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Designing and Construction of a Hybrid Energy Storage System using Filter Based Controller

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Abstract

With the world wide application of a large number of vehicles, more and more serious problems about environmental and human survival are caused. The efficient, clean and safety transportations are the perfect choices to deal with these environmental problems. So, in the last decades the electric vehicle (EV) and hybrid electric vehicle (HEV), have been developed in automotive industry. Different hybrid energy storage system (HESS) structures have been released to solve the problems and improve the performance of these vehicles. This paper, firstly reviewed several most conventional control strategy which used in different HESS configuration for advanced electric vehicle applications, then, proposed a new HESS with a novel control strategy, designed for the improvement of performance and energy efficiency, while also extending the battery life. The results show that the proposed HESS, improves the working conditions of ESS and also increased the operating life of the battery. For this purpose, simulations were made in MATLAB/SIMULINK environment.

Keyword: Control Strategy, Electric Vehicle (EV), Hybrid Energy Storage System (HESS), MATLAB/SIMULINK.

INTRODUCTION

Hybrid energy storage system has been proved to be a promising solution for the energy concern of EV with single energy storage device. While batteries, supercapacitors (SCs) and fuel cells (FCs) individually cannot meet all the requirements for EVs, the HESS could complement their drawbacks. Different HESS structures and control strategies have been addressed in the papers in the last few years [1, 2, and 3].

Paper [4] reviewed state of art of the battery, SC, and battery-SC HESS for advanced EV applications. The control methods for the HESS were discussed. In general, the structure of the existing HESS can be categorized into two types: the passive HESS and the active HESS, each of which has several types of topologies. Conventional active methods use one or multiple full size dc/dc converters to interface the energy storage device to the dc link. Compared with the passive HESS, an active HESS requires more sophisticated power electronic converters and controllers for batteries and SC.

References [5, 6] presented preliminary studies on the battery-SC sizing task, but fail to provide an accurate account of the energy losses in the powertrain components and ignore the important coupling between the sizing and energy management.

With regard to this last factor, recent studies on the design of FC-batteries [7, 8], hybrid [9], and plug-in [10] EVs have shown that, to maximize the benefits of hybridization, it is imperative to take into account the coupling between the sizing and the energy management. Accordingly, the present work extends these previous studies by contemplating the combined sizing energy management problem for the batteries-SCs hybridization.

In paper [11] three cases were studied. The first was designated as battery topology which uses a power electronics converter, to stabilize the DC-Link voltage, and a battery pack. The second one used a direct parallel between batteries and SCs and only one bidirectional DC-DC converter to the same purpose. This was designated as passive hybrid topology, the third was designated in the literature as parallel active hybrid topology, and was formed by two bidirectional DC-DC converters parallel linked, each devoted to the considered ESS (i.e. batteries and SCs), enhancing the performance facing the passive topology, but increasing the control complexity.

Paper [12] presented the utilization of an energy storage devices consisting of a SC bank for future EVs with a hydrogen FC as the main power source and also focused on the innovative control law based on the flatness properties for a FC/SC hybrid power source. Utilizing the flatness principle, they proposed simple solutions to the hybrid energy management and stabilization problems. ESS current control loops are supplied by two reference signals: the SC current reference and the FC current reference, generated by the energy management algorithm.

Paper [13] compared the near-optimal configurations for three topologies of vehicles: FC–battery, FC–SC, and FC–battery– SC and also, the control strategies developed for each vehicle are based on rules in order to make the best use of the power sources given their power, energy, efficiency, and durability characteristics.

Paper [14] proposed an optimal energy management scheme for HESS. For the optimal control of the energy flow, they suggest two main objectives: minimize the fluctuation of current flowing of battery, and minimize the energy loss in the HESS. Furthermore, the optimal solution for controlling the current flow in the HESS by formulating the optimization problem was obtained.

Paper [15] proposed a new control strategy, designed for the improvement of performance and energy efficiency, while also extending the battery life. The control strategy used classical controllers and provided good results with low computational cost. In a nutshell, the proposed control strategy regulates the output voltage and restores SC voltage after transients. It divides the power demand into low-frequency components and high-frequency components. The low frequency components are supplied by the battery, while high frequency components are supplied by the SC.

