Supercapacitor hybrid energy storage system applied to photovoltaic power generation

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Abstract. In order to solve the problem of power pulsation at the DC bus side caused by uneven illumination or load fluctuation, a hybrid energy storage system for supercapacitors is proposed. In the hybrid energy storage circuit, inductors are added to form a high-frequency filter with the supercapacitor, and the supercapacitor absorbs the high-frequency current component of the DC side. The traditional droop control strategy is adopted to effectively filter the high-frequency current component of the battery side, and the battery is responsible for processing the low-frequency current component. The simulation results show that the proposed hybrid energy storage system can reduce the voltage pulsation of the DC bus, and the response and recovery speed is faster, which can effectively suppress the power pulsation on the side of the photovoltaic DC bus.

1. Introduction

The abrupt change of light intensity, temperature environment and load in photovoltaic power generation will cause power pulsation of DC bus, which will directly affect the grid-connection quality of photovoltaic power generation [1]. At present, the hybrid energy storage system (HESS) is a better solution [2]. Literature [3] proposed a passive parallel configuration of battery and supercapacitor, which has the advantages of low cost, low maintenance and small size, and no need to control supercapacitor voltage or SOC separately. However, when the HESS output current enters the DC-DC converter, it will cause the switching pulsation and ripple current of the DC-DC converter, and the high-frequency current component is easy to leak to the battery side, thus affecting the service life of the battery. Literature [4] proposed a hybrid energy storage system that cascades the battery and the supercapacitor through DC-DC converter. The voltage droop control was adopted, and the experiment verified that the DC bus voltage maintains a small range of fluctuations in the set value. However, such cascaded hybrid energy storage system increases the volume, quality, cost and control complexity of the system. Literature [5] proposes a new hybrid energy storage configuration, which uses supercapacitors and inductors to smooth the battery current. However, the design and performance have not been fully verified. The combined model of the hybrid energy storage circuit and DC-DC converter has only been theoretically analyzed, and it has not been generalized to any type of DC-DC converter.

To sum up, through the analysis of the research status of HESS, a hybrid energy storage system for supercapacitors is proposed, in which the battery is connected with the supercapacitor through an inductor, which can reduce the voltage pulsation on the side of the DC bus, and the response is quick...
and the control is simple. The inductor and supercapacitor constitute a high frequency filter, which can effectively filter out the high frequency current ripples on the battery side.

2. Hybrid energy storage circuit

2.1. Design of hybrid energy storage circuit

The hybrid energy storage circuit is shown in Figure 1. PV panels absorb solar energy and output direct current to the DC bus side through the boost converter circuit [6]. At the same time, the hybrid energy storage circuit maintains the stability of the power on the DC bus side by charging and discharging to the DC bus side through the bidirectional DC-DC conversion circuit.

![Figure 1. Hybrid energy storage circuit.](image)

It can be seen from Figure 2 that the proposed hybrid energy storage circuit is connected in parallel with the DC bus through the bidirectional DC-DC conversion circuit. When the actual voltage of the DC bus is higher than the reference voltage, the controller controls the switch tubes S1 and S2 to charge the battery. When the actual voltage of the DC bus is lower than the reference voltage, the controller adjusts S1 and S2 to make the battery supply power to the DC bus side. $L_1$ and SC constitute a high frequency filter, which can smooth the battery current, make the battery only provide or receive low frequency current component, and improve the battery life. The control strategy is in Section 3.

2.2. Parameter configuration of hybrid energy storage

The configuration circuit of the proposed hybrid energy storage circuit is shown in Figure 2.

