A Bi-Directional DC/DC Converter for Battery-Supercapacitor Hybrid Energy Storage System

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Abstract

Renewable energy sources (RES) (such as solar energy and wind energy) is the inevitable trend of power system development in the future, but its output power is intermittent and random, which brings new challenges to the safe and stable operation of power system. Energy storage technology is an effective way to solve the power quality of RES power generation and a key technology to ensure the safe and stable operation of power grid. Energy storage system (ESS) is mainly divided into the ESS with single energy storage element and hybrid energy storage system (HESS) with multiple energy storage elements. Because the ESS with single energy storage element has the disadvantages of the low energy density or low power density, the HESS is more widely used in the power grid. Among them, a bi-directional DC/DC converter is the most important part of the ESS, which is a vital medium for energy storage unit and output side to realize power transmission. The research background of this paper is battery-supercapacitor HESS. A bi-directional DC/DC converter for battery-supercapacitor HESS is proposed in accordance with the characteristics of topology redundancy and poor economy of the existing battery-supercapacitor HESS. The energy storage unit of the HESS consists of a battery and a supercapacitor. Because of the high energy density of the battery and the high power density of the supercapacitor, the battery is the main power supply and the supercapacitor is the auxiliary power supply. Meanwhile, the system adds the diode D with a selection switch function and the cold stand-by charging circuit of supercapacitor to ensure the performance of energy storage unit. The working principle and three working modes of the HESS (supercapacitor pre-charging cold stand-by mode, boost mode and buck mode) are analysed in detail. The validity of the topology is verified by building the simulation model in MATLAB/Simulink. The results show that the system has the advantages of low voltage stress of switching devices, not changing the voltage conversion ratio of bi-directional DC/DC converters, providing high current and improving the life of battery. This paper provides theoretical basis and simulation experimental basis for the study of bidirectional DC/DC converter with the characteristics of topology optimization and low voltage stress of switching devices. At the same time, it is helpful to promote a more efficient bi-directional DC/DC converter to be used in ESS and provide a feasible research basis for the safe and stable operation of energy storage technology in power system.

Keywords: hybrid energy storage system (HESS); energy storage unit; bi-directional DC/DC converter; voltage conversion ratio; voltage stress

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1. Introduction

With the gradual reduction of fossil energy (such as oil and coal), humans pay more attention to the development and utilization of renewable energy such as solar energy and wind energy. Solar power generation (wind power generation) will be affected by external factors (such as weather and season, etc.), which may have a certain impact on the grid voltage. Therefore, it is particularly crucial to add a function of "storage" energy between the power generation equipment and power load of the grid [1]-[4].

Energy storage technology is a technology that converts power into other forms of energy stored in a medium and releases them in the form of power when needed. Compared with other forms of energy storage, chemical energy storage is more popular due to it is less restricted by environment and other conditions.

Among them, the battery (lead-acid battery, iron ion battery, etc.) has a high energy density, but the power density is low and the service life is short; the power density and cycle times of supercapacitor are high, but the energy density is low [5]. Therefore, combining the advantages of the battery and supercapacitor to form hybrid energy storage technology (HEST) is also a hot topic in the field of energy storage at present and in the future [6]-[8]. Especially in the field of electric vehicles (EV), the study of HEST can effectively improve the performance of EV and improve the life of batteries [9], [10]. In the structure of the existing battery-supercapacitor HESS connected with the DC bus, the units of supercapacitor and battery are connected in parallel at the DC bus side, and two sets of DC/DC converters and corresponding control circuits are required. The problem of the existing battery-supercapacitor HESS with parallel structure is that during the operation of the system, the energy released by the battery and supercapacitor must pass through their respective bi-directional DC/DC converters to supply power to the DC bus. Its control strategy is complex and energy loss is large. Therefore, the economy and complexity need to be improved.