Paper [16] proposed a new hybrid energy storage system (HESS) with batteries and SCs. The proposed topology adopts a smaller power capacity bi-directional dc-dc converter compared with the traditional HESS by adding two switches and diodes. The cost, volume and weight of the whole system can be reduced while the power demand of DC bus is satisfied.

To have smaller current ripple for the battery and SCs which results in improved electric mode efficiency in hybrid vehicle and to achieve more control flexibility, a three-port bidirectional DC-DC converter with novel controller is considered as an appropriate choice in this paper to interface the battery and SC .The current of each sources control via a filter based controller.

The rest of this paper is organized as follows, first section introduces the conventional control strategies for different kind of HESS configuration. For control of energy storage interface between, battery and SCs, three-port bidirectional converter with novel control strategy is presented in next section. Energy storage system with and without proposed HESS is discussed due to simulation results and finally conclusion is given in last section.

Conventional Control Strategies

Energy storage power management is one of the most important parameters which effects on control strategy and other parts of a hybrid vehicle, so there is an indisputable need for relevant control schemes to perform the power split. Controlling these systems comes down to splitting up the global electric power required by the vehicle into flows to be drained from the each kind of ESS (battery, SC and FC).

Paper [17] presented a new energy management strategy for Battery/SC HESS to minimize the both parameters: the sizing of the HESS and the stresses applied to the battery. The proposed strategy simulated and compared with the classical energy management methods. The optimal sizing of HESS and long lifetime of the battery are the main goals of this proposed strategy. For these reasons, this proposed strategy use the energy state of SC like main factor to change the power split between the two storage components. The optimal sizing of HESS and long lifetime of the battery are the main goals of their proposed strategy. In paper [18], from several linking possibilities of the storage system, a proper topology including DC-converter was derived.

The control strategy decides which proportion of the charge or discharge power the electric SC has to take and forces the reference current of the DC converter (see figure 1). The SOCs of battery and SC as well as the actual current in the intermediate circuit serve as input variables. Optionally the road speed v can be used for an extended control strategy.

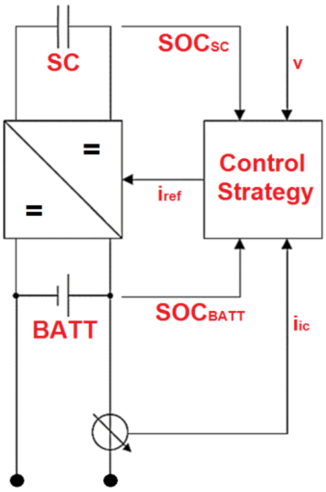

Figure 1. Block diagram of HESS and control strategy with input and output variables

In paper [19], control scheme enabled different energy management strategies using a distribution input to share the energy between battery and SC and also, a switching strategy and a frequency strategy tested using this same control scheme.

Paper [20], dealt with the simulation study of an SC based ESS for EV. A detailed performance analysis carried out on a configuration, where the SC is directly connected across the load and fed by the battery through a dc-dc converter. They simulation study mainly focused on performance of particular configuration pertaining to the charge/discharge cycles that capacitor is subjected to during forward torque and regenerative braking power. As the capacitor is responsible for the delivery and absorption of power, it is very vital that the capacitor's voltage is managed for better utilization of the capacitor. Hence a window comparator is used which compares the capacitor voltage with two upper and lower limits as shown in figure 2 so as to keep the capacitor voltage within a band.

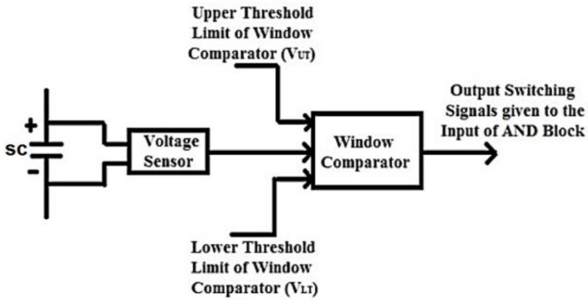

Figure 2. Block Diagram of Window Comparator.

