation of APHESS: Based on the operation mode of APHESS designed above and the mathematical model of the charge-discharge controller, we can get the control block for the operation of APHESS as shown by Fig. 5.

SIMULATION ANALYSIS

According to the configuration shown in Fig. 3, we develop the simulation system in Matlab/Simulink. We assume that the direction that APHESS releases energy is positive.

The simulation on the configuration of APHESS: We set the simulation parameters as follows. The battery unit is 200 V, 600 AH. The supercapacitor's capacitance is 2F. The threshold voltage of supercapacitor is 600 V. The supercapacitor's initial voltage is 500 V. The line voltage of grid is 690 V.

The PWM voltage source inverter holds the interface voltage of APHESS at the constant value of 1200 V. We set the operation process of APHESS as follows to verify the feasibility of the configuration of APHESS. During 0-0.5s, DC/DC(A) controls the APHESS to release energy as the power P_{whole} = 100 kW to supply energy to the wind power system. During 0.5-1s, P_{whole} drops to 50 kW. During 1.5 s, the APHESS absorbs energy from the wind power system as the power P_{whole} under the regulation of DC/DC(A). During that period, P_{whole} is -150 kW at first and then rises to -20 kW at 1.5 s. When the APHESS stores energy, DC/DC(B) controls the battery to be charged as the rated current I_b = -180A. When the APHESS releases energy, the battery discharges as the rated current I_b = -180A under the control of DC/DC(B). The simulation results are illustrated by Fig. 6 and 7.

In Fig. 6, curve (a) describes the charging-discharging power of APHESS and curve (b) shows the charging-discharging current of battery. It can be identified by (a) that DC/DC(A) could control the APHESS to release or store energy as the required power value. Hence, the accurate power exchange between the APHESS and the wind power system can be achieved. At the same time, curve (b) illustrates that DC/DC(B) is capable of regulating independently the battery to be charged or discharge as the rated current. In other words, the operation of DC/DC(B) is not affected by the working state of DC/DC(A).

In Fig. 7, curve (a) represents the terminal voltage of supercapacitor U_{cap} and curve (b) shows the interface voltage of APHESS. Curve (b) indicates that the PWM voltage source inverter could hold the interface voltage of APHESS constant. Therefore, the energy can be

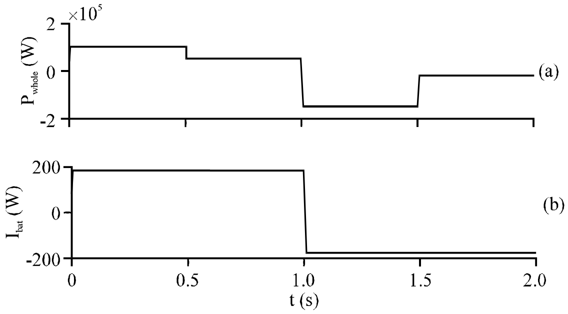

Fig. 6 (a-b): The charging-discharging power curve of APHESS and battery

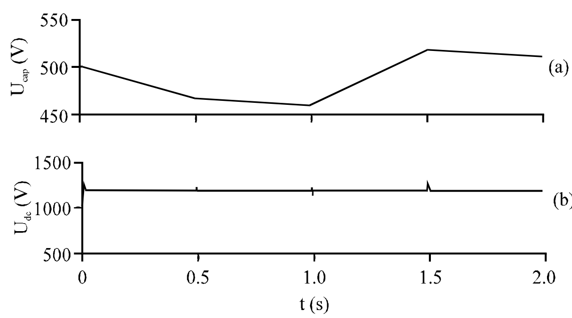

Fig. 7 (a-b): The terminal voltage of supercapacitor and APHESS

transferred efficiently between the APHESS and the wind power system. When APHESS operates, the supercapacitor is responsible for compensating for the difference between P_{bat} and P_{whole}. During 0-0.5 s the supercapacitor discharges as the power $P_{cap} = P_{whole}-P_{bat}$ because $P_{whole}>P_{bat}$. As a result, U_{cap} descends, as shown in Fig. 7. During 0.5-1 s, the descent speed of U_{cap} becomes slow because P_{whole} declines. During 1-2 s, the APHESS absorbs energy. During that period, U_{cap} first rises and then descends because P_{whole} is bigger than P_{bat} at first and then becomes smaller than P_{bat}. The curve (a) in Fig. 7 shows the variation of U_{cap}.