According to Figure 2, the battery current $i_b$ and the supercapacitor current $i_{SC}$ can be expressed by Equation (1):

\[
\begin{align*}
    i_b &= (V_{bat} - v_{sc}) / (R_b + Z_{L1}) \\
    i_{sc} &= v_{sc} / (R_{sc} + Z_{sc})
\end{align*}
\]

(1)

![Figure 2. Configuration circuit diagram of hybrid energy storage circuit.](image)
$R_b$ and $R_{SC}$ are the internal resistances of the battery and SC respectively, $Z_{L1}$ and $Z_{SC}$ are the impedances of $L_1$ and SC respectively. In the frequency domain, Equation (1) can be rewritten as:

$$\begin{align*}
    i_b &= -\frac{v_{sc}(s)}{(R_b + L_b(s))} \\
    i_{sc} &= \frac{v_{sc}(s)}{(R_{sc} + \frac{1}{C_{sc}s})}
\end{align*}$$

The total output current of mixed energy storage is expressed as:

$$i_{HE} = i_b - i_{sc}$$

Then, the transfer function $G_{HE}(s)$ of battery current $i_b$ and mixed energy storage output current $i_{HE}$ is obtained, as shown in Equation (4):

$$G_{HE}(s) = \frac{i_b}{i_{HE}} = \frac{1 + R_{sc}C_{sc}s}{1 + (R_{sc} + R_b)C_{sc}s + L_scCs}$$

It can be obtained that $G_{HE}(s)$ has a zero and two poles:

$$\begin{align*}
    z_{sc} &= -\frac{1}{(R_bC_{sc})} \\
    p_1 &= -\frac{(R_{sc} + R_b)C_{sc} + \sqrt{(R_{sc} + R_b)^2C_{sc}^2 - 4LC_{sc}}}{2LC_{sc}} \\
    p_2 &= -\frac{(R_{sc} + R_b)C_{sc} + \sqrt{(R_{sc} + R_b)^2C_{sc}^2 - 4LC_{sc}}}{2LC_{sc}}
\end{align*}$$

Parameter configuration design steps of hybrid energy storage circuit are as follows:

1. Calculate the steady-state time $t_s$. $t_s$ is defined as the time required for the hybrid energy storage system response to reach and remain within 10% of its final output current.

$$t_s = \frac{2.25}{2\pi f_c}$$

In Equation (6), $f_c$ is the decoupling frequency of the hybrid energy storage system, determined by the first pole of $G_{HE}(s)$: $f_c = -\frac{p_1}{2\pi}$

2. The capacitance of SC can be expressed as:

$$C_{sc} = \frac{t_s}{2.25(R_{sc} + R_b)}$$

When $L_1$ is small and the decoupling frequency is large, the capacitance of the SC does not affect the gain of $G_{HE}(s)$. Therefore, the battery side is not affected. By calculating, the voltage gain between the supercapacitor and the battery is approximately 1, it can be concluded that the voltage at both ends of the battery is basically equal to the voltage at both ends of the supercapacitor.

3. Determine the value of inductor $L_1$. According to calculation and analysis, when the gain $G_{HE}(s)$ is less than -20dB at the frequency of 100Hz, the filter can effectively filter out the high-frequency current component at the battery side, as shown in Equation (8):

$$G_{HE}(s)\mid_{f=100Hz} < -20dB$$

The value of inductor $L_1$ can be determined by Equation (8).

3. Control strategy of hybrid energy storage system

The droop control strategy of HESS is shown in Figure 3 [7]. Where $V_{nom}$ is the set value of DC bus voltage, $v_{out}$ is the set value of HESS output voltage, $i_{out}$ is the actual output current of HESS, $i_b*$ and $i_b$ are the given output current and actual output current of the battery respectively, and $R_d$ is the droop coefficient.
The droop controller is described as:

\[ v_{\text{out}}^* = V_{\text{nom}} - r_d i_{\text{out}} \]  \hspace{1cm} (9)

The droop coefficient is expressed as:

\[ r_d = \frac{V_{\text{min}}}{i_{\text{rated}}} \]  \hspace{1cm} (10)

where \( V_{\text{min}} \) is the minimum permissible voltage of the DC bus and \( i_{\text{rated}} \) is the rated current of the HESS converter. The reference output current \( i_{\text{b}}^* \) of the battery is obtained by PI voltage controller:

\[ i_{\text{b}}^* = \left( k_{Pv} + \frac{k_{Iv}}{s} \right) (v_{\text{out}}^* - v_{\text{out}}) \]  \hspace{1cm} (11)

where \( k_{Pv} \) and \( k_{Iv} \) are the PI gains of the voltage control loop. Then the inductor current is controlled by current controller:

\[ d = \left( k_{P} + \frac{k_{I}}{s} \right) (i_{\text{b}}^* - i_{\text{b}}) \]  \hspace{1cm} (12)

where \( k_{P} \) and \( k_{I} \) are the PI gains of the current control loop.