ESS is mainly composed of energy storage unit and bi-directional DC/DC converter [11]. A bi-directional three-phase DC/DC converter with a high conversion ratio is introduced in reference [12]. It can effectively address the problem of high voltage conversion ratio between the DC bus and the energy storage unit, and the switching stress decreases. However, the introduction of Y-Δ connected transformer will increase the control difficulty of the system. Reference [13] proposed that an isolated bi-directional DC/DC converter can achieve high power density and current isolation, but the leakage inductance and control of transformer should be considered when isolating transformer exists. The ESS based on supercapacitors is mentioned in reference [14], [15]. Unfortunately, the energy density of supercapacitors is low. Battery-based ESS is mentioned in reference [16], [17]. Unfortunately, the power density of batteries is low. A frequency division control strategy is proposed for fuel cell electric vehicles with supercapacitor energy storage system in reference [18]. Fuel cells are used for power supply in low frequency band and supercapacitors for power supply in high frequency band. Reference [19], [20] proposed a battery-supercapacitor HESS, which effectively combines the advantages of both. Nevertheless, the proposed HESS is two separate branches in parallel, requiring two sets of DC/DC converters, and the control is complex and inexpensive. Reference [21]-[23] respectively put forward the idea of HESS of supercapacitor and battery in EV, microgrid and wind power generation, and proved that HESS can combine their respective advantages.

Aiming at the problems of redundancy in topology and poor economy of traditional HESS, a bi-directional DC/DC converter for battery-supercapacitor HESS is proposed. The HESS uses batteries as the main power supply and supercapacitors as the auxiliary power supply, which can effectively combine the advantages of both. Meanwhile, the energy storage unit of HESS (supercapacitor and battery) have a set of bi-directional DC/DC converter. In order to ensure the normal operation of the supercapacitor, the supercapacitor pre-charging circuit is introduced to improve the reliability of the energy storage unit. The battery-supercapacitor HESS can reduce the voltage stress of switching devices, provide high current, reduce the size of storage battery and ameliorate the life of storage battery. At the same time, the battery-supercapacitor HESS has simple topology, convenient control and good economy. The specific arrangement of the paper is as follows: Section II exhibits the topological structure and working principle of the proposed novel battery-supercapacitor HESS, while section III displays the control strategy of the proposed HESS. Section IV introduces the simulation results and analysis of the battery-supercapacitor HESS. Finally, section V summarizes the article and shows the next work.

2. Novel Battery-Super Capacitor Hybrid Energy Storage

The topology diagram of the novel battery-supercapacitor HESS is shown in Figure 1. As shown in Figure 1, the energy storage unit consists of a battery and a supercapacitor, which share a set of DC/DC converters. In addition, a diode *D* with selective switching function and a pre-charging circuit as a cold stand-by state is added to ensure the performance of the energy storage unit.

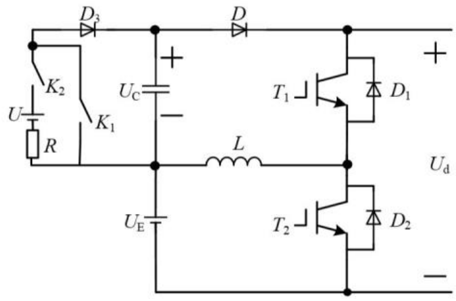


Figure 1. Structure of battery-supercapacitor hybrid energy storage system

The battery-supercapacitor HESS mentioned in Figure 1 above can well combine the advantages of battery and supercapacitor. U_E and U_C are respectively battery and supercapacitor terminal voltage, and U_d is bus terminal voltage. We might as well define switches K_1 and K_2 as follows:

$$K = \begin{cases} 1 & the\ K_1\ or\ K_2\ is\ closed \\ 0 & the\ K_1\ or\ K_2\ is\ turned\ on \end{cases} \tag{2.1}$$

Meanwhile, we introduce the following switch functions T to switches T_1 and T_2:

$$T = \begin{cases} 1 & the\ T_1\ or\ T_2\ is\ turned\ on \\ 0 & the\ T_1\ or\ T_2\ is\ turned\ off \end{cases} \tag{2.2}$$

The battery-supercapacitor HESS can be divided into two working modes: supercapacitor pre-charging mode (K_1K_2=01) and energy storage converter put into operation mode (K_1K_2=10). The operation mode of the energy storage converter can be divided into boost mode and buck mode. Therefore, we call the ESS has three main working modes: the supercapacitor pre-charging mode, the boost mode and buck mode.

1) When the DC bus voltage suddenly drops (such as when the EV starts or when the urban rail train starts frequently), the battery-supercapacitor HESS operates in the boost mode to stabilize the DC bus voltage. Supercapacitor has a high power density and can be switched on and off frequently. Therefore, for the boost mode, both batteries and supercapacitors supply power to the DC bus side to stabilize the DC bus side voltage rapidly. In the boost mode, the reverse parallel diode D_1 of the T_1 and the T_2 is turned on alternately. Therefore, boost mode has two working states: working state 1($K_1K_2T_1T_2$=1001) and working state 2 ($K_1K_2T_1T_2$=1000).

