Optimized Topology and Converter Control for Supercapacitor Based Energy Storage System of Electric Vehicles

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ABSTRACT: Hybrid energy storage system (HESS) is a potential solution for future electric vehicles (EV). In this paper, topologies of the two energy sources combination, battery and super capacitor (SC), and the aspect of converter control for power sharing, are introduced. Three types of converter topologies, operated as SC power interface linked to DC bus, are compared and analyzed. Power sharing strategy based on SC output current control is proposed for controlling the power flow. The controller design principles are given and the dynamic response of the current output is analyzed. The experiment results show the efficiency of the proposed method.

KEY WORDS: Electric Vehicle, Super Capacitor, Hybrid Energy Storage System, Converter control.

1. Introduction

The energy supply system is one of the major problems of EV because it does not achieve the same autonomy comparing with the internal combustion engine vehicles. There are many problems need to be solved, such as short-distance cruising, long-time charging, and high price and limited life of battery system. So high-performance energy storage system and advanced battery system are desired for recent EV.

On the other hand, the future electric vehicle, will be driven by motor, powered by capacitor, and charged by wireless transfer technology [1]. New approaches for energy storage and transformation system are needed to develop for the future EV system. Our laboratory has developed an EV for 20 minutes driving after 30second charging, only powered by SC [2][3]. Although a small size EV powered by SC is available to realize, now a commercial EV fully powered by the SC is difficult in recent days, because the energy density is still low and the price of the SC bank is unacceptable.

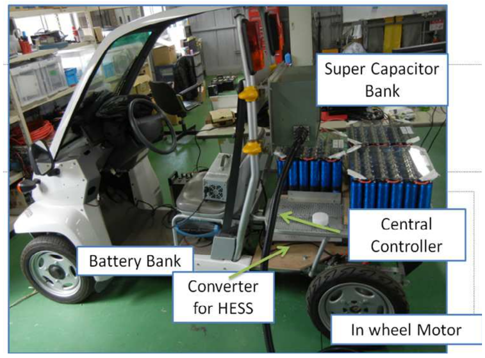


Fig. 1. EV Prototype powered by HESS

Hybrid energy storage system (HESS) is also a potential solution for future electric vehicles (EV). The aim of battery and super capacitor (SC) hybrid system is to realize high power density and high energy density in one system to satisfy the requirement from EV powertrain system. Based the combination of two energy devices, battery and super capacitor, aims to realize high-efficacy, high-performance, controllable, easy charging ESS for EV application. By applying HESS to EV, the battery life can be extended, and acceleration performance can be improved. More importantly, efficiency of energy recovery from regenerative break can be increased based on the characteristic of SC charging.

A prototype of small size of EV with battery and super-capacitor hybrid energy system and driven by in-wheel motor system is shown in the Fig.1, for our experiments and further research. The EV prototype is based on the Toyota EV COMS. The hybrid energy system with SC bank and converter control system is designed. The parameters of the hybrid EV prototype are shown in the Table 1. The DC bus voltage of the energy system is 72V, which is hold by the Lead Acid battery modules group. And the maximum current output from SC bank is designed up to 100A, considering the chopper size and the control algorithm.

Table 1 Parameters of Hybrid EV Prototype

EV body	Toyota Autobody COMS
In wheel Motor	Peak power 2KW X2
Max Speed	50Km/h
Weight	430Kg
DC bus Voltage	72V
Battery Bank	Lead Acid 12V 42Ah X6
SC Bank	90V 64F module X3
DC bus converter	Peak current 100A

2. Topologies analysis of HESS for EV

2.1 Introduction of battery and SC modeling

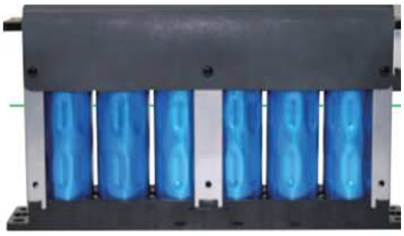


Fig. 2. Super capacitor Module

There are lots of modeling methods to consider the math model of super capacitor. We would like to confirm the electrical performance of SC. So power charging /discharging modeling is necessary for Super capacitor application.

