Loss Analysis of Hybrid Battery-Supercapacitor Energy Storage System in EVs

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Abstract–In this study, the losses of the hybrid energy storage system (HESS) including super-capacitor (SC) and battery in an electric vehicle (EV) are analyzed. Based on the presented vehicular system structure, the simulation model is proposed. With the controllable super-capacitor current, the operation of an EV with the hybrid battery-supercapacitor energy storage system is simulated under the European urban driving schedule ECE-15 and the losses of the hybrid energy system are computed and analyzed. The simulated results demonstrate that the super-capacitor current can be optimized under various operating conditions to minimize the losses of the hybrid battery-supercapacitor energy storage system in the EV. Thus, this study provides the valuable approach to maximize the operating efficiency of the hybrid battery-supercapacitor energy storage system in EVs.

Keywords–Battery, efficiency, electric vehicles (EV), hybrid energy storage system (HESS), losses, super-capacitor.

I. Introduction

Energy storage system is one of the important components in electric vehicles. In general, such an energy storage system consists of an energy storage component, two or more than two components. The latter is named as the hybrid energy storage system, such as the hybrid battery-supercapacitor energy storage system. As known well, battery has high specific energy and low specific power. However, super-capacitor has high specific power and low specific energy. Obviously, dynamic performance of super-capacitor energy storage system is better than battery energy storage system. Consequently, the hybrid battery-supercapacitor energy storage system can improve dynamic performance of battery energy storage system. Therefore, dynamic performance of the EV with hybrid battery-supercapacitor energy storage system can be better than the EV with battery energy storage system. In addition, the super-capacitor has the advantage of fast charge and the hybrid battery-supercapacitor energy storage system can extend battery life time.

For the constant car velocity, the study in [1] shows that the optimal ratio of the super-capacitor power to the bus power can be found to minimize the losses of the hybrid battery-supercapacitor energy storage system. An optimization algorithm is proposed to extend battery life time and simultaneously to improve the energy efficiency of the hybrid battery-supercapacitor energy storage system [2]. A power optimization method is proposed in [3] to have the minimum battery loss. In [4], the topologies of the converters for connecting super-capacitor to battery are analyzed and the current control method for bidirectional non-isolated converters is presented to realize the power flow arrangement. The reference [5] deals with a multi-objective optimization problem for optimizing the power split to extend the battery lifetime and to reduce the power losses of the hybrid battery-supercapacitor energy storage system, and the online energy management controller is proposed. Different converter topologies for the hybrid battery-supercapacitor energy storage system are discussed in [6].

This paper focuses on the loss analysis of the hybrid battery-supercapacitor energy storage system in EVs. In the remaining sections of this paper, the schematic system structure of the EV with hybrid battery-supercapacitor energy storage system will be presented. Then, the dynamic model of such a system structure will be proposed. Next, an EV prototype with the hybrid battery-supercapacitor energy storage system will be simulated under the European urban driving schedule ECE-15. After that, the losses of the battery and the super-capacitor will be studied and analyzed. Finally, the conclusion will be shown.

II. Model of EV System

1. System Structure of EV with Hybrid Battery-Supercapacitor Energy Storage System

The schematic system structure of the EV with hybrid battery-supercapacitor energy storage system is illustrated

