Equivalent Series Resistance-based Real-time Control of Battery-Ultracapacitor Hybrid Energy Storage Systems

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Abstract—This paper proposes an equivalent series resistance (ESR)-based control, namely a circuit-level approach, to efficiently distribute load in battery-UC hybrid energy storage systems (HESSs). The ESR circuit model of an example capacitor semiactive HESS is first built representing the energy losses at both circuit and system levels. The analytical derivations show that the overall energy loss of the HESS solely depends on the ratio of the dynamic load provided by the battery pack to the entire dynamic load. This energy loss is minimized following the load distribution determined by the ratio of the ESR of the battery pack to those of the UC pack and dc-dc converter. An ESR-based real-time control strategy is then developed to minimize the energy loss and regulate UC SOC to avoid overcharge/overdischarge. Both the simulation and experimental results verify the effectiveness of the proposed ESR-based control in terms of improvements in energy efficiency, usage of UC pack, and temperature rise reduction in batteries. The ESR-based control achieves a performance close to that using the ideal dynamic programming method. Compared with the battery-alone system, the total energy loss and battery temperature rise in the example HESS are averagely reduced by 44.9% and 51.9%, respectively, under the proposed ESR-based control.

Index Terms—Battery, equivalent series resistance, hybrid energy storage system, real-time control, ultracapacitor

I. INTRODUCTION

Lithium-ion batteries are now one of the most widely used energy storage devices thanks to their high energy density and low self-discharge rate. However, in real applications peak load demands often lead to an oversized battery pack and shorten battery cycle life. A possible solution is to add ultracapacitors (UCs) featuring a high power density to mostly meet peak and dynamic load demands. The UCs are well known to have high efficiency, long cycle life, but low

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energy density. Therefore, a battery-UC hybrid energy storage system (HESS), i.e., a combination of batteries and UCs, is expected to overcome weakness of each device.

Many energy management strategies have been proposed for HESSs to 1) improve energy efficiency of the overall system, 2) extend cycle lives of main storage devices, usually batteries, and 3) enhance flexibility, reliability, and cost effectiveness. All these existing strategies, mostly for electric vehicular applications, can be largely classified into two groups: rulebased and optimization-based strategies. A set of deterministic rules (i.e., if-then rules) was developed to assign the peak load to the UCs, thus alleviating stress of batteries [1]. Hysteresis control was proposed to regulate dc-dc converter power on UC open-circuit voltage [2]. High-pass filtering and wavelettransform were introduced to split high transient power and based power that should be supplied by UCs and batteries, respectively [3], [4]. As an extension to the deterministic rules, fuzzy logic control was applied to improve efficiency and maintain SOC of UCs and batteries [4], [5]. The rule-based strategies were popular because of their intuitive manner and simplicity of implementation. However, a major drawback is their difficulty in explicitly representing requirements such as from efficiency using the intuitive rules. This prevents achievement of optimal performance of the HESSs.

On the other hand, the optimization-based strategies minimize a given cost function representing energy efficiency, protection of battery, and/or variations in battery/UC current and voltage, during the control process. An optimal-controlmodel approach was proposed that minimizes the discharge of batteries in an onboard battery-UC HESS. However, the control strategy had to be approximated later by neural networks (NNs) for its real-time implementation [6]. Model predictive control (MPC) is known to be able to explicitly handle various constraints on currents, voltages, and SOCs, in a HESS [7], [8]. Again, a major challenge of MPC is its computational complexity for real-time implementation on low-cost hardware. The implicit MPC, an iterative numerical procedure, has been proposed to further lower the computational requirements [9]. A well-known off-line method, dynamic programming (DP), has been widely applied in the management of HESSs [10]. However, the basic DP method requires prior knowledge, i.e., future information, of an entire load profile. This assumption and its computational complexity prohibit direct realtime implementation. Meanwhile, DP methods with reduced computation have been developed to enhance the real-time capability, such as iterative DP (IDP) with reduced grid numbers of states and control signals [11]. Sliding-mode control was recently introduced to enable robust tracking of battery and UC reference currents [12]. Meanwhile, high-frequency oscillations (i.e., chattering) in the final currents and voltages are obvious. Various intelligent algorithms, such as NNs and particle swarm algorithm, have been proposed to predict power demand and optimize load power distribution and battery life [13], [14]. Their main disadvantages are the amount of required computation and implicit knowledge representation.

Most of the above existing works focused on discussions at the system level. However, it should be noted that battery-UC HESSs are first electrical systems. Their behaviors and actual performance essentially obey rules for circuits. Logically, an effective management strategy must well meet the requirement from the circuit level. Theoretical analysis is expected to further explore relationships among main circuits (i.e., devices) in the HESSs. This effort is important to enlighten accurate understanding towards physical requirement for the energy management strategies. The contribution of this paper is to develop a new control strategy that has a clear physical meaning at the circuit level and thus enables straightforward and fast implementation. A capacitor semiactive battery-UC HESS is taken as an example. An equivalent series resistance (ESR) circuit model of the HESS is analytically derived representing device-level and system-level energy losses. The model shows that total energy loss from the HESS is minimized when the dynamic load distribution follows an explicit control law determined by the ratio of the ESR of the battery pack to those of the UC pack and dc-dc converter. The new control strategy is then proposed based on the derived ESR ratio. In order to validate generality, the strategy is also extended to manage a different HESS, a battery semiactive HESS. Both simulation and experimental results validate improved energy efficiency and usage of UC pack, and reduced battery temperature rise under the proposed ESR-based control strategy.