Fig.3. is a simple RC model of SC, there are also the nonlinear section because the total capacitance of SC is voltage controlled capacitance [4] .

$$C_{sc} = C_0 + k_c \cdot U_c \tag{1}$$

C_0 is the initial capacitance that represents the electrostatic capacitance of the capacitor. k_C is a coefficient that represents effects of the diffused layer of the SC. The electrical performance of SC bank is as below,

$$I_{SC} = (C_0 + 2k_c U_c)\frac{dU_c}{dt} \tag{2}$$

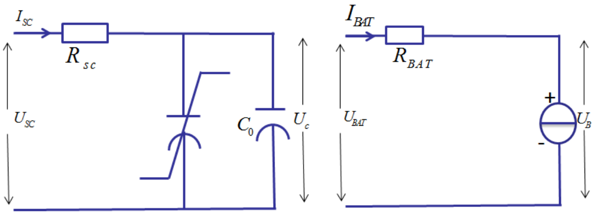


Fig.3 Simple dynamic model of

SC (left) and battery (right)

The battery modeling in Fig.3 is the constant voltage source with battery inner resistant. The battery is used as the DC bus voltage holder and parallel linked by dc bus filter in our system.

$$U_{BAT} = U_B + I_{BAT} R_{BAT} \tag{3}$$

The battery and super capacitor model can be used to calculate the state of charge of these two energy banks, also the loss in energy system can be evaluated by modeling simulation.

2.2. Topologies of battery and SC combination for HESS

The hybrid energy source is generally composed of different specific energy sources, such as batteries and SCs, which enable to provide both the permanent and transient powers demanded by the load.

Many power electronic architectures have been associated to hybrid energy sources. And the hybrid power-source structures mainly used, including serial, passive cascaded, one source cascaded, bi-active structure is compared in the table 2, based on different requirements for EV application.

The two-converter structure consists in associating a static converter and a control loop to each energy source belongs to bi-active cascaded topology. This control strategy generates a large number of degrees of freedom in the control design. However, its drawback is the inevitable losses associated with each converter.

The direct parallel structure consists in connecting the battery directly to the load is passive cascaded topology. Its main drawback is related to over sizing the SC necessary to fulfill the battery power requirements. The battery controllability is low.

The one-converter structure consists in adjusting the power fluxes. Its main advantages are simplicity and reduction of both losses and costs of the power management interfaces and a good controllability. So the structure in Fig. 4 is the best choice for our system. Simply speaking, the SC is linked by one bidirectional DC/DC converter as the power interface to the DC bus of the vehicle energy system. The battery hold the DC bus voltage by liked to the DC bus directly.

Table 2 Comparison among different HESS structures

Topologies	Controll-ability	Redundancy	Efficiency	Stability	Cost/ Complexity
Serial	N	N	N	G	G
Passive cascaded	N	A	N	G	G
Battery active cascaded	M	M	A	M	M
SC active cascaded	M	M	G	M	M
Bi-active cascaded	G	G	A	M	A

G=Good; M=Marginal; A= Acceptable; N= No Acceptable

In our energy system deisgn for our EV prototype, the dc bus is 72v linked with charger, HESS and Power train system. It gives us an flexiable structure for kinds of converter tests, not only for the supercapacitor interface, also the interface for charger sytem for the next step.

The next chapter is analyzing which kind of converter is most suitable in different voltage class as the power interface, specially for SC bank.