When the battery-supercapacitor HESS works in the working state 1 of the boost mode, K_2 is disconnected because K_1 is closed, and D_3 is cut off because of the reverse voltage U_C. U_C and U_E supply power to U_d through diode D, and U_E charges inductance L through T_2. When the ESS works in the working state 2 of the boost mode, K_2 is disconnected because K_1 is closed, and D_3 is cut off because of the reverse voltage U_C. The diode D is cut off due to reverse voltage, and U_E and L supply power to U_d of the DC bus voltage.

When the battery-supercapacitor HESS operates in the boost mode, it is assumed that the inductance current operates in a continuous state. Let the duty cycle of T_2 is d_1. From the above analysis, the boost mode has two working states (working state 1 and working state 2) in a switching period (T_s), and the specific work process has also been analysed. Now, analyse the voltage or current stress of components under different working states in boost mode, the T_2 trigger pulse is a series of trigger signals with T_s as cycle and d_1 as duty cycle. Meanwhile, we introduce the trigger physical quantity U_g:

$$U_g = \begin{cases} 1 & the\ T_1\ or\ T_2\ is\ turned\ on \\ 0 & the\ T_1\ or\ T_2\ is\ turned\ off \end{cases} \tag{2.3}$$

When the battery-supercapacitor HESS works in the working state 1 of the boost mode, the trigger pulse of T_2 is high level (U_g=1), and the switch tube T_2 is turned on (T=1). Therefore, the voltage U_{T2} at the T_2 end of the switch tube is

$$U_{T_2} = 0\ \mathrm{V} \tag{2.4}$$

The voltage U_{T1} at the T_1 end of the switch tube is

$$U_{T_1} = (U_C + U_L)\ \mathrm{V} \tag{2.5}$$

The voltage U_L at the inductance end is

$$U_L = U_E\ \mathrm{V} \tag{2.6}$$

In addition, the inductance current increases linearly. The terminal voltage U_D of diode D is

$$U_D = 0\ \mathrm{V} \tag{2.7}$$

Because the diode D is turned on at this stage. When the battery-supercapacitor HESS works in the working state 2 of the boost mode, the trigger pulse of T_2 is low level (U_g=0), and the switch tube T_2 is turned off (T=0). Therefore, the voltage U_{T2} at the T_2 end of the switch tube is

$$U_{T_2} = U_d\ \mathrm{V} \tag{2.8}$$

The voltage U_{T1} at the T_1 end of the switch tube is

$$U_{T_1} = 0\ \mathrm{V} \tag{2.9}$$

Because the diode D_1 is turned on. The voltage U_L at the inductance end is

$$U_L = (U_E - U_d)\ \mathrm{V} \tag{2.10}$$

In addition, the inductance current decreases linearly. The terminal voltage U_D of diode D is

$$U_D = (U_C + U_E - U_d)/2\ \mathrm{V} \tag{2.11}$$

Because the diode D is turned off at this stage, which will be subject to off voltage drop.

2) When the DC bus voltage suddenly rises, the system operates in the buck mode. Nevertheless, since there is a diode D having a selection switch function, only the battery is charged. For the reason that the battery is the main power supply, charging the battery can also properly increase the life of the battery and ensure the power quality of the battery. In the buck mode, the reverse parallel diode D_2 of the T_2 and the T_1 turns on alternately. Therefore, buck mode has two working states: working state 1 ($K_1K_2T_1T_2$=1010) and working state 2 ($K_1K_2T_1T_2$=1000).

When the battery-supercapacitor HESS works in the working state 1 of the buck mode, K_2 is disconnected because K_1 is closed, and D_3 is cut off because of the reverse voltage U_C. The DC side bus voltage U_d charges the inductance L and the battery U_E through T_1. When the battery-supercapacitor HESS works in the working state 2 of the buck mode, K_2 is disconnected because K_1 is closed, and D_3 is cut off because of the reverse voltage U_C. The diode D is cut off due to reverse voltage, and L supply power to U_E through D_2.

