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Optimal control strategy for a wind power hybrid energy storage system considering output power amendment

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Abstract: Aiming at meeting the requirement of balancing the fluctuating wind power, this study proposed an optimal control strategy for wind power hybrid energy storage system considering output power amendment. Firstly, fluctuant wind power is decomposed into low-frequency, sub-high frequency and high-frequency components. Low-frequency part is used as the expected value of wind power integration. Sub-high frequency and high-frequency components are used as the target value of output power of storage batteries and ultra-capacitor energy storage system. Secondly, a double power amendment is proposed. In the first-time power amendment, the amendment coefficient is calculated by fuzzy controller whose inputs are the target value of power and state of charge (SOC) of the energy storage system. On the other hand, complement of batteries and super-capacitors are utilised in the second amendment. Through simulation analysis, it can be indicated that the configuration of the hybrid energy storage system and the control system design are feasible. This system can be widely used in wind farm, undertaking the task of balancing the fluctuating wind power.

1 Introduction

Along with the exhaustion of fossil energy and ecological environment deterioration, renewable energies have been proper choices for achieving sustainable energy development and realising low-carbon transition [1]. Wind power is one of the most mature and commercialised renewable energies [2]. As the capacity of wind farm increases, the randomness, fluctuation and unpredictability of wind power has a bad influence on the safe operation of power system.

Energy storage technology is an effective measure for smoothing the fluctuation of wind power [3], especially battery storage technology which is more mature and has been widely applied. However, batteries have short cycle life, and they are not suitable for charging and discharging frequently. These shortcomings restrict their application in coordinated dispatch with wind power. Super-capacitors are new storage devices in recent years. The hybrid energy storage system, which makes use of the complementary property of super-capacitors and batteries, has become a hot research issue in recent years.

Normally, wind power is decomposed when hybrid energy storage system is used to smooth power fluctuation of a power system with wind generations. In [4, 5], wind power is decomposed by first-order low-pass filter, and high frequency of wind power is used as the reference value of super-capacitors. Variable time-constant low-pass filter is used in a hybrid energy storage system in [6], and SOC of the energy storage system is improved on the basis of smoothing wind output power. In [7], a hierarchical optimisation for battery SOC is proposed to improve the SOC of an energy storage system. Reference [8] proposes a method that time-constant low-pass filter changes by the SOC, and target power is confirmed by it. What is more, fuzzy control theory is used to optimise target power based on the SOC of batteries and super-capacitors, which avoids off-limits for SOC of energy storage devices and increasing batteries' service life.

The above researches have got certain results about the control strategy of wind power hybrid energy storage system. However, the time lag of low-pass filter and power balance after amendment should also be taken into consideration.

Fluctuation wind power is decomposed by wavelet packet in this paper, low frequency is used as grid-connected target value, sub-high frequency is used as the target power of battery and high frequency is used as the target power of super-capacitor. Target power of energy storage system and SOC are two inputs of fuzzy controller. Power correction coefficient which is calculated by fuzzy controller is used to correct target power. Besides, amendment power of battery and super-capacitor is used to correct target power again. Wind power hybrid energy storage system model is built on MATLAB/Simulink, the control strategy is verified superior performance by the grid-connected power and range of SOC.

2 Application of wavelet packet decomposition in wind hybrid energy storage system

2.1 Principle of wavelet packet decomposition

In essence, the decomposition of wind power is a process of filtering. Traditional first-order low-pass filter is not sensitive to signal change with strong fluctuation property. Singular signal would distort after traditional filtering. However, wavelet transform is more suitable for singular signal [9–13]. In this paper, wavelet packet decomposition is developed based on wavelet transform. Wind power is decomposed into low-frequency and high-frequency components by wavelet packet to analyse the signal accurately. First floor of the wavelet packet algorithm [10] is as follows:

$$\begin{cases} Y_{1,0}^{n}(t) = \sum_{k} a_{k-2l} Y_0(t) \\ Y_{1,1}^{n}(t) = \sum_{k} b_{k-2l} Y_0(t) \end{cases} \tag{1}$$

where $Y_0(t)$ is the original signal, a_{k-2l} and b_{k-2l} are low-pass and high-pass filter coefficients. $Y_{1,0}^{n}(t)$ is the low-frequency coefficient of the decomposition first floor. $Y_{1,1}^{n}(t)$ is the high-frequency coefficient. Signals after wavelet packet decomposition are