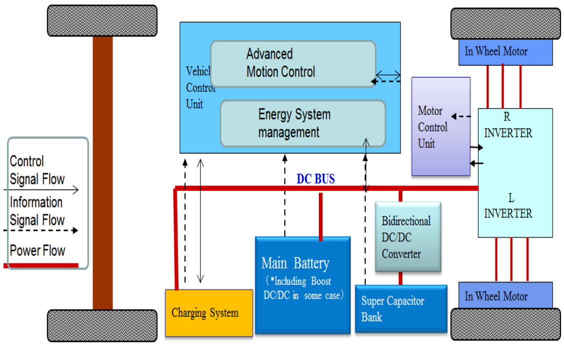
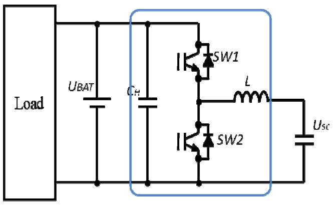
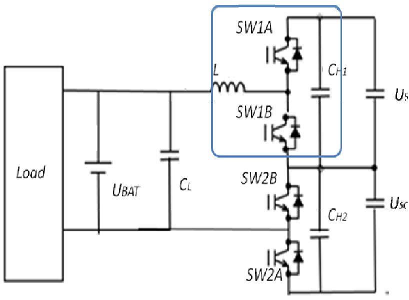


Fig.4 Topologies of HESS for EV prototype

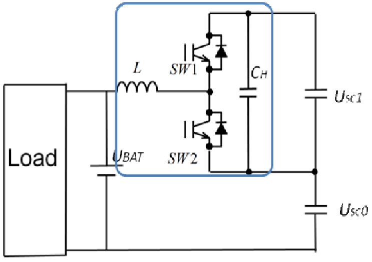
2.3. Topologies for converter connection with SC to DC bus



(a)Bidirectional half bridge converter



(b)Three-level (TL) Converter



(c) Half Controlled (HC) Converter

Fig.5 Converter Topologies for SC interface

Table 3 Comparison among different converters for SC

Bidirectional Converters For SC interface	**Bidirectional Boost Converter**	**Three Level converter**	**Half-Controlled Converter**
Operation Condition	$0<U_{sc}<U_{BAT}$	$(U_{SC1}+U_{SC2})/2<U_{BAT}$ $U_{BAT}<U_{SC1}+U_{SC2}$	$U_{sc0}<U_{BAT}$ $U_{BAT}<U_{SC0}+U_{SC1}$
Minimum SC Storage Energy	0	> 25%SoC	25% SoC
Switching Elements	2	2 (+ 2)	4
Designed Inductance Size	100%	50%	25%
SC banks Voltages balance	No	Need	Need

Based on the performance and the role of SC bank in HESS for EV, Non-isolated DC/DC converters are good options for super capacitor interface [5][7]. The DC/DC converter as the interface for the SC bank to DC bus must have the characteristics as below:

Bidirectional power flow;

Wide variable voltage on one side;

Relatively constant voltage on the other side;

Wide response bandwidth of output current is needed.

The standard bidirectional half bridge topology in Fig.5 (a) has been employed [5][6] [11]. This topology satisfies all the functional requirements listed above and is relatively simple, featuring a minimum number of switching devices.

However, the HB converter has several disadvantages. The silicon utilization is relatively poor due to the wide voltage ratio range between SC bank and DC bus. The inductance size should be considered, because the huge output current under relative wide voltage range.

Two improved topologies are introduced here. One is Three Level converter topology for SC application, shown in Fig.5 (b). Another topological approach first presented in our lab under the name of Half Controlled Converter (HCC), shown in Fig.5(C). [7][8]. The aims of both improved topologies are size reduction and efficiency improvement of the power interface. And both of these two improved topologies set the SC to the high voltage size to increase the efficiency. So the utilization of state of charge of the SC bank should be considered at first in the system design. For our design, 25% of SoC remains after every deep discharge for SC bank is acceptable, considering the size of SC energy bank and the SC modules protection.

The comparison among different converters for SC interface is given in the table 3. The Three-level converter used four switch elements for the output power from SC [11]. The upper group switch has 180 degree phase error with the lower group. It means the switching frequency of the whole chopper system is twice as the chopper using two switch elements. Naturally, if the requirement of the output ripple is the same, the inductance can be decrease to 25%, comparing with the conventional one. So the Three-Level converter is very suitable for the high voltage EV power train system. The cost is that the number of switch elements is increased.