It can be concluded from the above simulation that DC/DC(A) and DC/DC(B) can operate independently because the supercapacitor serves as a power/energy buffer between them. That configuration lays foundation for the precise power exchange between the energy storage system and the wind power system and for the flexible power allocation inside APHESS.

The simulation on balancing fluctuant wind power by APHESS: The fluctuant wind power extracted from Fig. 1 within 15 min is shown by curve (a) in Fig. 8. The power fluctuates from 118 to 643 kW.

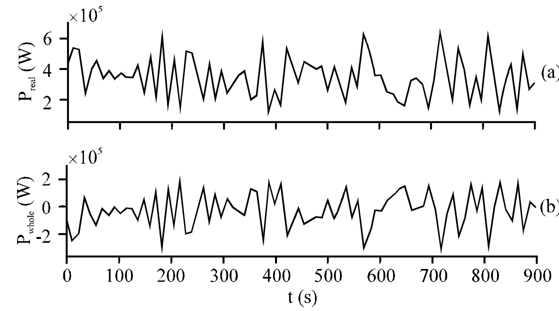

Fig. 8 (a-b): The simulation curve of balancing fluctuant wind power by APHESS

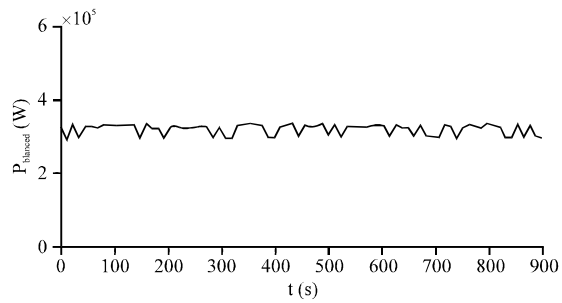

Fig. 9: The curve of the balanced wind power

In this simulation, the APHESS is made to operate as the operation mode devised in this paper to smoothen the fluctuant wind power. We assume the target value for wind power suppression to be 316 kW. The battery unit is enlarged to 300 V, 960 AH. The rated charging-discharging current of battery is 288 A. The supercapacitor's capacitance is 40 F. The threshold and initial voltage of supercapacitor are 800 and 460 V separately. We assume the optimum working scope of supercapacitor to be [450 V, 775 V]. The adjustment point of SOC of supercapacitor is set to be 510 V.

Curve (b) in Fig. 8 shows the charging-discharging power of APHESS. When the real-time wind power is bigger than the reference value, the APHESS absorbs energy from the wind power system. On the occasion of the deficiency of wind power generation, the APHESS discharges to supply energy to the wind power system.

Figure 9 shows the balanced wind power. It can be identified that the fluctuant wind power can be smoothed at the reference value of 316 kW by the precise power exchange between the APHESS and the wind power system. The remaining fluctuation is 6% or so. The suppression effect satisfies the technical rule of integrating wind farm into power system which is established by the state grid corporation of China.

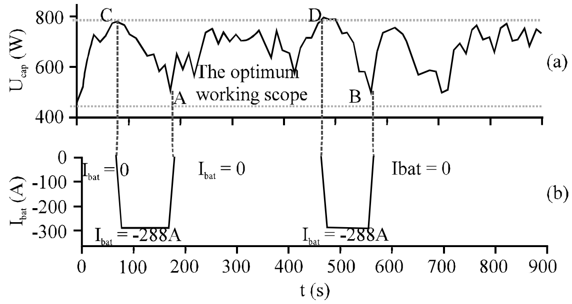

Fig. 10 (a-b): The operation curve of APHESS within 15 min

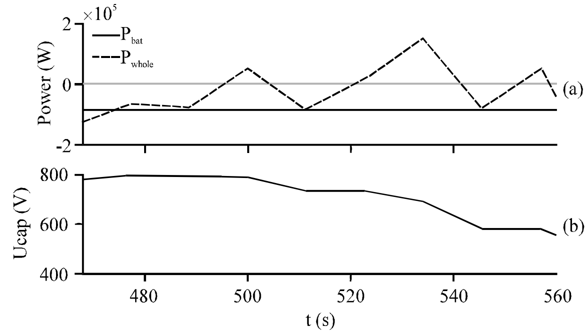

Fig. 11 (a-b): The operation curve of APHESS during 463s-560s

Therefore, we succeed in making the fluctuant wind power track the reference value.