When the battery-supercapacitor HESS operates in the buck mode, it is assumed that the inductance current operates in a continuous state. Let the duty cycle of T_1 is d_2. From the above analysis, the buck mode has two working states (working state 1 and working state 2) in a switching period (T_s), and the specific work process has also been analysed. Now, analyse the voltage or current stress of components under different working states in buck mode, the T_1 trigger pulse is a series of trigger signals with T_s as cycle and d_2 as duty cycle. When the battery-supercapacitor HESS works in the working state 1 of the buck mode, the trigger pulse of T_1 is high level (U_g=1), and the switch tube T_1 is turned on (T=1). Therefore, the voltage U_{T2} at the T_2 end of the switch tube is

$$U_{T_2} = U_d\ \mathrm{V} \tag{2.12}$$

The voltage U_{T1} at the T_1 end of the switch tube is

$$U_{T_1} = 0\ \mathrm{V} \tag{2.13}$$

The voltage U_L at the inductance end is

$$U_L = (U_E - U_d)\ \mathrm{V} \tag{2.14}$$

In addition, the inductance current increases linearly. The terminal voltage U_D of diode D is

$$U_D = (U_C + U_E - U_d)\ \mathrm{V} \tag{2.15}$$

Because the diode D is turned off at this stage, which will be subject to off voltage drop. When the battery-supercapacitor HESS works in the working state 2 of the buck mode, the trigger pulse of T_1 is low level (U_g=0), and the switch tube T_1 is turned off (T=0). Therefore, the voltage U_{T2} at the T_2 end of the switch tube is

$$U_{T_2} = 0\ \mathrm{V} \tag{2.16}$$

Because the diode D_2 is turned on at this stage, its voltage drop is 0 V, thus forcing the voltage on switch T_2 to be 0 V. The voltage U_{T1} at the T_1 end of the switch tube is

$$U_{T_1} = (U_C + U_E)/2\ \mathrm{V} \tag{2.17}$$

The voltage U_L at the inductance end is

$$U_{\mathrm{L}} = -U_{\mathrm{E}}\ \mathrm{V} \tag{2.18}$$

In addition, the inductance current decreases linearly. The terminal voltage U_D of diode D is

$$U_{\mathrm{D}} = (U_{\mathrm{C}} - U_{\mathrm{d}})\ \mathrm{V} \tag{2.19}$$

Because the diode D is turned off at this stage, which will be subject to off voltage drop.

3) Supercapacitor is prevailing because of its high power density and short charging time. The fast charging and discharging and high power density of supercapacitor can guarantee the power quality of power grid when the power quality such as voltage instantaneous drop, flash edge or interruption occurs.

However, the state of charge of supercapacitor will decrease with the use of supercapacitor. If the voltage of supercapacitor drops to the cut-off voltage, the supercapacitor will cease to work [24]. Therefore, the pre-charging circuit is added to ensure the normal operation of the supercapacitor.

When the battery-supercapacitor HESS is in stand-by state, if the supercapacitor terminal voltage is detected to be in safe working voltage, the K_1 is closed and the K_2 is opened (K_1K_2=10), and the supercapacitor pre-charge circuit does not work. If the supercapacitor terminal voltage is detected to be lower than the cut-off voltage, the K_1 is turned off and the K_2 is closed (K_1K_2=01), so that the supercapacitor is in the pre-charge mode. Therefore, the supercapacitor pre-charging mode has two working states: working state 1 (K_1K_2=10) and working state 2 (K_1K_2=01).

When the battery-supercapacitor HESS works in the working state 1 of the supercapacitor pre-charging mode, K_2 is disconnected because K_1 is closed, and the diode D_3 is cut off because of the reverse voltage U_C. U_C and U_E supply power to U_d, and the energy storage converter is in the stand-by state. If the supercapacitor terminal voltage is detected to be lower than the cut-off voltage, the battery-supercapacitor HESS works in the working state 2 of the supercapacitor pre-charging mode. K_1 is disconnected and K_2 is closed, and the supercapacitor pre-charging circuit works. The diode D is cut off due to reverse voltage, and U_E supply power to U_d of the DC bus voltage. Actually, supercapacitor pre-charging mode is a first-order RC circuit, which disconnects the K_1 and closes the K_2. Power supply U (power supply U is actually introduced from bus side voltage to improve the economy of battery-supercapacitor HESS) charges the super-capacitor through discharge resistance R.