II. SYSTEM TOPOLOGY AND MODELING

A. Topology

There are three types of topologies integrating batteries and UCs in a HESS, i.e., passive, semiactive, and fully active ones [15]. The passive HESS is the simplest, in which the battery and UC packs are directly connected in parallel. This topology requires a common dc bus shared by both the battery and UC packs, and thus limits the usage of the two devices, particularly the UC packs. Either the semiactive or fully active topologies can decouple the UC and battery packs by adding dc-dc converters. The converters enable the controllability of the HESS in terms of power flow and voltage regulation. Comparing with the semiactive topologies using one converter, the fully active one including two converters can decouple the dc bus from the HESS but with additional hardware and increased complexity. In this paper, the capacitor semiactive topology shown in Fig. 1 is chosen as an example to develop and evaluate the proposed ESR-based control strategy. Meanwhile, the control strategy itself is general that can be extended to other HESS topologies such as a battery semiactive HESS. This aspect will be explained in the following sections.



Fig. 1. Dynamic model of the example capacitor semiactive HESS. (a) Equivalent circuit model. (b) DC-DC converter circuit model.

B. Dynamic Models

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The dynamic models of the devices in the example capacitor semiactive HESS, the battery pack, UC pack, and the dc-dc converter, are discussed below. Due to the trade-off between model complexity and accuracy, the well-established equivalent circuit models are used to represent the dynamics of the above two electrochemical devices [16]. These intuitive models facilitate the following analytical derivations and discussions on an effective real-time control strategy.

1) Battery pack: The equivalent circuit model of the lithium-ion battery pack (4 series 2 parallel, 4S2P) in the HESS is shown in Fig. 1(a). $V_{o,b}$ is the open circuit voltage (OCV) of the battery and R_s is the battery internal resistance. The two RC networks with different time constants, $\tau_s = R_{t,s}C_{t,s}$ and $\tau_m = R_{t,m}C_{t,m}$, represent the dynamics of the battery output voltage at different time intervals [17]. It is known that the two RC networks enable an optimal tradeoff between accuracy and complexity [18]. $V_{o,b}$ and R_s are calculated by

$$V_{o,b} = a_0 + a_1 x + a_2 x^2 + \dots + a_6 x^6, \tag{1}$$

$$R_s = b_0 + b_1 x + b_2 x^2 + \dots + b_6 x^6, \tag{2}$$

where x is a specific state-of-charge of battery, SOC_b . The coefficients, a_0-a_6 and b_0-b_6 , are the identified parameters. $R_{t,s}$, $C_{t,s}$, $R_{t,m}$, and $C_{t,m}$, the parameters of the two RC networks, are assumed to be constant. $R_{t,s}$ and $R_{t,m}$ are usually smaller than R_s (e.g., 192 m Ω at 50% SOC in the example 4S2P battery pack). Their power losses are considered to be also small [refer to Table I]. Thus, for system-level analysis, the power loss of the battery pack $P_{loss,b}$ can be approximately written as

$$P_{loss,b} = R_s i_b^2 + \frac{V_{t,m}^2}{R_{t,m}} + \frac{V_{t,s}^2}{R_{t,s}} \approx R_s i_b^2,$$
(3)

where i_b is the battery current. Note that battery pack parameters in Table I are identified through a pulsed-current test, in which fully charged battery pack is first discharged at 1

C current with 10% capacity reduction and then rests for 5 minutes. The battery pack voltages during the 5-minute rests are used to identify parameters of the two RC networks with the least square method.

2) UC pack: Again the first-order equivalent circuit model of the UC pack (6S1P) is shown in Fig. 1(a) [19]. $V_{o,u}$ is the OCV of the UC pack and R_{sc} is its internal resistance. The leak current represented by R_{pc} is mainly considered during storage for a long time, and can generally be neglected in the loss calculation during the normal operation of UCs. Therefore, the power loss of the UC pack is simplified as

$$P_{loss,u} = R_{sc}i_u^2 + \frac{V_{o,u}^2}{R_{pc}} \approx R_{sc}i_u^2, \tag{4}$$

where i_u is the UC current.

3) DC-DC Converter: Here a half-bridge bidirectional dcdc converter is employed due to its simplicity and high efficiency [see Fig. 1(b)]. Its power loss, $P_{loss,d}$, can be modeled as follows [20],

$$P_{loss,d} = f_s \left[V_d Q_{mos} + \frac{1}{2} V_{bus} |i_L| (t_r + t_f) + \frac{1}{2} V_{bus}^2 C_{oss} + V_{bus} Q_{rr} \right] + (R_{mos} + R_L) i_L^2,$$
(5)

where i_L is average inductor current; f_s is switching frequency; V_d is MOSFET gate drive voltage; Q_{mos} is MOSFET gate charge; V_{bus} is dc bus voltage; t_r and t_f are rising time and falling time, respectively; C_{oss} is output capacitance of MOSFET; Q_{rr} is reverse recovery charge; R_{mos} is MOSFET on-resistance; and R_L is resistance of the inductor L. The above power loss model contains three components, gate drive loss, switching loss, and conduction loss. The switching loss and gate drive loss are usually constant at a fixed switching frequency, which is almost irrelevant to the control strategies. Therefore, for the sake of simplicity, in the following derivations the power loss of the dc-dc converter is represented by the conduction loss, namely

$$P_{loss,d} \approx (R_{mos} + R_L)i_L^2. \tag{6}$$

Note that, as mentioned above, the simplification in (6) does not mean that the switching loss is neglectable when comparing with the conduction loss, and in the present topology, the inductor current i_L equals to the current of the UC pack i_u . The parameters of all the three devices are listed in Table I.