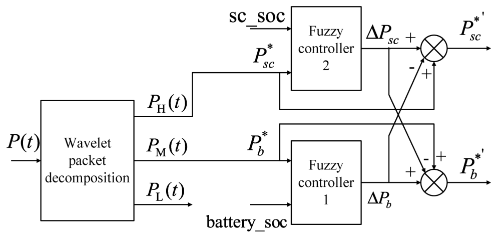

Fig. 1 *Fuzzy control strategy of hybrid energy storage system*

reconstructed into low-frequency and high-frequency parts as follows [10, 11]:

$$\begin{cases} Y_{1,0}(t) = \sum_k \left[h_{l-2k} Y_{1,0}^{2n}(t) + g_{l-2k} Y_{1,0}^{2n+1}(t)\right] \\ Y_{1,1}(t) = \sum_k \left[h_{l-2k} Y_{1,1}^{2n}(t) + g_{l-2k} Y_{1,1}^{2n+1}(t)\right] \end{cases} \quad (2)$$

where $Y_{1,0}(t)$ and $Y_{1,1}(t)$ are low-frequency and high-frequency signals after the first floor of wavelet packet decomposition. h_{l-2k} and g_{l-2k} are the coefficients of low-pass and high-pass filters.

2.2 Power distribution of hybrid energy storage system based on wavelet packet decomposition

Wind fluctuating power signal $P(t)$ is decomposed by n floors of wavelet packet, and dividing the signal into low-frequency, sub-high frequency and high-frequency, which are represented as

$$P(t) = P_L(t) + P_M(t) + P_H(t) \quad (3)$$

Refer to (3), $P_L(t)$ is low-frequency signal, $P_M(t)$ is sub-high frequency and $P_H(t)$ is high frequency.

Low-frequency signal $P_L(t)$ is $P_{n,0}(t)$ reconstruction signal decomposed by the nth floor of wavelet packet, n is decided by maximum power changing value of $P_L(t)$. Low-frequency signal is used as grid-connected target value. Besides, maximum power changing value of $P_L(t)$ should satisfy standard of wind power integration. So evaluation index of wavelet packet decomposition low-frequency signal is

$$\Delta P_{\max} = P_{\max}[t, t+T] - P_{\min}[t, t+T] \quad (4)$$

Refer to (4), $\Delta P_{\max}$ is maximum power changing value, T is sample time, $P_{\max}[t, t+T]$ and $P_{\min}[t, t+T]$ are maximum and minimum power within sample cycle, respectively. One minute fluctuation index is considered in this paper.

According to amplitude–frequency characteristic of reconstruction signals from $P_{n,1}(t)$ to $P_{n,n-1}(t)$, f_s is parting frequency. When $f_k < f_s$, reconstruction signal $P_{n,k}(t)$ belongs to sub-high frequency signal. When $f_k \geq f_s$, reconstruction signal $P_{n,k}(t)$ belongs to high frequency. The formula is given as

$$\begin{cases} P_M(t) = \sum_{m=1}^{s} P_{n,m}(t) \\ P_H(t) = \sum_{m=s+1}^{n-1} P_{n,m}(t) \end{cases} \quad (5)$$

Refer to (5), $P_M(t)$ is target power of battery system and $P_H(t)$ is target power of super-capacitor system.

3 Charging and discharging control strategy for hybrid energy storage system

3.1 Charging and discharging control strategy for hybrid energy storage system

By using battery and super-capacitor hybrid energy storage system to smooth the fluctuation of wind power, the phenomenon of frequent charging and discharging of battery energy storage is relieved in some degree. When capacity of battery and super-capacitor is constant, SOC of energy storage system will reach the limit and has bad influence on energy storage device. Fuzzy control strategy is set up in this paper, which is shown in Fig. 1.