Paper [21] presented a control strategy based on the DC voltage regulation via sliding mode control that changes the working conditions of battery and SC. When the SC voltage stays in the working range as designed, it will work as the auxiliary power source to maintain the DC voltage. When the SC voltage reaches the upper limit or the lower limit, the battery will be controlled to maintain the DC bus voltage, making the SC voltage remain in a proper range. The general structure of the power system used in paper [21] is shown in figure 3.

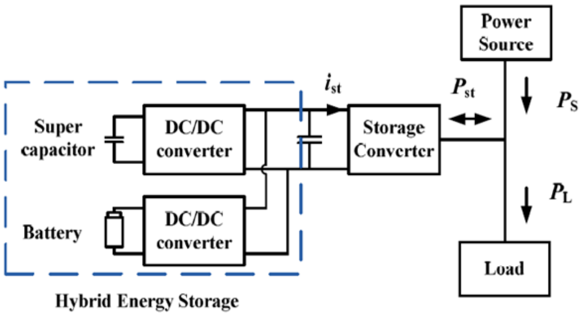

Figure 3. Power system structure.

All in all, the study results illustrated the benefits of hybrid energy sources in terms of energy source mass, vehicle range and system functionality:

(i) Reduce peak current of the battery pack
(ii) The recovery or regenerative energy
(iii) The reduction of battery current loading
(iv) The improvement of fuel cell energy conversion efficiency and
(v) The separation of drivetrain transients from the main energy source to the system power buffer.

Proposed Hess And Control Strategy

Multi-port bidirectional DC-DC converter, as a new type of power electronics converter, has attracted special interest in applications. It can effectively integrate energy storage and it also has a high power density, easy to implement centralized control and energy management and so on. There are several topologies have been reported recently [22, 23].

For feeding electric motor, to have smaller current ripple for the battery and SC which results in improved electric mode efficiency in hybrid vehicle and to achieve more control flexibility, a three-port bidirectional DC-DC converter is considered as an appropriate choice in this paper to interface the battery and SC. Figure 4 shows the circuit topology of this three-port bidirectional converter which can be seen as two current-fed ports and one voltage-fed port.

The power transfer between every two ports in the three-port converter is independent with the third port. P_{mk} can be derived in equation (1) based on methods of [24]:

$$P_{mk} = \frac{\varnothing_{mk}\left(n - |\varnothing_{mk}|\right)}{nwL_{mk}} V_m V_k \qquad (1)$$

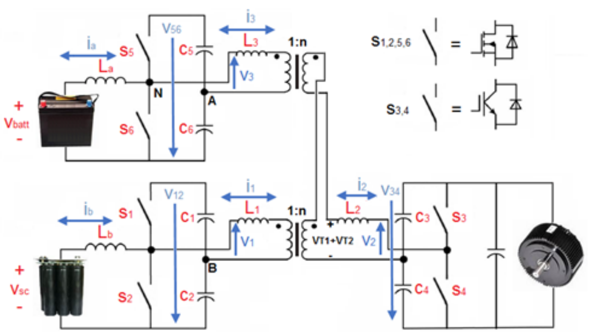

Figure 4. Three-port bidirectional DC-DC converter

Where m, k are (1, 2, 3), P_{mk} is the power between port m and port k, L_{mk} is the leakage inductance between m and k port, V_m and V_k are the magnitudes of transformer winding voltages (see Figure 4), $\varnothing_{mk}$ is shown in Figure 5.

The control variable is the time constant τ in the low-pass filter, which determines how much power is provided by the SC and battery. It was found to be more efficient to use only battery power when the percentage of SC current requested was less than nearly 10%; thus, this functionality is built into the control strategy. The SOC_{SC} used to diagnose available SC power, and the SOC_{Batt} used to regulate constant τ from low-pass filter.

After detecting the output power of each sources, phase shift of each half bridge is determined, therefore tuning block must be used to regulate each gate switches signals. Thus, by determining each half-bridge phase-shift, the power transfer between every two ports can be derived from equation (1). Figure 6 shows configuration of proposed control strategy.