III. ESR-BASED CONTROL STRATEGY

A. Dynamic Load Distribution

In order to simplify the following derivations, dc bus voltage of the capacitor semiactive HESS can be practically assumed to be constant thanks to the flat voltage plateau in the battery discharge/charge curves and limits on its fluctuation in real applications. Noted that the actual dc bus voltage may vary between 5–10%. Then the load demand can be represented by a current profile. In a given period of time, any load current demand can be decomposed as a constant average current and a dynamic current (see Fig. 2).



Fig. 2. The decomposition of a current load profile.

Here a current distribution factor C_d is defined to describe the ratio of the dynamic load current supplied by the battery pack,

$$C_d \triangleq \frac{i_{b,k} - I_{l,avg}}{i_{l,k} - I_{l,avg}} \text{ and } I_{l,avg} = \frac{1}{N_t} \sum_{k=1}^{N_t} i_{l,k},$$
 (7)

where $i_{b,k}$ and $i_{l,k}$ are the currents of the battery pack and load at time instant k, respectively; $I_{l,avg}$ is the average load current; N_t is the total number of sampling instants. Then the currents fed into the load through the battery pack $i_{b,k}$ and the converter (i.e., the UC pack) $i_{d,k}$ are

$$i_{b,k} = I_{l,avg} + C_d(i_{l,k} - I_{l,avg}) \text{ and } i_{d,k} = (1 - C_d)(i_{l,k} - I_{l,avg}),$$
(8)

respectively. A smaller C_d means that the battery pack supplies less dynamic load, vice versa.



Fig. 3. ESR circuit model of the example capacitor semiactive HESS.

The ESR-based model of the example HESS is shown in Fig. 3, which is based on the above discussions on the dynamic models and approximations. From (3)–(5), the ESRs are

$$R_{b}^{*} = \frac{P_{loss,b}}{i_{b}^{2}} \approx R_{s}, \quad R_{d}^{*} = \frac{P_{loss,d}}{i_{d}^{2}} \approx \frac{R_{L} + R_{mos}}{(1 - d_{s})^{2}}, \quad (9)$$
$$R_{u}^{*} = \frac{P_{loss,u}}{i_{d}^{2}} \approx \frac{R_{sc}}{(1 - d_{s})^{2}}, \quad (10)$$

where d_s is the duty cycle of the dc-dc converter. Then the overall energy loss of the capacitor semiactive HESS, E_{loss} , can be calculated as

$$E_{loss} = \sum_{k=1}^{N_t} \left[i_{b,k}^2 R_b^* + i_{d,k}^2 (R_d^* + R_u^*) \right] T_s,$$

$$= \sum_{k=1}^{N_t} \left[(i_{l,k} - I_{l,avg})^2 (R_d^* + R_u^* + R_b^*) \left(C_d - \frac{1}{1+K} \right)^2 + I_{l,a}^2 R_b^* + (i_{l,k} - I_{l,avg})^2 \frac{(R_d^* + R_u^*) R_b^*}{R_d^* + R_u^* + R_b^*} \right] T_s,$$

(11)

TABLE I PARAMETERS OF BATTERY PACK, UC PACK, AND DC-DC CONVERTER.

Batter	Battery Pack (4S2P)												
a_0	12.38	a_1	29.02	a_2	-129.51	a_3	299.09	a_4	-366.81	a_5	231.77	a_6	-59.23
b_0	0.49	b_1	-4.72	b_2	28.51	b_3	-83.27	b_4	125.62	b_5	-94.10	b_6	27.67
$R_{t,s}$	$40\mathrm{m}\Omega$	$C_{t,s}$	400 F	$R_{t,m}$	$8\mathrm{m}\Omega$	$C_{t,m}$	$3000\mathrm{F}$						
Battery	Battery Pack (2S4P)												
a_0	6.38	a_1	11.99	a_2	-51.75	a_3	116.28	a_4	-138.41	a_5	85.11	a_6	-21.23
b_0	0.13	b_1	-1.29	b_2	7.77	b_3	-22.50	b_4	33.64	b_5	-25.02	b_6	7.32
$R_{t,s}$	$14\mathrm{m}\Omega$	$C_{t,s}$	2500 F	$R_{t,m}$	$4\mathrm{m}\Omega$	$C_{t,m}$	$57000\mathrm{F}$						
UC Pack (6S1P)				DC-DC	Converter								
C_u	66 F	R_{sc}	$15\mathrm{m}\Omega$	R_{pc}	$10\mathrm{k}\Omega$	R_{mos}	$15\mathrm{m}\Omega$	R_L	$10\mathrm{m}\Omega$	Q_{mos}	75 nC	f_s	20 kHz

where T_s is the sampling interval and K is the ratio of the ESR of the battery pack to those of the dc-dc converter and UC pack, i.e., the ESR ratio,

$$K = \frac{R_b^*}{R_d^* + R_u^*}.$$
 (12)

It is interesting to note that the optimal current distribution factor C_d , which minimizes the overall energy loss in (11), is only determined by the ESR ratio K and irrelevant to the load profile. From (11), the optimal factor C_d should always be equal to $\frac{1}{K+1}$ in order to minimize the energy loss of the HESS. This result shows that the current distribution inside the HESS should follow a control law determined by the ESRs of the devices. It helps to develop a control strategy with a clear physical meaning at the circuit level. This advantage enables a straightforward control strategy that well fits the real-time implementation and further improves final performance.



Fig. 4. Block diagram of the ESR-based real-time control.