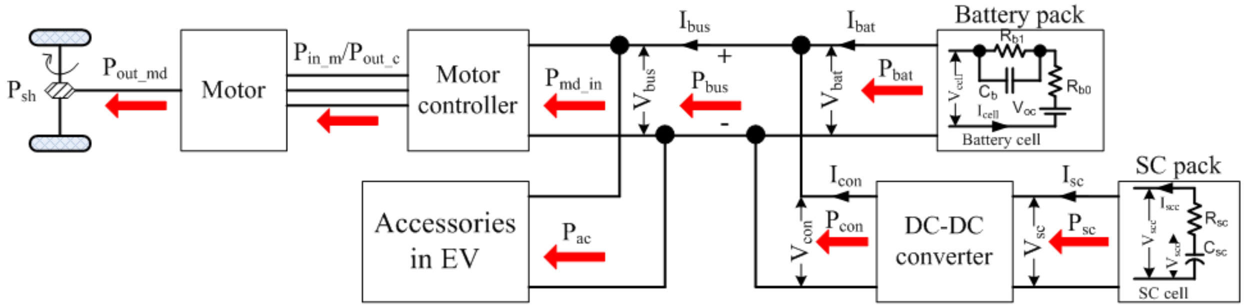


Fig. 1 Schematic structure of EV system with hybrid battery-supercapacitor energy storage system

in Fig. 1, where C_{sc} represents the capacitance of the SC cell, R_{sc} the internal resistance of the SC cell, I_{scc} the current of the SC cell, V_{sco} the open-circuit voltage of the SC cell, V_{scc} the voltage across the SC cell, I_{sc} the current of the SC pack, V_{sc} the voltage of the SC pack, V_{con} the voltage of the dc-dc converter, I_{con} the current of the dc-dc converter, C_b the equivalent capacitance of the battery cell, R_{b0} and R_{b1} the equivalent internal resistances of the battery cell, I_{cell} the current of the battery cell, V_{oc} the open-circuit voltage of the battery cell, V_{cell} the voltage across the battery cell, I_{bat} the current of the battery pack, V_{bat} the voltage of the battery pack, V_{bus} the bus voltage, I_{bus} the bus current, P_{sc} the power of the SC pack, P_{bat} the power of the battery pack, P_{bus} the bus power, P_{in_md} the input power of the motor drive including the motor and the motor controller, P_{out_c} the output power of the motor controller, P_{in_m} the input power of the motor, P_{out_c} is equal to P_{in_m}, P_{out_md} the output power of the motor drive, the P_{sh} the shaft power of the EV, and P_{ac} the average power of the accessories in the EV.

2. Model of EV System

Referring to Fig. 1, the discharging current of the SC cell is computed as

$$I_{scc} = \frac{V_{sco} - \sqrt{V_{sco}^2 - 4R_{sc}P_{scc}}}{2R_{sc}} \tag{1}$$

where P_{scc} is the power of the SC cell.

The charging current of the SC cell is expressed as

$$I_{scc} = -\frac{-V_{sco} + \sqrt{V_{sco}^2 - 4R_{sc}P_{scc}}}{2R_{sc}} \tag{2}$$

Moreover, I_{scc} can be computed as

$$I_{scc} = C_{sc}\frac{dV_{sco}}{dt} \tag{3}$$

The depth of discharge for the SC pack is computed as

$$DoD_{sc} = \frac{V_{scmax}^2 - V_{sc}^2}{V_{scmax}^2 - V_{scmin}^2} \tag{4}$$

where V_{scmax} represents the maximum operating voltage of the SC pack, and V_{scmin} the minimum operating voltage of the SC pack.

For the battery, the discharging current of the battery cell is computed as

$$I_{cell} = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4(R_{b0} + R_{b1})P_{cell}}}{2(R_{b0} + R_{b1})} \tag{5}$$

where P_{cell} represents the power of the battery cell.

The open-circuit voltage of the battery cell can be estimated as

$$V_{oc} = \sum_{j=0}^{19} c_j\,(SoC - SoC_{ave})^j \tag{6}$$

where SoC is the state of charge of the battery, c_j and SoC_{ave} are the constant values for the given lithium battery, respectively.

The battery SoC is can be expressed as

$$SoC = \frac{C_r}{C_n} \tag{7}$$

where C_r is the remaining charge and C_n the nominal charge.