The advantages of HCC is as below, the ratio between the Volt-Ampere Ratings of the switches in the HCC can be decreased to half of half bridge system. The inductor of the HCC can be decreased nearly 50% [7]. The Half Controlled Converter has smaller inductance than conventional one, also the switch elements is seldom. We applied this topology to our system, and the current control method mentioned in the next chapter will be based on this topology.

The one problem for Half controlled converter is that, the voltage balance system is needed, which adds the complex of the system. The optimized voltage balance principle is researched in [8]. And the size of balance circuit is very small if the voltage balance work dynamically and continuously.

3. Power sharing and converter current control for HESS

Power sharing strategy based on output current control from SC bank is proposed for controlling power flow to the motor system and recovering energy to SC in different EV driving stages. The controller design principles are given and the dynamic response of the output current from SC bank is analyzed. This control method is applied to the converter systems of the mentioned HESS topologies. Additionally, power sharing based on the output power decoupling principle is briefly introduced here.

3.1 Three-layer control for EMS of HESS

Here we proposed the three-layer control strategy for HESS [12].

Chopper level control loop is to realize the high speed response for the current tracking in high frequency domain

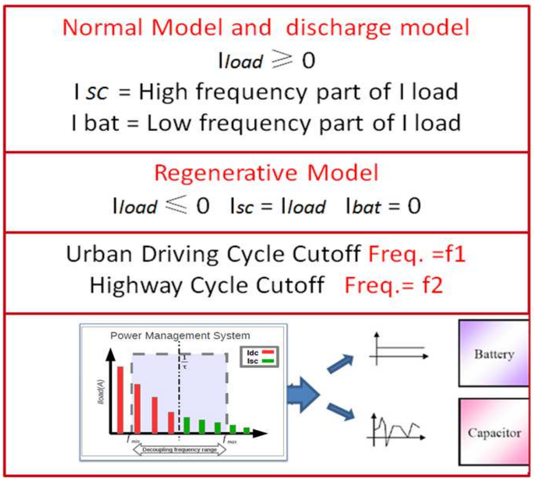
Power sharing control loop is to satisfy the dynamic requirement from the load power for the motion of the EV.

Energy State control: To the protection of the peak current for the SC bank and the state of charge of SC bank and battery bank is also considered. This represents the long term goal of the HESS.

There-layer control strategy lets the HESS work in optimized condition when the requirements from vehicle powertrain.

3.2 Introduction of Power Sharing principle

The algorithm of power sharing is introduced in the Figure. 6. The basic principle is based on the frequency decoupling of the powertrain current requirement. The high frequency section is provided by SC bank, and the left section is from battery passively. Also when regenerative break, the energy is recovered to SC bank completely. The efficiency of the whole system is increased.



Normal Model and discharge model

$Iload \geqslant 0$

I sc = High frequency part of I load

I bat = Low frequency part of I load

Regenerative Model

$Iload \leqslant 0$ $Isc = Iload$ $Ibat = 0$

Urban Driving Cycle Cutoff Freq. =f1

Highway Cycle Cutoff Freq.= f2

Fig. 6 Frequency-Varying Filter for Power sharing [12]

3.3 Current control for power sharing using HCC converter

The conventional control method of DC/DC converter is based on the state average model and the small signal analysis. Nonlinear system is considered usually. Here we use the decoupling method based on real-time voltage signal feed forward to get the transfer function for current continues model of DC/DC converter.

From Fig. 5, the sections in the blue block of the three bi-directional converters are the same structure of the basic half bridge, shown in the Fig. 7.

