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An Energy Recovery System of Regenerative Braking Based Permanent Magnet Synchronous Motor for Electric Vehicles

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Abstract —This paper presents a hybrid energy storage system (HES) composed of battery and ultracapacitor. Regenerative braking energy recovery can be effectively achieved with this system combining permanent magnet synchronous motor driving system. The performance of the battery and ultracapacitor is significantly different in the HES, and thus reasonable distribution between battery and ultracapacitor for output or input of energy is needed. In order to realize the allocation strategies of the HES, it should be connected to DC link through appropriate power electronic interface. Detailed analysis is carried out in respect of energy recovery system based on power electronic interface circuit and the energy load distribution scheme in this paper. The simulation is done on Matlab/Simulink, and then results prove that the HES works well.

I. INTRODUCTION

The further development of the conventional cars which use internal combustion engine as power source is plagued by several factors, such as increasingly serious problem of air pollution, widely concerned about the problem of carbon emissions and problems represented by limited oilreserves. So, around the world, as an environment-friendly product, electric vehicles (EVs) attract each big automobile manufacturer's great interest [1]. In past decade, on a technical opinion, the great development progress of the EVs has made. And as a proof, commercial products by multiple vendors have been on the road currently. On the other hand, the development of the EVs is always bothered by the performance of energy storage system. Recently, the technology of battery including fuel cells and lithium batteries has made great strides, but it is still difficult to meet the current EVs needs. The shortcoming of the battery is low power density, short cycle life and narrow operating temperature. In fact, a breakthrough in battery technology is still some way off, and then it is imperative that more pragmatic solution is to leverage existing technologies to improve the performance and efficiency of the energy storage system. Hybrid energy storage system comes into being in this situation.

Ultracapacitor has attracted the attention of researchers because it has excellent performance as high power density, long cycle life, easy maintenance and relatively wide operating temperature range [2, 3]. In spite of the energy density of ultracapacitor was far below the battery, the characteristics of ultracapacitor mentioned above can compensate for the lack of the battery. A lot of research has done for the HES, showing that the overall performance of the HES is inferior to the gasoline, meanwhile the significant improvement of power density and cycle life has achieved. We can get such a conclusion that the HES is the most feasible compromise solution currently.

Another issue of concern is that regenerative braking can greatly facilitate the implementation with the use of HES, which is mainly due to the use of ultracapacitor. Compared with the weak charge capacity of the battery, ultracapacitor has strong charge ability. As we know that the electric car is mainly used for transportation in the city, a typical feature of the urban road driving is that the driving process contains frequent starts, braking and acceleration, and braking uphill and downhill speed. On the view point of energy supply, not only requiring a lot of energy available to the vehicle for starting, acceleration, but also much energy will waste if the inertial energy could not be recovered. Studies indicate that this part of the energy consumption accounts of 25% of total [3]. Thus, if the inertial energy can put to good use, namely some can be effectively collected, the efficiency of the vehicle energy will be significantly improved. As a consequence, energy storage in the EV without changing the capacity will satisfy longer driving range. In the other words, under the premise of meeting the same driving range, the energy storage unit can be reduced, and as a result, the cost and the weight will be reduced.

In using of the HES, the current main research is focused on two aspects. The first one is selecting appropriate power electronic interface circuit for the HES. Since the characteristic differences between battery and ultracapacitor are obvious, so choosing respective interface circuit for battery and ultracapacitor is important. Proper selection will benefit their respective advantages, thus the key is solving the problem that how to be connected to the DC-bus. In [4], the review of the mainstream power electronic interface circuit solutions is given. In actual use, considering cost and reliability, the complicated interface circuit is not suitable. On the other hand, in order to achieve reasonable power and energy distribution between battery and ultracapacitor in the HES, researchers have given a variety of control strategies, say the rule-based optimizing fuzzy control [5-7].

Because of small size, high power density, permanent magnet synchronous motor has natural advantages in the application of EVs [8-11]. In this paper, the energy storage system combining with permanent magnet synchronous motor drive system is presented; the basic configuration is shown in Fig. 1. While the appropriate power electronic interface circuit and reasonable control strategies are determined for effectively implementing bi-direction flow of energy. This article focuses on realization of optimization working of the dual-energy source through the power electronic interface circuit during the process of starting, acceleration and braking,

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in particular the recovery of braking energy.