The set voltage \( V_{\text{nom}} \) at the DC bus side is controlled by droop control to obtain the given output voltage \( v_{\text{out}}^* \) of HESS. The \( v_{\text{out}}^* \) is compared with the actual measured output voltage \( v_{\text{out}} \), and the given output current \( i_{\text{b}}^* \) of the battery is obtained by the proportional integral voltage controller. Then, \( i_{\text{b}}^* \) is compared with the actual measured output current of the battery. The duty cycle \( d \) is obtained by the proportional integral current controller. Finally, two pulses PWM1 and PWM2 are outputs by the PWM generator to control the switches S1 and S2 of the bidirectional DC-DC converter respectively. In conclusion, this control strategy not only maintains the voltage stability of the DC bus side, but also tracks the output voltage and battery output current in HESS respectively, which ensures the stability of the output voltage and battery output current in HESS.

4. Simulation verification and analysis
MATLAB/Simulink simulation software is used to model HESS, as shown in Figure 1, and the basic parameters of the model are set as shown in Table 1 and Table 2.

| Table 1. Parameter setting of hybrid energy storage system. |
|-----------------------------------------------------------|
| Parameter | Symbol | Value |
| Battery rated voltage | \( V_{b}/V \) | 24 |
| Accumulator internal resistance | \( R_{b}/\Omega \) | 0.12 |
| inductor | \( L_{i}/\text{mH} \) | 0.47 |
| SC rated voltage | \( V_{SC}/V \) | 25 |
| SC Rated capacitance | \( C_{SC}/\text{F} \) | 4 |
| Filtering inductance | \( L_{2}/\text{mH} \) | 7.5 |
| Switching frequency | \( f_{s}/\text{kHz} \) | 20 |
| Droop coefficient | \( r_d \) | 0.3 |
Table 2. Parameters setting of photovoltaic power system.

| Parameter                  | Symbol | Value |
|----------------------------|--------|-------|
| DC bus rated voltage       | $V_{dc}$/V    | 48    |
| regulator capacitance      | $C_{dc}$/mF    | 20    |
| Filtering inductance        | $L$/mH     | 0.09  |
| AC side filter inductor    | $L_{a}$/mH    | 0.3   |
| AC side filter inductor    | $L_{b}$/mH    | 0.6   |
| AC side filter capacitor   | $C_{f}/\mu F$ | 5     |

In order to evaluate the effectiveness of the HESS in suppressing the voltage and power pulsation on the side of the DC bus of photovoltaic power generation and the advantages of the HESS, simulation verification and analysis were carried out in the following three cases.

4.1. Performance verification of HESS

The initial illumination intensity is set as $S=600W/m^2$ and the temperature is set as 25°C. $S$ drops to 400W/m$^2$ at 2s and rises to 600W/m$^2$ at 3s. The current and voltage waveforms on HESS are observed, as shown in Figure 4 and Figure 5.

![Figure 4. Output current waveforms of HESS.](image)

![Figure 5. Waveforms of voltage of battery and supercapacitor.](image)

By observing the simulation results in Figure 4, it can be seen that when the illumination intensity changes, the SC output current $i_{SC}$ responds quickly to the instantaneous pulsation, the battery output current $i_b$ is relatively gentle and basically has no pulsation, and the total output current $i_{HE}$ of HESS is relatively stable, which is conducive to stabilizing the DC bus voltage and power pulsation. From Figure 5, it can be seen that the voltage $v_b$ at both ends of the battery and the voltage $v_{SC}$ at both ends of the supercapacitor basically coincide, so the control of the voltage at both ends of the supercapacitor can be omitted.
4.2. DC bus voltage stability analysis

(1) The initial illumination intensity is set as $S=600\text{W/m}^2$ and the temperature is set as $25\degree\text{C}$. $S$ drops to $400\text{W/m}^2$ at $2\text{s}$ and rises to $600\text{W/m}^2$ at $3\text{s}$, load power is $600\text{W}$, the DC bus side voltage waveform is observed, as shown in Figure 6(a); (2) The initial illumination intensity $S=600\text{W/m}^2$, the temperature is $25\degree\text{C}$, the load suddenly drops from $600\text{W}$ to $300\text{W}$ at $2\text{s}$, and then rises to $600\text{W}$ at $3\text{s}$. The voltage waveform on the side of DC bus is observed, as shown in Figure 6(b).