According to the above analysis, it can be found that the battery-supercapacitor HESS operates in the boost mode, the maximum voltage stress that the T_2 receives during a T_s is U_d, and the maximum voltage stress that the T_1 receives during a T_s is (U_C+U_L). Meanwhile, the maximum voltage stress of the introduced diode D with selective switching function is (U_C+U_E-U_d)/2 in a T_s. Meanwhile, if the battery-supercapacitor HESS operates in the buck mode, the maximum voltage stress that the T_2 receives during a T_s is U_d, and the maximum voltage stress that the T_1 receives during a T_s is (U_C+U_E)/2. At the same time, the voltage stress of diode D with selective switch function is (U_C+U_E-U_d) when the T_1 is turned on, and the voltage stress is (U_C-U_d) when the T_1 is turned off. Compared with the HESS or single energy storage element system mentioned in the relevant literature, the voltage stress of the switch tube is reduced, and the voltage stress of the increased diode D with selective switching function is also low.

For convenience of calculation, we assume that all components are ideal components, whose switching action is instantaneous and the voltage is stable.

In the buck mode, the state equation of the battery-supercapacitor HESS in a T_s is as follows:

$$\begin{pmatrix} \frac{d_{i_{L1}}}{dt} \\ \frac{d_{i_{L2}}}{dt} \end{pmatrix} = \begin{pmatrix} \frac{1}{L} & -\frac{1}{L} \\ 1 & -\frac{1}{L} \end{pmatrix} \begin{pmatrix} T\cdot U_d \\ U_E \end{pmatrix} \tag{2.20}$$

Where i_{L1} is the charging current of inductance L when the battery-supercapacitor HESS works in the working state 1 of the buck mode, and i_{L2} is the pre-charging current of inductance L when the battery-supercapacitor HESS works in the working state 2 of the buck mode. Meanwhile, T is the switch function introduced above.

When the inductance is voltage-second (V-S) balanced in steady-state operation, the voltage gain M can be obtained from equation (2.20):

$$M = d_2 \tag{2.21}$$

Where d_2 is the duty cycle of the T_1.

Similarly, the voltage gain M' of the battery-supercapacitor HESS in the boost mode is:

$$M' = \frac{1}{d_1} \tag{2.22}$$

Where d_1 is the duty cycle of the T_2.

It can be known from equations (2.20) to (2.22) that the voltage gain of DC/DC converter is not affected by the novel battery-supercapacitor HESS.

3. Control Strategy Analysis

Due to the increasing peak load in the power grid, power grid companies need to continuously invest in power transmission and distribution equipment to meet the demand of peak load capacity, which will lead to low overall efficiency of the system and low comprehensive utilization of power assets. Therefore, the use of advanced and efficient energy storage technology in the power system can not only make more effective use of power equipment, reduce the cost of power supply, effectively alleviate the contradiction between supply and demand, eliminate the peak valley difference between day and night, but also promote the application of renewable energy. Therefore, energy storage technology has been regarded as an important part of the six links of 'mining, generation, transmission, distribution, use and storage' in the process of power grid operation in the modern power system. ESS is mainly divided into the ESS with single energy storage element and HESS with multiple energy storage elements. However, when the battery is used as energy storage equipment, in order to keep the voltage of the DC bus constant, the battery often needs to absorb and send out more power frequently, and often switch between charging and discharging states.

The battery-supercapacitor HESS can improve the working conditions of battery. Because the supercapacitor can keep the DC bus voltage stable in a very short time range when the load power fluctuation is large and the total power demand is small.

At the same time, the characteristics of supercapacitor fast charging and discharging also make it possible to ensure the normal power supply of the later stage load even if there are more times of instantaneous voltage interruption in the power grid or distribution network. The proposed battery-supercapacitor HESS uses battery as the main power supply and supercapacitor as the auxiliary power supply.

At the same time, the HESS is mainly composed of two parts: energy storage unit (battery and super capacitor) and bi-directional DC/DC converter. The bi-directional DC/DC converter is an important medium for energy exchange between the DC bus side and power supply that composed of a battery and a supercapacitor. It realizes charging and discharging of batteries and supercapacitors group by controlling bi-directional DC/DC converter. Specifically, the bi-directional DC/DC converter, as the interface between the energy storage device and the DC bus grid side, plays the role of energy transfer. Through the control of power electronic switch, the bi-directional power flow is achieved.

When the bi-directional DC/DC converter is on isolation state, the supercapacitor pre-charge circuit enters into operation mode, so as to guarantee the power quality of the energy storage unit.

When the bi-directional DC/DC converter works in boost mode, the energy storage unit supplies power to the DC side bus (dis-charge state).

When the bi-directional DC/DC converter works in the buck mode, the DC side bus supplies power to the energy storage unit (charging state). The control strategies of bi-directional DC/DC converters are mainly divided into complementary pulse width modulation (PWM) control and independent PWM control.