The power of the dc-dc converter is computed as

$$P_{con} = I_{con}V_{con} \tag{8}$$

If the SC pack runs under discharging, the relationship between the input and the output of the dc-dc converter can be expressed as

$$P_{con} = \eta_{con}P_{sc} \tag{9}$$

If the SC pack runs under charging, the relationship between the input and the output of the dc-dc converter can be expressed as

$$\eta_{con}P_{con} = P_{sc} \tag{10}$$

where η_{con} represents the efficiency of the dc-dc converter.

The power of the battery pack is expressed as

$$P_{bat} = I_{bat}V_{bat} \tag{11}$$

The bus power is calculated as

$$P_{bus} = P_{in\_md} + P_{ac} \tag{12}$$

and

$$P_{bus} = P_{bat} + P_{con} \tag{13}$$

The efficiency of the motor drive can be estimated as [7]

$$\eta_{md} = \frac{T_m\omega_m}{T_m\omega_m + k_{cu}T_m^2 + k_{fe}\omega_m + k_w\omega_m^3 + p_{lmd}} \tag{14}$$

where T_m is the motor torque, ω_m is the angular speed of the motor, k_{cu} is the coefficient of copper loss, k_{fe} the coefficient of iron loss, k_w the coefficient of windage loss, p_{lmd} the constant loss arising from the motor controller and the motor.

Under driving/motoring operation, one has

$$\eta_{md}P_{in\_md} = P_{out\_md} \tag{15}$$

$$\eta_g P_{out\_md} = P_{sh} \tag{16}$$

Under braking/generating operation, otherwise, one has

$$P_{out\_md} = \eta_g P_{sh} \tag{17}$$

$$P_{in\_md} = \eta_{md}P_{out\_md} \tag{18}$$

where η_g represents the efficiency of the gear device and can be regarded as a constant.

The shaft power can be expressed as

$$P_{sh} = \frac{G_r}{r_t}T_m v \tag{19}$$

where v is the velocity of the EV, G_r the gear ratio of the gear device connecting the motor to the shaft and is a constant, and r_t the radius of the tire.

The electromechanical dynamic equation of an EV can be expressed as

$$m\frac{dv}{dt} = \frac{G_r}{r_t}T_m - \mu_{rr}mg - \frac{1}{2}\rho AC_d v^2 - mgsin\theta \tag{20}$$

where m is the total mass of the EV, t the time, μ_{rr} the coefficient of rolling resistance and can be regarded as a constant, g the gravitational acceleration, ρ the density of the air and can be regarded as a constant, A the front area of the EV, C_d the drag coefficient and can be regarded as a constant, and θ the angle between the slope and the level ground.

The losses of the battery pack and the SC pack are calculated as, respectively,

$$P_{loss\_bat} = I_{bat}^2 r_{batp} \tag{21}$$

$$P_{loss\_sc} = I_{sc}^2 r_{scp} \tag{22}$$

where r_{batp} is the equivalent resistance of the battery pack and r_{scp} is the equivalent resistance of the SC pack.

In a driving cycle, the average battery loss and the average SC loss are computed as, respectively,

$$P_{loss\_bat\_c} = \sum(P_{loss\_bat}\Delta t)/T_c \tag{23}$$

$$P_{loss\_sc\_c} = \sum(P_{loss\_sc}\Delta t)/T_c \tag{24}$$

where Δt is the sampling time and T_c is the time of a driving cycle.

In a full discharging cycle, thus, the average battery loss and the average SC loss are computed as, respectively,

$$P_{loss\_bat\_r} = \sum(P_{loss\_bat\_c}T_c)/T_r \tag{25}$$

$$P_{loss\_bat\_r} = \sum(P_{loss\_sc\_c}T_c)/T_r \tag{26}$$

where T_r is the time of a full discharging cycle.

III. Simulation of EV Operation under European Urban Driving Schedule ECE-15

1. Main Data of EV Prototype

The main data of an EV prototype is shown in Table 1. Such an EV prototype is simulated to study the effects of both the SC current and the SC capacity on the losses of the hybrid battery-supercapacitor energy storage system.