In Fig. 1, control of hybrid energy storage system is divided into three sections:

1. Wind power $P(t)$ is decomposed by wavelet packet, sub-high frequency signal $P_M(t)$ is used as target power P_b^* and input into fuzzy controller 1. High-frequency signal $P_H(t)$ is used as target power P_{sc}^* and input into fuzzy controller 2.
2. The second input of fuzzy controller 1 is SOC of battery while the second input of fuzzy controller 2 is SOC of super-capacitor. Output of fuzzy controllers is power amendment value ΔP_b and ΔP_{sc}.
3. Using power correction value of super-capacitor as power compensation of battery. Besides, using power amendment value of battery as power compensation of super-capacitor. It is the second power amendment.

3.2 Design of fuzzy controller

Fuzzy control does not rely on accurate mathematical model of controlled object, and it can overcome the influence of nonlinear factor. Besides, it has better robustness to controlled object [14]. Fuzzy controller is used to optimise SOC of energy storage device, control strategy is

1. When SOC of energy storage device is middle, output power coefficient k_λ is zero. Target power of energy storage system does not change.
2. When SOC of energy storage device is exhaustion and state of energy storage system is discharging, coefficient k_λ is used to reduce target discharging power.
3. When SOC of energy storage device is saturation and state of energy storage system is charging, coefficient k_λ is used to reduce charging power.

In conclusion, when SOC of hybrid energy storage system is reaching the limit, fuzzy controller changes the target power of hybrid energy storage system and makes SOC within safe range.

In order to satisfy the symmetry of input of fuzzy controller, two inputs of fuzzy controller are changed in this paper. The first input δ_1 is the ratio of target power of hybrid energy storage system and maximum power. The formula is given as

$$\delta_1 = \frac{P^*}{P_{\max}} \quad (6)$$

The second input δ_2 is the ratio of SOC of energy storage system difference of present SOC and initial SOC. The formula is given as

$$\delta_2 = \frac{\text{SOC} - \text{SOC}_0}{\text{SOC}_0} \quad (7)$$

Power changing value of fuzzy controller is

$$\Delta P = P^* + k_\lambda P_{\max} \quad (8)$$

Fuzzy sets are

$$\delta_1 = \{\text{NB}, \text{NS}, \text{ZE}, \text{PS}, \text{PB}\}$$

$$\delta_2 = \{\text{NB}, \text{ZE}, \text{PB}\}$$

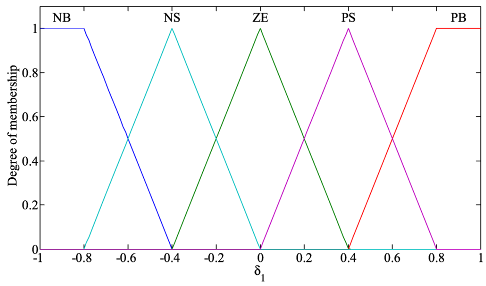

Fig. 2 *Degree of membership of the first input value of battery and super-capacitor*