Taking two groups of trigger signals as an example, each trigger signal of independent PWM is independent of each other and generated separately, while the two groups of trigger signals of complementary PWM share a carrier signal, and there is a certain initial phase angle between the trigger pulses. The difference between them is whether the driving signals of the T_1 and T_2 are complementary. As the complementary PWM control may have the phenomenon that the upper and lower arm switches are directly connected, in order to improve the stability of the battery-supercapacitor HESS, independent PWM control is adopted.

When the T_1 is turned off and the T_2 is in PWM modulation, the battery-supercapacitor HESS operates in the boost mode, and the battery and supercapacitor Group supply power to the DC bus side. When the switch T_2 is turned off and the T_1 is in PWM modulation, the battery-supercapacitor HESS operates in the buck mode. At this time, due to the existence of the diode *D* with selective switch function, the DC bus side only charges the battery.

The battery-supercapacitor HESS is controlled by independent PWM. In this battery-supercapacitor HESS, the inductance current is used as the control signal.

According to the output voltage deviation of the DC bus side, the reference value of inductance current i_L is ±3.0 V.

1) when the reference current i_L>0 A, the battery-supercapacitor HESS works in boost mode.

2) when the reference current i_L<0 A, the battery-supercapacitor HESS works in buck mode.

3) when the reference current i_L=0 A, the battery-supercapacitor HESS works in the supercapacitor pre-charging mode.

The specific generation method of independent PWM trigger pulse is as follows.

The steady-state error of inductance current is caused by the theoretical value and the actual value of inductive current, which is used to generate the modulation wave signal through PI controller and output limiting link. Then two groups of independent PWM trigger signals (the control signal of the T_1 or T_2) can be obtained by comparing two groups of carrier signals with initial phase difference of 180° with modulated wave signals respectively.

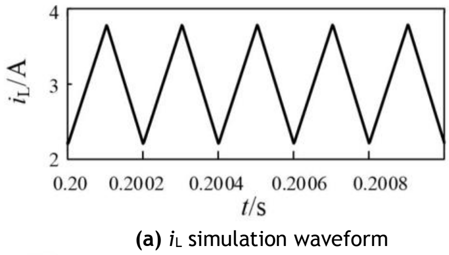
4. Simulation analysis

In order to verify the validity of the battery-supercapacitor HESS in this paper, a simulation model is established by MATLAB/Simulink. The main simulation parameters of the system are shown in Table 1.

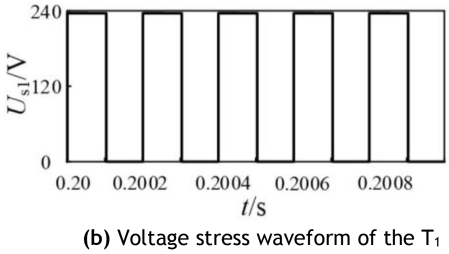
Table 1. Main simulation parameters of the battery-supercapacitor HESS

U_E=120 V	battery voltage
U_C=120 V	supercapacitor voltage
U_d=320 V	the DC bus side voltage
L=1×10^{-3} H	inductance value
R=6.94×10^{-5} Ω	pre-charge resistor
C=1.3×10^{-3} F	Output capacitance
U=120 V	power supply voltage of pre-charging circuit

The main waveform of each working state of the battery-supercapacitor HESS in the boost mode is shown in Figure 2.



(a) i_L simulation waveform



(b) Voltage stress waveform of the T_1

Figure 2. Main waveforms of the circuit in boost mode

1) According to the analysis of control strategy and simulation, the trigger signal of T_2 is a series of high-low level PWM pulses, which takes d_1 as duty cycle.

When the trigger signal is high, the battery-supercapacitor HESS works in the working state 1 of boost mode. When the trigger signal is low, the battery-supercapacitor HESS works in the working state 2 of boost mode.

2) Figure 2(a) shows the inductive current i_L waveform under 5 switching cycles T_s. The maximum value of inductive current i_L is 3.72 A, the minimum value of inductive current i_L is 2.28 A, and the average value of inductive current i_L is about 3.0 A.

When the battery-supercapacitor HESS works in the working state 1 of boost mode, the inductive current i_L increases linearly.

When the battery-supercapacitor HESS works in the working state 2 of boost mode, the inductive current i_L decreases linearly.