Table 1: Main data of EV prototype

Parameters	Value
Model of prototype	Two-door and two-seat light EV
Total mass	790 kg
Radius of tyre	0.275 m
Gear ratio	8.25
Rated velocity	50 km/m
Maximum velocity	70 km/m
Rated power of motor	5 kW
HESS	Lithium battery and super-capacitor

2. European Urban Driving Schedule ECE-15

The European urban driving schedule ECE-15 is suitable for examining the performance of the EV prototype in this paper. Fig. 2 shows a driving cycle of the European urban driving schedule ECE-15.

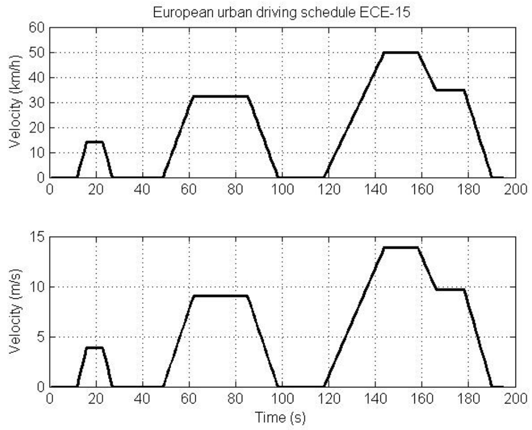


Fig. 2 Driving cycle of European urban driving schedule

3. Strategy of Energy Management

In this study, the strategy of the energy management is proposed as follows. (a) If the bus power is less than 0, the SC is only charged; (b) under the condition that the SC voltage is more than the minimum SC voltage and the battery DoD is less than 0.8, if the bus power is more than 0, both the SC and the battery discharge; (c) under the condition that the SC voltage is less than or equal to the minimum SC voltage and the battery DoD is less than 0.8, if the bus power is more than 0, the battery discharges; (d) under the condition that the SC voltage is more than the minimum SC voltage and the battery DoD is more than or equal to 0.8, if the bus power is more than 0, the SC discharges; and (e) if the SC voltage is less than or equal to the minimum SC voltage and the battery DoD is more than or equal to 0.8, both the SC and the battery do not operate and the simulation ends.

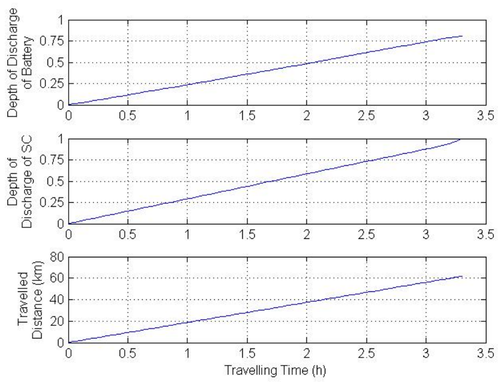
3. Simulated Results

If the battery capacity is 4477.0 Wh, the SC capacity is 1877.8 Wh and the ratio of the SC current to the battery is 0.5, the operating performances of the EV are simulated and shown in Fig. 3. Figs. 3a-3c illustrate the operating performances during a full discharging period and Figs. 3d-3i show the operating performances during the 40th driving cycle.

It can be seen from Figs. 3 that the simulated results indicate the real operation of the EV. Furthermore, it is easy that the simulated results are verified by the theoretical analysis.

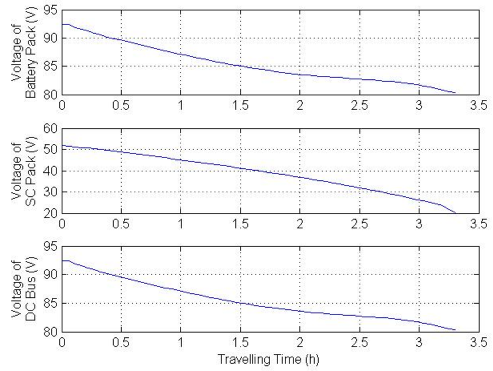
IV. Effects of SC Current and SC Capacity on Battery and SC Losses under European Urban Driving Schedule ECE-15