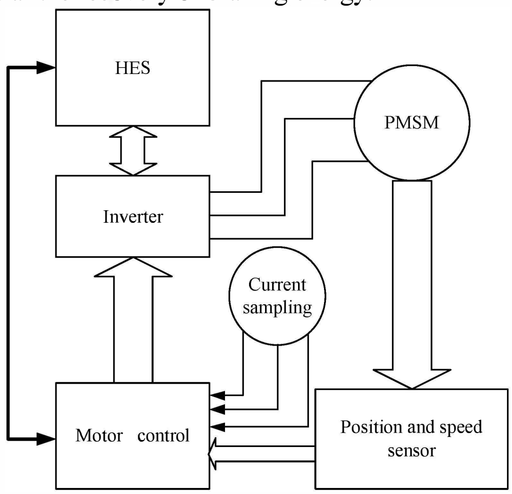


Fig. 1. Proposed configuration of the PMSM control system

The rest content is organized as follows: First, given the selected power electronic interface circuit and its working modes with corresponding vehicle driving state, and then the distribution strategies of the battery and ultracapacitor is analyzed, and then simulation results and explains are given, finally conclusion is drwan.

II. Power Electronic Interface Circuit

A. Topology Configuration

The interface circuit should be benefit realizing the advantages of different energy storage systems such as battery and ultracapacitor respectively. At same time, while on vehicle board, interface circuit should take relatively simple structure and high reliability solutions for HES.

As a dual-energy source, it consists of batteries and ulitracapacitor units, which have different operating characteristics. During the battery operation, small change is produced in its terminal voltage, and on the contrary dramatic variation of the terminal voltage is happened during the ultracapacitor operation. The battery has a strong discharge capacity, but the charging ability is very weak, which is determined by the electrochemical properties of the battery itself. While, the ultracapacitor has a strong ability to both charge and discharge. In view of above analysis, the selected power electronic interface circuit is shown in Fig. 2.

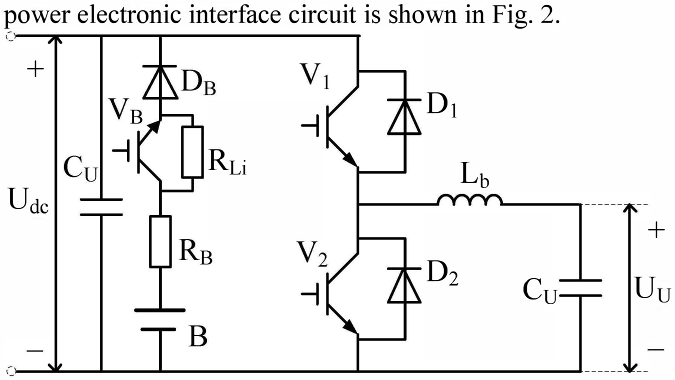


Fig. 2. Proposed topology of the power interface circuit

The symbols used in the circuit diagram in Fig.2 are explained below.

U_{dc}	DC-bus voltage
C	Filter regulator capacitor
B	Battery
R_B	Equivalent resistance of battery series resistance and Limiting resistance
V_B, R_{Li}, D_B	Components of the interface circuit for battery
V_1, D_1, V_2, D_2, L_b	Components of the bidirectional DC-converter for ultracapacitor
C_U	Ultracapacitor
U_U	Terminal voltage of the ultracapacitor

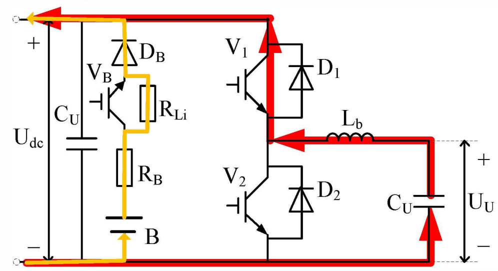
The power electronic interface presented in Fig. 2 can realize two functions:

The first is that the ultracapacitor is connected to the DC-bus through bidirectional DC-converter. Then, the number of ultracapacitors in series is reduced by placing the ultracapacitor in the low voltage side of the hand; as well the rapid variation of the terminal voltage of the ultracapacitro can be realized, which is conducive to fully exploit the ultracapacitor's advantage.

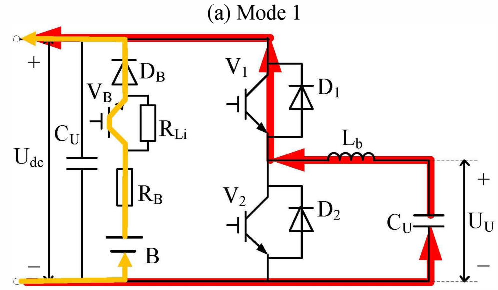
The second is that the battery is connected to the DC-bus through the circuit composed of V_B, R_{Li}, D_B and R_B. It can ensure that the discharge current of battery is controlled within a reasonable range. On the other hand, charging current is avoided flowing into battery during the process of braking energy recovery.