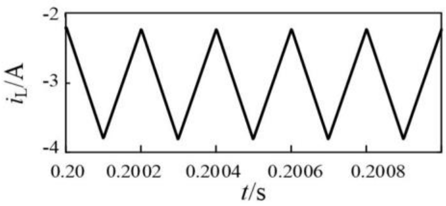
According to the above analysis, Figure 2(a) shows that i_L is in a continuous state during a T_s of the T_2, and the energy of inductance varies with the change of the T_2.

3) Figure 2(b) is the simulation waveform of the voltage stress of the switch tube T_1. It can be seen from Figure 2(b) that when the battery-supercapacitor HESS works in the working state 1 of boost mode, the voltage stress of switch tube T_1 at the conduction stage of switch tube T_2 is 235 V.

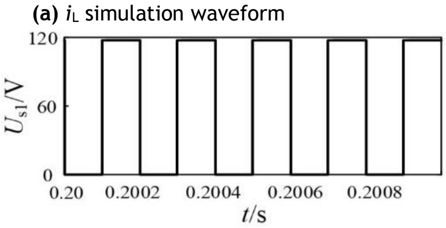
When the battery-supercapacitor HESS works in the working state 2 of boost mode, it is turned on due to the continuous current action of reverse parallel diode D_1 of switch tube T_1. At this time, the voltage stress of switch tube T_1 is 0 V when switch tube T_2 is turned off. Therefore, it can be seen that the maximum voltage stress of the T_1 in a T_s is 235 V, which is close to 240 V.

Therefore, the simulation results are basically consistent with the theoretical analysis.

The main waveform of the battery-supercapacitor HESS in the buck mode is shown in Figure 3.



(a) i_L simulation waveform



(b) Voltage Stress Waveform of the T_1

Figure 3. Main waveforms of the circuit in buck mode

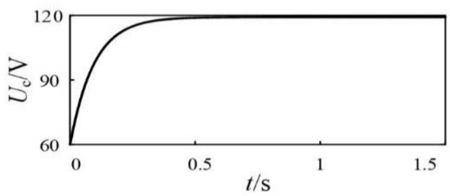
1) According to the analysis of control strategy and simulation, the trigger signal of T_1 is a series of high-low level PWM pulses, which takes d_2 as duty cycle. When the trigger signal is high, the battery-supercapacitor HESS works in the working state 1 of buck mode. When the trigger signal is low, the battery-supercapacitor HESS works in the working state 2 of buck mode.

2) Figure 3(a) shows the inductive current i_L waveform under 5 switching cycles T_s. The maximum value of inductive current i_L is -3.78 A, the minimum value of inductive current i_L is -2.22 A, and the average value of inductive current i_L is about -3.0 A. When the battery-supercapacitor HESS works in the working state 1 of buck mode, the inductive current i_L increases linearly. When the battery-supercapacitor HESS works in the working state 2 of buck mode, the inductive current i_L decreases linearly. According to the above analysis, Figure 3(a) shows that i_L is in continuous state during a T_s of the T_1, and the inductance energy varies with the switching state of the T_1.

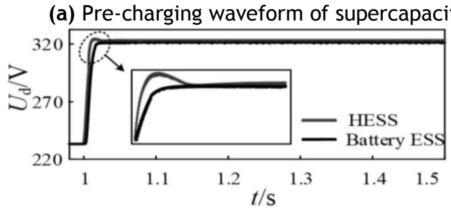
3) Figure 3(b) is the simulation waveform of the voltage stress of the switch tube T_1. It can be seen from Figure 3(b) that when the battery-supercapacitor HESS works in the working state 1 of buck mode, the voltage stress of switch tube T_1 at the conduction stage of switch tube T_1 is 0 V because the switch tube T_1 is turned on. When the battery-supercapacitor HESS works in the working state 2 of buck mode, it is turned on due to the continuous current action of reverse parallel diode D_2 of switch tube T_2. At this time, the voltage stress of switch tube T_1 is 118 V when switch tube T_1 is turned off. Therefore, it can be seen that the maximum voltage stress of the T_1 in a T_s is 118 V, which is close to 120 V.

Therefore, the simulation results are basically consistent with the theoretical analysis.

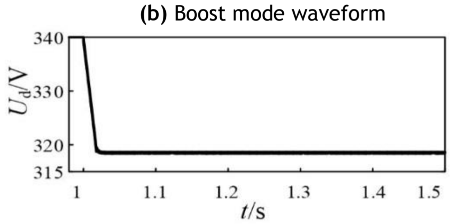
The simulation waveform of the three working modes is shown in Figure 4.