1. Case A

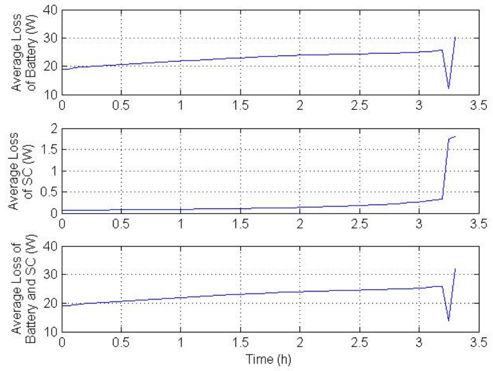


(a) Battery DoD, SC DoD and travelled distance during a full discharging period

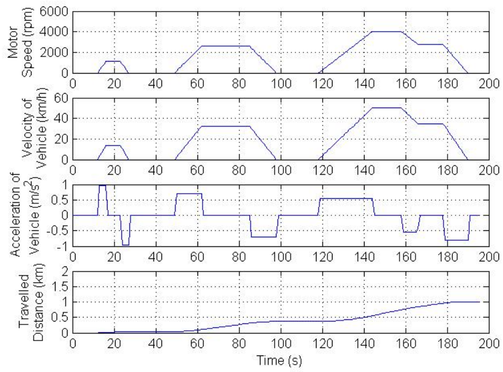
In the case A, the capacity of the battery is 4477.0 Wh and the capacity of the SC is 1877.8 Wh. Thus, the ratio of the



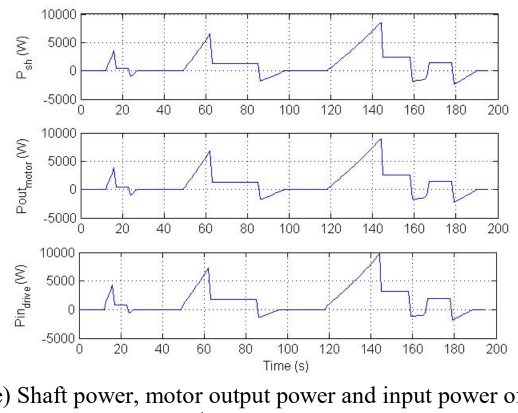
(b) Battery voltage, SC voltage, DC bus voltage during a full discharging period



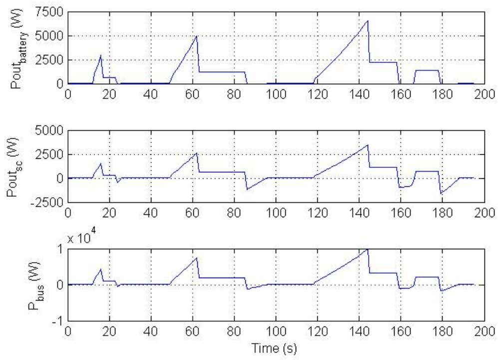
(c) Average battery loss, average SC loss and sum of both during a full discharging period



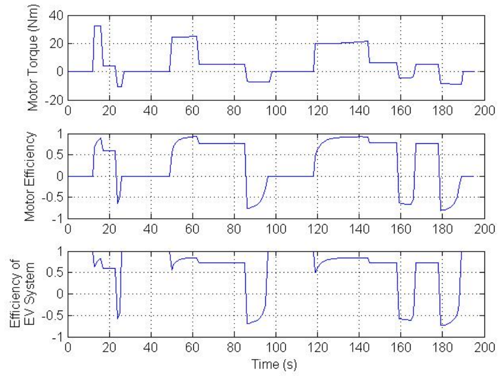
(d) Motor speed, car velocity, car acceleration and travelled distance during 40th driving cycle



