Lithium battery and super capacitor hybrid energy storage system control method research

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Abstract. Because single energy storage element is difficult to meet the requirements of system for the power density and energy density, this paper uses two energy storage elements, including lithium battery (LB) and super capacitor (SC), to constitute hybrid energy storage system. When bus voltage fluctuation occurs, through first-order low-pass filter to complete power allocation. Super capacitor will deal with high frequency wave component and lithium battery will handle low frequency wave component to maintain the stability of bus voltage. Finally, compared with a single energy storage element of charging and discharging experiments to show the effectiveness of the proposed method by the MATLAB simulation software.

Keywords: Lithium Battery; Super Capacitor; Hybrid Energy Storage System; Power Allocation

1. Introduction

In micro power grid, the energy storage system is an indispensable part [1]. Because energy storage technology can provide short-term power supply, improve micro grid power quality and improve the performance of micro power supply, research on the energy storage system is of great significance. Super capacitor is a new type of energy storage component [2, 3]. Super capacitor has big power density, long life and other advantages except low energy density, to some extent, which limits the use of it. Lithium battery is the most common energy storage battery in our life. Because its interior is chemical change, lithium battery has the characteristics of high energy density. However, low power density and short life similarly limit the use of it. In this paper, lithium battery and super capacitor are used to constitute hybrid energy storage system [4, 5]. Through the charge and discharge simulation experiment, compared with single energy storage element system, to show the superiority of the hybrid energy storage.

2. Mathematical modeling of hybrid energy storage system

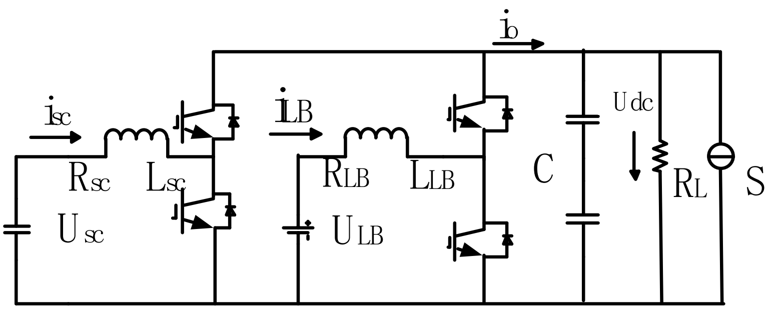

Fig 1. Hybrid energy storage system structure

In Figure 1, super capacitor and lithium battery respectively connect to the dc bus by two-way DC - DC converter. Isc represents the super capacitance current. I_{LB} represents the lithium battery current. Usc represents the super capacitance voltage. U_{LB} represents the lithium battery voltage. U_{dc} represents output voltage. C represents dc bus capacitors. S represents photovoltaic simulation power supply. Establishing a system of switch cycle average model [6]:

$$\begin{cases} L_{LB}\dfrac{di_{LB}}{dt} = U_{LB} - d_{LB}U_{dc} - i_{LB}R_{LB} \\ L_{SC}\dfrac{di_{SC}}{dt} = U_{SC} - d_{SC}U_{dc} - i_{SC}R_{SC} \\ C\dfrac{dU_{dc}}{dt} = d_{LB}i_{LB} + d_{SC}i_{SC} - \dfrac{U_{dc}}{R_L} \end{cases} \tag{1}$$

In type (1), d_{LB} and dsc represent respectively the lithium battery and super capacitor duty ratio. R_{LB} and L_{LB} represent respectively lithium battery side inductance resistance and inductance. Rsc and Lsc represent respectively super capacitor side inductance resistance and inductance. To type (1), small signal linearization at the stable point is needed and the high frequency dynamic characteristics will be ignored.

$$\begin{cases} L_{LB}\dfrac{d\hat{i}_{LB}}{dt} = -D_{LB}\hat{u}_{dc} - U_{dc}\hat{d}_{LB} - \hat{i}_{LB}R_{LB} \\ L_{SC}\dfrac{d\hat{i}_{SC}}{dt} = -D_{SC}\hat{u}_{dc} - U_{dc}\hat{d}_{SC} - \hat{i}_{SC}R_{SC} \\ C\dfrac{d\hat{u}_{dc}}{dt} = D_{LB}\hat{i}_{LB} + \hat{d}_{LB}I_{LB} + D_{SC}\hat{i}_{SC} + I_{SC}\hat{d}_{SC} - \dfrac{\hat{u}_{dc}}{R_L} \end{cases} \tag{2}$$

$$\begin{cases} 0 = U_{LB} - D_{LB}U_{dc} - I_{LB}R_{LB} \\ 0 = U_{SC} - D_{SC}U_{dc} - I_{SC}R_{SC} \\ 0 = D_{LB}I_{LB} + D_{SC}I_{SC} - \dfrac{U_{dc}}{R_L} \end{cases} \tag{3}$$