(a) Pre-charging waveform of supercapacitor



(b) Boost mode waveform



(c) Buck mode waveform

Figure 4. Waveform in three working modes

1) When the discharge depth of supercapacitor is 50%, the pre-charge waveform of supercapacitor is shown in Figure 4(a).

From Figure 4(a), it can be seen that when the supercapacitor voltage is detected to be reduced to 60V or below, the supercapacitor pre-charging circuit will be activated to charge the supercapacitor. At 600 ms, the supercapacitor voltage reaches 119.2 V, and the power supply will be restored to the normal working voltage.

2) When the DC bus side voltage drops suddenly (e.g. the motor starts, etc.), the proposed HESS operates in the boost mode.

Figure 4(b) shows the waveform of the DC bus-side voltage U_d of the proposed HESS and battery-based ESS in the boost mode when the DC bus-side voltage is reduced to 230 V. As can be seen from Figure 4(b), the maximum voltage U_d of the DC bus side of the proposed HESS is 322.3 V and the stable value of U_d of the proposed HESS is 321.3 V. The overshoot of the proposed HESS is about 0.4 %, and the rise time of the proposed HESS is 0.006 s. At the same time, the regulation time of the proposed HESS is 0.03 s, and the voltage ripple of the proposed HESS is about 0.06 %, less than 2 %. Meanwhile, it can be seen that the stable value of U_d of the battery-based ESS is 320.5 V, and the system overshoot has not overshoot. In addition, the regulation time of the battery-based ESS is 0.12 s. Therefore, the DC bus-side voltage recovery effect and dynamic performance of the battery-supercapacitor HESS under the boost mode are superior to that of the battery-based ESS.

3) When the DC bus voltage suddenly rises (such as locomotive braking process, etc.), the proposed HESS operates in the buck mode.

Figure 4(c) shows the waveform of the DC bus side voltage U_d in buck mode when the DC bus side voltage rises 340 V. From Figure 4(c), it can be seen that the U_d stability value of the DC bus side voltage is 318.55 V, the system regulation time is 0.04 s, and the voltage ripple is about 0.08 %, less than 2 %.

According to the above simulation waveforms and analysis, the battery-supercapacitor HESS can work independently in three working modes (supercapacitor pre-charging mode, boost mode and buck mode). The DC side bus voltage U_d of the battery-supercapacitor HESS is stable at about 320 V. Moreover, the power quality and dynamic performance of the battery-supercapacitor HESS are better than that of the battery ESS.

5. Conclusions

A bi-directional DC/DC converter is the core part of power conversion in the battery-supercapacitor HESS. Its reasonable topological structure and good circuit performance are conducive to improving energy storage conversion efficiency, reducing system volume, weight and system cost, so as to better realize the efficient and comprehensive utilization of energy, optimization of energy structure and guarantee of energy security supply. In view of the disadvantages of the existing HESS such as redundant topology and low voltage stress of switching devices, this paper proposes a bi-directional DC/DC converter for battery-supercapacitor HESS. The theoretical analysis and simulation results show that the system topology effectively reduces the voltage stress of the switching device and the switching loss. Moreover, the cold stand-by state of the supercapacitor pre-charging and boost and buck modes work independently. The Diode *D* with switching function and supercapacitor pre-charging circuit as cold stand-by can effectively guarantee the performance of energy storage unit. Then, the battery and supercapacitor share a set of bi-directional DC/DC converter, which effectively overcomes the disadvantage of redundancy in the topology of HESS, improves the economy of bi-directional DC/DC converter, and then improves the economy of HESS. In addition, the battery-supercapacitor HESS has small voltage ripple, can provide large current to the load, effectively reduces the size of the battery, and improves the life and economy of the battery.

The application of energy storage technology covers all aspects of the power system, such as generation, transmission, supply, distribution and use. It can improve the energy consumption capacity of the power grid, alleviate the demand for peak load power supply, improve the power quality and efficiency, and ensure the demand for high-quality, safe, reliable power supply and efficient power consumption of the power grid. The next step is to verify the proposed bi-directional DC/DC converter in practical engineering, and further explore the bi-directional DC/DC converter with high topology utilization, low voltage and current stress, and higher voltage conversion ratio, and apply it to the HESS, so as to get a more efficient HESS.

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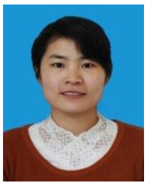

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