During the short sampling interval, R_b^* , R_d^* , and R_u^* in (11) can be treated as constants. Meanwhile, the above three ESRs actually vary over the entire profile [refer to (9) and (10)]. Thus the optimal C_d changes with different SOC_b and SOC_u. It is known that maintaining a high SOC_u helps to

increase the efficiency of the dc-dc converter, and thus to reduce overall energy loss of the HESS, E_{loss} [21]. In addition, because the UC pack works as an energy buffer in the HESS, its SOC should be regulated around a certain target value to maintain its charging/discharge capability. As discussed in the below subsection, other practical limitations should also be considered for real implementation. Therefore, as shown in Fig. 4, block diagram of the finalized ESR-based control scheme, a correction factor Q and a moving average filter (MAF) are introduced. They address important limitations in engineering practice. The purpose of Q is to regulate variation of SOC_u . Besides the calculation of the ESR ratio K, a moving average filter (MAF) is added to estimate the average load current. In order to avoid overcharge and overdischarge of the UC pack, the ideal dynamic current distribution, which is determined by K, is modified using the correction factor, Q.

B. Load Estimation and Correction Factor

As shown in Fig. 4, a MAF with a time window of N seconds is applied to estimate the average load current using historical data. The estimated average load current $I_{l,avg,k}^N$ and dynamic load current $i_{l,dyn,k}$ at time instant k are calculated as follows,

$$I_{l,avg,k}^{N} = \begin{cases} \frac{1}{k} \left[I_{l,avg,k-1}^{N} \cdot (k-1) + i_{l,k} \right] & \text{if } k \le N, \\ \frac{1}{N} \left[I_{l,avg,k-1}^{N} \cdot N + i_{l,k} - i_{l,k-N} \right] & \text{else}, \end{cases}$$
(13)

$$i_{l,dyn,k} = i_{l,k} - I_{l,avg,k}^N, \quad i_{l,k} = \frac{P_{l,k}}{V_{bus,k}}$$
 (14)

where $i_{l,k}$, $P_{l,k}$, and $V_{bus,k}$ are the present load current, load power, and dc bus voltage, respectively; $I_{l,avg,k-1}^N$ is the estimated average load current at the previous time instant, k-1.

In the battery-UC HESS, the UC pack mainly works as an energy buffer to provide the dynamic current. Due to the limited energy density of the UC pack, the regulation of its SOC, SOC_u , is required to avoid overcharge and overdischarge, which also helps to reduce the energy loss, as discussed above. This physical limitation should be included when determining a practical load current distribution. Here a correction factor Q

is added to linearly modify the original optimal C_d such that the SOC_u is regulated around a target value such as 50% [1]. Here the 50% SOC_u is chosen assuming equal probabilities of charging and discharging of the UC pack in a dynamic environment. Actual operation also imposes other practical limitations. The converter's duty cycle is $1 - \frac{V_u}{V_h}$. The UC pack voltage should satisfy $(1 - d_{s,max})V_b < V_u < (1 - d_{s,min})V_b$. $d_{s,max}$ and $d_{s,min}$ are the maximum and minimum achievable duty cycles of the converter. They are physically determined by specifications of the MOSFETs and switching frequency of the converter. Once the UC pack voltage is beyond the above range (i.e., close to full charge or full discharge of the UC pack), the converter should stop working, namely setting C_d^* as one. Similarly, due to the maximum permissible input current of the dc-dc converter, $I_{d,in,max}$, the modified current distribution C_d^* should always larger than $1 - \frac{I_{d,in,max}V_u}{|i_{l,k} - I_{l,avg}|V_b}$. Thus modified C_d^* and Q are finalized as follows,

$$C_{d}^{*} = \begin{cases} 1 & \text{if } V_{u} > (1 - d_{s,max})V_{b} \text{ or } V_{u} < (1 - d_{s,min})V_{b}, \\ \max\left[Q\frac{1}{1 + K}, 1 - \frac{I_{d,in,max}V_{u}}{|i_{l,k} - I_{l,avg}|V_{b}}\right] & \text{else}, \end{cases}$$
(15)

$$Q = \begin{cases} (2\text{SOC}_u - 1) K^{\frac{1+2}{2}} + 1 & \text{if } i_{l,dyn,k} \le 0, \\ (1 - 2\text{SOC}_u) K^{\frac{1-s}{2}} + 1 & \text{else}, \end{cases}$$
(16)

$$s = \text{sign}(\text{SOC}_u - 0.5), \quad \text{SOC}_u = \frac{V_{u,k}^2 - V_{u,min}^2}{V_{u,max}^2 - V_{u,min}^2},$$

where $V_{u,max}$ and $V_{u,min}$ are the maximum and minimum permissible voltages of the UC pack. Note that the usable voltage range when operating a UC pack is usually between 50% and 100% of its maximum voltage $V_{u,max}$ [15].



Fig. 5. Modified current distribution versus SOC of UC pack.

Fig. 5 shows the modified C_d , namely C_d^* , versus the SOC of the UC pack, SOC_u, assuming that the ESR ratio K is two. If SOC_u equals to 50%, the modified current distribution C_d^* is simply equal to its optimal value, $\frac{1}{1+K}$, which minimizes the energy loss. If SOC_u is higher than 50%, C_d^* becomes smaller than the optimal value in case of discharging (i.e. a positive dynamic current, $i_{l,dyn,k}$). On the contrary, it becomes larger during charging (i.e. negative $i_{l,dyn,k}$). Thus the UC pack supplies more power during discharge and receives less power during charge. This operation enforces the SOC of the UC pack to decrease and reach the ideal 50%. The operations when SOC_u is smaller than 50% can be similarly explained.