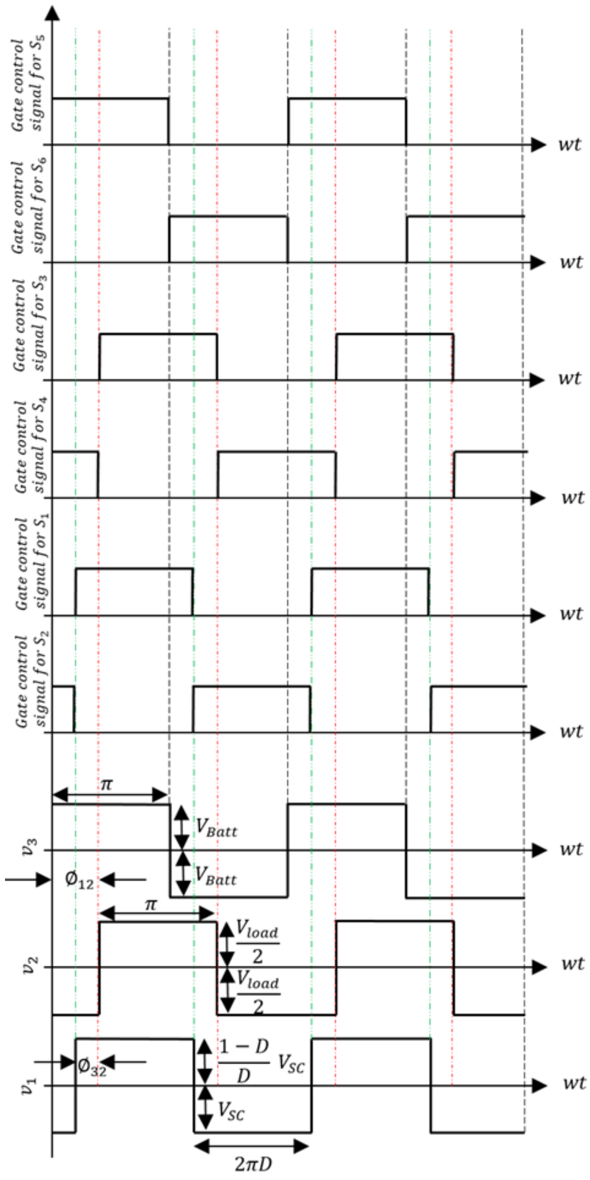

Figure 5. Idealized transformer voltage waveforms at fixed 50% duty cycle control.

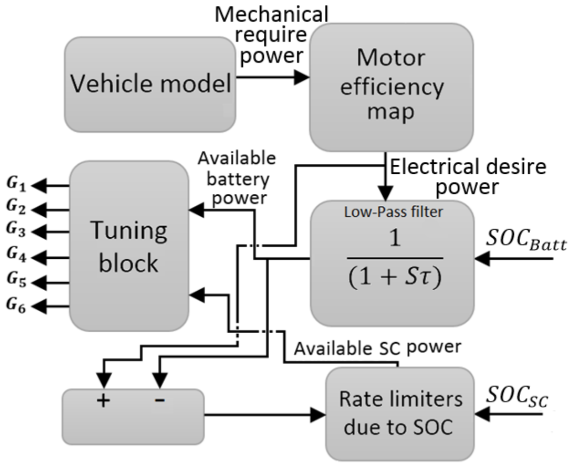

Figure 6. Proposed control strategy.

RESULTS AND DISCUSSION

Performance of ESS was investigated through simulation in case of following electric motor rpm schedule in MATLAB/SIMULINK environment.

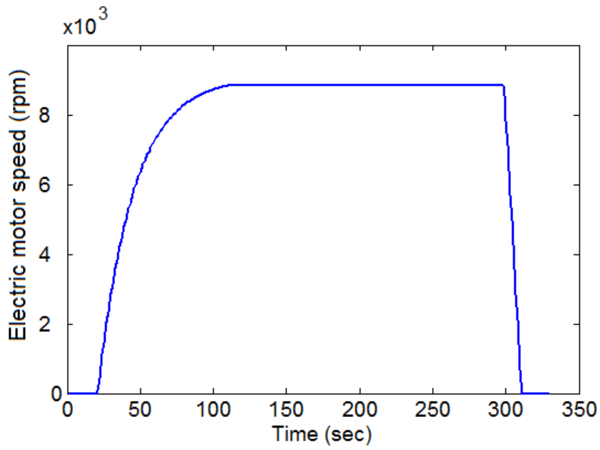

Figure 7. Electric motor speed.