B. Operation Modes

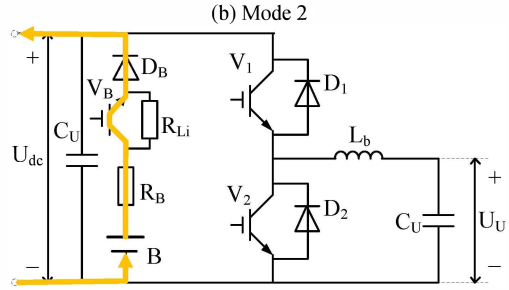
According to different operation states, namely different current flow directions, five operating modes of the interface circuit are shown in Figure 3. The arrows represent the flow direction of the current.



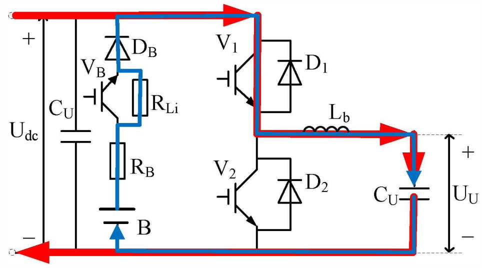
(a) Mode 1



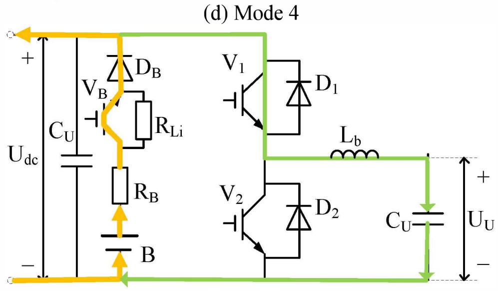
(b) Mode 2



(c) Mode 3



(d) Mode 4



(e) Mode 5

Fig. 3. Operation modes of the power interface circuit.

The corresponding driving states of EVs to the operation modes are as follows:

Mode 1: Starting. The overload starting of permanent magnet synchronous motor is carried out while EV is starting. Thus the rash start-up current is required at this time. So, it should take full use of the ultracapacitor's power density advantage. The high starting current is provided by the ultracapacitor via the bidirectional DC-converter which works as a boost converter. V_B is off, battery provides clamping voltage for DC-bus through limiting resistor R_{Li}. The current from battery is small because of big limiting resistance.

Mode 2: Acceleration. Compared with the starting process, the current required by permanent magnet synchronous motor has been reduced during the acceleration of EVs. In addition, the ultracapacitor has released a considerable part of the energy for starting. So battery and ultracapacitor should simultaneously work this time, but neither deplete ultracapacitor's energy, nor let the battery to withstand excessive current.

Mode 3: Cruising state. The variation of vehicle speed is in small range at this state. So the required current of permanent magnet synchronous motor drive system is relatively stable, and its amplitude is within the rated current of the battery. The battery can provide power independently.

Mode 4: Regenerative braking. The inertial energy of the vehicle is consumed by way of friction and converting into electromagnetic energy of the permanent magnet motor drive system at braking process. Because of very short braking time, the amplitude of feedback current is large. The ultracapacitor can absorb the feedback power efficiently with the powerful charging ability. Similar with mode 1, battery provides clamping voltage for DC-bus through limiting resistor.

Mode 5:Replenishing ultracapacitor. It is noteworthy that ultracapacitor is charged by battery when battery providing power to motor in cruising state. Why such operation is happened? In many case, the most part of energy storing in ultracapacitor is exhausted during starting and especially during acceleration. On the other hand, the installed capacity of ultracapacitor in vehicle is relatively limited by the vehicle storage space. So replenishing energy timely is necessary. Then, ultracapacitor can make adequate preparations for the next acceleration. In cruising time, the current need from permanent magnet synchronous motor driving system is relatively small, so the battery is fully able to charge ultracapacitor under the premise of satisfying electric drive system. This operation will not be discussed in detail in this paper.

III. Control Principle of The Dual Energy Storage

During starting and acceleration, the pulse current is mainly provided by the ultracapacitor. Thus, the power electronic interface circuit is operated as a boost DC converter. When the current flowing through the DC bus is large, the bus voltage will be lifted. If the voltage of DC-bus is higher than the terminal voltage of battery, the battery will not output current. In a sense, it protects the battery from releasing large current. And at the same time, controlling the boost converter to maintain a constant bus voltage is necessary to the motor driving system.