In real implementation, the resistance of the battery R_s is first obtained based on (2) and the estimated battery SOC, SOC_b, such as using the well-known Ah counting. The ESR's, R_b^* , R_d^* , and R_u^* , are thus calculated from (9)–(10) and the duty-cycle of the dc-dc converter, d_s . Then (12) gives the ESR ratio, K. The ideal load current distribution, $C_d = \frac{1}{1+K}$, is further modified by the correction factor Q defined in (16). The final current distribution, i.e., $i_{b,k}$ and $i_{d,k}$, is eventually determined by replacing C_d and $I_{l,avg}$ with C_d^* and $I_{l,avg,k}^N$, respectively, in (8). Again the above procedures are summarized in the flowchart, Fig. 4. It is obvious that the ESRbased control is fast enough for a real-time implementation.

C. Extension to Battery Semiactive HESS

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As mentioned in section II-A, the ESR-based control strategy itself is general that can be extended to other battery-UC HESS topologies such as a battery semiactive HESS. In this HESS, a dc-dc converter is placed between the battery pack (2S4P) and the load, and the UC pack (6S1P) is directly connected to the load. Their parameters are co-listed in Table I. The ESR ratio K' for the battery semiactive HESS is

$$K' = \frac{R_b^{*'} + R_d^{*'}}{R_u^{*'}}, \quad R_u^{*'} = R_{sc},$$
(17)

$$R_b^{*'} = \frac{R_s^{'}}{(1 - d_s^{'})^2}, \quad R_d^{*'} = \frac{R_L + R_{mos}}{(1 - d_s^{'})^2}, \quad (18)$$

where R'_s is the resistance of the battery pack (2S4P). d'_s is the duty cycle of the dc-dc converter. Then the currents of the dc-dc converter and the UC pack at time instant k are

$$i'_{d,k} = I^N_{l,avg,k} + C^{*'}_d(i_{l,k} - I^N_{l,avg,k}),$$
(19)

$$i'_{u,k} = (1 - C_d^{*'})(i_{l,k} - I_{l,avg,k}^N),$$
(20)

where

$$C_d^{*'} = Q' \frac{1}{1 + K'},$$
(21)

and Q' is calculated by replacing K with K' in (16).

IV. A SIMULATION-BASED CASE STUDY

The above ESR-based control strategy is evaluated under three well-known test cycles, urban dynamometer driving schedule (UDDS), new European driving cycles (NEDC), and Japanese urban driving cycle (JC08). The power profiles of the three cycles in Fig. 6 are generated based on the vehicle longitudinal dynamics, and then downscaled to meet the maximum output power of the battery pack in the following experimental setup, 200 W [see section V]. Each cycle runs three times to represent a long-term and dynamic load demand. The energy consumptions under the so-called continuous high power demand are calculated and listed in Table II. The continuous high power demand corresponds to a continuous period, in which the HESS is expected to be mostly discharged (see Fig. 6). It determines the selected sizing of the UC pack, 66 F here. Note that in the NEDC cycle, there is a period of long and fast acceleration due to highway driving, i.e., under the continuous high power demand, within 904-1130 s. It requires a 198 F UC pack, which is oversized for the UDDS and JC08 cycles, two cycles representing congested urban driving. For consistency, the 66 F UC pack is finally chosen for all the three cycles.



Fig. 6. Downscaled power profiles of the three test cycles.

TABLE II ENERGY CONSUMPTION UNDER CONTINUOUS HIGH POWER DEMAND.

Cycle	UDDS	NEDC	JC08
Energy [J]	5760	14752	4864

In the capacitor semiactive HESS, the initial SOC_b and SOC_u are set to be 80% and 50%, respectively. Again the parameters of the battery pack, UC pack, and dc-dc converter are listed in Table I. Two indices are defined to evaluate the effectiveness of the proposed ESR-based control, the energy efficiency of the overall HESS, η_{sys} , and SOC variation range of the UC pack, ΔSOC_u ,

$$\Delta \text{SOC}_u = \max_{1 \le k \le N_t} \text{SOC}_{u,k} - \min_{1 \le k \le N_t} \text{SOC}_{u,k}, \quad (22)$$

$$\eta_{sys} = \frac{E_{load}}{E_{dis}},\tag{23}$$

where

$$E_{dis} = \sum_{k=1}^{N_t} \left(i_{b,k} V_{o,b} + i_{u,k} V_{o,u} \right) T_s.$$
(24)

 N_t is the total number of the sampling instants. The final energy consumption and the supplied energy from the battery and UC packs are E_{total} and E_{dis} , respectively. The sampling period, T_s , is taken as one second, and the window sizes, N's, are 1400, 1200, and 1200 (i.e., as same as the number of the total sampling instants in a single cycle) for calculating the average load currents in the UDDS, NEDC, and JC08 cycles, respectively. Note that the computation load of the average load currents is quite light [refer to (13)].

The performance of the proposed ESR-based control is compared with those of the well-known off-line dynamic programming (DP) method and rule-based control [3], [10]. In the DP method, the voltage of the UC pack, i.e., the state variable, is discretized to define the state grid. The DP method employs the Bellman's principle of optimality to numerically search the optimal path from the initial state to final state with the lowest overall energy loss among all the acceptable control sequences. Similarly, the initial and final SOCs of the UC pack, SOC_u 's, are both 50%. Note that the solution searched by the DP method is a global optimal one. However, as explained in the introduction, the DP method is impractical to be implemented in real time due to the required heavy computation and prior knowledge of load power at each time instant. Here this ideal method is introduced only for reference purposes. In the rule-based control, a first-order high-pass filter is applied to assign the high-frequency component of the load current to the UC pack. Thus in the capacitor semiactive HESS, the output current of the dc-dc converter $i_{d,k}$, which is supplied by the UC pack, is given by

$$i_{d,k} = F \cdot i_{l,hp} + k(V_{u,k} - V_{u,ini}),$$
 (25)

where

$$F = \begin{cases} \frac{V_{u,max} - V_{u,k}}{V_{u,max} - V_{u,ini}}, & \text{if } i_{l,hp} < 0 \text{ and } V_{u,k} > V_{u,ini}, \\ \frac{V_{u,k} - V_{u,min}}{V_{u,ini} - V_{u,min}}, & \text{if } i_{l,hp} > 0 \text{ and } V_{u,k} < V_{u,ini}, \\ 1 & \text{else}, \end{cases}$$

$$i_{l,hp} = \text{High}_{\text{pass}} \text{filter}(i_{l,k}).$$
 (26)