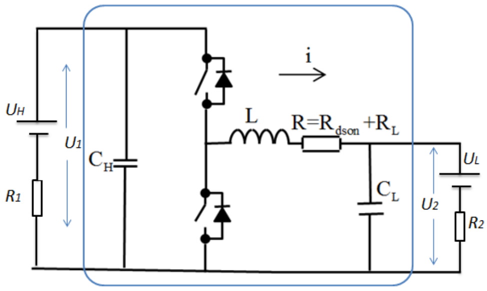


Fig7. Basic bidirectional half bridge

Using the state space average method, the system can be described as below,

$$\begin{cases} L\dfrac{di}{dt} = dU_1 - U_2 - iR & (3.1) \\ C_H\dfrac{dU_1}{dt} = -di - \dfrac{U_1 - U_H}{R_1} & (3.2) \\ C_L\dfrac{dU_2}{dt} = i - \dfrac{U_2 - U_L}{R_2} & (3.3) \end{cases}$$

Here d is the PWM duty of the chopper system.

Usually, the system is considered as no linear system because there is dU_1 in the equation of 3.1. And d is input, and U_1 is one of the outputs. Then the small signal modeling is done at system operation point, and linear model is realized. The controller can be designed based on the small signal model [9].

Now we only consider current control and the voltages U_1 and U_2 are measurable using voltage sensors in real-time.

Set $$d = \frac{u + U_2}{U_1} \qquad (4)$$

The relationship of the current and input, Equation(3.1), can be transferred to

$$L\frac{di}{dt} = u - iR \qquad (5)$$

Set u is the system input, and i is the output. The current control system is an one order linear system.

The transfer function is:

$$\frac{i(s)}{u(s)} = \frac{1}{L + Rs} \qquad (6)$$

It means that, only considering current control loop, if the voltage signal can be measured and feed back in real time, the system can be transferred to one linear system.

Based on the same principle, the current control loop of the HC Converter can be designed as below.

$$L\frac{di}{dt} = dU_{SC1} - U_{BAT} + U_{SC0} - iR \qquad (7)$$

d is the PWM input duty of the chopper, R includes inductance resistance and chopper turn on resistance, i is the output current from SC to DC bus.

Set $$d = \frac{u_{in} + U_{BAT} - U_{SC0}}{U_{SC1}} \qquad (8)$$

The realization imagine is shown in the figure below:

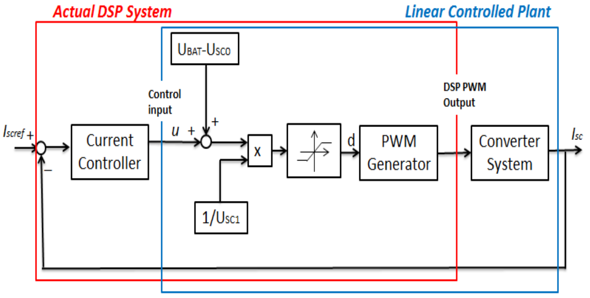


Fig. 8 Current control block for HC converter

The read block is realized completely in the Digital Signal Professor. The signals U_{SC1}, U_{SC0}, U_{BAT}, I_{SC} are obtained by the AD converter of DSP with real-time digital sampling. Other sections are used to calculate the duty of output PWM signal.

The blue block can be explained by the system transfer function,

$$\frac{i(s)}{u_{in}(s)} = \frac{1}{L + Rs} \qquad (9)$$

In fact, the linear control plant is combined by the converter system and one part of the algorithms in DSP.

PI controller is designed as current controller, shown in Fig.7.

The system open loop transfer function is

$$\frac{I(s)}{I_{ref}(s)} = \frac{K_P K_I s + 1}{K_I s(L + Rs)} \qquad (10)$$

So the PI controller parameters K_P, K_I are set to realize the high performance of the system response.

Therefore, the current controller can be design using the classic control method without small signal analysis.

4. EXPERIEMNT SYSTEM DESIGN AND EXPERIMENT ANALYSIS

The design of a HESS test platform, especially for the converter section, is introduced in [10] in detail. The system is tested before EV prototype setup.