In type (2), '∧' represents small semaphore. According to type (2, 3), the small signal transfer function can be obtained in complex frequency domain.

$$\hat{i}_{LB} = \frac{-[D_{LB}I_{LB} + sCU_{dc} + \dfrac{sCU_{dc}}{R_L}]\hat{d}_{LB} - D_{LB}D_{SC}\hat{i}_{SC} - D_{LB}I_{SC}\hat{d}_{SC}}{s^2L_{LB}C + \dfrac{s^2L_{LB}C}{R_L} + sR_{LB}C + \dfrac{sR_{LB}C}{R_L} + D_{LB}{}^2} \tag{4}$$

$$\hat{i}_{SC} = \frac{-(D_{SC}I_{SC} + sCU_{dc} + \dfrac{sCU_{dc}}{R_L})\hat{d}_{SC} - D_{SC}D_{LB}\hat{i}_{LB} - D_{SC}I_{LB}\hat{d}_{LB}}{s^2L_{SC}C + \dfrac{s^2L_{SC}C}{R_L} + sR_{SC}C + \dfrac{sR_{SC}C}{R_L} + D_{SC}{}^2} \tag{5}$$

$$\hat{u}_{dc} = \frac{(U_{LB} - sL_{LB}I_{LB})\hat{i}_{LB} + (U_{SC} - sL_{SC}I_{SC})\hat{i}_{SC}}{sU_{dc}C + \dfrac{sU_{dc}C}{R_L} + D_{LB}I_{LB} + D_{SC}I_{SC}} \tag{6}$$

In type (4, 5), bus capacitance coupling will cause a disturbance between the super capacitor and the lithium battery current, but the disturbance can be suppressed by closed loop control. Type (6) is the basis of parallel double loop design of bus voltage.

The corresponding transfer function expression can be got by a simplified calculation.

$$G_{id-LB} = \frac{\hat{i}_{LB}(s)}{\hat{d}_{LB}(s)} = \frac{-\left(D_{LB}I_{LB} + CU_{dc}s + \dfrac{CU_{dc}s}{R_L}\right)}{L_{LB}Cs^2 + \dfrac{L_{LB}Cs^2}{R_L} + L_{LB}R_{LB}s + \dfrac{L_{LB}R_{LB}s}{R_L} + D_{LB}{}^2} \tag{7}$$

$$G_{id-SC}=\frac{\hat{i}_{SC}(s)}{\hat{d}_{SC}(s)}=\frac{-\left(D_{SC}I_{SC}+CU_{dc}s+\frac{CU_{dc}s}{R_L}\right)}{L_{SC}Cs^2+\frac{L_{SC}Cs^2}{R_L}+L_{SC}R_{SC}s+\frac{L_{SC}R_{SC}s}{R_L}+D_{SC}{}^2} \tag{8}$$

$$G_{ui-LB}=\frac{\hat{u}_{dc}(s)}{\hat{i}_{LB}(s)}=\frac{U_{LB}-L_{LB}I_{LB}s}{U_{dc}Cs+\frac{U_{dc}Cs}{R_L}+D_{LB}I_{LB}+D_{SC}I_{SC}} \tag{9}$$

$$G_{ui-SC}=\frac{\hat{u}_{dc}(s)}{\hat{i}_{SC}(s)}=\frac{U_{SC}-L_{SC}I_{SC}s}{U_{dc}Cs+\frac{U_{dc}Cs}{R_L}+D_{LB}I_{LB}+D_{SC}I_{SC}} \tag{10}$$

Among them, G_{id-LB} represents the transfer function from the battery side inductance current I_{LB} to the battery side duty ratio d_{LB} and G_{id-SC} represents the transfer function from the super capacitor side inductance current I_{SC} to the super capacitor side duty ratio dsc. G_{ui-LB} and G_{ui-SC} represents the transfer function from the dc bus voltage U_{dc} to the battery side inductance current I_{LB} and to the super capacitor side inductance current I_{SC}.

3. Power allocation of hybrid energy storage system

The first-order low-pass filter has the advantage of simple design and convenient control, so this paper uses the low-pass filter to complete the power allocation. The cut-off frequency of the filter is f_L. Taking into account the response speed of lithium battery, the value should not be too large. However, the low value will lead super capacitor to bear greater energy. After overall consideration, f_L will set up 2Hz. As shown in Figure 2, p_0 represents total power of load mutation. p_{LBref} represents lithium battery output power. p_{SCref} represents super capacitor output power.