According to Figure 6, it can be seen that the bus voltage on the DC side is maintained at $48\text{V}$ as a whole no matter the illumination intensity changes or the load changes. At $2\text{s}$, $3\text{s}$, there are voltage fluctuations, but the voltage fluctuations are less than $6\%$, and they all recover to stability within $0.2\text{s}$. The voltage fluctuation of the traditional hybrid energy storage system is more than $10\%$, which requires about $0.5\text{s}$ to restore stability [8]. So the voltage fluctuation of DC bus under HESS control is smaller and the response recovery time is faster. It is verified that the proposed HESS can effectively suppress the voltage fluctuation of the DC bus side.

4.3. Changes of system input and output power

Set the initial illumination intensity $S=600\text{W/m}^2$ and the temperature at $25\degree\text{C}$. The load power rises sharply from $600\text{W}$ to $1200\text{W}$ at $2\text{s}$, and then drops sharply to $600\text{W}$ at $3\text{s}$. Observe the system output power, as shown in Figure 7.

According to Figure 7, when the photovoltaic output power is higher than the load power, the battery absorbs the excess power from the DC bus. When the photovoltaic output power is lower than the load power, the battery compensates the average power to the DC bus, and the SC quickly responds to compensate the instantaneous power. The proposed hybrid energy storage system can effectively compensate the DC bus side power balance.

Through the analysis of three cases, the proposed HESS can reduce the DC bus side voltage ripple and respond quickly. The output current of the battery has no pulsation basically, and it does not need to control SC separately, so the control is simple. The charge and discharge of HESS can ensure the power balance of DC bus.
5. Conclusions
The HESS proposed in this paper uses an inductor to replace the DC-DC converter in the traditional hybrid energy storage system. It does not need to control the SC separately, and uses the traditional droop control strategy to solve the voltage and power ripple problems of the DC bus side in photovoltaic power generation. The simulation results show that HESS can reduce the voltage ripple of DC bus side of photovoltaic power generation system within 6%, restore the voltage stability within 0.2 s, the output current of battery has no ripple basically, and the supercapacitor responds quickly.

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References
[1] Zhou Chunsheng 2021 Application of energy storage technology in photovoltaic grid-connected power generation system Development orientation of building materials 19(1) 193-194
[2] Sahin M E and Blaabjerg F 2020 A hybrid PV-battery/supercapacitor system and a basic active power control proposal in MATLAB/Simulink Electronics 9(1) 129
[3] Wendi Zheng and Jinding Cai 2012 Energy management strategy of fuel cell/supercapacitor hybrid power generation system Power Automation Equipment 32(12) 28-32
[4] Bo Wen, Wenping Qin, Han Xiaoqing, et al 2015 Control strategy of DC Micro-grid hybrid energy storage system based on voltage sagging method Power Grid Technology (4) 892-898
[5] Dam D H, Hoang D K, Chun, T W and Lee H H 2018 A hybrid energy storage system for transient load and its multiple operation in DC microgrid In: 2018 IEEE International Conference on Industrial Electronics for Sustainable Energy Systems (IESES) pp 314-319
[6] Yueqiang Yang and Longji Zhu 2021 Control strategy of super capacitor hybrid energy storage system in microgrid Journal of Guangxi Normal University (Natural Science Edition) 39(02) 71-80
[7] DuyHung Dam and HongHee Lee 2020 Battery–inductor–supercapacitor hybrid energy storage system for DC microgrids Journal of Electronic 20) 308-318
[8] Xinhao Zheng and Longji Zhu 2020 Research on energy storage control strategy of photovoltaic DC Micro-grid supercapacitors Renewable Energy 38(04) 497-501