When the SC is installed in parallel configuration with battery pack, the peak current is 12A and the working current of the battery varied greatly, which will reduce the operating life of the battery. When the SC is coupled with the battery via proposed controller, it is clear from Figure 8 that the battery peak current is decreased to 8A. In addition, there are fewer spikes of current from the battery, therefore producing a steadier current.

When the current from the battery is closer to a constant value with fewer spikes, the battery has a potential for an increased efficiency and life expectancy, further reducing the cost of the energy source.

The resulting current surges in and out of the battery tend to generate extensive heat inside the battery, which leads to increased battery losses, thus lower efficiency and ultimately premature failure (see figure 9). Therefore, as can be seen from figure 10 the value of battery SOC with and without proposed HESS at the same amount of battery charge are different.

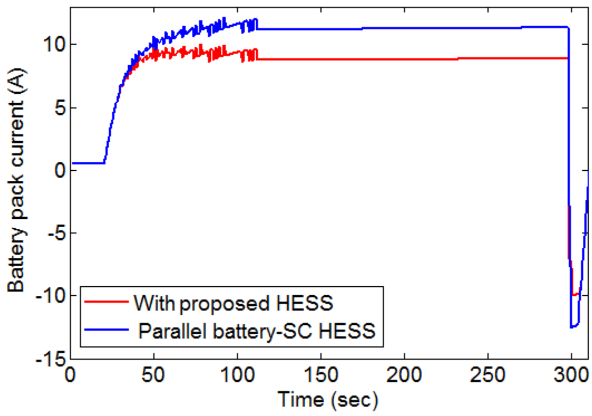

Figure 8. Battery pack current due to different speed off electric motor.

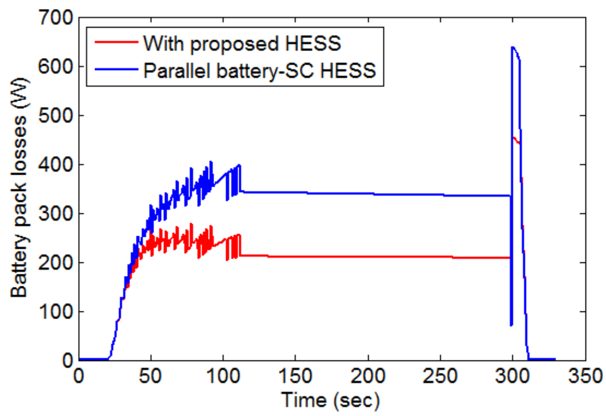

Figure 9. Battery pack losses due to different speed off electric motor.

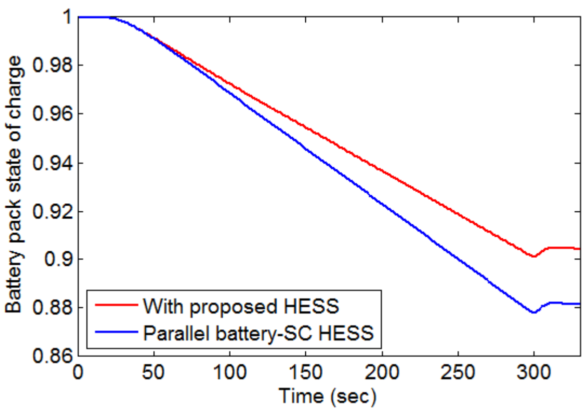

Figure 10. Battery pack state of charge due to different speed off electric motor.

CONCLUSION

This paper is modeled an HESS with a battery, a SCs and a three-port bidirectional converter, furthermore, novel filter based control strategy has been proposed for energy exchange between battery and SCs .Simulation results showed that the presence of the SCs with three-port bidirectional converter, especially during the initial seconds of imposing load current, led to significant reduction of battery current. In these situations, the battery will remain close to a constant current supply while the SCs will meet the high demands of the electrical loads of the car. This configuration can significantly reduce the volume and weight of the overall ESS. Furthermore, overall battery life can be drastically improved due to the decrease in the output current and also can reduce the battery module temperature.

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