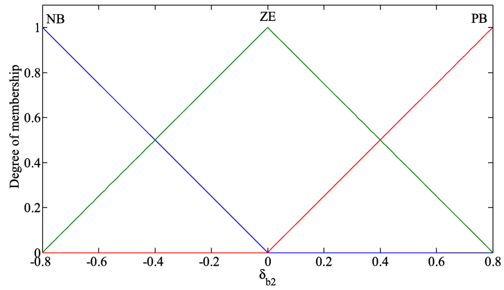

Fig. 3 *Degree of membership of the second input value of battery*

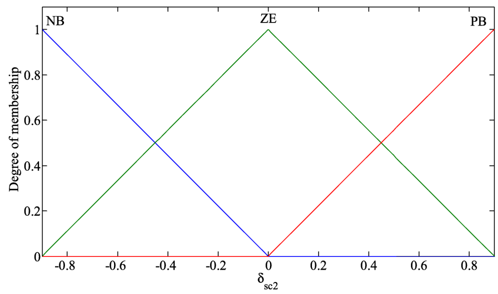

Fig. 4 *Degree of membership of the second input value of super-capacitor*

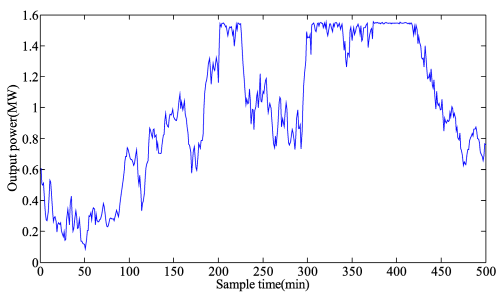

Fig. 5 *Curve of wind output power*

$$k_\lambda = \{\mathrm{NB, NS, ZE, PS, PB}\}$$

Domain of discourse of first input of fuzzy controller 1 and 2 is [−1, 1]. Membership degree function is shown in Fig. 2. Domain of discourse of second input of fuzzy controller is [−0.8, 0.8]. Membership degree function is shown in Fig. 3. Also domain of discourse of second input of fuzzy controller 2 is [−0.9,0.9]. Membership degree function is shown in Fig. 4.

Fuzzy control rule of battery energy storage system is shown in Table 1. Rule of super-capacitor is the same as battery, but domain of discourse of first input is different.

4 Analysis of examples

Data of a 1.5 MW double-fed wind generator is used in this paper. Grid-connected voltage is 690 V. The number of sample data is 500, and the sample time is 1 min. The curve of output power is shown in Fig. 5.

Table 1 Fuzzy control rule of battery energy storage

δ_1/δ_2	NB	ZE	PB
NB	ZE	ZE	PB
NS	ZE	ZE	PS
ZE	ZE	ZE	ZE
PS	NS	ZE	ZE
PB	NB	ZE	ZE

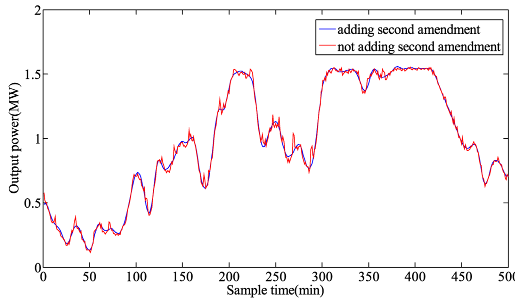

Fig. 6 *Contrast of grid-connected wind power with and without the second amendment*

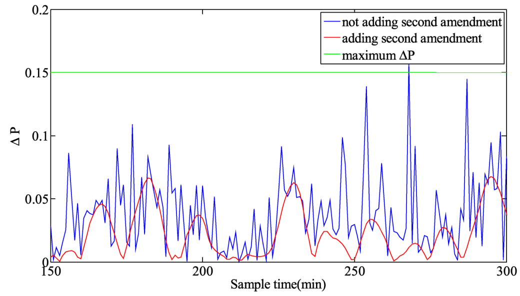

Fig. 7 *Contrast of the maximum ΔP with and without the second amendment added*

Other crucial parameters for the simulation are shown as follows: battery style is M12-0.33 lead-acid battery and 105 in series. Capacity of battery is 0.672 MWh. Super-capacitor style is UCPY3000F and 10 in series. Capacity of super-capacitor is 0.3 MWh. Initial SOC of battery and super-capacitor are 0.5. DC voltage of the inverter of battery energy storage system is 1300 V, and boost inductance is 0.03 H. DC capacitor is 0.1 F. In addition, the floor of wavelet packet decomposition is 3.

In order to reflect the effect of the second amendment, contrast of grid-connected wind power with and without the second amendment is shown in Fig. 6.

With Fig. 5 and 6 compared, it is not difficult to conclude that the grid-connected power curve is smoother when an energy storage device is added. In addition, by comparing with the first and second amendment added, there comes a conclusion that when the frequency is higher, grid-connected power without the second amendment added is more fluctuant. The worst situation is that grid-connected power cannot satisfy the standard of wind power integration. Contrast of the maximum power range ΔP when adding with and without the second amendment added is displayed in Fig. 7. In order to highlight the advantage of the second amendment, Fig. 7 only shows samples which sampling time ranges from 150 to 300.