The factor F and the proportional term $k(V_{u,k} - V_{u,ini})$ force the voltage of UC pack, $V_{u,k}$, to converge to its initial value, $V_{u,ini}$, again a voltage corresponding to the 50% UC SOC here. $I_{l,hp}$ is the current after high-pass filtering of the original load current, $I_{l,k}$. The cut-off frequency of the first-order highpass filter is 0.01 Hz and k is 0.5 [3].

Fig. 7 graphically compares the simulation results of the ESR-based control, DP method, and rule-based control taking the UDDS cycle as an example. As shown in Fig. 7(a)(b), due to the lack of the prior knowledge of the cycle, both the two real-time control strategies, the ESR- and rule-based ones, result in a larger peak battery current during the period of the continuous high power demand. It is because that thanks to the prior knowledge of the cycle, the DP method can more sufficiently use the UC pack, i.e., a wider variation of SOC_u . More energy extracted from the UC pack leads to a smaller battery current. At the same time, the variation trend of SOC_u under the ESR-based control better matches that under the ideal DP method. As shown in Fig. 7(c), the overall energy loss under the ESR-based control is obviously improved compared to the existing rule-based control because the strategy is explicitly derived for minimizing the overall energy loss.

Table III summarizes the performances of the control methods, the range of UC SOC, total energy loss, and system efficiency, under the three cycles. The energy loss using the ESR-based control is averagely 24.1% lower than that of the rule-based control (about 2% improvement in efficiency, η_{sys}). When comparing with the existing rule-based method, physically the ESR-based control enables smaller root mean square (RMS) values of battery pack, dc-dc converter, and UC



Fig. 7. Simulation results of the ESR-based control, DP method, and rule-based control under the UDDS cycle. (a) Current of battery pack. (b) SOC of UC pack. (c) Overall energy loss.



Fig. 8. Battery pack, dc-dc converter, and UC pack RMS currents.

pack currents, namely smaller energy losses [see Fig 8]. The difference in efficiency is about 1% between the ESR-based control and the ideal DP method when working under the UDDS or JC08 cycles. This verifies that the ESR-based control achieves a near-optimal solution. The difference becomes larger, 2.9%, under the NEDC cycle due to the long and fast acceleration in the cycle between 904 and 1130 s. Thus the ideal DP method is naturally more favored because the prior knowledge of the entire cycle is assumed to be available. The

range of UC SOC, SOC_u , in the ESR-based control is also larger than that of the rule-based control. The more sufficient usage of the UC pack helps to improve the energy efficiency. The ranges of SOC_u using the ESR-based control and the DP method are close under the UDDS and NEDC cycles. The highly dynamic JC08 cycle results in a relatively large difference in the range of SOC_u . Again the ideal DP method is more efficient in terms of the usage of the UC pack because the entire cycle is assumed to be pre-known.

 TABLE III
 SIMULATION RESULTS OF CAPACITOR SEMIACTIVE HESS.

Test cycle	Control Strategy	ΔSOC_u	$E_{loss}[J]$	η_{sys} [%]	Improvement in $E_{loss}[\%]$
	Rule-based	0.45	5283	92.7	-
UDDS	ESR-based	0.57	4037	94.3	23.6
	DP method	0.55	3533	95.1	33.1
	Rule-based	0.59	7293	90.8	-
NEDC	ESR-based	0.80	5863	92.4	19.6
	DP method	0.82	3604	95.3	49.4
	Rule-based	0.48	7743	90.7	-
JC08	ESR-based	0.63	5484	93.2	29.2
	DP method	0.79	4560	94.4	41.1

TABLE IV SIMULATION RESULTS OF BATTERY SEMIACTIVE HESS.

Test Cycle	Control Strategy	ΔSOC_u	$E_{loss}[\mathbf{J}]$	$\eta_s[\%]$	Improvement in E_{loss} [%]
	Rule-based	0.47	5769	92.0	-
UDDS	ESR-based	0.66	4689	93.4	18.7
	DP method	0.78	3259	95.4	43.5
	Rule-based	0.63	10578	87.1	-
NEDC	ESR-based	0.92	8439	89.4	20.2
	DP method	0.91	4747	93.8	55.1
	Rule-based	0.52	8643	89.6	-
JC08	ESR-based	0.67	6377	92.1	26.2
	DP method	0.76	4814	94.0	44.3

Robustness performance of the proposed ESR-based control is further investigated assuming a changed d_s , the dc-dc converter duty cycle. Note that this also leads to a changed equivalent resistance of the converter, i.e., R_d^* in (9). It is known that d_s mainly depends of the voltage ratio between battery and UC packs. Thus performance of the two strategies, the ESR-based and rule-based ones, are compared under different initial SOCs of the UC pack, $SOC_{u,ini}$. The correction factor Q in the ESR-based control is accordingly modified to be general for any initial UC pack SOC, not necessarily 0.5.

$$Q = \begin{cases} \frac{\text{SOC}_{u} - S_{0}}{S_{0}} \left(\frac{S_{0}}{1 - S_{0}}K\right)^{\frac{1 + s}{2}} + 1 & \text{if } i_{l,dyn,k} \le 0, \\ \frac{S_{0} - \text{SOC}_{u}}{1 - S_{0}} \left(\frac{1 - S_{0}}{S_{0}}K\right)^{\frac{1 - s}{2}} + 1 & \text{else}, \end{cases}$$

$$s = \text{sign}(\text{SOC}_{u} - S_{0}), \quad S_{0} = \text{SOC}_{u,ini}, \end{cases}$$
(27)

Fig. 9 shows that, with a largely changed $SOC_{u,ini}$ (i.e., a changed d_s), the efficiency under ESR-based control is again higher than that under rule-based control. The efficiency under ESR-based control decreases when $SOC_{u,ini}$ is larger than

0.65. It is because more regeneration energy is absorbed by the battery pack when the UC pack SOC is already high. This leads to more energy loss in the HESS.