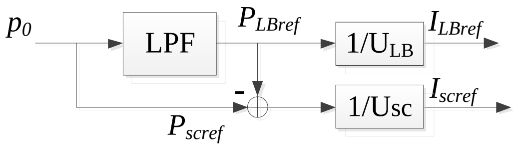

Fig 2. Hybrid energy storage power allocation diagram

$$p_{LBref}=\frac{1}{Ts+1}p_0 \tag{11}$$

$$p_{SCref}=p_0-p_{LBref} \tag{12}$$

In order to combine the power allocation strategy with the PI controller, P_{LBref} and p_{SCref} divide by their respective terminal voltage. I_{LBref} represents current reference value of lithium battery and I_{SCref} represents current reference value of super capacitor.

4. Control strategy of hybrid energy storage system

As shown in Figure 3, the double closed loop PI control method is used in the super capacitor and lithium battery. When the bus voltage fluctuates, energy storage battery will maintain its stability. K_{pwm} represents PWM modulation coefficient. Inside, the transfer function of the PI controller is

$$PI(s)=K_p+\frac{K_i}{s} \tag{13}$$

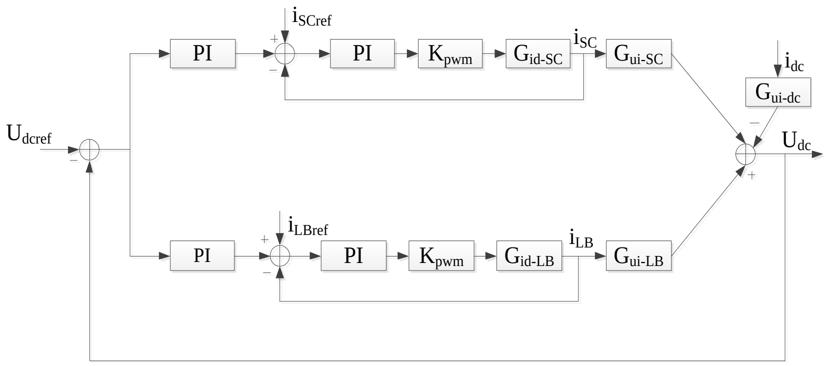

Fig 3. Control strategy diagram

5. Simulation

The stable value of bus voltage is 350V in this paper. Selecting 100V, 27F super capacitor, 200V and capacity of 100Ah lithium battery. Bus side capacitance for C is 0.0065F. Energy storage device side resistance R is 0.5Ω and Inductance value is 2mH uniformly. The switching period is 50μs. In simulation, Load R_L changes from 30Ω to 50Ω in 1.3 seconds and Photovoltaic analog power supply S starts in 2.5seconds.