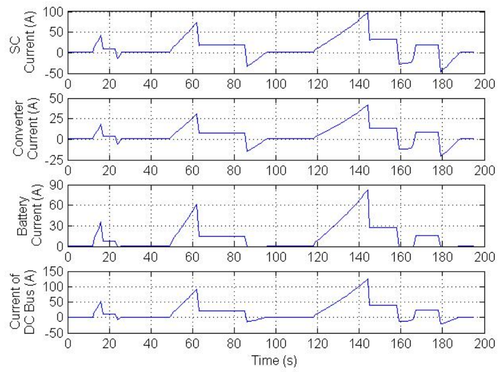
(e) Shaft power, motor output power and input power of motor drive during 40th driving cycle



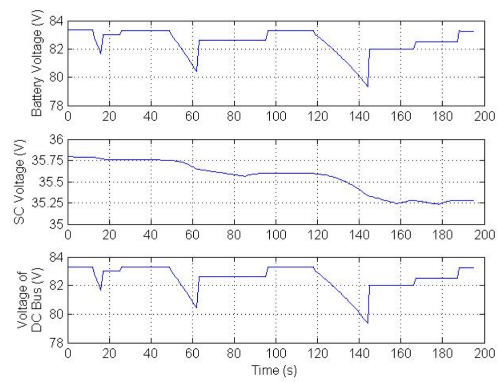
(f) Battery power, SC power and bus power during 40th driving cycle



(g) Motor torque, efficiency of motor drive and efficiency of EV system during 40th driving cycle



(h) SC current, converter current, battery current, and bus current during 40th driving cycle



(i) Battery voltage, SC voltage, and bus voltage during 40th driving cycle

Fig. 3 Simulated waveforms under European urban driving schedule ECE-15

SC capacity to the battery capacity is 0.41943. The effects of the SC current on the battery loss, the SC loss and the sum of both are illustrated in Fig. 4. It can be seen from Fig. 4 that (a) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 0.5, to obtain the minimum average battery loss during a full discharging period, (b) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 0.6, to obtain the minimum average SC loss during a full discharging period, and (c) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 0.5, to obtain the minimum sum of the average battery loss and the average SC loss during a full discharging period.

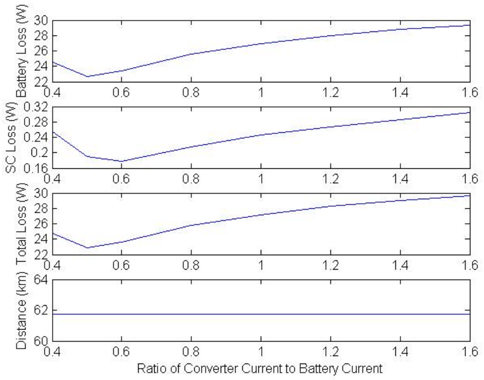


Fig. 4 Effect of SC current on losses (Battery capacity = 4477.0 Wh and SC capacity = 1877.8 Wh)

2. Case B

In this case, the capacity of the battery is 4477.0 Wh and the capacity of the SC is 3755.6 Wh. Thus, the ratio of the SC capacity to the battery capacity is 0.83886. The effects of the SC current on the battery loss, the SC loss and the sum of both are illustrated in Fig. 5. It can be seen from Fig. 5 that (a) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 1.0, to obtain the minimum average battery loss during a full discharging period, (b) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 1.0, to obtain the minimum average SC loss during a full discharging period, and (c) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 1.0, to obtain the minimum sum of the average battery loss and the average SC loss during a full discharging period.