During regenerative braking, the feedback current of permanent motor is fed to DC-bus via inverter. This current cannot flow into battery because of the reverse blocking diode D_B. With the decrease in motor speed, the EMF will reduce. The voltage of DC-bus is clamped by battery through R_{Li}, so the feedback current is absorbed by ultracapacitor via the bidirectional DC-converter which is worked as buck converter. It can be seen from the analysis above, the ultracapacitor works in a controllable state, and the battery works in a passive controllable state. The operation of ultracapacitor, such as charging and discharging, is controlled by bidirectional DC-converter. Discharging of battery is controlled by the comparison of terminal voltage of battery and DC-bus voltage. The input and output current of the HES is determined by the i_q of the motor. Ignoring the complex control process of the inverter in this paper, the current of DC-bus i_D is directly related to i_q.

Based on the analysis above, we can obtain the following relationship:

$$i_D = i_B + K_1 i_{UC} \tag{1}$$

$$U_D = \begin{cases} K_2 U_{UC} & i_B = 0 \\ U_B & I_B \neq 0 \end{cases} \tag{2}$$

where i_D is the current of DC-bus, i_B, i_{UC} are the current of battery and ultracapacitor respectively, U_D is the voltage of DC-bus, U_{DC}, U_B are the terminal voltage of the battery and ultracapacitor. K_1 and K_2 are the current and voltage amplification factors of the bidirectional DC-converter. They are determined by PWM on DC-converter. In (1) and (2), the voltage drop across the conductor resistance and the internal resistance of the energy storage device is ignored.

When the battery is just playing role for clamping DC-bus voltage, the current discharging from battery can approximately be ignored. So Further conclusion is following:

When $i_B = 0$:

$$\begin{cases} i_D = K_2 i_{UC} \\ U_D = K_2 U_{UC} \\ K_1 = 1/K_2 \end{cases} \tag{3}$$

When $i_B \neq 0$:

$$
\begin{cases} i_D = i_B + K_2 i_{UC} \\ U_D = K_2 U_{UC} \\ K_1 = {1}/{K_2} \end{cases} \tag{4}
$$

In order to simplify the control programs to improve the robustness, several control rules is established as follows. Under these control rules, the energy and power distribution is realized, and as well the braking energy recovery is implemented efficiently.

Rule1: When starting, the discharging current of ultracapacitor i_{UC} must satisfy the need of i_D. At the same time, the stability of DC-bus voltage is maintained by controlling the PWM drive signal on boost converter.

Rule2: When the motor speed reaches half of the rated speed, it can be considered that the starting process ends, and the acceleration process begins. Controlling i_{UC} ensures that the discharging current of battery i_B does not exceed the rated current of battery. The goal of output voltage is still to maintain DC-bus voltage stabile.

Rule3: When the motor operates at the rated speed, turning off DC converter, battery works independently.

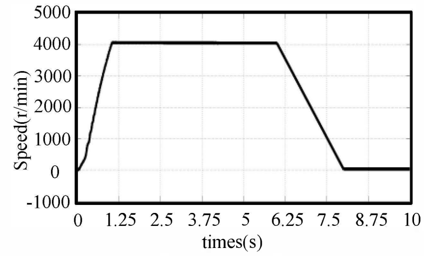
Rule4: When regenerative braking occurs, turning off VT_B, the DC-bus voltage is clamped by battery via R_{Li}. Then, the charging current of ultracapacitor is controlled in a constant value by controlling the buck converter,which is benefit to the health of ultracapacitor.

IV. SIMULATION RESULTS

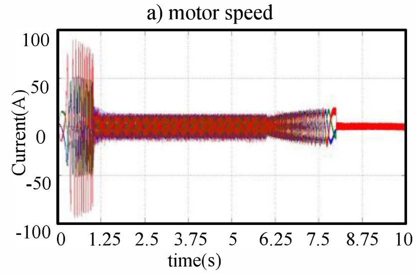
The system is simulated by using the Matlab/Simulink. Herein, VT_B, VT_1 are VT2 are IGBTs. The parameters of the permanent magnet synchronous motor are as follows: L_d=2mH, L_q=2mH, R_s=2.875Ω, J=0.008kg·m^2, the pole pairs p_r=2, the rated speed is 4000r/min. The nominal voltage of the battery is 400V and the initial SOC of the battery is 85% and the ESR of the battery is 4Ω. The inductance L_{UC} is 7.5mH, and the capacitance of the ultracapacitors is 10F, and the ESR of the ultracapacitor is 7.8mΩ. The rated voltage of ultracapacitor is selected as 100V. The limiter resistance R_{Li} is 200Ω. The energy and power distribution of HES is achieved by controlling power switches and bidirectional DC-converter.