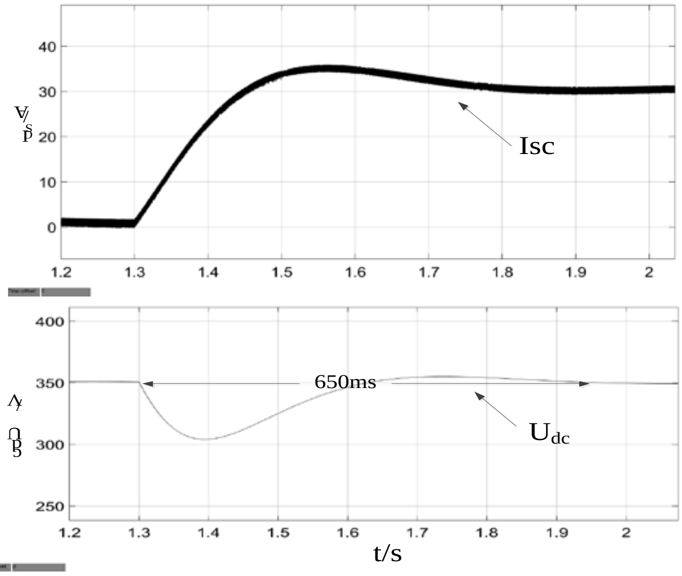

Fig4. Discharging simulation graph when super capacitor works alone

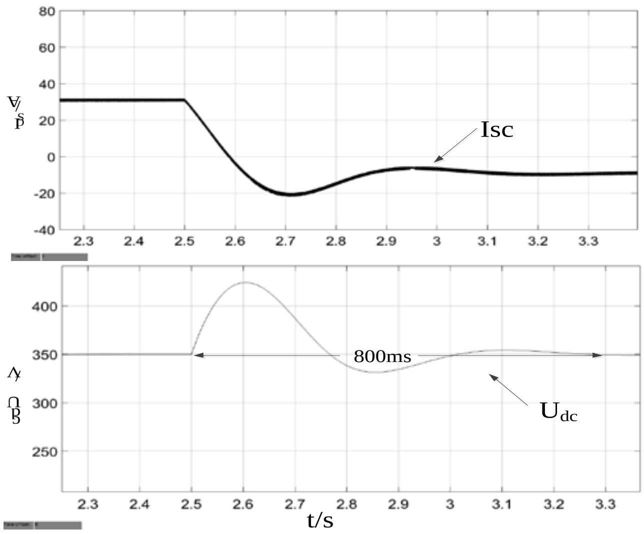

Fig5. Charging simulation graph when super capacitor works alone

As shown in Figure 4 and Figure 5, super capacitor works alone. Picture above means super capacitor current response wave form and picture below means bus voltage wave form. When the load changes in 1.3 seconds, super capacitor can respond immediately and bus voltage can be stable to 350V. The results show that super capacitor which works alone can maintain the power balance and the stability of the bus voltage. In Figure 4, the recovery time of bus voltage requires 650ms and bus voltage drops 48V. In Figure 5, when photovoltaic analog power supply starts in 2.5seconds, bus voltage can be still stable to 350V. However, the recovery time of bus voltage requires 800ms and bus voltage rises 75V.

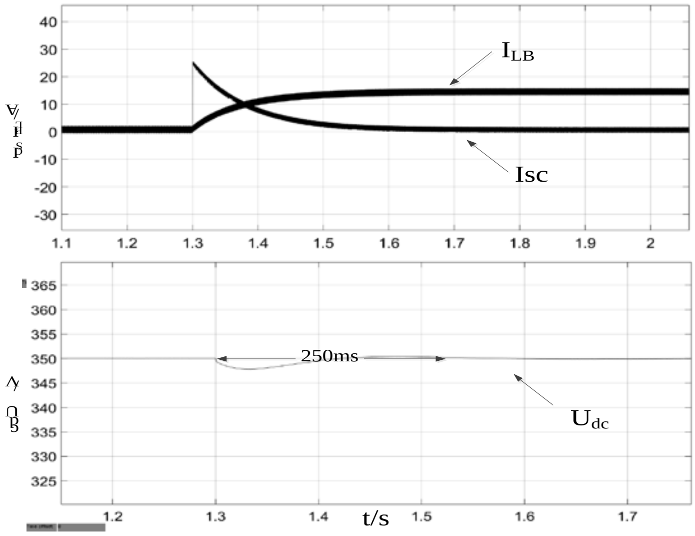

Fig6. Discharging simulation graph of hybrid energy storage

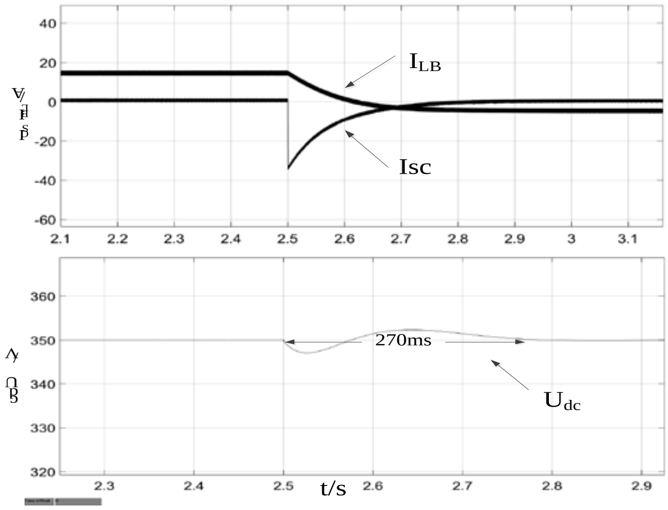

Fig7. Charging simulation graph of hybrid energy storage

Adding lithium battery to form hybrid energy storage system. Lithium battery will deal with low frequency component of bus voltage fluctuation after the power allocation. As shown in Figure 6 and Figure 7, picture above means current response wave form and picture below means bus voltage wave form of two energy storage elements. When the load changes in 1.3 seconds, bus voltage is fluctuating. Super capacitor and lithium battery immediately response. After super capacitor dealing with high frequency power fluctuation and lithium battery dealing with low frequency power fluctuation, the time of bus voltage recovery to stable value 350V only needs 250ms and bus voltage only drops 2.5V. When photovoltaic analog power supply starts in 2.5seconds, super capacitor and lithium battery immediately response. The time of bus voltage recovery to stable value 350V only needs 270ms and bus voltage only rises 3V, which shows excellent performance.

6. Summary

This paper uses super capacitor and lithium battery to form hybrid energy storage system, which gives full play to the advantages of two energy storage components. Hybrid energy storage system satisfies the requirements of high power density and high energy density. According to simulation results of charge and discharge, using hybrid energy storage system is better than super capacitor alone. The time of bus voltage recovery to stable value greatly shortened and bus voltage fluctuation is smaller.

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