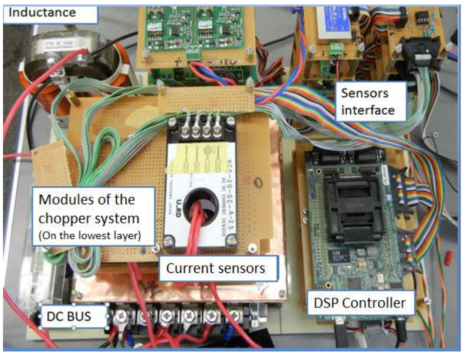


Fig.9. Converter Prototype for SC power interface

In our experiments, the basic parameters for the half controlled converter control for HESS is as below,

Table 3. Parameters of converter and HESS platform

Inductance	0.5mH
R	20 m Ohm
SC0	45V
SC1	35V
DC bus Voltage	60V
Load DC Motor Power	max400W
Controller DSP	150Mhz
PWM Frequency	10Khz

KI and KP are set to 0.02 and 0.0001 for our experiment, and the dynamic response of the output current from SC is as below:

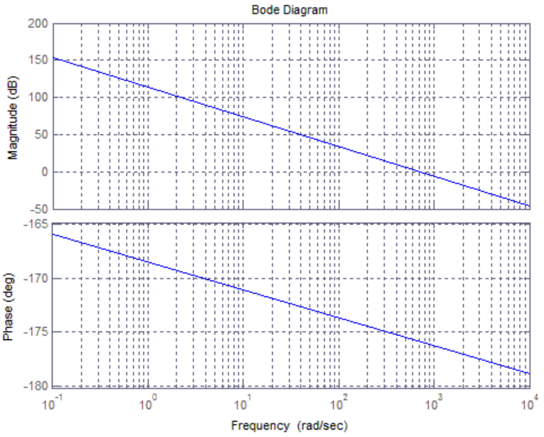


Fig.10 Bode plot of output current response

Fig. 11 and Fig. 12 show the hybrid energy system operation with the current control of SC converter. In experiment of Fig. 11, the load is variable resistant. The frequency decoupling method is applied to the power sharing between two energy sources. In the experiment of Fig.11, DC motor worked as the load of HESS with constant acceleration in every seven seconds.

Based on the analysis of output response and the experiment results, we can see clearly that the SC output current tracking ability using the current control method can satisfy the requirement of power sharing strategy for HESS operation. Also all the regenerative energy can be recovered to SC bank based on current control and the application of bidirectional half controlled converter.

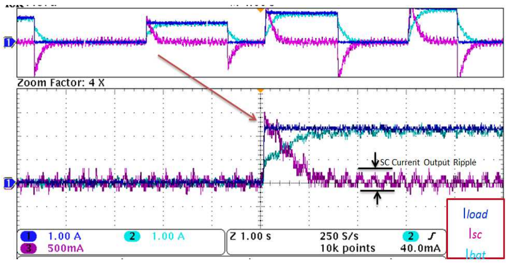


Fig.11. HESS Power sharing experiment

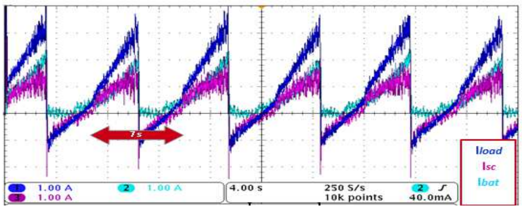


Fig.12 Experiment of HESS recovery energy from motor break

5. Conclusion

In this paper, the battery and super capacitor hybrid energy system with optimized topology is analyzed. Three types of converter topologies, operated as power interface for SC linked to DC bus, are compared and analyzed. Power sharing strategy based on current control from SC bank is presented for controlling the power flow. The controller design is introduced and the dynamic response is analyzed. HESS power sharing experiments using variable resistance load, and energy recovery experiment using motor generator system, show the efficiency of the proposed method. The next step is HESS energy management strategy verification using the ground test of our EV prototype.

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