It is shown in Fig. 7 that the maximum power ranges from 0 to 0.158 MW ΔP without the second amendment added. One sample point exceeds maximum ΔP, and several sample points approach to maximum ΔP. In contrast, the maximum power ranges from 0 to 0.06 MW with the second amendment added. It is obvious that all sample points are under maximum ΔP. Therefore, the second amendment for energy storage system is verified to result in smooth and stable power when wind power is frequently fluctuating. Fig. 8 shows the contrast of output power of battery and super-capacitor.

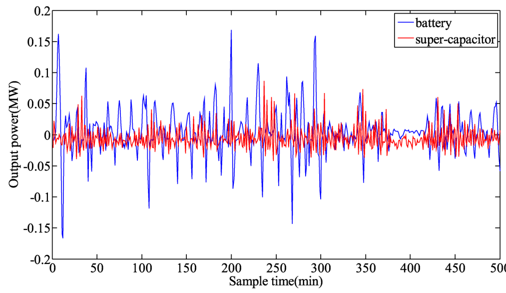

Fig. 8 *Contrast of battery and super-capacitor power*

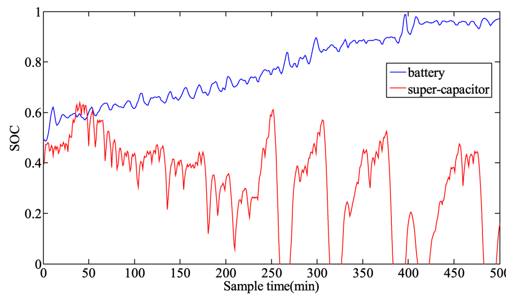

Fig. 9 *SOC of energy storage system without fuzzy controller added*

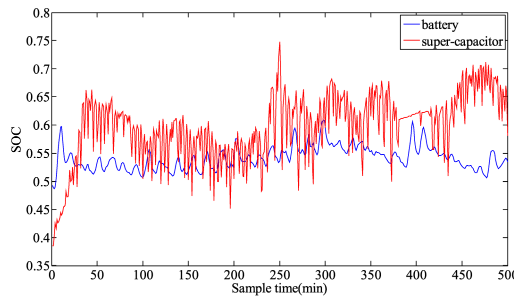

Fig. 10 *SOC of energy storage system with fuzzy controller added*

Fig. 8 shows that the amplitude of battery power is −0.17 to 0.18 MW, and the amplitude of super-capacitor power is −0.1 to 0.09 MW. Besides, the frequency of super-capacitor is higher than battery [15, 16]. Therefore, complementary of battery and super-capacitor is fully utilised. Application of super-capacitor reduces the charging and discharging time of battery, so that l battery life can be longer.

SOC is one of key factors which make influence on the life of energy storage system [17, 18]. If energy storage devices are connected in series, SOC of each device should be safe. Safe range for SOC of batteries is 0.1 to 0.9 while that of super-capacitor is 0.05 to 0.95. SOC of battery and super-capacitor without fuzzy controller added is shown in Fig. 9. SOC of hybrid energy storage system with fuzzy controller added is shown in Fig. 10.

By comparing Fig. 9 and 10, it is not difficult to figure out that SOC of battery decreases from [0.48, 0.98] to [0.48, 0.6], and SOC of super-capacitor increases from [0, 0.64] to [0.39, 0.75]. Through adding fuzzy controller, the SOC fluctuations of battery and super-capacitor are both in a safe range, which proves that the fuzzy control strategy effectively optimises SOC of energy storage device and increases the life of energy storage system.

5 Conclusion

Based on wavelet packet decomposition and fuzzy control, a new control strategy for wind power hybrid energy storage system is set up in this paper. The method stabilises the fluctuation of wind power through battery super-capacitor hybrid energy storage system, decomposes wind power into low-frequency, sub-high frequency and high-frequency components through wavelet packet decomposition, and stabilises sub-high and high-frequency components through complementary property of battery and super-capacitor. Grid-connected power and SOC of energy storage device is optimised by first and second power amendment. So control strategy is verified more superior.

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