3. Case C

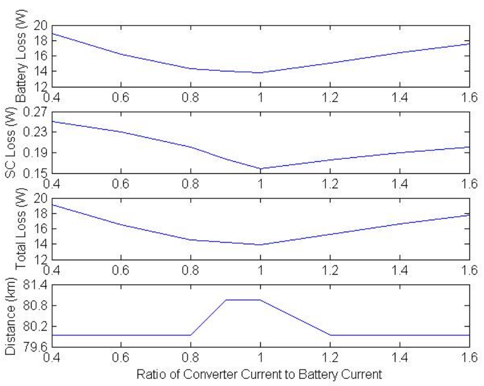


Fig. 5 Effect of SC current on losses (Battery capacity = 4477.0 Wh and SC capacity = 3755.6 Wh)

In the case C, the capacity of the battery is 4477.0 Wh and the capacity of the SC is 5633.3 Wh. Thus, the ratio of the SC capacity to the battery capacity is 1.2583. The effects of the SC current on the battery loss, the SC loss and the sum of both are illustrated in Fig. 6. It can be seen from Fig. 6 that (a) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 1.4, to obtain the minimum average battery loss during a full discharging period, (b) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 1.4, to obtain the minimum average SC loss during a full discharging period, and (c) there is the optimal SC current and the optimal ratio of the SC current to the battery current is 1.4, to obtain the minimum sum of the average battery loss and the average SC loss during a full discharging period.

4. Relationship between Optimal SC Current and Capacities

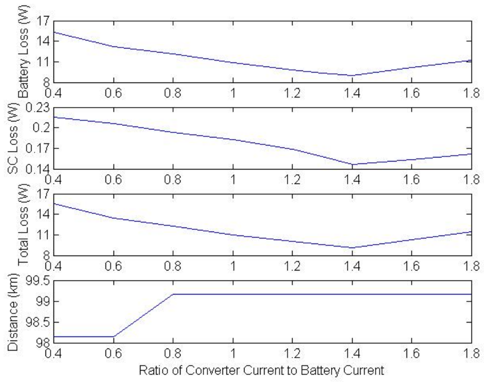


Fig. 6 Effect of SC current on losses (Battery capacity = 4477.0 Wh and SC capacity = 5633.3 Wh)

From the aforementioned simulated results and analysis, it can be seen that the SC current can be optimized for the minimum battery loss, the minimum SC loss or the minimum sum of both, and that the optimal SC current depends on the ratio of the SC capacity to the battery capacity. The effect of the ratio of the SC capacity to the battery capacity on the optimal ratio of the SC current to the battery is illustrated in Fig. 7. It can be observed from Fig. 7 that the optimal ratio of the SC current to the battery current changes with the ratio of the SC capacity to the battery capacity.

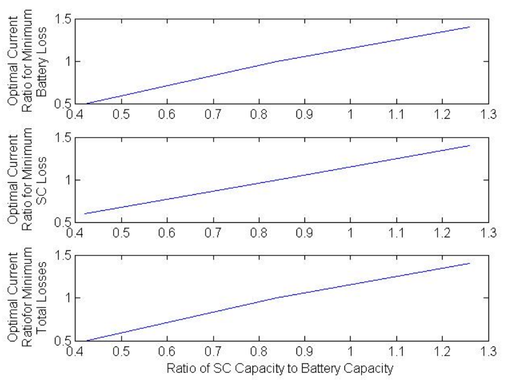


Fig. 7 Effect of ratio of SC capacity to battery capacity on optimal ratio of SC current to battery current

V. CONCLUSION

The dynamic model of the EV with the hybrid battery-supercapacitor energy storage system is proposed. Based on the proposed dynamic model, an EV prototype has been simulated under the European urban driving schedule and the proposed energy management strategy. The study shows that (a) for an EV with a hybrid battery-supercapacitor energy storage system the super-capacitor current can be optimized to have the minimum battery loss, the minimum super-capacitor loss, or the minimum sum of the battery loss and the super-capacitor loss, (b) the optimal super-capacitor current depends on both the battery capacity and the super-capacitor capacity, and (c) the optimal ratio of the super-capacitor current to the battery current increases with increase in the ratio of the super-capacitor capacity to the battery capacity. Thus, this paper offers the valuable investigation for the maximum efficiency control of the hybrid battery-supercapacitor energy storage system in EVs.

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