Fig. 9. System efficiencies of ESR-based control and rule-based control versus largely changed $SOC_{u,ini}$.

For reference purposes, the control methods are also applied in the battery semiactive HESS. The results are shown in Table IV. Note that the output current of the dc-dc converter under the rule-based control $i'_{d,k}$ is modified as

$$i'_{d,k} = i_{l,k} - [F \cdot i_{l,hp} + k(V_{u,k} - V_{u,ini})], \qquad (28)$$

because the dc-dc converter is now placed between the battery pack and the load. The initial SOC_u is set to be 80% in order to make the dc bus voltages of two HESSs close. Similar improvements in the energy efficiency and the usage of the UC pack are observed when using the ESR-based control. These results explain the generality of the control strategy.

Note that, in the NEDC cycle, improvement using the proposed ESR-based control is relatively limited when comparing to the DP method. It is again because of the highway driving between 904–1130 s in the cycle. The ideal DP method, which assumes availability of future load demand, enables the UC pack to be pre-charged before entering the highway driving. Further verification is conducted using another test cycle, WLTC (World-wide harmonized Light duty Test Cycle) Class 3b cycle. This cycle is even more challenging because it has two times of 455 s and 323 s long highway driving. Similar results are obtained, as shown in Table V.

TABLE V SIMULATION RESULTS USING WLTC CLASS 3B TEST CYCLE.

System Topology	Control Strategy	ΔSOC_u	$E_{loss}[J]$	$\eta_s[\%]$	Improvement in E_{loss} [%]
Capacitor	Rule-based	0.62	10556	89.3	-
Semiactive	ESR-based	0.74	9232	90.5	12.5
	DP method	0.79	4559	94.4	56.8
Battery	Rule-based	0.65	18338	82.7	-
Semiactive	ESR-based	0.93	16661	84.1	9.1
	DP method	0.97	8718	91.0	52.5

V. EXPERIMENTAL VALIDATION

The performance of the proposed ESR-based control is experimentally validated as follows. It is known that the battery temperature is one of the key factors affecting the battery cycle life [22]. Thus in the experiments, a new index



Fig. 10. Experimental setup.

regarding the battery temperature rise is added for evaluation purposes,

$$\Delta T_b = \max_{1 \le k \le N_t} T_{b,k} - T_{b,ini},\tag{29}$$

where $T_{b,k}$ is the battery temperature at the sampling instant k, and $T_{b,ini}$ is the initial temperature. They are directly measured using thermocouples.

The final experimental system, a capacitor semiactive HESS, is shown in Fig. 10. The system can be reconfigured into the battery-alone system and battery semiactive HESS. The three test cycles, UDDS, NEDC, and JC08 cycles, are implemented through the combination of the power supply and electronic load. A buck-boost bidirectional converter is used to connect the UC pack to the dc bus. A widely used rapid-prototyping platform, National Instruments (NI) compactRIO, calculates the reference output current of the dc-dc converter (i.e., $i_{d,k}$) based on a specific control strategy, and performs accordingly the pulse width modulation (PWM) control of the converter. As discussed above, the proposed ESR-based control does not require powerful computation for real-time implementation. The NI compactRIO also collects data including the voltages and currents of battery and UC packs, converter output current, load current, battery and ambient temperatures. The three 0.01Ω high-accuracy sampling resistors are used to measure currents, and the two T-type thermocouples read the battery and ambient temperatures. The detailed specifications of the experimental setup are listed in Table VI.

■ The experimental results for the battery-alone, capacitor semiactive, and battery semiactive systems are summarized in —Table VII—IX. The two control strategies, the rule- and ESR-based ones, are respectively applied in the two semiactive _HESSs. Note that, as discussed above, the DP method is _impractical for a real-time implementation. Compared with the conventional battery-alone system, the energy efficiencies of The HESSs are obviously improved in the most cases. The ESR-based control outpaces its counterpart, the rule-based one, with averagely 26.1% reduction of the total energy loss and 2.3% improvement in efficiency. Note that the energy efficiencies of the battery semiactive HESS actually become worse than that of the battery-alone system in the NEDC cycle. Again, due to the long and fast acceleration (904–1130 s) in the NEDC cycle, the UC pack reaches its capacity limitation,

 TABLE VI

 SPECIFICATIONS FOR MAJOR COMPONENTS.