The speed and current waveforms of the motor are presented in Fig. 4. The voltage and current waveforms of DC bus, battery and UC are presented in Figs. 5-7. It shows that the current of the motor is satisfied by HES during acceleration and staring as well as breaking. The peak charging and discharging current is undertook by the ultracapacitor, on the contrary, the battery pack provides the average current during curising. The current from the battery is limited within a suitable value. They confirm that the desired HES is able to meet the requirement of the DC bus under the control rules above, while the ultracapacitor can provide the desired pulsating capacitive charging current and can absorb the transient regeneration current.

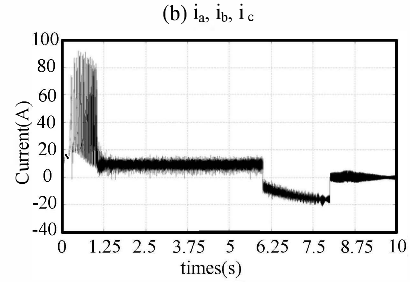
Since the battery provides the clamping voltage to the DC-bus,hence the voltage of DC-bus has little variation during acceleration and breaking. Because of electrochemical inertia of the battery itself, establishing current and voltage needs a lag time.



a) motor speed

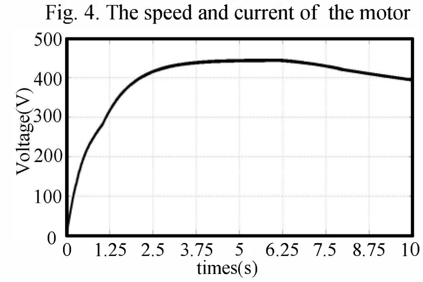


(b) i_a, i_b, i_c

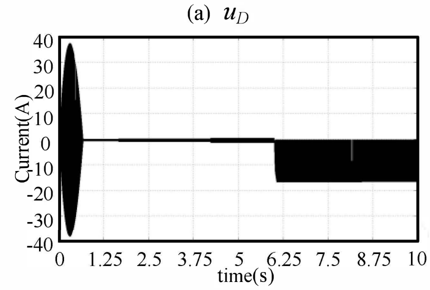


(c) i_q

Fig. 4. The speed and current of the motor

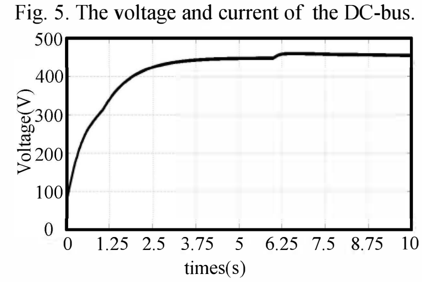


(a) u_D

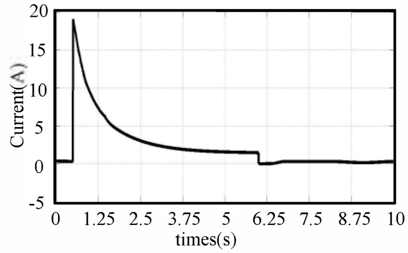


(b) i_D

Fig. 5. The voltage and current of the DC-bus.

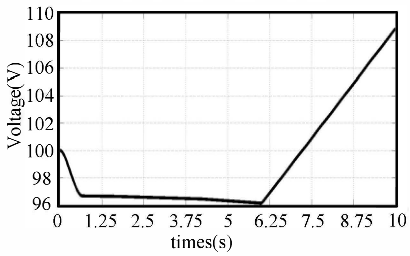


(a) u_B

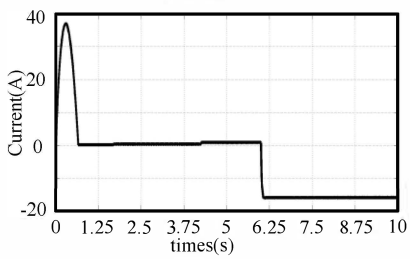


(b) i_B

Fig. 6. The voltage and current of the battery.



(a) u_{UC}



(b) i_{UC}

Fig. 7. The voltage and current of the ultracapacitor.

V. Conclusion

Energy storage for EVs is one of the most critical systems, and its performance will directly affect the performance of EVs. The HES proposed in this paper can achieve braking energy recovery efficiently with simple control principles and low cost. The simulation results confirm effectiveness of the proposed HES and control method. Further research will focus on optimizing control strategy and volume economy of the energy storage unit.

Acknowledgment

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