Curve (a) in Fig. 10 shows the variation of supercapacitor's terminal voltage. Curve (b) displays the charging-discharging current of the battery. In Fig. 10, the area between the two horizontal dotted lines represents the optimum working scope of the supercapacitor. It can be concluded from Fig. 10 that the supercapacitor balances the fluctuant wind power alone when U_{cap} is within the optimum working scope. At that moment, the battery in APHESS stops working and the power relationship inside APHESS is expressed by Eq. 14 and 15. As a result, P_{recy} and P_{peak} will be suppressed by the supercapacitor. It is clear from Fig. 10 that the battery keeps being charged or discharging for only three minutes which is 20% of the total time. The reduction of the charging-discharging frequency of battery contributes to prolonging the service life of APHESS.

As the majority of the fluctuation within 15 min is towards the positive direction, the supercapacitor has to absorb lots of energy. It can be found from Fig. 10 that U_{cap} exceeds the upper bound of the optimum working scope for twice. At that moment, the battery absorbs energy as the rated current (I_{bat} = -288 A) from the supercapacitor under the domination of DC/DC(B) until U_{cap} drops to the adjustment point of SOC (the point A and B in Fig. 10). As a result, the fluctuation P_{steady} is smoothened by the battery and the battery develops fully its property of high energy density. As shown by the two areas divided by the vertical dotted lines in Fig. 10, U_{cap} descends rapidly when the battery absorbs energy.

Figure 11 describes the operation state of APHESS during 463-560 s (the section D-B in Fig. 10). During that period, the battery is absorbing energy from the supercapacitor to regulate U_{cap} from the point that U_{cap} is beyond the upper bound of the optimum working scope to the adjustment point of SOC. When the battery participates in regulating the SOC of supercapacitor, the power relationship inside APHESS can be analyzed as follows.

In Fig. 11, curve (a) shows the charging-discharging power of APEHSS and battery and curve (b) displays the terminal voltage of supercapacitor. Because the terminal voltage of battery is nearly invariable, P_{bat} remains constant. When both the APHESS and the battery absorb energy (P_{bat}<0, P_{whole}<0), the power allocation of the APHESS is expressed in (16). If $|P_{whole}|<|P_{bat}|$, the supercapacitor discharges as the power $P_{cap} = |P_{bat}|-|P_{whole}|$. Consequently, U_{cap} descends. If $|P_{whole}|>|P_{bat}|$, supercapacitor absorbs the excessive energy as the power $P_{cap} = |P_{whole}|-|P_{bat}|$. Therefore, U_{cap} ascends (as shown in Fig. 11 during 463-475 s). When the battery absorbs energy (P_{bat}<0) and the APHESS releases energy (P_{whole}>0), the power relationship of the APHESS is given by (17). At that moment, the supercapacitor discharges as the power $P_{cap} = |P_{whole}|+|P_{bat}|$. As a result, U_{cap} descends steeply.

It can be identified from the above simulation that the accurate power exchange between the APHESS and the wind power system and the logical power allocation of APHESS can be realized by the operation mode designed in this paper. As a result, the fluctuant wind power can be balanced effectively and the energy storage properties of the battery and supercapacitor can be fully utilized to prolong the service life of APHESS.

CONCLUSION

According to the classification on the fluctuant wind power, an Active-Parallel Hybrid Energy Storage System (APHESS) is proposed to balance the fluctuant wind power. By combing the battery with the supercapacitor, the APHESS meets the performance requirement for energy storage system in the course of balancing fluctuant wind power. As the two charge-discharge controllers in APHESS can operate independently, the operation mode of APHESS devised in this paper is realized. Thus, the fluctuant wind power is balanced effectively. At the same time, the battery and supercapacitor balance P_{steady}, P_{peak} and P_{recy} separately, with their own energy storage properties fully utilized. By the method proposed in this study, the ability of the power regulation of wind farm can be improved and the investment cost of energy storage system is reduced. Also, the service life of energy storage system is prolonged.

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