Battery Pack (4S2P)	2.5 Ah/cell, V_b : 2.75–4.2 V/cell, ESR: 118m Ω /cell
(Sanyo 18650 Li-ion battery)	$I_{max,dis}$: 5A/cell, $I_{max,ch}$: 1.75A/cell
UC Pack (6S1P)	350 F/cell
(Maxwell BCAP0350)	I_{max} : 20 A, V_u : 0–2.7 V/cell
Power Supply	Max Power: 800 W
(Takasago ZX-800L)	(0-80 V, 0-80 A)
Electronic Load	Max Power: 600 W
(Kikusui PLZ-50F/150U)	1.5–150 V, 0–120 A
DC-DC Converter	P_{max} : 400 W, $V_{in,max}$:20 V, $I_{in,max}$: 20 A
(Design/fabricate in house)	$\eta_d:$ $>$ 90%, $V_{out,max}:$ 30 V, $I_{out,max}:$ 13 A
Thermocouples (Fluke TT-T-30)	Insulation range: -267-260 °C
Sampling Resistors	Three RH250M4 0.01 Ω
(PCN Corporation RH series)	Accuracy: ±0.02%
Control and DAQ System	I/O board: NI 9401
(NI compactRIO)	A/D boards: NI 9219×2, NI 9203

and thus cannot fully involve any longer during the continuous high power demand. The most power actually is supplied from the battery pack through the dc-dc converter. The larger battery current (due to the dc-dc conversion) and the additional loss from the converter result in the lower energy efficiencies when comparing with the battery-alone system. This result is a good example to show the influence of a specific topology over the energy efficiency of a HESS.

 TABLE VII

 OVERALL ENERGY LOSSES IN THREE SYSTEMS [J].

Cycle	Battery	Battery Capacitor Semiactive		Battery Semiactive	
	-alone	Rule-based	ESR-based	Rule-based	ESR-based
UDDS	8602	5802	4248	6692	5150
NEDC	8487	7624	5959	13193	10195
JC08	12727	9048	5802	9829	7261

 TABLE VIII

 EFFICIENCIES OF THREE SYSTEMS [%].

Cycle	Battery	Capacitor	Semiactive	Battery S	emiactive
	-alone	Rule-based	ESR-based	Rule-based	ESR-based
UDDS	88.5	91.8	93.9	91.1	93.0
NEDC	89.4	90.6	92.4	84.6	87.4
JC08	85.4	90.6	92.8	88.6	91.3

The improvements in the battery temperature rises, ΔT_b 's, are promising. In all the cases, the battery temperature rises are effectively suppressed by involving the UC pack and proper control of the HESSs. In the challenging NEDC cycle, even the energy losses in the two battery semiactive HESSs are higher, the battery current is largely smoothed thanks to the assistance from the UC pack. Thus ΔT_b 's in the two HESS are also reduced in the NEDC cycle. Compare with the battery-alone system, the average temperature rise, ΔT_b , under the ESR-based control is reduced by 5.42 °C, 53.4% in percentage, when the test cycles run three times continuously. Again, the ESR-based control can better reduce the battery temperature rise, averagely 1.65 °C or 15.7% more than that under the rule-based control. This significant reduction of the battery

temperature rise is expected to further prolong the battery cycle life in real applications.

TABLE IX BATTERY TEMPERATURE RISES IN THREE SYSTEMS [℃].

_ '	Cycle	Battery	Capacitor	Semiactive	Battery Semiactive		
		-alone	Rule-based	ESR-based	Rule-based	ESR-based	
_	UDDS	8.31	4.09	3.10	4.08	2.81	
	NEDC	11.17	8.61	7.79	10.80	7.63	
_	JC08	11.67	5.71	4.36	6.40	4.11	

For reference purposes, the experimental results of the -efficiency of the dc-dc converter and peak UC pack output power are shown in Fig. 11 and Table X, respectively. As shown in the efficiencies maps in Fig. 11 taking the capacitor semiactive HESS and UDDS test cycle as an example, the ESR-based control also improves the efficiency of the dcdc converter. As mentioned in section III-A, in the capacitor semiactive HESS a higher UC pack voltage (i.e., a higher SOC_u) enhances the dc-dc converter efficiency, which can be observed in Fig. 11(a) and (b). Similarly, in the battery semiactive HESS a higher battery pack voltage helps to improve the dc-dc converter efficiency. In addition, as listed in Table X, ESR-based control enables lower peak UC pack output powers in order to improve the efficiency than those under the rulebased control. In real applications of the battery-UC HESSs, there are always tradeoffs among energy efficiency, battery protection, and power density enhancement.



Fig. 11. Efficiency maps of the dc-dc converter in the capacitor semiactive HESS and under the UDDS test cycle. (a) ESR-based Control. (b) Rule-based Control.

TABLE X PEAK UC PACK OUTPUT POWER IN BATTERY-UC HESSS [W].

Cycle	Capacitor	Semiactive	Battery S	emiactive
	Rule-based	ESR-based	Rule-based	ESR-based
UDDS	149	134	160	152
NEDC	75	65	154	91
JC08	183	126	196	157

VI. CONCLUSION

This paper first provides a circuit-level analysis of the energy losses in an example capacitor semiactive HESS. The analytical derivations show that the total energy loss from the HESS is solely determined by the ratio of the dynamic load contributed by the battery pack to the entire dynamic load. This total energy loss can be minimized by following the dynamic load distribution determined by the ratio of ESR of battery pack to those of UC pack and dc-dc converter. The control strategy is then developed based on this ESR ratio and the avoidance of the overcharge and discharge of the UC pack. This ESR-based control strategy is also extended to manage another battery-UC HESS, a battery semiactive HESS, which explains the generality of the concept. The proposed strategy is compared with the existing rule-based and ideal DP methods. Both the simulation and experimental results validate the effectiveness of the ESR-based strategy including its realtime implementation and improvements in energy efficiency, usage of the UC pack, and reduction of battery temperature rise. The ESR-based control achieves a performance close to that using the ideal DP method. Compared with the batteryalone system, the total energy loss and battery temperature rise in the example capacitor semiactive HESS are reduced averagely by 44.9% and 51.9%, respectively, when applying the ESR-based control.

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